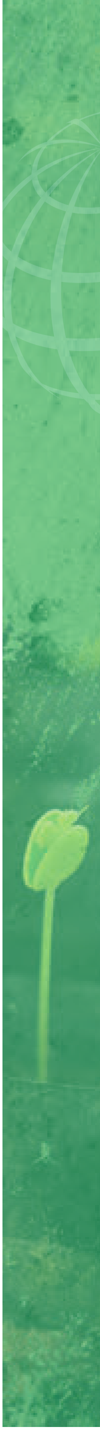
# THE STATE
# OF THE WORLD's
# FOREST GENETIC RESOURCES

COMMISSION ON
GENETIC RESOURCES
FOR FOOD AND
AGRICULTURE



# THE STATE
# OF THE WORLD's
# FORDFOREST GENETIC RESOURCES

COMMISSION ON GENETIC RESOURCES FOR FOOD AND AGRICULTURE
FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2014

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# Foreword

Forests cover nearly one-third of the world's land area. They provide vital environmental services such as soil and water protection, regulate the climate and preserve biodiversity, produce valuable raw materials and food, and sustain the livelihoods of millions of people.

Forest genetic resources – the heritable materials maintained within and among trees and other woody plant species – are essential for the adaptation and the evolutionary processes of forests and trees as well as for improving their resilience and productivity.

The conservation of forest genetic resources is more topical than ever at a time when the world is increasingly confronted with challenges from increased human population, land-use changes and climate change. These pressures, and related increases in unsustainable use, wildfire, pests and diseases, as documented in the *Climate change 2013* report of the Intergovernmental Panel on Climate Change (IPCC), are causing losses of forest cover and of forest biodiversity, both among and within species. Lack of information limits the capacity of many countries and the international community to develop appropriate policy tools to address the issues or to integrate forest genetic resources management into relevant cross-cutting sectorial policies.

Reliable data on the status and trends of forest genetic resources are required for decision-makers and stakeholders to provide adequate support for their sustainable management. Recognizing this need for information and the urgency of addressing the conservation and sustainable use of forest genetic resources, the Commission on Genetic Resources for Food and Agriculture requested and guided the preparation of *The State of the World's Forest Genetic Resources,* and agreed, in response to its findings, on strategic priorities which the FAO Conference adopted in June 2013 as the G*lobal Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources*.

This first ever report on *The State of the World's Forest Genetic Resources* constitutes a milestone in building the information and knowledge base required for action at the national, regional and international levels. It has been developed through a country-driven process, building on 86 country reports – representing over 85 percent of global forest cover – and with the participation of representatives from national institutions and non-governmental and community-based organizations. Its recommendations are based on these reports, which indicate that about half of the forest species in reporting countries are threatened or subject to genetic erosion, and only about one-quarter are actively managed for their products and/or services. This publication provides the basis for renewed efforts to realize national and international commitments to improved conservation, sustainable use and management of forest genetic resources.

As established in its Reviewed Strategic Framework 2010-2019 and in particular through its Strategic Objective 2, FAO is striving to "increase and improve provision of goods and services from agriculture, forestry and fisheries in a sustainable manner". Measures include strengthening its technical support to countries in the area of forest genetic resources and promoting the integration of forest genetic resources into broader forest resource management programmes at the national, regional and international levels. This report is a key ingredient in this effort.

I am confident that the information in *The State of the World's Forest Genetic Resources* will be used as the basis for policy and technical decisions to strengthen national efforts in conservation and sustainable management of forest genetic resources, efforts that will contribute to meeting the world's current and future needs for forest products and environmental services while enhancing food security.

José Graziano da Silva
FAO Director-General

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Listing every person by name is not easy and carries with it the risk that someone may be overlooked. Apologies are conveyed to anyone who may have provided assistance whose name has been inadvertently omitted.

# About this publication

*The State of the World's Forest Genetic Resources* addresses the conservation, management and sustainable use of forest tree and other woody plant genetic resources of actual and potential value for human well-being in the broad range of management systems.

This report complements two other FAO flagship publications in the field of forestry, the annual *State of the World's Forests* and the periodic Global Forest Resources Assessment (FRA). *State of the World's Forests* reports on the status of forests, recent major policy and institutional developments and key issues concerning the forest sector. FRA provides comprehensive data on forest distribution and status, including on matters influencing forest genetic resource (FGR) conservation and management, such as indicators of sustainable forest management, extent of permanent forest estate and protected areas, and regeneration methods used. However, forest cover and related data cannot be used as a surrogate for assessment of the status of FGR. This first edition of *The State of the World's Forest Genetic Resources* will help to differentiate between the state of the world's forest resources and the state of the genetic resources on which they depend for their utility, adaptability and health.

*The State of the World's Forest Genetic Resources* also complements two flagship publications in the field of genetic resources for food and agriculture: *The State of the World's Animal Genetic Resources for Food and Agriculture*, published in 2007, and *The Second Report on the State of the World's Plant Genetic Resources for Food and Agriculture*, published in 2010. The three reports have in common that they have been initiated by and prepared under the guidance of FAO's Commission on Genetic Resources for Food and Agriculture (the Commission) (see Box).

This is the first synthesis of its kind for FGR and constitutes a baseline against which future status assessments can be compared. Sources of information include national reports prepared by countries, regional summaries prepared following regional workshops and commissioned thematic studies (see section on the reporting and preparatory process

### The Commission on Genetic Resources for Food and Agriculture

With its 177 member countries, the Commission on Genetic Resources for Food and Agriculture offers an intergovernmental forum where global consensus can be reached on policies relevant to biodiversity for food and agriculture. The main objective of the Commission is to ensure the conservation and sustainable use of genetic resources for food and agriculture and the fair and equitable sharing of benefits derived from their use, for present and future generations.

The work of the Commission focuses on developing and overseeing the implementation of policies and supporting initiatives that not only raise awareness but also seek ways to solve emerging problems. It guides the preparation of periodic global assessments of the status and trends of genetic diversity, the threats facing genetic diversity and the measures being taken to promote its conservation and sustainable use. The Commission also negotiates global action plans, codes of conduct and other instruments relevant to the conservation and sustainable use of genetic resources for food and agriculture.

below) as well as published literature. Of necessity the treatment of knowledge of FGR in this report is selective, as volumes would be required to capture all the available knowledge.

Part 1 provides an overview of basic definitions and concepts in forest genetics, the value of FGR (recognition of which is essential to ensuring their conservation), FGR conservation approaches, and the state of knowledge and information in this field.

Part 2 addresses drivers of change, including forest conversion and expansion of crop land, demand for wood energy, and unsustainable harvesting and use. Next it presents the global forest trends affecting FGR, with data on trends in forest cover, biodiversity conservation and ownership, drawn primarily from FRA 2010. The consequences of these trends for FGR are also outlined, in terms of loss of ecosystems, tree species and intraspecific diversity.

Part 3 examines the current and emerging technologies in the field of FGR, including information on indigenous and traditional knowledge and classical tree improvement, modern advances including the use of molecular markers and genetic modification, and FGR conservation-related knowledge. This part also addresses research on climate change and FGR and genetic technologies for reducing illegal forest harvesting.

Part 4 reviews the state of FGR conservation and management. This part, based on the reports submitted by countries, addresses countries' FGR strategies and programmes, their progress in characterizing their genetic diversity, and the state of *in situ* and *ex situ* conservation and management. It also reviews progress in breeding and genetic improvement of forest tree species, and the systems for producing and distributing forest genetic materials for use on farms, in natural and planted forests and in research. Finally, it presents the state of the institutional framework for FGR conservation and management, including national institutions dealing with FGR, policies and laws, education and training, research, communication and public awareness raising, and international and regional collaboration, including networks.

The concluding section, Part 5, addresses the needs and responses required to improve FGR conservation and management in the future. It provides recommendations for improving practices and technologies in FGR conservation and management; and for enhancing national polices and institutions, capacity building, knowledge and information availability, and public awareness for improved conservation and management of FGR worldwide.

## The reporting and preparatory process

In considering the status of conservation and use of forest genetic resources, the Commission, at its eleventh regular session in 2007, emphasized their importance for food security, poverty alleviation and environmental sustainability and recognized that the lack of information limits international, regional and local decision-making and action on these vital resources. The Commission included the preparation of *The State of the World's Forest Genetic Resources* in its Multi-year Programme of Work and requested that FAO begin to prepare it. The Commission's request was supported by the FAO Committee on Forestry (COFO) at its nineteenth session (March 2009). At its twelfth regular session (October 2009), the Commission endorsed a proposed outline of the report and agreed on an indicative timeline and the process for country involvement. The Commission also established an Intergovernmental Technical Working Group on Forest Genetic Resources (ITWG-FGR) to address issues relevant to the conservation and sustainable use of FGR, and to advise and make recommendations on the report preparation process.

In April 2010, following the process established by the Commission, FAO invited countries to nominate National Focal Points and to prepare and submit country reports, which have been the main source of information for the preparation of *The State of the World's Forest Genetic Resources* following a country-driven process. FAO provided guidelines for the preparation of the country reports, including a recommended structure and methodology (FAO, 2011). The guidelines suggested that the preparation of country reports represented an opportunity to conduct a national strategic exercise to assess the status of FGR in the countries and to reflect on needs and priorities for their conservation and sustainable use. A participatory approach, engaging a wide range of stakeholders, was encouraged.

At its twentieth session in October 2010, COFO welcomed the initiative to develop *The State of the World's Forest Genetic Resources* and recommended that FAO continue this important effort. It also invited the governing bodies of the member organizations of the Collaborative Partnership on Forests to consider the information and analysis provided by FRA and this report in their work.

From November 2010 to September 2011, FAO organized regional and subregional workshops to train National Focal Points and other national and regional experts on the preparation of country reports following the approach promoted in the guidelines. These workshops were organized in collaboration with international partners such as Bioversity International, the World Agroforestry Centre (ICRAF), the Secretariat of the Convention on Biological Diversity (CBD) and the World Wide Fund for Nature (WWF), as well as regional institutions such as the Central African Forests Commission (COMIFAC) and the Secretariat of the Pacific Community (SPC) and regional networks and programmes such as the Asia Pacific Association of Forestry Research Institutions (APAFRI), the Asia Pacific Forest Genetic Resources Programme (APFORGEN), the Latin American Forest Genetic Resources Network (LAFORGEN) and the Sub-Saharan African Forest Genetic Resources Network (SAFORGEN). The workshops covered 82 countries and gathered 137 experts.

A total of 86 countries submitted reports (see Figure), accounting for 76 percent of the world's land area and 85 percent of the global forest area, with good latitudinal and ecoregional representation.

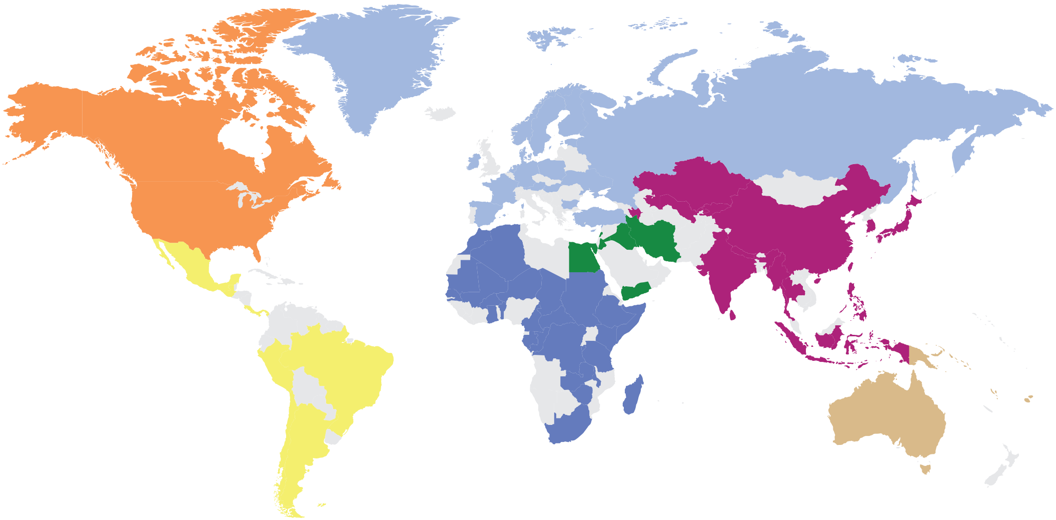
Five thematic studies were prepared on issues relevant to the conservation and sustainable use of FGR at the global level:

- Indicators of forest genetic diversity, erosion and vulnerability
- Role of FGR in adaptation to biotic and abiotic factors in a changing climate
- Trees, tree genetic resources and the livelihoods of rural communities in the tropics
- Genetic considerations in ecosystem restoration using native tree species
- Genetic effects of forest management practices

The country reports and the thematic background studies prepared for *The State of the World's Forest Genetic Resources* will be made available on a dedicated page on FAO's website.

A draft of the present report was reviewed by ITWG-FGR at its second session in January 2013 and presented to the Commission at its fourteenth regular session in April of the same year. Countries were invited to provide comments on the final draft, which were taken into consideration in the finalization of the report.

## Countries reporting for *The State of the World's Forest Genetic Resources*



🟦 **Africa (31 countries)**
Algeria, Benin, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Democratic Republic of the Congo, Ethiopia, Gabon, Ghana, Kenya, Lesotho, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Niger, Republic of the Congo, Senegal, Seychelles, Somalia, South Africa, Sudan, Swaziland, Tunisia, United Republic of Tanzania, Zambia, Zimbabwe

🟪 **Asia (14 countries)**
Azerbaijan, China, India, Indonesia, Japan, Kazakhstan, Kyrgyzstan, Myanmar, Nepal, Philippines, Republic of Korea, Sri Lanka, Thailand, Uzbekistan

🟦 **Europe (18 countries)**
Austria, Bulgaria, Cyprus, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Netherlands, Norway, Poland, Russian Federation, Spain, Sweden, Turkey, Ukraine

🟨 **Latin America and the Caribbean (9 countries)**
Argentina, Brazil, Chile, Costa Rica, Ecuador, Guatemala, Mexico, Panama, Peru

🟩 **Near East (6 countries)**
Egypt, Iran, Iraq, Jordan, Lebanon, Yemen

🟧 **North America (2 countries)**
Canada, United States of America

🟫 **Oceania (6 countries)**
Australia, Cook Islands, Fiji, Papua New Guinea, Solomon Islands, Vanuatu

Note: The region referred to as Oceania – for consistency with data reported in the Global Forest Resources Assessment and *State of the World's Forests* – is synonymous with the Commission's South West Pacific region.

Based on the findings of *The State of the World's Forest Genetic Resources*, ITWG-FGR and subsequently the Commission agreed on strategic priorities for forest genetic resources, adopted by the Conference of FAO at its thirty-eighth session in June 2013 as the Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources. This Global Plan of Action identifies 27 strategic priorities grouped into four areas:

- improving the availability of, and access to, information on FGR;
- conservation of FGR (*in situ* and *ex situ*);
- sustainable use, development and management of FGR;
- policies, institutions and capacity building.

Implementation of the Global Plan of Action will strengthen the sustainability of forest management while contributing towards the Millennium Development Goals, the post-2015 development agenda and the Aichi Biodiversity Targets.

# Executive summary

Forests and trees enhance and protect landscapes, ecosystems and production systems. They provide goods and services which are essential to the survival and well-being of all humanity. Forest genetic resources (FGR) are the heritable materials maintained within and among tree and other woody plant species that are of actual or potential economic, environmental, scientific or societal value. FGR are essential for the adaptation and evolutionary processes of forests and trees as well as for improving their productivity.

The world's current population of 7.2 billion is projected to reach 9.6 billion by 2050. Along with population growth, the demand for energy and wood products for both industrial and domestic uses is expected to increase by 40 percent in the next 20 years. The demand for other forest-related goods (food, medicine, fodder and other commodities) is also predicted to increase.

A major consequence of population pressure is land-use change. Forest conversion to crop and pasture land, together with overexploitation, selective harvesting and high tree mortality due to extreme climatic events, in combination with regeneration failure, can result in local population extinction and the loss of FGR.

Conservation and sustainable management of FGR is therefore a must to ensure that present and future generations continue to benefit from forests and trees.

## *The State of the World's Forest Genetic Resources*

This first *The State of the World's Forest Genetic Resources* constitutes a major step in building the information and knowledge base required for action towards better conservation and sustainable management of FGR at national, regional and international levels.

The report was prepared based on information provided by 86 countries, outcomes from regional and subregional consultations and information compiled in thematic studies. It includes:

- an overview of definitions and concepts related to FGR and a review of their value;
- a description of the main drivers of change;
- the presentation of key emerging technologies;
- an analysis of the current status of FGR conservation, use and related developments;
- recommendations addressing the challenges and needs.

### Preparation of the report

Recognizing that the lack of information limits the capacity of decision-makers to determine the action needed on FGR at the international, regional and local levels, the Commission on Genetic Resources for Food and Agriculture (the Commission), at its eleventh session (2007), emphasized the importance of FGR for food security, poverty alleviation and environmental sustainability. The Commission stressed the urgency of addressing the conservation and sustainable use of FGR through sustainable forest management, especially those resources that are under threat at the global level, and requested FAO to prepare a report on the state of the world's FGR based on country reports.

To assist countries in their reporting, FAO carried out regional training workshops which covered 82 countries and gathered 137 experts. A total of 86 countries submitted reports, accounting for 76 percent of the world's land area and 85 percent of the global forest area. The Commission established an Intergovernmental Technical Working Group on Forest Genetic Resources.

### The state of knowledge of forest genetic resources: A summary

- Knowledge of FGR is reported to be inadequate for well-informed policy or management in most countries.
- Studies have described genetic parameters for less than 1 percent of tree species, although both the number of studies and the number of species studied have increased significantly in the past decade.
- Most studies conducted during the past two decades have been at the molecular level, either using DNA markers or genomic technologies to characterize genetic resources. Molecular information is accumulating much faster than whole-organism information, with the consequence that little of the accumulating knowledge has direct application in management, improvement or conservation.
- A few species have been well researched – through both molecular and quantitative studies – and genetically characterized; these mainly comprise temperate conifers, eucalypts, several acacias, teak and a few other broadly adapted, widely planted and rapidly growing species.
- Quantitative genetic knowledge has led to significant productivity gains in a small number of high-value planted timber species.
- Genomic knowledge of forest trees lags behind that of model herbaceous crop species, including the important agricultural crops, but for several tree species the entire genome has been or is in the process of being sequenced, and novel approaches have been developed to link markers to important traits. Genomic or marker-assisted selection is close to being realized, but phenotyping and data management are the biggest bottlenecks.
- Many of the species identified as priorities, especially for local use, have received little or no research attention, indicating a need to associate funding with priority-setting exercises.

The draft report was reviewed by the working group, the Commission and individual experts; it was finalized by FAO incorporating the comments received. Based on the findings of *The State of the World's Forest Genetic Resources*, the Commission agreed on strategic priorities at the national, regional and international levels. In 2013, the Conference of FAO adopted these priorities as the Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources.

## Key findings

### Access to information and knowledge on FGR needs to be improved

Adequate management of FGR requires the availability of accurate knowledge and information on ecosystems and species. Although a range of 80 000 to 100 000 is the most widely used estimate for the number of tree species, the range of published estimates is much wider, from 50 000 to 100 000, indicating the need for further efforts in botanic assessment to obtain more accurate figures.

The status of botanical knowledge varies from country to country. Very few countries have detailed tree species checklists that include species characteristics allowing distinction between different plant life forms, e.g. trees, shrubs, palms and bamboo. Information on the conservation status of species populations is not available in many countries.

The country reports mention 8 000 species of trees, s, palms and bamboo; of these, genetic-level information is available for only 500 to 600 species.

The collaborative development of an FGR database is urgently needed to enhance access to valuable information and avoid duplication efforts and waste of resources.

### Economic value is the main factor in setting management priorities

Priority setting is fundamental to effective FGR conservation and management, given the vast number of tree and other woody species and the typically considerable intraspecific variation across their natural range. Reasons for nominating species as priorities include their economic value (timber, pulp, food, wood energy, and non-wood forest products), social and cultural value, conservation value (biodiversity, threatened species, endemic species, genetic conservation, scientific value), environmental value (e.g. soil and water protection, soil fertility and watershed management) and invasiveness.

Results from the country reports indicate economic and conservation value as the two main reasons for nominating species for priority for FGR conservation and management; each accounts for two-thirds of species nominations.

### Half of the forest species reported by countries are threatened

Loss of plant species or species genetic erosion in forest ecosystems is mostly due to conversion of forest to other land use types, overexploitation and effects of climate. The proportion of threatened species reported by the countries varies widely, from 7 percent in Oceania to 46 percent in North America. However, some countries included threats at population level, which may account for the great variation in number of threatened species reported.

### 8 000 forest species are used and one-third of them actively managed

Of the 8 000 species of trees, shrubs, palms and bamboo cited in country reports, around 2 400 are mentioned as actively managed, in other words managed specifically for their products and/or services.

The main products and functions targeted through management activities are reported by the countries as timber (42 percent), non-wood forest products (41 percent) and energy (mainly fuelwood) (19 percent).

The high number of species used and their multiplicity of products and services indicates the enormous value of FGR; it suggests their great potential to support agriculture, forestry and environmental sustainability, as well as food and nutrition security, if better evaluated and developed.

### Species distribution maps are vital, but rarely available

Adequate management of FGR and monitoring of their *in situ* conservation status requires reliable baseline information. Development of species distribution maps showing locations of all populations is an essential step in conservation. However, not many countries have the resources to include the development of such maps in their conservation strategies. Mapping at the regional level can make it possible to cover a large portion if not all of a species' distribution range.

## Most species are conserved *in situ*, in naturally regenerated and planted forests

FGR management actions are usually undertaken at forest ecosystem, species (interspecific) or genetic (intraspecific) levels. FGR are to a large extent preserved in wild populations and managed in naturally regenerated forest except for some commercial wood-producing genera and species undergoing intensive tree breeding (e.g. *Acacia* spp., *Eucalyptus* spp., *Populus* spp., *Pinus* spp. and *Tectona grandis*).

In many countries plant wild populations and crop wild relatives are conserved in protected areas and/or in naturally regenerated forest lands. Examples include *Malus* spp. in central Asia, *Coffea arabica* in Ethiopia and *Eucalyptus* spp. in Australia.

In addition, farmers contribute to the conservation of populations of many tree species through traditional agroforestry practices. *Vitellaria* spp. (shea) is an example from semi-arid tropical Africa.

## Effective *ex situ* conservation programmes are restricted to limited species and populations

*Ex situ* conservation programmes remain confined to some economically important species undergoing intensive breeding or under serious threat with high financial implications.

The Millennium Seed Bank Partnership, based in Kew, United Kingdom, hosts the world's largest collection of wild plant species in long-term seed storage. It covers 10 percent of the world's wild plant species – including many woody species – and aims to conserve 25 percent by 2020.

Of the 2 400 actively managed species, about 700 are managed in planted forests and approximately the same number is included in tree improvement programmes. In some countries planted forests and trials contribute to *ex situ* conservation programmes.

## Tree improvement greatly enhances productivity and offers potential for adaptation to changing climate

In recent decades government agencies and the private sector have subjected a wider range of tree species to domestication and formal breeding programmes to produce timber, pulp, fuelwood and non-wood forest products and to provide forest service functions. Tree breeding programmes have the potential to improve the production of planted forests and trees in a sustainable way and are necessary to meet growing global demand for forest products and services. Through tree improvement programmes, productivity can be increased by 10 to more than 60 percent depending on the targeted products (wood, fruit, leaves, resins) and the species.

Examples of tree species in countries' intensive selection and breeding programmes include *Eucalyptus* spp., *Pinus* spp., *Populus* spp. and *Tectona grandis*. Hybrid breeding is used in many countries to produce trees with superior productive capabilities (through heterosis) and also to introduce genes for disease resistance. Examples include eucalypt hybrids, *Larix* and *Populus* hybrids and *Pinus* hybrids.

Tree improvement also has an important role in targeting traits suitable for adaptation to varying environmental conditions, including those associated with climate change. These efforts rely on improved understanding of the genetic structure within and between species populations.

### Emerging technology opens new avenues in FGR management and conservation

An array of biotechnological tools are contributing to the knowledge of forest genetic resources. For natural forests, biotechnology contributes to the knowledge of genetic variation within and between species populations. In tree improvement programmes, biotechnology tools such as enhanced vegetative propagation techniques and marker-assisted tree selection are making significant contributions. Genomics is also being used in forestry as a tool to enhance conservation, for example through the development of DNA banks. Biotechnology offers innovative means of controlling illegal forest harvesting, with DNA fingerprints now used in timber tracking. Genetic modification has been explored to increase or improve wood production in a few countries. However, no commercial planting has been reported.

Of the over 700 tree species reported by countries as subject to tree improvement programmes, 241 species are included in biotechnology research. The development of large-scale clonal plantations of some economically important species (e.g. *Eucalyptus* spp., *Tectona grandis*) using biotechnology has been reported by a number of countries, including tropical countries.

### Policies and institutional frameworks are insufficient

Because of insufficient awareness on the importance of forest genetic resources in improving forest production, enhancing ecosystems and improving adaptation of tree species to changing environmental conditions, national policies and regulatory frameworks for FGR are, in general, partial, ineffective or non-existent. Most developing countries lack the funding and the institutional and technical capacities required to address FGR issues. The institutional and policy framework therefore needs to be improved to address the constraints related to the conservation, sustainable use and development of FGR. Many countries identify integration of FGR concerns into broader forest-related policy as a priority.

## What needs to be done?

### Improve the availability of, and access to, information on FGR

- Establish and strengthen national FGR assessment, characterization and monitoring systems.
- Develop national and subnational systems for the assessment and management of traditional knowledge on FGR.
- Develop international technical standards and protocols for FGR inventory, characterization and monitoring of trends and risks.
- Promote the establishment and reinforcement of FGR information systems (databases) to cover available scientific and traditional knowledge on uses, distribution, habitats, biology and genetic variation of species and species populations.

### Enhance *in situ* and *ex situ* conservation of FGR

- Strengthen the contribution of primary forests and protected areas to *in situ* conservation of FGR.

- Promote the establishment and development of efficient and sustainable *ex situ* conservation systems, including *in vivo* collections and gene banks.
- Support and strengthen the role of indigenous and local communities in the sustainable management and conservation of FGR.
- Identify priority species for action.
- Harmonize measures for *in situ* and *ex situ* conservation, including through regional cooperation and networking.

## Improve sustainable use and management of FGR

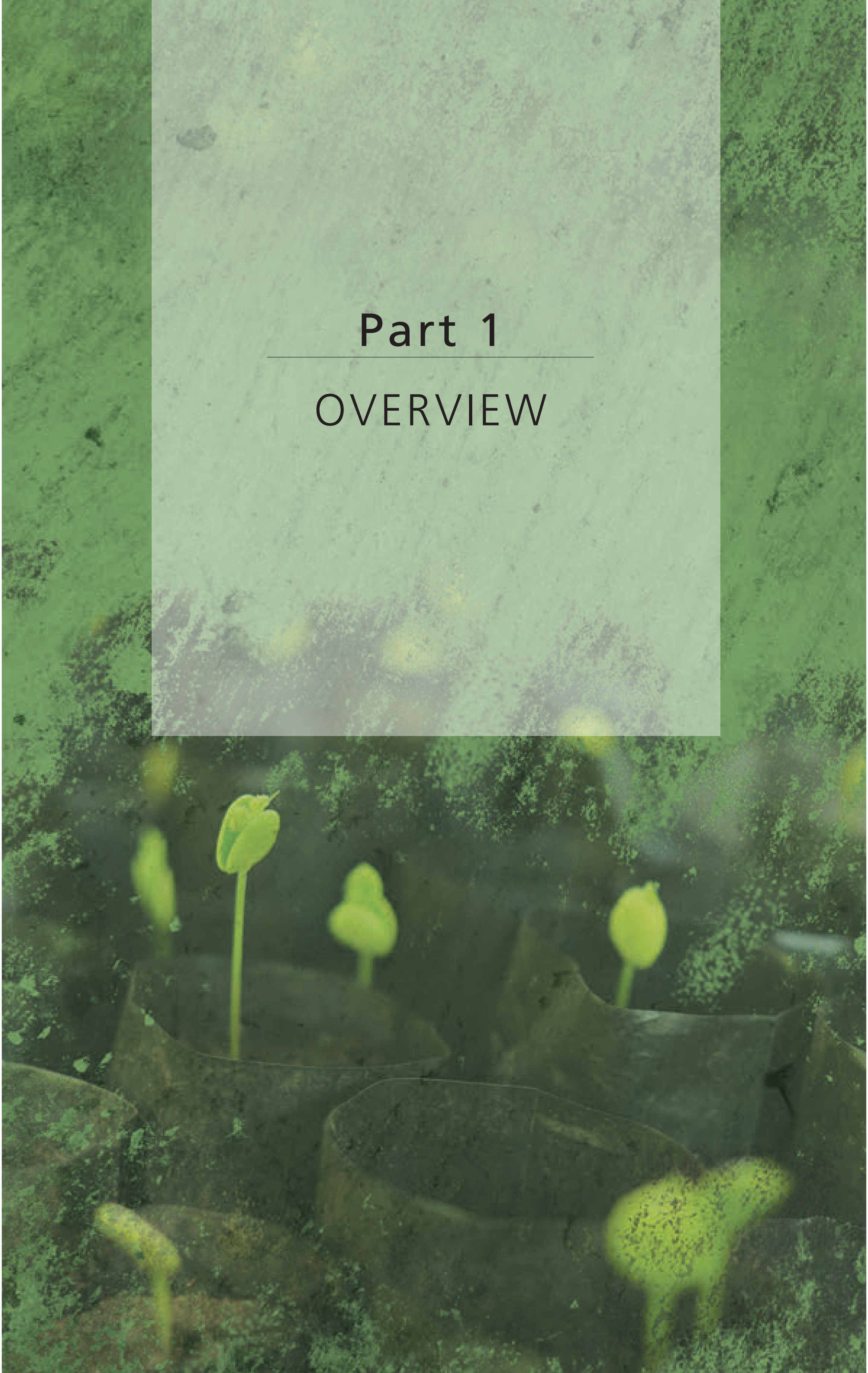
- Develop and reinforce national seed programmes to ensure the availability of genetically appropriate tree seeds in the quantities and of the quality needed for national plantation programmes.
- Promote restoration and rehabilitation of ecosystems using genetically appropriate material.
- Support climate change adaptation and mitigation through proper management and use of FGR.
- Promote good practices and appropriate use of emerging technology to support the conservation, development and sustainable use of FGR.
- Develop and reinforce research programmes on tree breeding, domestication and bioprospecting.
- Develop and promote networking and collaboration among concerned countries to combat invasive species affecting FGR.

## Strengthen policies and institutional capacity

- Develop national strategies for *in situ* and *ex situ* conservation and sustainable use of FGR.
- Integrate FGR conservation and management into wider policies, programmes and frameworks of action at the national, regional and global levels.
- Develop collaboration and promote coordination of national institutions and programmes related to FGR.
- Establish and strengthen educational and research capacities on FGR.
- Promote the participation of indigenous and local communities in FGR management in the context of decentralization.
- Promote and apply mechanisms for regional germplasm exchange for research and development, in agreement with international conventions.
- Reinforce regional and international cooperation, including networking, to support education, knowledge dissemination, research, and conservation and sustainable management of FGR.
- Promote public and international awareness of the roles and value of FGR.
- Strengthen efforts to mobilize the necessary resources, including financing, for the conservation, sustainable use and development of FGR.

# Part 1

# OVERVIEW



## Chapter 1

# Basic concepts

Genetic diversity provides the fundamental basis for the evolution of forest tree species and for their adaptation to change. The enormous range of goods and services provided by trees and forests is both a function of and testimony to the genetic variability contained within them. Conserving forest genetic resources (FGR) is therefore vital, as FGR constitute a unique and irreplaceable resource for the future, including for sustainable economic growth and progress and environmental adaption. The sustainable management of forests and of trees in agroforestry systems requires a better understanding of the specific features of forest trees and their genetic diversity, and how they can be best conserved, managed and utilized. Forest tree species are generally long lived and extremely diverse. One species can naturally occur in a broad range of ecological conditions. In addition, many forest species have evolved under several periods of major climatic change, and their genetic variability is needed for adaptation to climatic regimes different from those in which they have evolved. FGR have provided the potential for adaptation in the past, and will continue to play this vital role as humankind addresses the challenge of mitigating or adapting to further climate changes.

Forestry practices that maintain genetic diversity over the long term will be required as an integral component of sustainable forest management. In future more proactive management of FGR may be needed to accelerate adaptation of forest trees to climate change including through breeding and deliberate movement and relocation of germplasm. Much remains to be discovered concerning how genes function and are regulated in different tree species and further research will likely yield findings of immense economic, social and environmental importance. As a precautionary principle, until there is an improved understanding of tree genetics, there is a need to conserve as much FGR as possible, i.e. the heritable materials of important, including locally important, tree and woody plant species. There is also a need to ensure the survival of the vast majority of, and preferably all, tree and other woody plant species likely to have values hitherto unknown and/or novel products and services which may be required by future generations. Especially critical are those tree species in monotypic families or genera which are genetically more distinctive and irreplaceable.

This report addresses the conservation, management and sustainable use of forest tree and other woody species' genetic resources of actual and potential value for human well-being in the broad range of management systems (see Table 1.1). The definition of forest used in FAO's Global Forest Resources Assessment 2010 (FRA 2010) is "land spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 percent or trees able to reach these thresholds *in situ*". Palms and bamboo forests are included if these criteria are met, as tree-like monocotyledons such as palms, climbing rattans and bamboos generally are considered as FGR and fall under the responsibility of forestry agencies. This report, reflecting the national reports on which it is based, focuses mainly on tree and larger woody species present in forests, both natural and planted. However, it also deals with tree and other woody species outside forests which are arboreal components in more open situations, including agroforestry systems, woodlands and home gardens.

Forest cover is commonly used as a proxy to assess FGR conservation. However, it is only a crude measure, as the type of forest may range from, at one extreme, well connected, highly biodiverse, well managed tree-species-rich communities with limited immediate threats to their integrity, which conserve substantial amounts of FGR, to, at the other extreme, clonal monocultures which usually have a much more limited FGR conservation role. Primary and naturally managed forest cover may be more relevant than total forest cover as crude surrogates of FGR conserved.

At the country level, a major concern is that most forest loss is occurring in biodiverse tropical countries (see Part 2 on drivers of change). Extensive losses in biodiverse forest cover are likely to be accompanied by loss of genetic diversity in socio-economically useful and potentially useful tree species. Gross losses of undocumented and poorly documented FGR in many tropical countries are of extreme concern, and this dire situation requires urgent action involving inventory and conservation measures which must be adequately funded and prioritized at both national and international levels.

Primary forests, which include some of the most FGR-rich forests, account for 36 percent of the global forested area, but have decreased by more than 40 million hectares since 2000 (0.37 percent per annum) (FAO, 2010a) – in most cases with a permanent loss of associated forest genetic resources.

Around the globe the area of planted forest is increasing and now accounts for 7 percent of total forest area, with the highest proportion in Asia (almost 20 percent) (FAO, 2010a). These figures underscore the need to consider carefully the genetic materials used to establish planted forests or to assist regeneration. There is a need to ensure that such forests utilize appropriate, diverse, adapted (including for predicted new climatic conditions) and useful genetic materials and that information on their genetic makeup is well documented. It is noted that for planted forests that have production of wood or biomass as their prime objective, production may be maximized with minimal diversity (e.g. a single clone in clonal eucalyptus plantations) and in these cases it is necessary to weigh risk against productivity. There is also a need for safe movement of germplasm to ensure that pests and diseases are not inadvertently introduced, especially as forest tree species may become more vulnerable to pests and diseases as climate changes.

## Definitions

**Forest genetic resources** (FGR) refers to the heritable materials maintained within and among tree and other woody plant species that are of actual or potential economic, environmental, scientific or societal value. Some country reports included woody shrub species which may be regarded marginally as FGR because they are often of low stature when grown in difficult and arid environments. Fruit- and nut-trees and their wild ancestors were in general included in the reporting as they are frequently multipurpose, providing timber, medicine and services and often being handled by forestry agencies. The term FGR is also sometimes used incorrectly to cover more generally the tree and forest resources and products themselves.

**Forest biodiversity** has a broader connotation than FGR and denotes the variability among forest-dwelling organisms and the ecological processes of which they are a part. It includes variation at forest ecosystem, species and molecular levels.

FGR comprise one subset of **plant genetic resources for food and agriculture** (PGRFA). PGRFA are defined as any genetic material of plant origin of actual or potential value for food and agriculture (which in the UN system is taken broadly to include forestry). FGR are also included as a subset of **agrobiodiversity**, which is defined as the variety and variability of animals,

**TABLE 1.1**
Main types of forest and tree resources management

| Naturally regenerated forests | | | Planted forests | | | Trees outside forests and agroforestry systems |
|---|---|---|---|---|---|---|
| Primary | Modified natural | Seminatural | | Plantations | | |
| | | Assisted natural regeneration | Planted component | Productive | Protective | |
| Forests of native species, where there are no clearly visible indications of human activities and the ecological processes are not directly disturbed by humans | Forests of naturally regenerated native species where there are clearly visible indications of significant human activities | Silvicultural practices in natural forest by intensive management:<br>• weeding<br>• fertilizing<br>• thinning<br>• selective logging | Forests of native species, established through planting or seeding, intensively managed | Forests of introduced and/ or native species established through planting or seeding mainly for production of wood or non-wood goods | Forests of introduced and/ or native species, established through planting or seeding mainly for provision of services | Stands smaller than 0.5 ha;<br>tree cover in agricultural land (agroforestry systems, home gardens, orchards);<br>trees in urban environments; and scattered along roads and in landscapes |

*Source*: Modified from FAO, 2006.

plants and micro-organisms that are used directly or indirectly for food and agriculture, including crops, livestock, forestry and fisheries. Agrobiodiversity includes the diversity of genetic resources (varieties, breeds) and species used for food, fodder, fibre, fuel and pharmaceuticals. It also includes the diversity of non-harvested species that support production (soil micro-organisms, predators, pollinators) and those in the wider environment that support agro-ecosystems (agricultural, pastoral, forest and aquatic) as well as the diversity of the agro-ecosystems (FAO, 1999a). Traditional knowledge of biodiversity or ethnobiodiversity is increasingly understood to be an integral component of agrobiodiversity (Thaman, 2008), and its loss may threaten diversity at different levels – in ecosystems and within and among species.

**Intraspecific diversity,** or the genetic variation within species, may be considered from several perspectives, ranging from formally recognized taxonomic categories of subspecies and varieties through to genetic differences between and within populations. **Subspecies** are usually morphologically or otherwise distinctive entities within a species which have evolved in geographic and reproductive isolation. If they continue to be separated for many generations, subspecies may become distinctive enough from each other, or develop reproductive barriers, to become separate species. **Ecotypes** are an intraspecific group having distinctive characters which result from the selective pressures of the local environment. **Genotypes** can be considered as the sum of the total genetic information in an individual or the genetic constitution of an individual with respect to genetic loci under consideration. Individual long-lived trees of different species may develop into chimeras of many genotypes owing to the accumulation of spontaneous mutations of neutral selective fitness in nuclear genes in bud meristems, but this topic has been little researched.

An organism's **genome** represents its total genetic material, and in plants comprises three separate genomes: nuclear (about 50 000–100 000 genes), chloroplast (about 100–120 genes) and mitochondrial (about 40–50 genes) (Murray, Young and Boyle, 2000). Understanding of genetics and the nature of heritable materials in trees is rapidly evolving, informed by genomic studies in economically important forest trees such as *Eucalyptus* and *Populus* (both angiosperms), woody fruit-trees such as *Malus domestica* (apple) and *Citrus sinensis* (sweet orange), the ancestral flowering plant *Amborella trichopoda* and coniferous families through transcriptome (ribonucleic acid [RNA]) sequencing (e.g. Lorenz *et al.*, 2012), as well as genetic research on other plants and other organisms. Advances in gene sequencing technologies have made possible the sequencing of conifer giga-genomes; several such studies have been completed, e.g. for *Picea abies* (Nysted *et al.*, 2013) and *Pinus taeda* (Neves *et al.*, 2014), while others are in progress or planned (see e.g. Mackay *et al.*, 2012).

**Genes** are nuclear deoxyribonucleic acid (DNA) sequences to which specific functions can be assigned, while **alleles** are alternative forms of a gene located on the corresponding loci of homologous chromosomes. In plants, as well as other higher organisms, a variable proportion of the nuclear genome is composed of non-protein coding, repeat DNA sequences, which have several origins. Some of these sequences have specific regulatory functions and/or may donate segments of DNA which can become incorporated into genes. Angiosperms possess genomes with considerable gene redundancy, much of which is the result of ancient polyploidization events (Soltis *et al.*, 2009).

DNA present in cellular organelles, notably chloroplasts and mitochondria, is a vital component of a tree's heritable materials. While nuclear DNA is always inherited biparentally (i.e. from both male and female parents), organellar DNA may have different modes of inheritance. Chloroplast DNA is usually maternally inherited in angiosperms (e.g. in poplars [Rajora and Dancik, 1992] and in eucalypts [Byrne, Moran and Tibbits, 1993]) but may also be inherited from both parents (Birky, 1995) or rarely from the male (Chat, Chalak and Petit, 1999). In gymnosperms, chloroplast DNA is mainly inherited paternally or infrequently from both parents (e.g. Neale, Marshall and Sederoff, 1989; Neale and Sederoff, 1989; White, 1990; Wagner, 1992). The mitochondrial genome is most often maternally inherited in angiosperms (e.g. Reboud and Zeyl, 1994; Vaillancourt, Petty and McKinnon, 2004) but may be maternally, paternally or biparentally inherited in gymnosperms (e.g. Neale, Marshall and Sederoff, 1989; Neale and Sederoff, 1989; Wagner, 1992; Birky, 1995). Chloroplast DNA is strongly conserved and therefore useful for evolutionary studies (e.g. in *Eucalyptus* spp. [Freeman *et al.*, 2001] and in *Juglans* spp. [Bai, Liao and Zhang, 2010]), while mitochondrial DNA is commonly used as a source of genetic markers in studies of gene flow and phylogeography. Heritable changes in gene expression or cellular phenotype may be caused by several mechanisms which do not involve any change in the underlying DNA sequence; these are the realm of the poorly understood science of epigenetics.

A **population** of a particular tree species comprises all the individuals of that species in the same geographical area and genetically isolated from other populations of the same species. In sexually reproducing species the population comprises a continuous group of interbreeding individuals. A **metapopulation** of a forest tree species comprises a set of spatially separated local populations or subpopulations, coexisting in time, which interact infrequently via pollen and seed dispersal among them.

The term **provenance** is particularly important in relation to forest tree germplasm and refers to the geographic origin of a particular germplasm source, although it is sometimes used synonymously and interchangeably with "population". The field performance of seed sourced from a particular representatively sampled provenance, if from a rather narrow geographic area (including same soil type and little altitudinal variation), will generally be more consistent than that of a population, which may vary considerably owing to clinal variation arising from gradients in selective pressures.

***In situ* conservation** refers to the conservation of ecosystems and natural habitats and the maintenance and recovery of viable populations of species in their natural surroundings. In the case of domesticated or cultivated species it refers to their conservation in the surroundings in which they have developed their distinctive properties (UN, 1992). ***Circa situm* conservation** is a type of conservation that emphasizes the role of regenerating saplings in linking vegetation remnants in heavily modified or fragmented landscapes such as those of traditional agroforestry and farming systems (Barrance, 1999). The related term **matrix management** has been coined to refer to approaches for conserving and managing biodiversity in forests outside protected areas (Lindenmayer and Franklin, 2002); dynamic conservation of FGR will mainly occur in the matrix and will involve management of trees on farms, in forest fragments and especially in sustainably managed production forests. ***Ex situ* conservation** refers to the conservation of components of biodiversity outside their natural habitats, including FGR in planted forests, tree breeding programmes, *ex situ* gene conservation stands or field gene banks, seed and pollen banks, *in vitro* storage and DNA storage (FAO, FLD and IPGRI, 2004).

**Evolutionary or dynamic conservation of FGR** essentially involves a natural system in which the evolutionary forces and natural selective processes which gave rise to diversity are allowed to operate and over time modify allelic frequencies. The past few decades represent the beginning of an era of unprecedented change in selective pressures on almost all trees species. These altered selective forces include more extreme climatic events, gradual increases in temperature and altered rainfall regimes, changed fire regimes, increased air pollution and elevated atmospheric $CO_2$ levels, habitat fragmentation, increases in pest and disease outbreaks and the appearance of new pest and disease species, competition with invasive exotic plant species including transformer species capable of changing the ecology of entire ecosystems, and the loss of or changes in pollinators and dispersal agents. Dynamic *in situ* conservation allows species adaptation through continuous “selection of the fittest”, co-adaptation of host-pathogen systems and other complex biological interactions (Kjær, Graudal and Nathan, 2001; Byrne, 2000).

*In situ* conservation of the FGR associated with identified superior provenances of economically important tree species is vital even when they may be relatively well conserved *ex situ*, e.g. through planting and breeding programmes. This is because tree breeders may need to resample in original populations for infusion in later breeding populations and/or to identify new desired traits in already well known and adapted populations. Selective forces may differ in the native and exotic/planted environments, and this difference is the basis of the often remarkably swift evolution of **landraces** (local varieties of a tree species undergoing domestication which have developed through selection and adaptation to the new environment in which they are growing) which are much better adapted than the original introduction after just one or two generations of selection. Increasingly rapid climate change and associated extreme climatic events are altering the selective forces in both the native and exotic/planted environments and creating new challenges for FGR conservation.

**Static conservation** of FGR involves conserving individual genotypes – for example in the field as clonal archives and *in vitro* in tissue culture and cryopreserved embryo culture – and groups of genotypes in long-term seed storage for tree species with orthodox seed storage behaviour (Kjær *et al.*, 2004). This approach has generally been viewed as a complementary approach to dynamic *in situ* conservation and more often as a short-term conservation strategy and a means of safety duplication in the case of cryopreservation. Given the unprecedented scale of threats to FGR and the likely losses of diversity and changes in selective forces which will drive rapid changes in the genetic makeup of natural (and artificial)

populations of tree species, it might be timely to reconsider the potential value and cost effectiveness of static conservation activities.

## Characteristics of forest genetic resources

Trees and other woody species differ from other organisms in several key respects. Forest tree species are generally long-lived and have developed natural mechanisms to maintain high levels of genetic variation within species. They include high rates of outcrossing and often long-distance dispersal of pollen and seed. These mechanisms, combined with native environments that are often variable, have enabled forest tree species to evolve into some of the most genetically diverse organisms in existence. Forest community ecosystem processes, including evolution of species, have been found to be closely related to the genetic diversity in structurally dominant and keystone tree species (e.g. Whitham *et al*., 2006 and references therein). This section describes some differences between trees and other organisms.

### Chromosomes and DNA

Large and seemingly inexplicable differences and variations in chromosome number, ploidy level and genome size occur both among trees, and between trees and other organisms. The two major groups of trees – gymnosperms (including conifers) and angiosperms – appear to have been separated by more than 290 million years of independent evolution. Angiosperms have high levels of genetic diversity – both a high number of genes, e.g. more than 40 000 for poplar (JGI and CIG, 2006–2014), and high allelic variation. Conifers typically have very large genomes, or giga-genomes, with an order of magnitude more DNA than other organisms, but with numerous highly repetitive, non-coding sequences (Ahuja and Neale, 2005; Rigault *et al*., 2011; Mackay *et al*., 2012). DNA sequencing studies of selected model plant species in these two groups are providing different perspectives and insights into plant genome biology and evolution. While large sets of DNA sequences overlap between conifers and angiosperms (e.g. Pozo *et al*., 2011), about 30 percent of conifer genes have little or no sequence similarity to angiosperm plant genes of known function (Pavy *et al*., 2007; Parchman *et al*., 2010).

### Whole-genome duplication (polyploidization)

While polyploidization or whole-genome duplication is rare in animals and conifers,[1] it is now considered ubiquitous in angiosperms and has occurred frequently through their evolution. Polyploidization is a mechanism of sympatric speciation because polyploids are usually unable to interbreed and produce fertile offspring with their diploid ancestors. Polyploidization may involve autopolyploidy (spontaneous multiplication involving the chromosomes of a single species) or allopolyploidy (involving more than one genome or species).

Whole-genome duplication is considered likely to have led to a dramatic increase in species richness in several angiosperm lineages including families with important FGR such as the legumes (Fabaceae) and to be a major diversifying force in angiosperms (Soltis *et al*., 2009). In animals, aneuploidy is usually lethal and so is rarely encountered, whereas in angiosperms the addition or elimination of a small number of individual chromosomes appears to be better tolerated. New research has indicated that aneuploidization may be a leading cause of genome duplication; Considine *et al*. (2012) have found that autotriploidization is important for speciation in apples (*Malus* spp.) and that such polyploidization confers both genetic stability and diversity and presents heterozygosity, heterosis and adaptability for evolutionary selection. The monotypic small tree *Strasburgeria robusta* from New Caledonia (France) has an extremely

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[1] Polyploids in conifers include *Sequioa sempervirens* (hexaploid) and *Fiztroya cupressoides* (tetraploid) (see Ahuja, 2005 for a review of polyploidy in gymnosperms).

### Box 1.1
### Examples of some of the oldest known trees and woody shrubs

- One clone of *Populus tremuloides* in central Utah (United States of America) is estimated to be 80 000 years old (DeWoody *et al*., 2008); 5 000- to 10 000-year-old clones are reputedly common.
- A sterile triploid clone of the woody angiosperm shrub king *Lomatia tasmanica* has been determined to be at least 43 600 years old (Lynch *et al*., 1998).
- A colony of *Lagarostrobus franklinii* trees covering 1 ha on Mount Read, Tasmania (Australia) is estimated to be around 10 000 years old, with individual tree stems in this group more than 2 500 years old, as determined by tree ring samples (Earle, 2013).
- A specimen of *Picea abies* in Dalarna Province (Sweden) has been found to be at least 9 550 years old. It has survived by resprouting from layered stems, rather than underground root suckering (Umeå University, 2008).
- Three species of bristlecone pines in the United States of America may live for several thousand years, with one specimen of *Pinus longaeva* in California determined to be about 4 900 years old (Currey, 1965).

high ploidy level ($20n$ with $n = 25$) which may have enabled it to adapt to an extreme edaphic environment, i.e. ultramafic soil (Oginuma, Munzinger and Tobe, 2006).

## Longevity

Trees and other woody species are perennial, often long-lived, organisms. For long-term survival at a particular site, they need to be able to endure environmental extremes and changes and/or to persist in the soil seed bank or regrow from root suckers and coppice. The high genetic diversity that characterizes tree populations and individuals, and associated stress tolerance and disease resistance mechanisms, help explain their capacity to persist and thrive for long periods. Indeed the only organisms with a life span comparable to that of the oldest trees are corals, fungal mats and other clonal suckering plants such as *Larrea tridentata* (creosote bush).

The life span of trees typically ranges from about 10 to 15 years (for short-lived pioneer species) to 200 to 300 years (for many larger species and those found in arid zones). Root suckering clones provide the oldest known woody species; some examples are given in Box 1.1.

Almost all of the world's oldest recorded trees are conifers (Rocky Mountain Tree-Ring Research, 2013). It is likely that their xylem structure, which differs from that of angiosperms, and the associated ability to survive lower conductivities and drought (Choat *et al*., 2012) contributes to their great longevity. Ancient trees occur in all three orders of conifers: Pinales, Araucariales, and Cupressales (see Table 1.2).

**Species longevity.** The capacity of gymnosperms to persist over millions of years, often almost unchanged in form, is evidenced by *Ginkgo biloba*, recently rediscovered in the wild in southwestern China where glaciation was relatively weak (Tang *et al*., 2012); it was previously only known from fossils and from cultivation in Japanese and Chinese temple gardens. Likewise, *Wollemia nobilis*, discovered in 1994 in a valley near Sydney, eastern Australia, is presumed to be the last remnant of a genus that evolved about 61 million years ago (Liu *et al*., 2009).[2] It includes less than 100 stems of this tree, all appearing to be genetically identical, and likely comprising a single clonal root suckering clump.

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[2] *Wollemia nobilis* may die out in the wild because of the recent introduction of the virulent root rot pathogen *Phytophthora cinnamomi*, but it has been well conserved globally *ex situ* through a successful campaign to promote its use as an ornamental.

**TABLE 1.2**
Life span of some of the longest-lived conifers

| > 1 000 years | > 2 000 years | >3 000 years | > 4 000 years |
|---|---|---|---|
| *Xanthocyparis nootkatensis*<br>*Cryptomeria japonica*<br>*Juniperus scopulorum*<br>*Larix lyalli*<br>*Pinus albicaulis*<br>*Pinus edulis*<br>*Pinus flexilis*<br>*Pseudotsuga menziesii*<br>*Taxodium distichum* | *Juniperus occidentalis*<br>*Lagarostrobus franklinii*<br>*Pinus aristata*<br>*Pinus balfouriana*<br>*Sequoia sempervirens* | *Fitzroya cupressoides*<br>*Sequoiadendron giganteum* | *Pinus longaeva*<br>*Picea abies* |

*Source*: Wikipedia, n.d.

## Size

Trees include the biggest and tallest organisms on the planet. *Sequoia sempervirens* has been recorded up to 115 m tall and weighing up to 530 tonnes (Preston, 2007). The world's tallest and biggest angiosperms are eucalypts in southeastern Australia, specifically *Eucalyptus regnans* from Victoria and Tasmania, with trees measuring over 100 m; historically, examples were known with height of at least 114 m and trunk volumes to 360 m$^3$ (Carder, 1995).

Trees are the dominant structural element in forests and several other terrestrial ecosystems (agroforests, woodlands and gardens), intercepting much of the radiant sunlight, dominating photosynthetic processes and carbon flows and comprising a large proportion of the biomass.

Populations of large old trees are rapidly declining in many parts of the world, with detrimental implications for ecosystem integrity and biodiversity (Lindenmayer, Laurance and Franklin, 2012). Throughout the tropics the biggest forest trees are disappearing, partly as a result of selective targeting by loggers, but more recently as a result of forest fragmentation, climate change and exposure to drought.

## Diverse breeding systems

Trees are notable for their diverse breeding and reproductive systems, which are in turn major determinants of spatial patterns of tree species genetic diversity. Most tree species reproduce sexually, although many have a combination of sexual and asexual reproductive means, while a few have lost the ability to reproduce sexually and are maintained as sterile, root-suckering clones in certain parts of their range, e.g. *Acacia anomala* in southwestern Australia (Coates, 1988), *Casuarina obesa* in western Victoria (Australia), and *Santalum insularis* on Mangaia (Cook Islands). It is possible that a long-distance pollen or seed dispersal event could cause such plants to regain a sexual mode of reproduction.

Tree species reproducing by sexual means have diverse reproductive biologies including monoecious (with separate male and female flowers on the same tree), dioecious (with individual trees bearing either male or female flowers), hermaphroditic (with functional bisexual flowers) and polygamous (with male, female and bisexual flowers on the same tree). Almost all flower sex combinations are possible; trees may have male and bisexual flowers; female and bisexual flowers; and bisexual flowers with a small number of male and female flowers. At the global level, populations of flowering plant species are mainly hermaphroditic (72 percent), with smaller proportions as follows: monoecious, 4 percent; dioecious, 7 percent; gynodioecious (having female flowers on some plants and bisexual flowers on other plants) or androdioecious (having male flowers on some plants and bisexual flowers on other plants), 7 percent; and trioecious (with male, female and bisexual flowers in three different plants), 10 percent (Yampolsky and Yampolsky, 1922; Dellaporta and Calderon-Urrea, 1993). However, these proportions vary regionally, and they also vary between trees and other flowering plants, For example, dioecy, an obligate outcrossing pollination arrangement, was found to be higher (>20 percent) in tree species (Bawa, Perry and Beach, 1985).

Most angiosperm species with hermaphroditic flowers have preferential outcrossing systems such that fertilized, viable seeds are generally derived from outcrossing. Reported outcrossing rates in tropical angiosperm tree species from different families, and including those occurring at low density, were typically in the range of 60 to 100 percent, but with considerable variation (Byrne, 2008; Butcher, Glaubitz and Moran, 1999; Gandara, 1996; Hamrick and Murawski, 1990; Kitamura *et al.*, 1994; Lepsch-Cunha, Gascon and Kageyama, 2001; Lepsch-Cunha *et al.*, 2001; Mandal, Ennos and Fagg, 1994; Moran, Muona and Bell, 1989; Muluvi *et al.*, 2004; Murawski and Hamrick, 1991; Murawski and Bawa, 1994; Murawski, Dayanandan and Bawa, 1994; Murawski, Gunatilleke and Bawa, 1994; Murawski, 1995; Nason and Hamrick, 1997; O'Malley and Bawa, 1987; Olng'otie, 1991; Sebbenn *et al.* 2000; Stacy *et al.*, 1996; Ward *et al.*, 2005).

Outcrossing rates vary within species and populations and among different flowering events. For example, tropical acacias from humid zones in Papua New Guinea and northern Australia typically have rates of 93 to 100 percent outcrossing, but lower rates (30 to 80 percent) have been found in more southerly populations of *Acacia mangium* (Moran, Muona and Bell, 1989; Butcher, Glaubitz and Moran, 1999), while polyploid dry-zone African acacias had low outcrossing rates of between 35 and 38 percent (Mandal, Ennos and Fagg, 1994; Olng'otie, 1991). Plasticity in mating systems has also been observed in response to changes in pollinators. *Ceiba pentanda* (kapok), for instance, had a predominantly self-incompatible system in situations of high bat pollinator visitation, but changed to a mixed mating system with high levels of self-pollination in situations with low pollinator visitation rates (Lobo, Quesada and Stoner, 2005).

Conifers are wind pollinated and either monoecious or dioecious (with obligate outcrossing). Species in the families Pinaceae and Cupressaceae are monoecious (with the exception of *Juniperus* spp., which are usually dioecious); Araucariaceae, Podocarpaceae and Taxaceae may be monoecious or dioecious; and Cephalotaxaceae are mainly dioecious but occasionally monoecious (Earle, 2013). Mating systems in conifers vary in space and time, mainly owing to variation in self-pollen availability (Mitton, 1992). Mechanisms to promote outcrossing have been identified in monoecious conifers, e.g. *Pinus taeda* (Williams, Zhou and Hall, 2001). The outcrossing rate for most conifer species is above 80 percent (e.g. for 52 species reviewed in O'Connell, 2003). Through their long evolution, plasticity in the reproductive systems of conifers may have helped them to survive. For example, *Cupressus dupreziana* has evolved a unique reproductive system of male apomixis whereby the seeds develop entirely from the genetic content of the pollen (Pichot, Fady and Hochu, 2000). *Sequoia sempervirens* reproduces by both asexual (basal suckering) and sexual means but with low seed set (1 to 10 percent) owing to irregular meiosis and associated with its hexaploid condition; dual reproductive systems have enabled redwoods to maintain heterozygosity and adaptability for survival (Ahuja, 2005).

## Species diversity

The future well-being of the human race, and the health and productivity of various ecosystems and communities, will often rely on genetic diversity both within and among tree species. While this report is mainly concerned with intraspecific diversity, it is also appropriate to consider the economic and other uses of trees and other woody species provided through diversity at species level.

### Interspecific (between species) diversity

Approximately 80 000 to 100 000 tree species have been described and currently accepted as valid and unique (Oldfield, Lusty and MacKinven, 1998; Turok and Geburek, 2000); together with larger woody shrubs they likely represent about 50 percent of all vascular plant species.

Considerable research has been undertaken to understand how tropical forests develop and maintain their typically vast tree species diversity, but answers remain elusive (e.g. Denslow, 1987; Cannon, Peart and Leighton, 1998; Ricklefs and Renner, 2012). Tree diversity in complex ecosystems, moist tropical forest gaps and regeneration niches may have been generated in part, and may be maintained, by host-pathogen and host-parasite interactions (Grubb, 1977; Wills *et al*., 1997).

Research, development, conservation and use of tree species, in particular tropical species, has often been frustrated by insufficient and inadequate taxonomic knowledge, e.g. assessment of conservation status of different species (Newton and Oldfield, 2008). An array of more powerful and efficient genetic technologies are increasingly available to complement traditional, morphology-based taxonomy and field studies, and these are leading to better circumscription of tree species and understanding of their phylogenetic relationships. The nature of variation in trees is such that species boundaries will not always be easily defined, as in the following examples (Whitmore, 1976):

- species existing as morphologically distinctive and geographically disjunct populations which rarely exchange genetic materials and are best considered as provenances, varieties or subspecies;
- species that are readily discernible in most of their natural range and have evidently been reproductively isolated for much of their recent evolution, but which form fertile hybrid swarms in small overlapping contact zones;
- species with polyploid races, often coupled with apomictic reproduction;
- ochlospecies, i.e. species whose complex variation patterns cannot be satisfactorily accounted for by conventional taxonomic categories.

Based on a literature review carried out for this report, it is conservatively estimated that more than 34 000 tree species in more than 1 000 genera are of socio-economic, environmental and scientific importance and used on a regular (daily or weekly) basis by people throughout the world. This number includes large woody shrubs attaining more than 2 to 3 m in height, given that the boundary between trees and woody shrubs is unclear and individual species may exist as either trees or shrubs depending on environmental factors. Also included are fruit- and nut-trees and their wild relatives. The total comprises both angiosperms (33 500 species in 976 genera and 131 families, including bamboos and palms) and gymnosperms (530 species in 67 genera and nine plant families, excluding cycads).

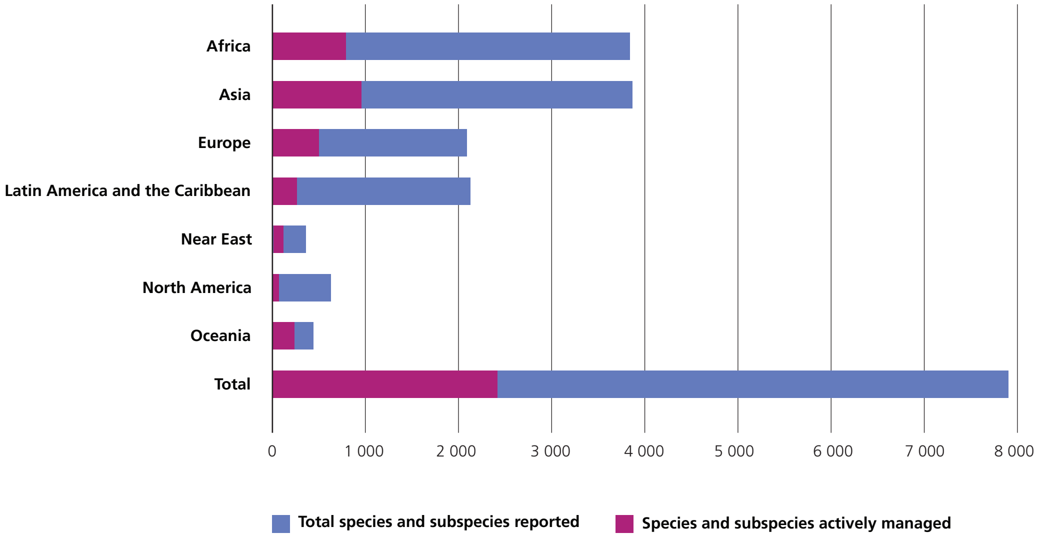
In total nearly 8 000 species and subspecies were mentioned in country reports, and about 2 360 species and subspecies were mentioned as being actively managed (i.e. managed specifically for their products and/or services) in various systems (Figure 1.1).

In practice, this vast diversity at species level in trees means that, for a given product or service, local people and foresters may have a choice among hundreds of species which are locally available and/or suitable options in different ecological conditions. As well as providing opportunities, this vast species genetic resource can also present challenges in ascertaining which species to prioritize for research and development and for planting.

Area measures of forest tree species richness are used to define biodiversity hotspots and megadiverse countries and have been used to prioritize conservation efforts both internationally and within countries. However, the identification and protection of areas particularly rich in FGR should not detract from other efforts to conserve and manage FGR throughout the world. Some forests may contain few species in comparison with

**FIGURE 1.1**

Number of species and subspecies mentioned as actively managed in country reports, by region



other, more floristically diverse areas, but these few species may be vital for local communities (e.g. atoll island communities in Oceania) or may be genetically unique and have extremely high value for conservation of FGR (as in Seychelles, which has only 93 highly distinct indigenous tree species with endemism of more than 50 percent).

Many country reports indicated that conservation of FGR, including the vast diversity at the tree species level, is seriously hampered by a lack of taxonomic skills, inventory and knowledge of species distributions. Accordingly there is an urgent and ongoing need to strengthen national FGR assessment, characterization and monitoring systems.

## Intraspecific (within species) diversity

Intraspecific diversity or genetic diversity within tree species is manifested in different ways and can be characterized at different levels. It can be assessed at the molecular level through nuclear DNA (e.g. using neutral markers such as random amplified polymorphism DNA [RAPD], chloroplast DNA (especially useful for providing evolutionary information), direct RNA sequencing (providing information on gene regulation and proteins) and enzyme variation (gene products assessed through isozyme electrophoresis). Genetic variation is also observed at expressed levels, for example through quantitative variation in growth and other traits as assessed through field trials and through morphological, physiological, entomological and pathology studies. Sometimes variation is discontinuous, giving rise to the identification of varieties including chemotypes, morphotypes and the like. Intraspecific patterns of genetic variation in tree species have been found to vary as a result of factors such as the evolutionary history of the species; distribution of populations and connectivity; reproductive biology and mating system; dispersal of pollen and seed; introgression and hybridization with

related species; chance factors; and genetic drift. Observed patterns of genetic variation can vary between different genomes of the same tree species, if these genomes are inherited differently, with associated differences in dispersal of pollen and seed, as described by Tomaru *et al.* (1998) in *Fagus crenata* in Japan.

Humans have long been interested in using and influencing diversity within tree species, especially tree species producing edible fruits and nuts; an example is the domestication and selection of *Juglans regia* (walnut) described in the Azerbaijan country report. Another well documented case is the selection, translocation and domestication of tropical nut-trees in arboricultural systems in Papua New Guinea and Solomon Islands, dating back more than 3 000 years (Yen, 1974; Lepofsky, 1992; Lepofsky, Kirch and Lertzman, 1998). However, for the most part traditional knowledge and activities related to improvement of FGR are undocumented. National-level assessments should be made a priority, especially in tropical countries, before the information dies out with those who hold it.

The forestry profession has had a long interest in studying and using variation in trees, including geographic variation in economically important planted forest tree species, which was investigated through field trials early in the last century. The International Union of Forest Research Organizations (IUFRO) coordinated provenance trials of *Pinus sylvestris* established in 1907, 1938 and 1939 in Europe and the United States of America (Wright and Baldwin, 1957; Langlet, 1959; Giertych, 1979). After the hiatus of the Second World War, provenance field trial research recommenced in earnest, with *Pinus ponderosa* provenance trials established in the United States of America in 1947 (Callaham, 1962) and new *P. sylvestris* provenance trials in Sweden from 1952 to 1954 (Eiche, 1966; Eriksson *et al*., 1976). During the 1960s and 1970s, assessments of genetic diversity in forest tree species gathered pace and extended to tropical and Southern Hemisphere species. These assessments were focused mainly on morphological attributes including wood traits, adaptiveness, quantitative growth characters, disease tolerance, and genotype × environment interaction. These attributes were examined through series of field trials, often undertaken in several countries and referred to as provenance trials. Some of the tree species studied in these early investigations included:

- *Betula alleghaniensis* (Clausen, 1975)
- *Cordia alliodora* (Sebbenn *et al*., 2007)
- *Eucalyptus camaldulensis* (Lacaze, 1978)
- *Eucalyptus urophylla* (Vercoe and Clarke, 1994)
- *Fagus sylvatica* (Giertych, 1990)
- *Gmelina arborea* (Lauridsen, Wellendorf and Keiding, 1987)
- *Pinus kesiya* (Barnes and Keiding, 1989)
- *Pinus patula* (Barnes and Mullin, 1984)
- *Pinus radiata* (Nicholls and Eldridge, 1980)
- *Tectona grandis* (Lauridsen, Wellendorf and Keiding, 1989)
- *Terminalia superba* (Delaunay, 1978)

Based on the success of the earlier provenance trials, the provenance trial approach has been continued and extended, including to national trials with native species. Some examples include:

- *Acacia aneura* (Ræbild, Graudal and Nimbkar, 2003)
- *Acacia auriculiformis* (Awang *et al*., 1994)
- *Acacia senegal* (Ræbild, Graudal and Ouédraogo, 2003)
- *Alnus rubra* (Xie, 2008)
- *Azadirachta indica* (Hansen, Lunde and Jørgensen, 2000)
- *Casuarina equisetifolia* (Pinyopusarerk *et al*., 2004)
- *Chukrasia tabularis* (Ratanaporncharern, 2002)
- *Endospermum medullosum* (Vutilolo *et al.*, 2005)
- *Faidherbia albida* (IRBET/CTFT, 1985-1988)
- *Pachira quinata* (Hodge *et al*., 2002)
- *Parkia biglobosa* (Ouédraogo *et al*., 2012)
- *Pinus caribaea* (Hodge and Dvorak, 2001)
- *Pinus tecunumanii* (Hodge and Dvorak, 1999)
- *Sterculia apetala* (Dvorak *et al*., 1998)

Provenance/progeny trials continue to be one of the first steps in domestication and improvement of wild tree species. The range of attributes assessed is becoming more diverse according to the particular and sometimes specialized end uses envisaged, and can include pulping and fibre properties and timber uniformity, or characteristics of wood, essential oils, fruit and nuts for multipurpose species.

Countries reported on species/provenance trials, and this information is covered in Chapter 11. Many of the trials are in progress, have not been reported or are not readily available in the published scientific literature.

Internationally coordinated provenance trials of tree species will become increasingly important in providing data to assess the modelled impacts of climate change on productivity of planted forests and to determine which species or provenances will be best adapted to new, modified climates (e.g. Booth *et al.*, 1999; Leibing *et al.*, 2009). Provenance trial data can also be used to assist interpretation of the likely impacts of predicted climate change on native species and populations, as has been done for *Pinus* species in tropical Asia and the Americas (van Zonneveld *et al.*, 2009a, 2009b) and for *Eucalyptus* species in Australia, where minor changes in climate will expose at least 200 *Eucalyptus* species to completely new climatic envelopes (Hughes, Cawsey and Westoby, 1996), for which their adaptation potentials are unknown.

Increasingly, with gathering momentum over the past 20 years, detailed genetic information is being obtained for tree species often selected for study on the basis of their economic importance or conservation status or for use as representative model species. Many of the early molecular studies of diversity in tree species, in the 1980s and 1990s, focused on high-priority timber trees and were mainly undertaken in forest genetic laboratories in developed countries using electrophoresis techniques. Detailed genetic evaluations using DNA and enzyme markers have now been undertaken for many important forest tree species in Europe and North America; for example, Canada reported intraspecific genetic studies for 32 Canadian tree species. Until recently, there have been few detailed studies of intraspecific genetic variation in developing countries. Such studies are needed for the formulation of scientifically based gene conservation programmes.

Increasingly, as evidenced in the scientific literature and reported in the country reports, the patterns of genetic diversity for a much greater range of tree species from throughout the world are being determined using a wide range of genetic markers; for example, more than 100 tree species in China have been characterized over the past decade.

The planning of specific and effective programmes for both conserving and exploiting the genetic diversity in target forest tree species requires detailed knowledge of the species' patterns of intraspecific diversity, notably knowledge of how genetic diversity is distributed between and among populations (genetic snapshot). This must be complemented by understanding of the species' ecology, especially regeneration ecology, reproductive biology and relationships with other species (e.g. pollinators, dispersers, symbionts, predators, parasites and competitors) – in short, the selective and evolutionary forces that resulted in its genetic makeup.

Data from genetic studies are increasingly being used to inform conservation of FGR in particular tree species (see also Box 1.2). For example, Canada's country report refers to this application for *Xanthocyparis nootkatensis* and *Thuja plicata*. Other examples in the published literature include the following.

- Genetic data for four evolutionarily significant populations of *Calliandra calothyrsus* in Mexico and Central America indicated the need to conserve representative populations (Chamberlain, 1998).
- Data for *Caesalpinia echinata* in Brazil indicated the need to conserve different populations in different geographic areas (Cardoso *et al.*, 1998).

- Data for *Sclerocarya birrea* in Kenya indicated the need to conserve specific populations with high genetic diversity (Cardoso *et al*., 1998).
- Genetic studies together with quantitative variation data from provenance trials have been used to inform conservation plans for *Pinus maximinoi* (Dvorak *et al*., 2002).
- Genetic and quantitative morphological data have been used to inform conservation plans for *Paramichelia baillonii* in China (Li *et al*., 2008).

Various genetic studies are demonstrating the importance of glacial refugia for conserving tree species and their diversity, e.g. for broad-leaved trees such as *Quercus* spp. in Europe (Iberian Peninsula, Appenine Peninsula and the Balkans) (Potyralska and Siwecki, 2000); for *Irvingia* spp. in Central and West Africa (Lowe *et al*., 2000); and for *Cunninghamia* spp. in East Asia (Hwang *et al*., 2003). In addition, species growing in marginal environments or at the extremes of their range (in terms of climate and soils) may contain unique diversity and specific adapatations that warrant special attention for evaluation and conservation.

The increased information being generated through DNA studies is also being used to make generalized recommendations on how to conserve genetic diversity. A review by Newton *et al.* (1999) noted that application of molecular techniques to diversity studies in a variety of tree species had highlighted a greater degree of population differentiation than indicated by previous isozyme analyses; thus in the absence of detailed information on the genetic structuring of a species, it may be prudent to conserve as many

### Box 1.2
### Conserving distinct and unique tree lineages

It is logical that national conservation efforts will focus on maintaining the genetic diversity and evolutionary potential of high-priority tree species at the national level, and that international efforts will focus on those priority species whose distributions overlap national boundaries and have greater socio-economic importance outside the country of origin as planted exotics. There is also a case to be made, from both an international and a scientific viewpoint, for conserving those tree species (families and genera) that are genetically most distinctive, e.g. monotypic families and genera, and those that represent the most evolutionarily divergent lineages. These genetically distinctive lineages and assemblages may later be found to hold genes or combinations of genes that could be extremely useful to future generations; they need be considered in prioritizing genera or species of scientific importance.

The gymnosperms (cone-bearing plants) are replete with ancient, separate evolutionary lineages, of which many are vital FGR. Some examples follow.

- The order Ginkophytes comprises one family, Ginkgoaceae, of which there is only one living tree species, *Ginkgo biloba,* a living fossil apparently almost unchanged in form for nearly 175 million years and an important source of herbal medicine.
- *Cunninghamia lanceolata* is in its own subfamily, Cunninghamhioideae.
- Taiwanioideae consists solely of the species *Taiwania cryptomerioides*.
- The subfamily Sequoioideae includes three renowned monotypic tree genera, *Metasequoia, Sequoia* and *Sequoiadendron*, each with one living species.

Many other coniferous genera comprise a single tree species which is highly valued for its timber, non-wood forest products (NWFPs) and/or cultural and/or environmental uses, e.g. *Cathaya, Fitzroya, Fokienia, Lagarostrobos, Manoao, Nothotsuga, Papuacedrus, Platycladus, Pilgerodendron, Pseudolarix, Sundacarpus, Taxodium, Tetraclinis* and *Thujopsis*.

## Box 1.2 *cont.*
## Conserving distinct and unique tree lineages

Several of these monotypic conifer genera are at high risk of loss of intraspecific diversity. Some, including *Neocallitropis pancheri* in New Caledonia (France), are endangered according to the International Union for Conservation of Nature (IUCN). Many of the endangered and evolutionarily unique lines of conifer subfamilies, genera and species are endemic to China, Viet Nam, New Caledonia (France) and other countries in the Southern Hemisphere, and a strong conservation effort for these taxa is important in these countries.

The most primitive angiosperm or flowering plant is considered to be *Amborella trichopoda;* this species has been placed in its own order, Amborellales, and is of major scientific importance. While its conservation status has yet to be assessed, it is likely to be at risk from climate change and fire in previously unburnt, wet forest ecosystems in New Caledonia (France). The monotypic *Arillastrum gummiferum* from New Caledonia (France) is important for forest science as an ancestral genus and species for eucalypts. Many angiosperm genera comprise a single tree species which may be endangered or highly valued for its timber, NWFPs, or cultural or environmental purposes (or a combination of the above). These include *Antiaris, Aralidium, Argania, Aphloia, Aucomea, Bagassa, Baillonella, Bertholletia, Bosqueiopsis, Cantleya, Chloroxylon, Crossopteryx, Cyclocarya, Deckenia, Delavaya, Elingamita, Eusideroxylon, Faidherbia, Falcataria, Franklinia, Gomortega, Gymnostemon, Haldinia, Hartogiella, Itaya, Ixerba, Jablonskia, Jubaea, Kigelia, Kleinhovia, Koordersiodendron, Kostermansia, Krugiodendron, Laguncularia, Limonia, Litchi, Maesopsis, Muntungia, Neobalanocarpus, Noltea, Ochroma, Olneya, Oroxylum, Platycarya, Pleiogynium, Rhoiptelea, Spathodea, Ticodendron, Triplochiton, Umbellularia, Umtiza, Veillonia, Vitellaria, Xanthoceras* and *Zombia*. Monotypic wild fruit-tree ancestors, such as *Clymenia polyandra* from Melanesia, may hold importance for future citrus breeding. The monotypic *Cordeauxia edulis*, an important multipurpose woody shrub in Ethiopia and Somalia, is classified as vulnerable on the IUCN Red List of Threatened Species (www.iucnredlist.org), and the monotypic *Canacomyrica monitcola*, endemic to New Caledonia (France), is classified as endangered.

Several angiosperm orders and whole families of woody tree species are represented by one or very few taxa. The family Barbeyaceae comprises the monotypic *Barbeya oleoides*, a small tree with medicinal uses present in northeastern Africa and the Arabian Peninsula. The Degeneriaceae include two Fijian timber tree species, ancestral angiosperms in the genus *Degeneria*. The Sladeniaceae include three tree species in two genera: *Ficalhoa laurifolia,* a timber tree from montane forests in East Africa, and two Chinese tree species of the genus *Sladenia* which have potential as sources of novel biochemicals, including for use in insecticides. The order Trochodendrales and family Trochodendraceae include two East Asian tree species each in a monotypic genus, *Trochodendron araloides* and *Tetracentron* sinense. These two tree species are notable in angiosperms for their absence of vessel elements in the wood, which is thought to be a secondarily evolved character and of scientific interest. The 194 palm species in Madagascar, almost all endemic, and several monotypic palm genera in Seychelles include unique and endangered genetic lineages.

*Sources*: *The Plant List*, 2013; ILDIS, 2012; Earle, 2013.

populations as feasible. In many countries, DNA research on trees is carried out by institutions such as universities and research agencies that are not the same as or well linked with the institutions tasked with developing and implementing FGR conservation strategies (e.g. forestry and environment departments, land managers). Accordingly, improved FGR conservation and management planning and outcomes will require closer communication between these two groups, both in identifying priority species for study and subsequent planning and in implementation and monitoring of conservation and management strategies based on research findings.

## Chapter 2

# Value and importance of forest genetic resources

> "Sustainable forest management of both natural and planted forests and for timber and non-timber products is essential to achieving sustainable development and is a critical means to eradicate poverty, significantly reduce deforestation, halt the loss of forest biodiversity and land and resource degradation, and improve food security and access to safe drinking water and affordable energy… The achievement of sustainable forest management, nationally and globally, including through partnerships among interested governments and stakeholders, including the private sector, indigenous and local communities and non-governmental organizations, is an essential goal of sustainable development…"
>
> Paragraph 45, Plan of Implementation of the World Summit on
> Sustainable Development (UN, 2002)

In its 2012 *Millennium Development Goals Report*, the UN (2012) estimates that, despite progress in eradication of extreme poverty, almost 1 billion people will be living on an income below USD 1.25 per day in 2015; and that (citing FAO) 850 million people, or 15.5 percent of the world's population, were living in hunger in the period 2006–2008. In this context of poverty and hunger, the sustainable use of timber and non-wood forest products (NWFPs) from forests, without depletion of the supporting FGR, is becoming increasingly challenging. Limited options for economic development and an imperative to focus on immediate needs are difficulties that promote short-term perspectives in the use and management of natural resources, including forests and FGR. The increasing global population is placing additional pressures on forests, especially in the tropical developing regions (see Chapter 5). It is estimated that about 60 million people (mainly indigenous and tribal groups) are almost wholly dependent on forests for their livelihoods. In 2008, for the first time in history, more than half of the world's population was living in towns and cities (UNFPA, 2007), but despite the marked urbanization trend, the demand has not diminished for wood and fibre for building, fuel, paper and NWFPs and agroforestry tree products (AFTPs) such as herbal medicines and foods.

This chapter reviews the immense value for humankind, and more generally for life on Earth, that FGR represent. It is often difficult to quantify these contributions. While the country reports note the importance of FGR to the formal and informal economies and their social, cultural and environmental value, limited attempts were made to assign monetary value to any of the specific contributions of FGR. Nevertheless, and although the absolute and relative value of forests and trees and their products and services vary tremendously from country to country, an underlying and unifying theme from the country reports is that this value depends on the continued availability, access and use of FGR.

## Economic value

### Economic importance of forests and forest industries

The specific economic benefits arising from conservation and use of FGR are difficult to isolate from the economic benefits and impacts of forest and tree resources and the industries that rely on them. FAO (2013b) estimates that close to 1.6 billion people – more than 25 percent of the world's population – rely on forest resources for their livelihoods. The key economic values associated with FGR occur both in formal sectors, e.g. production, trade and employment (associated mainly with timber, pulp and paper industries but also with agriculture, horticulture and pharmacy), and in informal sectors, which are often poorly documented, such as local uses of forest foods, fuelwood and herbal medicines. Most countries reported the economic value of forest industries in the formal sector (such as contribution to GDP, exports, employment), but could not address with precision the value of forests and trees in the informal sector and their contribution to rural livelihoods and poverty alleviation.

The forest products industry alone is a major source of economic growth and employment, with global forest products traded internationally in the order of USD 255 billion in 2011. Some 40 percent of this value is generated in developing countries, where forest-based employment provides 49 million jobs (FAO, 2014). The forest sector is a major provider of rural employment in many countries; in Africa, for example, it supports 16 to 18 percent of the workforce in Swaziland and 20 to 30 percent of the workforce in Gabon.

The forest sector contributes substantially to exports in many countries. At over USD 16 million, Canada's forest balance of trade is the largest in the world, while in Ghana the sector ranks fourth in contribution to export earnings. The Solomon Islands report that the export of roundwood (1.4 million cubic metres in 2008) provided over 70 percent of export earnings and 18 percent of total government revenue and is the mainstay of the economy.

In all, several billion people worldwide in the informal economy depend in some form on wood products and NWFPs from forests and trees (see Box 2.1). The World Bank (2002) has estimated that about 1 billion people worldwide depend on drugs derived from forest plants for their medicinal needs. In many developing countries fuelwood is the primary source of energy, meeting in some cases as much as 90 percent of energy requirements (Trossero, 2002). Harvesting of NWFPs from trees and forests in impoverished rural areas provides income-earning opportunities for women in particular, contributing to gender equality. In rural areas of one state in India, women obtained 2.5 to 3.5 times as much income from forests and common lands as men (India country report). NWFPs may also provide significant additional income to small forest owners and traditional communities in developed countries; in Canada, for example, maple syrup products and Christmas trees generate USD 324 million and USD 36 million worth of sales, respectively, each year (Natural Resources Canada, 2011). The conservation of FGR and the development, distribution and deployment of improved forest trees for use by rural communities therefore offers immense potential to improve and increase security of livelihoods.

Trees have an extremely important role in supporting agricultural production, particularly in developing countries, by providing shelter, shade, soil structure and fertility improvement; reducing erosion and mitigating floods; and furnishing materials such as fencing, processing equipment, and tools. In Ghana, for example, "the use of non-timber forest products in agriculture technologies is such that in their absence most farming activities would be impaired" (Ghana country report). Trees also provide fodder, which may be critical during the dry season or in times of drought; for example, in India nearly 39 percent of cattle depend partly or fully on forests for fodder (India country report). Biochar, a non-labile carbon soil additive obtained from biomass, including forest biomass, can also be used to increase agricultural productivity (Dawson *et al*., 2014).

Forests and trees also have an important role in alleviating poverty in times of hardship and crop failure, for example by providing fuelwood when other fuels are inaccessible. Tree food crops are vital in times of drought, when other annual, rain-dependent crops may fail. The role of trees as food sources to help alleviate famine is likely to increase with predicted negative impact of climate change and associated environmental stress on agriculture.

## Economic contribution of genetic diversity

The genetic diversity available in tree species is often of economic utility. In planted forests, including agroforests, improved, better adapted and diverse germplasm directly contributes to improved economic well-being by increasing the output of superior forest products for lower inputs (e.g. labour, water and fertilizer), in a wider range of conditions and environments,

### Box 2.1
### Valuing non-wood forest products demand

Non-wood forest products are essential to people's livelihoods and national economies. Recent estimates (FAO, 2010a) indicate the global value of NWFPs to be less than USD 17 billion annually (Table 2.1). However, their reported value remains underestimated because of lack of information and relevant assessment tools at the country level.

The country reports on the state of forest genetic resources identified over 1 000 tree species as actively managed for NWFPs. However, this number is far below the estimates usually found in publications. For example FAO (2011) indicates that 75 percent of the overall tropical tee species are used for their NWFP value.

**TABLE 2.1**

Value of removals of plant-based NWFPs (and bee products) by category and region

| NWFP category | Total value (million USD) | Share of each category in total value (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | World | Europe | Asia | Americas | Oceania | Africa |
| Food | 8 614 | 51 | 48 | 67 | 23 | 47 | 93 |
| Other plant products | 2 792 | 17 | 3 | 22 | 61 | 3 | 7 |
| Wild honey and beeswax | 1 805 | 11 | 21 | n.s. | n.s. | 12 | n.s. |
| Ornamental plants | 984 | 6 | 10 | 1 | 3 | 4 | 0 |
| Exudates | 631 | 4 | 1 | 7 | 5 | 0 | 25 |
| Plant materials for medicines, etc. | 628 | 4 | 5 | 2 | 1 | 9 | 18 |
| Material for construction, tools, etc. | 427 | 3 | 3 | 1 | 3 | 18 | n.s. |
| Fodder | 21 | n.s. | n.s. | n.s. | n.s. | 0 | 2 |
| Colourants and dies | 18 | n.s. | n.s. | n.s. | n.s. | 0 | n.s. |

*Source*: FAO, 2010a.
Note: n.s. = not significant.

with fewer losses to pests and diseases. FGR are the basis of tree improvement and improved forest plantation crops, and countries in all regions reported significant gains in productivity and utility from improvement programmes and/or widespread use and adoption of improved materials. Increased yields of superior forest products generated at lower cost from genetically improved trees can reduce the harvest pressure on natural forests and allow them to be harvested in a less intensive, more sustainable manner, better enabling them to fulfil service roles.

The use of selected better-performing seed sources (provenances) will often give increases of 10 to 25 percent, and sometimes several hundred percent, in wood yield above the mean or the yield of the prior seed source. Given that seed accounts for a small proportion (e.g. 0.1 to 3 percent of plantation establishment cost, major economic benefits accrue from using appropriate germplasm in plantation establishment and agroforestry (e.g. FAO, 2002). Economically important, although often threatened, diversity is contained in wild tree relatives of fruit- and nut-tree species. For example, germplasm of a wild and threatened Central Asian apple species, *Malus sieversii*, collected in the 1990s from Kazakhstan, has shown resistance to apple scab, fire blight, drought and numerous soil pathogens and is being used by the United States Department of Agriculture (USDA) Agricultural Research Service to improve disease resistance in current apple cultivars in the United States of America (Forsline *et al*., 2003; Pons, 2006) for industry worth USD 2.7 billion in 2011.

Many NWFP species have a wide genetically determined variation in the yield and quality of their products, and indeed some industries are only possible because of this variation. An example is "unique manuka factor®" (UMF) honey, a honey with highly antimicrobial properties produced only by bees feeding on the nectar of particular populations of *Leptospermum* spp., such as some populations of *Leptospermum scoparium* in New Zealand (Stephens, 2006). In Vanuatu certain individuals and populations of *Santalum austrocaledonicum* from the islands of Malekula and Santo produce a sandalwood oil that meets the international standard for East Indian Sandalwood oil and accordingly have much higher value as seed and wood sources (Page *et al*., 2010); future replanting will increasingly be based on these sources (Stephens, 2006). The rich species diversity of tropical forests directly contributes to their provision of a wide range of NWFPs; in Brazil, for example, honey bees have been found to produce a new type of medicinal red propolis through collection of resin from the bark of *Dalbergia ecastaphyllum* (Silva *et al*., 2008).

## Environmental value, ecosystem services and resilience

Trees and forests provide a wide variety of environmental services. As well as holding a greater proportion of the world's biodiversity than any other terrestrial ecosystem, they have an increasingly recognized role in environmental protection and rehabilitation. They contribute to water catchment management, carbon sequestration and storage, nutrient cycling, improvement of soil fertility, erosion management and landscape protection, promotion of agricultural production, animal habitat, and maintenance of ecological and ecosystem processes. All trees and woody plants, whether planted or of natural origin, fulfil ecological and environmental functions and provide a huge range of environmental services. Nevertheless, vital environmental services have traditionally been undervalued owing to lack of markets for these services.

### Biodiversity

Forest ecosystems are repositories of huge reservoirs of biodiversity. They support a vast number and wide range of species, most of which are forest dependent. Nearly 90 percent of terrestrial biodiversity is found in the world's forests.

The most species-diverse ecosystems on Earth are moist tropical lowland forests, which are principally located in developing countries. The vast richness of herbivorous insects in these forests has recently been shown to be driven by the phylogenetic diversity of their plant assemblages (Novotny *et al*., 2006).

Temperate forests and forest tree species support and provide habitat for myriad other life forms. For example, two thirds of Canada's 140 000 species occur in forest ecosystems. In the United Kingdom, 285 different species of phytophageous insect have been found on *Quercus robur* (Southwood *et al*., 2004). In Australia, 306 species of invertebrates have been found on *Eucalyptus obliqua* (Bar-Ness, Kirkpatrick and McQuillan, 2006). In Australia, a poster produced by the Conservation Commission of the Northern Territory has referred to the native *Eucalyptus camaldulensis*, widely planted globally, as "nature's boarding house" in recognition of the number of mammals and birds that use it for food, shelter and nesting sites. In less tree-species rich temperate forests, the role of trees in promoting biodiversity is likely to be more associated with and attributable to their level of intraspecific genetic variation (e.g. Whitham *et al*., 2006).

## Ecosystem function

Trees contribute major photosynthetic inputs. They drive carbon, water and nutrient cycling, especially absorbing and returning nutrients from deeper root zones, mobilizing mineral elements through associations with mycorrhizal fungi and fixing atmospheric nitrogen through symbiosis with bacteria. In addition, they provide diverse substrates and physical structure to forested terrestrial ecosystems.

## Carbon sequestration, climate change mitigation and resilience

Climate change poses a major threat to forestry, biodiversity, agriculture and food security through extreme climatic events, droughts, increases in temperature, more frequent and intense wildfires, and increased activity of pests and diseases. Effective FGR conservation and management will take on even greater significance against a background of such climate change impacts and associated changes to forest structure and composition. It will be increasingly vital to provide the deepest possible reservoir of genetic variability on which natural and artificial selection can act, facilitating adaptation to changed conditions.

Under more extreme climatic conditions the use of trees and forests for food and fibre is likely to become even more important, for example because of increased risks of failure of rain-fed agriculture and annual crops. Trees and forests, and their genetic resources, will also have an essential and central role in helping to limit rises in atmospheric carbon and slow climate change through sequestration and storage of atmospheric carbon. Mature, new and planted forests can sequester substantial amounts of carbon. Vigorously growing planted forests sequester vast amounts of carbon; for example, eucalypt hybrids in Brazil can sequester as much as about 80 tonnes of $CO_2$ per hectare. Brazil also remarked on the importance of retaining healthy natural forests (such as the Amazon forest) to maintain global climatic conditions, noting that this would also maintain a competitive agricultural sector. Estimates put the carbon storage of boreal forest at 703 gigatonnes, tropical forests at 375 gigatonnes and temperate forests at 121 gigatonnes (Kasischke, 2000). Furthermore, billions of people use woodfuel rather than burning fossil fuels.

While mature forests are more or less in carbon balance, their between- and within-species diversity helps to buffer them against change and destruction (whether related to climate, biotic factors, fire or a combination of these) which might otherwise result in damaging releases of $CO_2$. Tree breeders will require genetic diversity to develop faster growing, well adapted trees for a diverse range of environmental conditions for carbon sequestration and production of woodfuels.

Resilience capacities of forest ecosystems are conferred at multiple scales, through genetic, species and landscape heterogeneity (Thompson

*et al*., 2009, 2012). The abilities of different species, including tree species and genotypes, to substitute functions is key to their buffering of impacts of environmental change and maintenance of ecosystem functioning (Walker, 1992; Lavorel, 1999; Yachi and Loreau, 1999; Elmqvist *et al*., 2003; Hooper *et al*., 2005; Winfree and Kremen, 2009; Thompson *et al*., 2012). Accordingly, the ability of an individual forest stand to adapt to and recover from environmental changes will depend on the number of species, their diversity, individual adaptive capacities and abilities to substitute different functions. The roles of forest genetic diversity in ecosystem adaptation and resilience are fertile topics for research, but in-depth scientific investigations are still in their infancy.

## Social, cultural, medicinal and scientific value

Forest genetic resources have major social, cultural and spiritual values, mainly at tree species level, with many individual tree species distinguished and named in local languages. In Fiji, for instance, *Intsia bijuga* – a tree that has spiritual significance throughout the Pacific islands – is called "vesi", which is also the name reserved for village chiefs. Various native tree species are intertwined with local cultures, customs, folklore, stories, poems, and cultural identity and are integral to the daily lives of indigenous peoples. Many thousands of tree species are used in products, customs, ceremonies and rituals, often developed over millennia, that help give meaning to and enrich the lives of hundreds of millions of people. In many parts of sub-Saharan Africa, for example, certain trees are considered sacred and are maintained in sacred groves or church plantings. In India between 100 000 and 150 000 sacred groves have been reserved (India country report), and certain tree species have tremendous social and cultural importance, e.g. *Ficus religiosa* in religious ceremonies, *Santalum album* in burial ceremonies and *Azadirachta indica* in traditional medicinal culture. In the Russian Federation, 7 980 ha of forest were opened to the public in 2012 for religious activities.

There are also numerous examples where intraspecific tree diversity has cultural importance. For example, in the Pacific islands there are hundreds of named varieties of *Pandanus tectorius*, mostly selected female plants propagated vegetatively. Different varieties are used at different times for food, for different types of leis, and in different types of thatched mats and other plaited wares (Thomson *et al*., 2006). *Pandanus tectorius* is also important for construction materials, medicines, decorations, perfumes, and many other cultural uses. For most people in Kiribati it is the ancestral tree from which, according to legend, their progenitors came (Luomala, 1953).

Country reports noted that medicinal uses of forest resources are extremely important in some regions and countries. Many more trees are utilized for medicine in Africa than in other regions, with medical use named in 14.4 percent of total reported uses. As an example, in Zimbabwe over 78 percent of the rural population uses traditional medicines, mostly derived from trees and woody plants, at least once a year for humans and livestock. In the Pacific island countries, medicinal use accounted for 8.6 percent of reported uses, and medicinal uses are also important in Indian Ocean island countries such as Madagascar and Seychelles. Medicinal uses of trees were also noted as important throughout Asia, including China (with nearly 1 000 medicinal plants used, mainly woody species), India, Indonesia (with 2 039 medicinal plants used) and Nepal.

The search for medicinal compounds, or bioprospecting, has potential to yield dividends to supplier countries where sound benefit-sharing arrangements are in place. Many tree and shrub species are exploited or being investigated for medicinal purposes. Among them are *Homalanthus nutans* from Oceania, *Prunus africana* from the humid tropics of Africa, *Cinchona* spp. from Latin America, *Emblica* *officinalis* from India and *Pinus sylvestris* from Europe, to mention some. In some countries (including among others India, Madagascar and Solomon Islands), the chemistry and medicinal value of the flora are being investigated. Given the vital importance of FGR for traditional medicines and the potential benefits from bioprospecting, there is a vital need for more research on the medicinal value of forest trees to help unlock the full potential of FGR.

FGR are of major scientific value. Intraspecific diversity can be used, for example, to help understand the genetic, biochemical and physiological basis for resistance to pests and diseases or environmental stresses such as extreme climatic events (drought, flooding) and edaphic extremes (salinity, acidity, etc.). It can also be used to identify biosynthetic pathways for production of important products and metabolites. A recent and surprising example of the potential scientific importance of a previously little-known tree species is provided by *Amborella trichopoda*, a small understorey tree endemic to the wet upland forests of New Caledonia (France), which is endangered by habitat destruction. *Amborella trichopoda* appears to have diverged earlier than other flowering plants (about 130 million years ago) and lacks vessels in the wood which are characteristic of other angiosperms. In 2012 the *Amborella* Genome Project (www.amborella.org) produced a draft genomic sequence which will be used as key evidence for understanding the ancestral state of every gene, gene family, and protein sequence in flowering plants and their radiation through the history of flowering plants. This genomic information may provide insights into the evolution of flowering and vessel formation in wood.

## Preserving options for future development and adaptation

One of the most important characteristics of FGR is that they will be vital for adaptation to future changes – not only to those that are becoming evident such as climatic extremes and new warmer climates brought about by increases in atmospheric $CO_2$, but also to others of which little is known. Based on geological records, the Earth is likely to return to a new period of glaciation possibly 3 000 to 20 000 years hence, but the possible long-term impacts of human-induced global warming on a future glaciation event are unknown. In the meantime it would be reprehensible to allow useful tree species and populations adapted to cooler climates to become extinct from global warming and other factors when their germplasm might be conserved safely and relatively cheaply in cold storage such as the Svalbard Global Seed Vault in Norway (–18°C) for several hundred to thousands of years.

The importance of maintaining FGR to preserve options applies to both natural forests, where a vital dimension is the capacity to adapt to changing environments, and planted forests, which may hold the key to new products and services while at same time proving resilient. In the case of planted forest tree species, there is a need to maintain as much intraspecific diversity as possible to allow tree breeders to continue to select and develop improved and adapted germplasm to cope with new demands and growing conditions. Conservation of intraspecific diversity will also serve the development of new wood products and NWFPs, especially pharmaceuticals and neutriceuticals such as sources of antioxidants, anti-inflammatories and other chemoprotective natural compounds. Novel uses may be elaborated, such as breeding of trees specifically to sequester carbon or to recycle plant nutrients from beyond crop root depth, or "harvesting" of precious minerals through phytomining. Wood and Grauke (2010), for example, have found that tetraploid *Carya* species accumulate high amounts of rare-earth metals (almost 0.1 percent dry weight), much more than diploid *Carya* species and other tree species. In New Caledonia (France), Boyd and Jaffré (2009) recorded several tree species, including *Geissois pruinosa* and *Homalium kanaliense*, as hypernickelophores, i.e. species that can accumulate large amounts (up to 1 percent of leaf dry mass) of nickel. The differential ability of plants to accumulate gold is also well known (e.g. Girling and Peterson, 1980) but has not been commercially exploited to date. In future, certain tree species and genotypes might be used or selected and bred for phytoremediation, i.e. to remove or neutralize contaminants, say from polluted soil or water (e.g. Raskin and Ensley, 2000; Pilon-Smits, 2004).

To sum up, it is evident that well characterized (in terms of growth and adaptability attributes, including genotype by environment interactions, and the type and quality of end products and/or services), genetically diverse wild populations (or provenances) of different tree species will provide extremely useful genetic materials both for immediate planting programmes and as the basis for future selection and improvement programmes. The diverse values and uses of forests, trees and FGR identified in country reports underscore the need for national FGR strategies and effective programmes and action plans to address not only the applications and requirements of the formal forest and forest industry sectors, but also the role of FGR in the informal economy, in alleviating poverty, in social, cultural and spiritual areas, and in environmental services and rehabilitation. The major contribution of FGR to the informal economy highlights the need to consult with the widest range of forest users possible when preparing national strategies and programmes.

## Chapter 3

# Conservation of forest genetic resources

Individual trees contain genetic variations that distinguish them from other members of their own species and other species. Variation is continuously generated through sexual recombination and mutations, and natural selection acts on this background of variability through the process of evolution, producing new variants that are better adapted to survive, to compete and to cope with changing environmental conditions. Genetic variation provides the basis for selection of genotypes and varieties better suited to meeting human needs (i.e. able to provide more useful products or services in a more efficient manner) in a wider range of settings and under changing environmental conditions. Provision of forest-derived goods and services depends on the presence of FGR and also has implications for their survival.

The future value of FGR will be determined by the way humans manage these resources and act in their role as the primary agents of environmental change in today's world. Humans influence the value of FGR even when they are not aware of doing so, by using trees and forest resources and altering environmental conditions, as much as through conscious efforts to better conserve and manage them. Indeed, the growing awareness of how human actions, or lack thereof, have impact on FGR is a recurrent theme in country reports. However for the purposes of this report, and given the imperative to recognize that the future of FGR depends on conscious, effective human intervention through deliberate management, the term "management" is used to describe deliberate planned actions taken to conserve and protect FGR.

Conservation of forest genetic resources can be defined as the policies and management actions taken to assure their continued availability and existence. Conservation and management of FGR are inextricably intertwined. Conservation of FGR requires implementation of well planned, scientifically sound strategies, including management of FGR in breeding programmes and in production populations.

The strategies and methodologies applied in conservation depend on the nature of the material, the timescale of concern, and the specific objectives and scope of the programme. Two basic strategies are used for genetic conservation: *in situ* (on site) and *ex situ* (off site, e.g. in designated conservation stands, field gene banks, arboreta and botanic gardens). These two strategies are generally viewed as complementary and are best carried out in parallel when the aim is conservation of species and intraspecific genetic variation. Coordination is required among the various agencies and organizations concerned, i.e. forestry departments managing reserved forests and *in situ* gene conservation stands; environment departments managing protected areas; government agencies, private forestry companies and cooperatives carrying out tree improvement programmes; government research agencies, botanical gardens and universities maintaining gene banks of seed and tissue cultures; and private landholders and communities managing privately owned

managed forests, planted forests, agroforests and farmlands. Both the general and particular strategies and programmes to be pursued will depend on factors such as the available financial, human and land resources; human population and resource use pressures on land, forests and trees; technological options for particular species; and the nature and dimensions of the conservation challenges, e.g. whether the aim is to conserve a large number of forest species, a smaller number of rare and endangered species, or the genetic diversity and evolutionary potential of a smaller number of high-priority species for planting programmes. Additional challenges and opportunities arise in situations where there is an international dimension, e.g. when the natural range of a species crosses national borders; when a species has greater economic importance as a planted exotic than it has in its native habitat; and when opportunities for *ex situ* conservation in well resourced facilities (such as tree seed banks or tissue culture facilities) are available abroad.

The management of forest genetic resources to ensure their conservation, improvement and sustainable use simultaneously is a complex technological and managerial challenge. Fortunately, when simple basic principles are applied, the production of goods and services from managed forests forming part of a legislated permanent forest estate is generally compatible with the genetic conservation and development of particular forest tree species, as discussed in the next section.

## Management systems in the field (*in situ* and *circa situm* conservation)

Forest genetic resources conservation and management in the field should ideally be considered and integrated into all land uses and management systems containing trees. The most important of these are sustainably managed multiple-use production forests, protected forests and agroforests, described in the following sections.

Ecosystem- and landscape-based conservation approaches and management regimes can also conserve a wide array of forest tree species and their diversity *in situ*. These approaches lack a focus on particular tree species except in the case of keystone species whose continued existence and diversity are vital for maintaining the ecosystem's health. The ecosystem approach is well suited to areas with high tree species diversity, such as lowland moist tropical forests; it can ensure the continued survival and availability of large numbers of useful tree species which may have localized and/or potential importance. However, in locations where local human populations rely on a vast number of tree and woody species to provide diverse products, sustainable management of multiple-use production forest is a more effective approach.

Conserving and managing the variability of FGR *in situ* provides the basis for selection and adaptation and will promote continued ecosystem function and services. Forest genetic diversity helps ensure healthier, more resilient forests better able to deliver essential functions. Adaptation to changing environmental influences requires a high degree of genetic diversity in tree species because of their immobility and perennial, long-lived life forms. Where forests have been degraded, the use of appropriate species and provenances, selected from the pool of natural variability maintained through effective FGR conservation and management, can assist forest restoration (Box 3.1). Increasingly the diversity within and between tree species is being found to be critical to promoting and maintaining almost all other life forms present in forest ecosystems.

Increasingly many socio-economically important tree species are being conserved through use; they are often planted for productive and other purposes in planted forests, agroforests, orchards and urban landscapes (in home gardens and parks and along streets). The conservation of FGR in these cases is often incidental, unplanned, and suboptimal; an exception is breeding programmes and seed orchards which are often

### Box 3.1
### Application of genetic principles in forest ecosystem restoration and management

Forest ecosystem restoration is of growing interest as a means of mitigating climate change and of combating its negative impacts, which are associated with continued deforestation and degradation of forest ecosystems worldwide. Typically, however, little attention is paid in restoration initiatives to ensuring the use of appropriate sources of forest reproductive material. While geographical origin of planting material is often considered – i.e. it is commonly understood that local sources are preferable – other genetic factors are rarely considered (Bozzano *et al*., 2014). Guidelines recommending the number of source trees needed for provision of reproductive material are sometimes available, but they are often inadequate. While tree planting for production is regulated with regard to provenance seed source delineation and the use of certified or source-identified seed stand collections, restoration projects are not legally required to use certified or identified seeds.

Examples of knowledge gaps in the genetics of forest ecosystem restoration include quantification of the risks associated with genetic mismatching of source of planting material to site conditions or narrow genetic base, particularly considering climate change; thresholds for optimal genetic diversity in restoration material; and genotype × environment interactions. It would also be valuable to understand the potential for combining species rescue with ecosystem restoration, i.e. the potential of individual restoration projects to contribute to species conservation and serve as future seed sources, especially for rare, endemic and endangered tree species.

designed for improvement and to maintain a balance of diversity. Urban landscapes, farms, hotel resorts, golf courses, etc. offer opportunities for conserving substantial tree species diversity (including within-species diversity) if managers of these areas are made aware of the importance of tree conservation activities and are linked into national FGR programmes. However trees outside forests in non-agricultural land-use systems such as urban landscapes are outside the scope of this report.

Species selection and availability of reproductive material is another issue of concern. Exotic species or seed sources are commonly used for restoration and in some cases are clearly justified. In other cases, however, the use of exotic species not only can result in wasted efforts, but can threaten native species if the exotic ones become invasive. Often the reason for using exotic species is simply local availability in nurseries and level of knowledge about nursery production requirements. Expanded knowledge of native tree species is needed in order to understand their potential to achieve diverse restoration objectives in different states of site degradation and different ecological, environmental and socio-economic contexts. It is also important to understand the trade-offs (again, ecological, environmental and socio-economic) related to the use of exotic versus native species, as well as the factors that currently constrain wider use of native species.

## Sustainably managed multiple-use production forests

Sustainable forest management involves the management of forests in a manner that ensures that their overall capacity to provide environmental and socio-economic benefits is not diminished over time. Central to the sustainable development of forests is the challenge of balancing resource use and conservation. Sustainable forest management and the maintenance of FGR must be considered as interdependent: Forest owners, custodians and managers need to understand and appreciate the essential underpinning role of FGR in forest and natural resource management practice in order to implement effective interventions for their conservation and use (Ratnam *et al*., 2014). Many management measures have been developed to maintain diversity in forest ecosystems and simultaneously to promote the sustainable use of this diversity (see e.g. FAO, 1993; Thomson, 2004). What is lacking is their constant application and monitoring. Furthermore, harmonization of conservation objectives and utilization practices in production-oriented, multiple-use native forests will be essential for conservation of the diversity of most of the tree species, given that they are not well represented in protected areas, planted forests and *ex situ* collections (Thomson, 2004).

Diverse indigenous forest management systems and practices have employed technologies for managing and using native forests in a manner that does not diminish, and preferably enriches, their FGR. Forest agencies and private forestry companies can readily integrate FGR management practices into modern silvicultural systems. However, in many parts of the world, tree species diversity and intraspecific diversity are declining because best-practice forest management systems are not being implemented or are breaking down for various reasons, often as a result of increased population pressure and associated unsustainable use including overharvesting of timber, fuelwood and NWFPs; reduction in seed sources of pioneer and early secondary trees; and insufficient time for deep-rooted perennial vegetation to replenish soil fertility between shortened fallow periods. Furthermore the area under production forests, considered vital for conservation of FGR, has continued to decline at an increasing rate, by about 2 million hectares per year during the 1990s and 3 million hectares per year between 2000 and 2010 (FAO, 2010a) (see Part 2 on drivers of change).

Some 80 percent of the world's forests are under public ownership, and 80 percent of publicly owned forests are under public administration (FAO, 2005a), suggesting that national governments are in a strong position to directly influence and control forest management practices. However, in the developing tropics, many production forests are under private logging concessions, and governments frequently lack resources to develop sustainable best practices such as codes of logging practice and reduced impact logging guidelines, or to enforce their implementation by private operators. The problem is compounded where concessions are issued for a short term or only once, as the logging concessionaire in such cases is likely to harvest in a manner that will maximize profits, possibly with little consideration for regeneration and subsequent harvests.

Sustainable production of goods from natural forests is expected to be increasingly challenged by more extreme climatic events in future (particularly more intense tropical cyclones, droughts and associated bushfire, intense rainfall events with landslips and flooding, and melting of permafrost). Interactions of climate change with existing and new pests, diseases and invasive weeds, as well as climate change impacts on pollinators and dispersers, will affect production, selective forces and the future forest composition. The genetic diversity contained within and among tree species will provide essential buffering for these impacts on many productive and service functions of forests, but a much greater level of management intervention and manipulation may be required, including movement of tree germplasm to respond to new climates, changed pests and diseases and new selective pressures.

Sustainable forest management cannot by itself ensure conservation of all FGR. Some tree species and populations require special and immediate attention, and many species that are of no or little current utilitarian value will probably receive little attention from forest managers. Some of these lesser-known or less economically important species may depend on complicated ecological interaction and may suffer from what is believed to be gentle use of the forest resources.

Therefore, an integrated approach encompassing management of natural stands and establishment of specific conservation populations is advocated.

## Protected areas

Existing national protected area systems are often a valuable starting point for a network of conservation stands of a particular species. Indeed it is likely that several thousand tree species only occur within the existing protected area network. However, the security of forest protected areas remains a major concern, especially in developing nations, where it is likely that many face threats to their integrity and existence in the medium term. Fully protected areas are only likely to succeed long term in areas of low population pressure.

On a positive note, FRA 2010 (FAO, 2010a) found that the area of forest designated for conservation of biological diversity increased by about 6.3 million hectares per year during the decade from 2000 to 2010, and a similar increase occurred in the area of forest in protected areas. In both cases the increase is equivalent to nearly 2 percent per year.

## Agroforestry systems, including trees on farms

The development of context-specific agroforestry systems, integrating traditional knowledge and scientific advances and based on diverse, adapted tree germplasm – as in the work of the World Agroforestry Centre (ICRAF) and national and non-governmental organization (NGO) partners – offers one of the most promising solutions for addressing problems of overpopulation and limited land base. It is estimated that 1.2 billion people use trees on farms to generate food and cash (World Bank, 2002), and almost half of the agricultural land in the world, or more than 1 billion hectares, has a tree cover of more than 10 percent (Zomer *et al*., 2009). The importance of using appropriate, matching, diverse and improved germplasm in agroforestry systems has been increasingly appreciated over the past two decades, including the need for appropriate seed and seedling production and dissemination systems (see Box 3.2). Many indigenous fruit- and nut-tree species have been domesticated to provide a source of nutrition and income for rural households. ICRAF coined the term "agroforestry tree product" (AFTP) for these new products. The research and development and extension efforts in agroforestry will continue to show results as long as the genetic diversity on which they rely is both conserved and accessible. In addition, knowledge on the importance of germplasm and on its selection and improvement has spilled over from conventional plantation forestry to agroforestry research and development.

### Box 3.2

### Evolving use of tree germplasm in modern agroforestry in South Pacific islands

In Fiji and other island nations of Oceania, through the mid-1970s and early 1980s the official promotion of village forestry mainly consisted of distribution of seedlings of *Pinus caribaea*, including those left over from *P. caribaea* planting programmes. During the 1980s the emphasis moved to alley cropping systems with fast-growing nitrogen-fixing exotic trees, supported by the Fiji-German Forestry Project. *Calliandra calothyrsus* was shown to be suitable, but farmers did not adopt the systems. During the mid-1990s and 2000s the South Pacific Regional Initiative on Forest Genetic Resources (SPRIG) project, funded by Australia, worked with national partners to develop and domesticate a much broader selection of native tree species and a few key exotics, such as *Swietenia macrophylla* and *Tectona grandis*, which are now being incorporated into a diverse range of agroforestry systems, including modified traditional polycultural systems. The extremely cyclone tolerant, multipurpose timber tree *Terminalia richii*, which had been reduced to scattered trees by the mid-1980s, is now being widely planted by smallholder farmers and tree growers in Samoa.

## *Ex situ* conservation

The primary aim of *ex situ* conservation has always been to ensure the survival of genetic resources which otherwise would have disappeared. For forest genetic resources, *ex situ* conservation has generally referred to storage as seed, when practical, usually under conditions of low moisture content. Having evolved over millennia to ensure the dispersal of the species genomes, pollen and seed are ideal starting materials for innovative conservation programmes. *Ex situ* approaches of significance include enhancing seed production through artificial pollination and treatments ensuring efficient seed germination to generate the next cohort of plants (which are beyond the scope of this review). Such work is underpinned by knowledge of the species distribution and the application of horticultural skills to seedling growth.

Where species are intolerant of seed storage conditions, it has been necessary to rely on field or glasshouse collections. However, such collections are costly to maintain and are at risk from pest and disease outbreaks and climate variability and extremes, and therefore are not as safe as seed storage for long-term conservation. For these reasons *in vitro* technology has been proposed as an alternative strategy.

To improve the *ex situ* conservation of forest genetic resources using seed storage, significant effort has to be spent in developing postharvest technology for proper handling and identification of storage behaviour. Once seeds of a particular species have been classified, then strategies can be developed for their conservation according to their storage behaviour.

### Gene banks

Conventional seed storage is believed to be a safe, effective and inexpensive method of conservation for seed-propagated species. Many countries have national tree seed banks, but these are often active collections with rapid turnover and use of collected seedlots, in which conservation is a supplementary or incidental benefit. Yet large numbers of trees and woody species can be conserved long term in seed banks. A major international example of this conservation strategy for trees and woody species is the Kew Millennium Seed Bank Partnership (see Box 3.3). As an example of the partnership in action, the National Forest Seed Centre (CNSF) in Burkina Faso has 160 tree species in long-term cold storage (Burkina Faso country report). In the Russian Federation a notably large number of seed banks contribute to the collection and storage of forest seeds; among them is the Vavilov Research Institute of Plant Industry (www.vir.nw.ru), which stores some 323 000 samples of 2 169 plant species.

For successful long-term conservation through seed storage, it is necessary to determine the factors that regulate seed viability and vigour. Viability must be monitored continuously, with recollection or regeneration whenever the

#### Box 3.3
#### Millennium Seed Bank Partnership

The Millennium Seed Bank Partnership, based in the United Kingdom (see www.kew.org/science-conservation/millennium-seed-bank), is the largest *ex situ* conservation project based on seed storage in the world; the project has banked 10 percent of the world's wild plant species, including many woody species, and aims to conserve 25 percent of wild plant species by 2020. This expansive global partnership involves about 50 countries and agencies such as FAO and Bioversity International. It was developed in part to enable countries to meet international conservation objectives set by the Global Strategy for Plant Conservation of the Convention on Biological Diversity (CBD) and the UN Millennium Development Goals (MDGs).

The research being conducted by the project into the challenges of seed banking, such as postharvest handling (including seed sensitivity to drying) will significantly expand existing possibilities for conservation of forest genetic resources. To date the seeds of more than 20 important palm species and around 100 dryland species have been tested for tolerance to drying.

viability drops below an acceptable level. Scientific collaboration in plant conservation has led to substantial innovation in seed storage in recent years, particularly in diagnosing tree seed storage behaviour, increasing tree seed longevity in the dry state and improving storage biotechnology (Pritchard *et al*., 2014).

Seeds can be categorized according to their storage behaviour, which is a reflection of the seed moisture content. The final moisture content in the seeds depends on the species and the external environment. Before the seed from any species can be considered for storage, its response to desiccation and chilling must be determined.

- Orthodox seeds dry out to 5 to 10 percent moisture during maturation. They are shed in a highly hydrated condition, endure a chilling period during maturation and are therefore adapted to the low temperatures used for orthodox seed storage. They can be stored for long periods at seed moisture contents of 3 to 7 percent (on a fresh weight basis) at –18°C or below (Theilade and Petri, 2003).
- In contrast, recalcitrant seeds maintain relatively high moisture content, generally greater than 40 to 50 percent, and cannot be stored in conventional seed banks because of the sensitivity of the seeds to desiccation. Many forest tree species from temperate and especially tropical regions produce recalcitrant seeds.
  - Seeds of temperate recalcitrant species can be stored at near freezing temperatures for several years but are intolerant of drying. For example, *Quercus* species can be stored for three to five years as long as a high (35 to 40 percent) seed moisture content is maintained.
  - Seeds of tropical recalcitrant species require the same gas and moisture levels but are very sensitive to low temperatures. For example, species from the genera *Shorea, Hopea* and several tropical fruit-trees will lose viability at 10° to 15°C (Phartyal e*t al*., 2002).
- An intermediate category has been identified in which seeds are partly tolerant to dehydration and cold. The longevity of these seeds is quite short, which is a significant constraint for conservation in a number of species, including many tropical forest trees (Joët *et al*., 2009).

Seed behaviour is generally considered as a continuum from orthodox to recalcitrant. The number of species identified with non-orthodox behaviour is increasing, and the basis of such behaviour is more complex than initially envisaged (Berjak and Pammenter, 2008). Following application of new knowledge of seed physiology and some success with seed drying around the world, some species once considered recalcitrant have later been identified as orthodox. *Fagus sylvatica* and two tropical species, *Citrus limon* and *Elaeis guineensis*, for example, fall into this category (Phartyal *et al*., 2002). Techniques have also been developed for extending the viability of non-orthodox seed.

Some genera, such as *Acer* (Phartyal *et al*., 2002) and *Shorea* (Theilade and Petri, 2003), include both orthodox and recalcitrant species. Infrequently, apparent seed storage behaviour may vary geographically within the same species, as in *Dipterocarpus alatus*, in which populations from drier zones have more desiccation-tolerant seeds, and *Santalum austrocaledonicum* (Thomson, 2006). Behaviour may even vary depending on the stage of maturation at collection and the storage and rehydration regimes, as in *Azadirachta indica* (Sacandé and Hoekstra, 2003).

It is estimated that approximately 60 percent of the tree species in the Amazon Basin produce recalcitrant seeds. In comparative studies of seed morphology in relation to desiccation tolerance and other physiological responses in nearly 200 moist tropical forest species on three continents, from 42 to 62 percent of species were found to have non-orthodox behaviour, with an overall average of 51 percent (Hamilton *et al*., 2013; Ferraz *et al*., 2004; Ellis *et al*., 2007).

Recalcitrance reduces the effectiveness of seed banks in areas where threats to tree species and their populations are greatest. However, during the past 20 years, considerable progress has been made in:

- understanding the mechanisms of desiccation-induced loss of viability on drying, including the role of reactive oxygen species and programmed cell death (Kranner *et al*., 2006);
- estimating the proportion of the world's flora that produces such seeds (diagnosis);
- developing methods that can help conserve such species in *ex situ* cryobanks (storage biotechnology).

Short- to medium-term storage of recalcitrant seeds can be achieved by maintaining the seeds at the lowest temperature they will tolerate, under conditions that do not allow water loss. However, these conditions will encourage the growth of micro-organisms which must be managed through appropriate action, such as fungicide treatment (Berjak and Pammenter, 2008). Fungicide treatment was effective in extending the storage life of *Hopea parviflora* (Sunilkumar and Sudhakara, 1998). Problems with seed handling and storage affect the implementation of conservation programmes.

Generally a relationship between seed size and tolerance for desiccation holds (Hamilton *et al*., 2013). As Daws and Pritchard (2008) discovered, working with *Acer pseudoplatanus*, it is important to pay attention to phenotypic plasticity in the seed storage response between plants growing inside and outside the native distribution range, as this can be responsible for species appearing to be in a different seed storage category or being misclassified.

The half-life (time for viability to fall from 97.9 to 50 percent) of seed in storage varies greatly, in part depending on the oil content of the seed in relation to mass. Estimates range, for example, from 0.95 for *Dipterocarpus alatus* to 342 years for *Liquidambar styraciflua* (Daws, Garwood and Pritchard, 2006). The information required to predict half-life is not available for most tree species, but recent advances have improved the accuracy of predictions (see also Box 3.4). The shortest life spans are driven by the need to store the seeds partially hydrated at 10 to 17 percent moisture content. In contrast, the longest-lived

### Box 3.4
### Biological models for predicting risk associated with seed storage for tree species

It is important to develop predictive biological models to indicate risks associated with handling of seed with particular characteristics because the large number of tree and other higher plant species, estimated to be as many as 353 000 (Scotland and Wortley, 2003; Chapman, 2009), renders the physiological screening of all species unlikely in the foreseeable future. Early studies revealed broad associations between heavier seed in the Araucariaceae (Tompsett, 1984) and Dipterocarpaceae with seed desiccation sensitivity. Hong and Ellis (1998), for example, using multiple criteria, identified associations between habitat and desiccation intolerance across a broad range of vegetation types, finding a low frequency (about 10 percent or less) in the driest regions of the world and a high frequency (close to 50 percent) for tropical moist evergreen forests. For about 70 African tree species, Pritchard *et al*. (2004) confirmed predictions that in seasonally dry environments (more than in areas that are moist year-round), species that produce recalcitrant seeds disperse their seed in the rainy season, as they must maintain water status or else they die. Another ecological prediction that has proved useful is that recalcitrant seeds should not need as great a defence mechanism against consumption, e.g. thick seed coats, since their germination is relatively quick (Hong and Ellis, 1998). Using this relationship, Daws, Garwood and Pritchard (2006) developed a predictive model for the probability of recalcitrant seed among 104 trees in Panama.

seeds can be stored in a much drier environment, at around 3 percent moisture content. Some species have very long-lived seed; some seeds of three woody species of the Cape Flora of South Africa were germinated after about 200 years storage under museum or cellar conditions.

Seed storage duration varies across different plant species, hence the Millennium Seed Bank Partnership (see Box 3.3) is evaluating the impact on seed storage duration of various factors such as structure of the seed embryo and climate conditions during seed development and ripening. Baseline data on the desiccation tolerance and longevity of tree seeds are very limited (Hong, Linington and Ellis, 1998; Dickie and Pritchard, 2002). The DANIDA Forest Seed Centre (now part of Forest Landscape Denmark) and Bioversity International led a global initiative from 1996 to 2002, involving about 20 countries, which screened recalcitrant and intermediate (with partial desiccation tolerance but with sensitivity to storage at –20°C and 0°C) seeds of 52 tropical forest trees belonging to 27 families (summarized in Sacandé *et al*., 2005). The project assessed seed responses to multiple desiccation states and subsequent storage at a range of temperatures (Hong and Ellis, 1996) to understand seed storage behaviour.

An alternative screening approach, called the 100-seed test as that is the target number of seeds to use (many less than the previous protocol), deals only with aspects of the effects of drying and short-term storage on the initial moisture content of the seed sample (at receipt or harvest). This approach gives a good indication of tolerance to rapid artificial drying similar to that used in seed banks; in addition, the moist-stored control can show reduced germination (rapid loss of viability and thus short life span), no effect on germination, or increased germination (evidence of seed maturity during the storage period). This method has been adopted by tree seed experts at the Instituto Nacional de Pesquisas da Amazônia (INPA), Brazil; the University of Queensland, Australia; and the University of KwaZulu Natal, Durban, South Africa.

However, knowledge of the seed biology of forest tree species is limited, and the resources that are available are scattered. The University of Copenhagen, in collaboration with the World Agroforestry Centre (ICRAF), has published a series of seed leaflets since 2000, which are posted online together with leaflets published by the DANIDA Forest Seed Centre from 1983 to 1986 (http://sl.ku.dk/rapporter/seed-leaflets). A study of seed from 100 Panamanian tree species has also generated important information (Sautu *et al*., 2006). The *Tropical tree seed manual* (Vozzo, 2002), which includes 175 tree species, is another highly useful publication. It would be beneficial to bring all of the information together on one portal so that *ex situ* conservation actions can be supported. More information is needed on the control of tree seed germination, including how dormancy can be alleviated and the factors influencing varying degrees of dormancy, such as time of collection and climatic conditions. Sources of information should include compendia of national and regional forest seed programmes.

Under the Millennium Seed Bank Partnership, a unique seed database has been established which provides information on a wide range of functional traits or characters, including, among others, seed desiccation tolerance, germination and dormancy, and classifies seeds accordingly. At the same time the lack of knowledge for tropical species is acknowledged. ICRAF maintains the Agroforestree Database, which provides storage information for 670 agroforestry tree species.

### *In vitro* conservation

Many commercially valuable tropical tree species are estimated to have recalcitrant or intermediate seeds (Ouédraogo *et al*., 1999), for which long-term conservation using conventional seed storage is not possible. For this reason significant effort has gone into establishing *in vitro* approaches for conserving forest genetic resources. However, woody species are often difficult to establish *in vitro*, with problems

occurring at any one of the multiple stages of shoot culture establishment.

The first stage of establishing cultures derived from mature forest trees can be challenging because of high levels of contamination and/or high secretion of polyphenols and tannins. A review of the progress made in establishing tissue cultures of threatened plants (Sarasan *et al*., 2006) highlights a range of methods that have been developed to initiate cultures of often recalcitrant plants of limited number, as well as different approaches to managing tissue and medium browning. Successful initiation of *in vitro* cultures is not the only challenge; of key importance is the establishment of stabilized shoot cultures to provide a stock of plants that are more reproducible and stable than those in the field or greenhouse. Despite progress in this area, *in vitro* shoot growth stabilization – that is, culture with uniform and continuous shoot growth – is not well understood (McCown and McCown, 1987). However, rejuvenation is undoubtedly a major contributing factor; explants derived from juvenile sources are easier to establish *in vitro* than adult plants of the same genotype. The use of juvenile tissue has been successful in a number of species, for example, *Acacia auriculiformis, Acacia mangium, Aqualaria malaccense, Azadirachta excela, Calamus manan, Dyera costulata* and *Tectona grandis* (Krishnapillay, 2000).

Episodic species, such as many nut-trees and conifers, are highly problematic for tissue culture as compared with the sympodial species (such as many pioneer trees), which show continuous seasonal shoot growth. Success using *in vitro* approaches is generally found in non-episodic species, for example *Eucalyptus* and *Populus* species (McCown, 2000). Episodic trees tend to maintain their episodic growth pattern in culture, so that random flushes of growth are followed by periods of inactivity during which the cultures deteriorate. However, two approaches to culturing highly episodic species have been successful. One approach uses the generation of shoots *de novo*, the actual induction of adventitious meristems being a rejuvenation process in itself. This approach has been very successful with conifers (Ahuja, 1993). The second approach focuses on rejuvenation either of the stock source or of the tissue-cultured tissues (Greenwood, 1987; McComb and Bennett, 1982). Multiplication and rooting of shoot culture systems for tree species can be demanding, with very specific requirements depending on the species and often the variety. For example, multiplication and rooting of the endangered tree *Ginkgo biloba* was promoted by incorporating the endosperm from mature seeds of the same species in the culture medium (Tommasi and Scaramuzzi, 2004). Pijut *et al*. (2012) reviewed *in vitro* culture of tropical hardwood tree species from 2001 to 2011, outlining methods used for a wide range of species of this commercially important group.

Only once an efficient and effective system for generating stabilized shoot cultures is established should there be any attempt to develop an *in vitro* storage protocol. *In vitro* conservation technology provides two options: restricted or minimal growth conditions and cryopreservation.

**Minimal growth culture.** The most popular methods for minimal growth storage are modification of the culture medium and reduction of the culture temperature or light intensity. Minimal growth storage has been reported for several tree species such as *Eucalyptus grandis* (Watt *et al*., 2000), *Eucalyptus citriodora* (Mascarenhas and Agrawal, 1991) and *Populus* spp. (Hausman *et al*., 1994). Malik, Chaudhury and Rajwant (2005) reported *in vitro* conservation of *Garcinia indica* with subculture duration of up to 11 months after the establishment of cultures from adventitious bud-derived plantlets.

Minimal growth culture is generally only considered as a short- to medium-term conservation approach because of problems in the management of collections even if the intervals between transfers are extended, and also because of concerns of genetic instability caused by somaclonal variation. In addition, it is generally very difficult to apply one protocol to conserve genetically diverse material. A study of *in vitro* storage of African coffee germplasm, which included 21 accessions, showed large variability in the responses: some accessions experienced losses whereas others were safely conserved (Dussert *et al.*, 1997). Technical guidelines are available on establishing and maintaining *in vitro* germplasm collections, although not specifically for forest genetic resources (Reed *et al.*, 2004).

**Cryopreservation.** Besides improvements in seed storage protocols, the main innovation for recalcitrant seed has been improved techniques for cryopreservation, which is needed for species that produce fully hydrated recalcitrant seeds. Cryopreservation is the storage of biological material at ultra-low temperatures, usually that of liquid nitrogen, –196°C. At this temperature all cellular divisions and metabolic processes are stopped, and therefore the material can be stored without alteration or modification, theoretically for an unlimited period of time. In addition, cultures are stored in a small volume, are protected from contamination and require very little maintenance (Engelmann, 2004). One of the disadvantages of minimal growth storage is the possibility of somaclonal variation. Cryopreservation reduces this possibility because the metabolism of the plant cells is suspended and subculturing is not part of the process. However, the cryoprotocol does expose plant tissues to physical, chemical and physiological stresses which can all cause injury. Although few studies have examined the risk of genetic and epigenetic alterations, there is no clear evidence that cryopreservation causes morphological, cytological or genetic alterations (Harding, 2004). For example, the genetic fidelity of *Melia azedarach* after cryopreservation was confirmed using isoenzyme analysis and RAPD markers (Scocchi *et al.*, 2004). Cryopreservation is particularly useful for conserving embryogenic cultures of conifers whose growth and embryogenic potential could be affected by regular subculturing in conventional *in vitro* storage.

Cryopreservation is also more cost effective than minimal growth storage. To date studies on cost effectiveness have only been conducted on crop plants, but the annual maintenance of the cassava collection (about 5 000 accessions) at the International Centre for Tropical Agriculture (CIAT) is USD 30 000 for slow growth storage and USD 5 000 for cryopreservation (Engelmann, 2010).

The extent to which the seeds can be safely cooled is limited by the risk of ice crystal formation for temperate species and chilling stress for tropical species. Ice crystals can cause irreparable damage to cell membranes, destroying their semipermeability. The primary development of the past 25 years in plant cryopreservation has been improvement in methods for vitrification to avoid crystal formation (Fabre and Dereuddre, 1990) and the use of complex solutions of cryoprotectants that reduce the risk of ice crystal formation of partially hydrated tissues during cooling and rewarming.

Vitrification – the formation of an amorphous or glassy state (non-crystalline) from an aqueous state – significantly reduces cellular water. For cells to vitrify, a concentrated cellular solution and rapid freezing rates are required. Three categories of explants can be cryopreserved for woody species: shoot-tips for species that are vegetatively propagated, seeds or isolated embryo axes for species that reproduce using seeds, and embryogenic calluses.

Most of the research has been on species that are of interest to commercial forestry or are valuable fruit-trees. Many studies report successful vitrification of the intracellular constituents when cooling followed partial drying in air; for example, the embryos or embryonic axes of five citrus species were cryopreserved after desiccation to about 15 percent moisture content (Malik, Chaudhury and Pritchard, 2012). In this example, longevity of the embryos at –20°C was limited to a few months, while the cryopreserved samples retained high viability after six to eight years.

Cryopreservation of hardwood trees has become increasingly successful since the introduction of PVS2 (plant vitrification solution 2), which contains penetrating and non-penetrating cryoprotectant solutions. Species for which the vitrification/one-step freezing protocol using PVS2 has been successful, with survival rates higher than 50 percent, include *Malus, Pyrus, Prunus* and *Populus* species (Lambardi and De Carlo, 2003). Over 90 percent survival rates have been reported for *Cerasus jamasakura* (Niino *et al*., 1997) and *Populus alba* (Lambardi, Fabbri and Caccavale, 2000). Vitrification has proved successful (71 percent recovery rate) with *Betula pendula*, and morphology and RAPD analysis of regenerated plants in the greenhouse suggests that the genetic fidelity remains unchanged (Ryynanen and Aronen, 2005). Compared with results from shoot tips, cryopreservation of embryogenic calluses and somatic embryos from hardwood trees has been limited. Success using the vitrification/one-step freezing protocol has been achieved with *Castanea sativa* (Correidoira *et al*., 2004) and *Quercus suber* (Valladares *et al*., 2004).

Cryopreservation of embryogenic cultures of conifers is well advanced; it has been applied successfully to species in a range of genera including *Abies, Larix, Picea, Pinus* and *Pseudotsuga*. Over 5 000 genotypes of 14 conifer species are cryostored in a facility in British Columbia, Canada (Cyr, 2000). The technique used is mainly based on slow cooling to –40°C, which concentrates the intracellular solution sufficiently for its vitrification upon plunging into liquid nitrogen. Other cryobank collections of tree species include (Panis and Lambardi, 2005):

- 2 100 accessions of *Malus* spp. (apple) (dormant buds) at the National Seed Storage Laboratory, Fort Collins, United States of America;
- over 100 accessions of *Pyrus* spp. (pear) (shoot-tips) at the National Clonal Germplasm Repository in Corvallis, Oregon, United States of America;
- over 100 accessions of *Ulmus* spp. (elm) (dormant buds) at the Association Forêt-cellulose (AFOCEL), France;
- about 50 accessions of *Morus* spp. (mulberry) at the National Institute of Agrobiological Resources, Japan.

In addition, some tropical and subtropical species are being cryopreserved:

- 80 accessions of *Elaeis guineensis* (oil palm) at the Institut de Recherche pour le Développement (IRD), France (Engelmann, 2004);
- collections of *Citrus* spp., *Artocarpus heterophyllus* (jackfruit), *Prunus dulcis* (almond) and *Litchi chinensis* (lychee) held at the National Bureau of Plant Genetic Resources, India (Reed, 2001).

Despite the progress made with cryopreservation, only a limited number of truly recalcitrant tree species have been successfully cryopreserved. There are many reasons for this slow progress. A relatively large number of species, many of which are wild, have recalcitrant seeds, and little is known about their biology and seed storage behaviour. The seeds are difficult to cryopreserve because they tend to be large and to have high moisture content when shed. Excised embryos or embryonic axes can be an option; however, viable tissue culture protocols needed to regrow embryos and embryonic axes after freezing are often lacking or not fully operational. In addition, provenances, seed lots and successive harvests often demonstrate significant variation in the moisture content and maturity stage of seeds and embryos of recalcitrant species, which makes cryopreservation difficult (Engelmann, 2010). Despite these hurdles, groups throughout the world are working to improve knowledge of the mechanisms responsible for seed recalcitrance and are exploring various technical approaches to understand and control desiccation sensitivity.

### Field gene banks and planted stands

Arguably the most effective way to conserve long-lived tree species *ex situ* is by planting them in specific *ex situ* gene conservation stands or field gene banks, arboreta, clone banks, seed orchards and operational plantings. *Ex situ* field gene banks maintain sources of variation of functional traits for direct use in production through propagation and breeding programmes.

Experience has shown that it can be difficult to identify the species and provenances or populations most in need of specific *ex situ* conservation activities. Provenances of *Eucalyptus camaldulensis* conserved in FAO-supported *ex situ* gene conservation stands at Petford and Lake Albacutya, Australia, have turned out to be some of the most widely planted operationally and therefore have been conserved *de facto* in such plantings. *Ex situ* conservation stands are often less expensive, more effective and in many ways more practical for maintaining diversity than seed storage and *in vitro* methods, which are better suited to agricultural crops and short-lived species with plantings that only last a season. Other examples of *ex situ* conservation in planted field gene banks, both from South Australia, include *ex situ* plantings and grafted trees of *Eucalyptus globulus* established by the Southern Tree Breeding Association at the National Genetic Resources Centre at Mount Gambier; and the Currency Creek Arboretum, a largely self-funded arboretum specifically for eucalypts (genera *Angophora, Corymbia* and *Eucalyptus*) which has the largest global *ex situ* collection of living eucalypt species – over 900 species, subspecies and varieties and over 8 000 individual plants – established on a single site.

Morphological and biochemical characterization of conserved accessions provides a wealth of trait-based knowledge. Such collections are established for tree species that are considered important for agroforestry or arboriculture production and include many fruit-tree species. Most of these collections are field gene banks because in some cases the species are recalcitrant and because field gene banks generally facilitate characterization. For example, an exercise with national agricultural research institutions in the Amazon to explore the status of *ex situ* conservation, characterization and evaluation demonstrated a high number of collections and promising advances in morphological characterization of prioritized local fruit-tree species including *Bactris gasipaes, Euterpe* spp., *Mauritia flexuosa, Myrciaria dubia, Platonia insignis, Pouteria caimito* and *Theobroma grandiflorum* (Scheldeman *et al.*, 2006).

However, field gene banks are also costly to maintain (Dawson *et al.*, 2013). Their existence can only be justified when gene bank material can be accessed by users and meets their needs. The National Genetic Resources Program of the United States Department of Agriculture, for example, holds collections of a list of tree species that are characterized (www.ars-grin.gov/cgi-bin/npgs/html/croplist.pl). They include many temperate fruit-tree species, but also tropical ones such as *Bactris gasipaes, Canarium ovatum* and *Averrhoa carambola*. Data on traits can be consulted freely online and germplasm can be requested accordingly.

There is no centralized information system for tree species collections, however; thus characterization information, if collected, is generally not accessible, especially for collections in developing countries. When germplasm maintained in characterized collections is not accessible for potential users, the gene banks lose their connection with users and their needs.

Thus even though *ex situ* field collections exist for only a limited number of tree species, a considerable number of these collections are already morphologically characterized. Unfortunately, many of these collections are not known to the general public, and it is difficult to gain access to existing characterization data. To enhance the use of gene bank characterization, such information should be systematized and made accessible at a central point.

## Targeted species-based approach

This conservation approach, typically highly resource intensive, is used to conserve as much intraspecific diversity as reasonably possible for forest tree species with a high priority rating (usually given to species with major national and/or international economic importance). It may also be used for endangered tree species; in these cases the genetic conservation effort is directed towards maintaining enough diversity, in preferably more than one population, to ensure the species' survival. In the ideal species-based conservation plan the distribution of the species' intraspecific diversity and associated relevant factors will be well known. Populations for conservation are selected with the aim of efficiently and securely conserving as much genetic diversity as possible, including rare alleles and co-adapted gene complexes of identified high value populations or seed sources, in a network of managed *in situ* FGR reserves. For species exhibiting clinal variation, connectivity and gene flow between populations can be maintained through vegetation corridors and/or linked by *circa situm* plantings. In many instances implementation involves a diverse group of land managers and interested parties, and in some cases international collaboration. Ideally, safety duplication of the material conserved *in situ* is also undertaken through *ex situ* methods such as long-term seed storage banks for species with orthodox seed storage behaviour or tissue culture banks and field gene banks for species with recalcitrant seed storage behaviour.

Although this approach has major benefits and has been widely promoted by FAO and forest geneticists over the past 30 or more years, it has not been implemented widely. Most examples are from developed countries in Europe and North America, for example *Picea abies* in Finland (Koski, 1996). Only a few cases have been documented in tropical countries, including *Pinus merkusii* in Thailand (Theilade, Graudal and Kjær, 2000) and *Terminalia richii* and *Manilkara samoensis* in Samoa (Pouli, Alatimu and Thomson, 2002). Since 2007, the European Information System on Forest Genetic Resources (EUFGIS), hosted by Bioversity International, has undertaken considerable preparatory work for many species in 36 European countries, including through creation of a national network of FGR inventories and development of minimum requirements for dynamic conservation units of forest trees.

## Chapter 4

# Knowledge and information on forest genetic resources

Although basic genetic principles are consistent across plant and animal taxa, forest trees differ from agricultural crops in significant ways, and the study, management and conservation of their genetic resources have had to be adapted accordingly. Thus the knowledge of and focus on particular genetic technologies also differ between forest trees and domesticated plants and animals in some regards. Even the relatively few forest tree species that are undergoing incipient domestication typically also exist as large wild, randomly mating and unstructured populations (Neale and Kremer, 2011). Many forest tree species have narrow regional adaptation, so the number of species planted commercially is much higher than for food crops (Pautasso, 2009).

Trees are long-lived and their generation times and juvenile phases are generally long. Many tree species encompass enormous genetic diversity (Hamrick *et al.*, 1992); even breeding populations in improvement programmes represent relatively large gene pools in comparison to agricultural crops, and tree genomes may be orders of magnitude larger than those of cultivated crops (Neale and Kremer, 2011). Tree species are predominantly outcrossing, and in fact none are known to be predominantly selfing (Petit and Hampe, 2006) – a potential evolutionarily selected pathway of long-lived species against inbreeding depression (Duminil *et al.*, 2009). With a few exceptions, tree breeders do not aim to develop varieties as with agricultural crops, and tree species that have known or potential value for forestry number in the tens of thousands. Thus, forest geneticists and genomicists face different challenges and require different tools and techniques than those who work with agricultural crops.

According to the country reports prepared for *The State of the World's Forest Genetic Resources*, approximately 2 400 species are actively managed in forestry. The total count of forest species, however, remains inconclusive (Box 4.1). Only approximately 700 tree species are subject to some level of selection and improvement globally, and progeny tests have been established for no more than two-thirds of these species. In addition, a number of non-planted tree species have been studied, mainly using molecular markers. Assuming a total global count of at least 80 000 tree species, little more than 1 percent of the tree species have been subject to genetic study, and less than 1 percent have been studied with the aim of improving resources for human use. Undoubtedly many not yet studied species have untapped potential that could be realized given sufficient resources, interest and survival of sufficiently diverse populations.

The tree species that have been most studied using scientific approaches (since about 1950) fall in two categories: those that have been extensively planted in commercial planted forests for wood, and species that are valuable in agriculture for fruit and other livelihood benefits. Commercial planted forests represent about 7 percent of the world's forests but are responsible for more than 50 percent of the world's industrial roundwood production

(FAO, 2010a). Approximately 30 tree species from just four genera (*Acacia, Eucalyptus, Pinus* and *Populus*) account for much of the area planted globally (Carle *et al*., 2008). Most of these species have been studied in detail, including quantitative and molecular and/or genomic analyses. Some of the most studied species include: *Acacia mangium, Acacia nilotica, Cunninghamia lanceolata, Eucalyptus camaldulensis, Eucalyptus globulus, Eucalyptus grandis, Gmelina arborea, Larix gmelinii, Larix sibirica, Picea abies, Picea obovata, Picea sitchensis, Pinus caribaea, Pinus elliottii, Pinus massoniana, Pinus nigra, Pinus patula, Pinus pinaster, Pinus radiata, Pinus sibirica, Pinus sylvestris, Pinus taeda, Populus deltoides, Populus nigra, Populus tremula, Populus tremuloides, Populus trichocarpa, Pseudotsuga menzesii* and *Tectona grandis.*

Tree species producing fruit and other food-related crops of global significance have a much longer history of domestication and accumulation of knowledge. Unlike the tree species that have been managed for wood production, well recognized varieties of fruit-tree species have been developed over centuries to millennia. Yet unlike most agricultural crops, the original fruit-tree species still exist as wild populations capable of sharing genetic material with domesticated varieties. Some of these populations are under threat; examples include several globally significant fruit-tree species that originated in Central Asia such as apple, apricot and other species from the Rosaceae family (Eastwood *et al*., 2009).

Tree species are much better characterized in some regions than others. In Europe, North America and Australia, at least some genetic knowledge has been generated for most native tree species. Species in South and Central America have received more attention than those of Asia or Africa, in general, although there are exceptions at the country level. Even in countries where significant funds and capacity have been allocated for study of FGR, the evenness of species coverage is variable, with key species studied intensively and little or no information for many. At the species level, approaches vary widely, from single population studies which are common for tropical species, to range-wide surveys for temperate species of broad commercial interest.

## What constitutes knowledge of forest genetic resources?

Since forest genetic resources are defined as materials of actual or potential economic, environmental, scientific or societal value (see p. 4), for the purposes of this overview it is assumed that any species that has been studied has such value. Relevant knowledge encompasses quantitative, molecular and genomic information. In addition to such genetic information, other types of information can provide insight into the genetic variability of a species, such as: knowledge of species distribution and environmental variability within the species range; population size and relative degree of contiguity; and observable morphological variation (in a natural population). Traditional or indigenous knowledge predates published information; it is less well documented but often valuable.

The concept of FGR is also often used in a practical sense to designate clones, varieties and populations (i.e. genetic units) that hold special interest for conservation or use. Many planted tree species of high commercial value have been subject to some degree of selection, testing and breeding which have generated particular knowledge. Other highly valuable species are harvested exclusively in the wild, and very little may be known about their genetic resources.

### Why study forest genetic resources?

Uses of forest resources and FGR, management practices and priorities for research vary by type of tree species, region and socio-economic situation of the users. Much scientific genetic research on trees has been devoted to species having commercial value for timber, and most of these are temperate species. About 30 species have been studied intensively, tested and bred for increased wood production, improved quality

## Box 4.1
## Filling the knowledge gap in botany: how many tree species are there on Earth?

Although knowledge of species and their conservation status has been improving over time (Figure 4.1), it is still insufficient, and insufficiently accurate, to provide adequate support to conservation and sustainable management of forest genetic resources at the global level. Estimates of the number of plant species vary widely from 25 000 to more than 400 000 (Stebbins, 1974; Bramwell, 2002; Miller *et al*., 2013), and perhaps more than a quarter of all flowering plants have not yet been named or discovered (Miller *et al*., 2013).

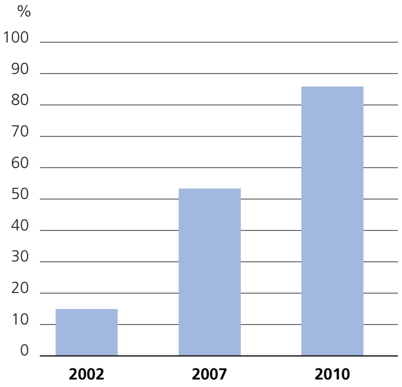
Major challenges to filling the gap in knowledge on plant species include frequent synonymy, the difficulty of discriminating certain species by morphology alone, and the fact that many undiscovered species are small in size, difficult to find, or have a small geographic range (Scheffers *et al*., 2012). A recent, major effort is the Global Taxonomy Initiative, which enables the international community to acknowledge the existence of a "taxonomic impediment" to the sound management of biodiversity and to initiate a programme with the objective of removing or reducing the knowledge gaps in the taxonomic system.

In response to the CBD's Global Strategy for the Conservation of Biodiversity, adopted in 2002, the Royal Botanic Gardens, Kew, United Kingdom, and the Missouri Botanical Garden, United States of America, developed *The Plant List* (www.theplantlist.org), intended as a widely accessible working list of known plant species. It aims to be comprehensive in coverage at species level for all mosses and liverworts and their allies (bryophytes) and vascular plants which include the flowering plants (angiosperms), conifers, cycads and their allies (gymnosperms) and the ferns and their allies including horsetails and club mosses (pteridophytes). The last update (September 2013) includes names of 1 064 035 species in 642 plant families and 17 020 plant genera. Of the total, 350 699 are accepted species names, 470 624 are synonyms and 242 712 are unresolved (*The Plant List*, 2013).

The status of botanical knowledge of plant species varies from country to country. Few countries have a relatively accurate estimate of the number of their vascular plants. Some have completed flora lists, but very few have a detailed plant species checklist that includes species characteristics and life forms, which could make it possible to distinguish forest plants, e.g. trees, shrubs, palms and bamboos.

Moreover, the answer to the question "how many trees species are there on Earth?" remains very rough, varying from 50 000 (National Academy of Sciences, 1991) to between 80 000 and 100 000 species (Oldfield, Lusty and MacKinven, 1998; Turok and Geburek, 2000). These estimates are even more confusing in light of the different definitions of a tree. This report on *The State of the World's Forest Genetic Resources* includes plant species identified by countries as part of their forest resources. In the country reports, FGR are often taken to include trees, shrubs, palms, bamboos, lianas, cycads and ferns, and in a few cases some herbaceous plants..

**FIGURE 4.1**
Proportion of the world's plants in accessible plant lists



*Source*: CBD Secretariat (2009).

(Neale and Kremer, 2011) and/or resistance to pests and diseases (Yanchuk and Allard, 2009).

A body of knowledge has also accumulated over a longer time and in a much more fragmented way on tree species that are important for non-wood forest products including fruit- and nut-bearing trees, species with valuable medicinal properties, oil- or latex-producing trees, and species having shade or ornamental value. Traditional knowledge of phenotypic variation extends from informally recorded traditional knowledge to recent scientific studies. Few NWFP species have been thoroughly studied using modern techniques, with the exception of those having high commercial value; in those cases, the objectives and the techniques employed resemble those of genetic research on agricultural crops.

## Conservation

During the last three decades, since the development and broad use of molecular markers, many studies have been conducted applying these tools to inform conservation strategies and approaches. Neutral genetic markers are used, for example, to deduce population-level parameters that are informative about spatial patterns of genetic diversity, reproductive biology (mating system, pollen- and seed-mediated gene flow), species evolutionary history and demography (for example, existence of genetic bottlenecks, localization of refugia sites, founder populations).

Aims of conservation genetic studies are to understand levels and patterns of genetic diversity, impacts of land use changes on intraspecific variation, and vulnerability of populations to threats; and to identify populations having high conservation priority and design approaches for their conservation. A combination of neutral molecular markers and either phenotypic measurements or genomic markers for adaptive traits is ideal for defining priority populations, but in most cases, especially in tropical countries, resource limitations have resulted in the sole use of neutral markers.

Most tropical timber species are managed in semi-natural forests – in many cases selectively harvested – and depend on natural regeneration for their renewal. In some cases the genetic resources of such species may be degraded through dysgenic selection; this can occur when the best-quality trees are cut and only badly shaped trees are left as contributors to the next generation. Thus in the absence of an improvement strategy and planting, selective harvesting could be expected to have dramatic effects on the resource sustainability. However, few conclusive studies have evaluated this hypothesis, and one of the few that has been published found little evidence (Cornelius *et al*., 2005).

In general, little is known about the sustainability of the genetic resources of selectively harvested tree species, especially those in the tropics (Wernsdorfer *et al*., 2011). Effective long-term management of these species requires knowledge of population genetic parameters such as gene flow dynamics and the structure of genetic variation in economically and adaptively important traits. Such knowledge is important to ensure that viable populations are maintained in harvested areas and that harvest does not have a dysgenic impact on seed trees.

Genetic markers that can be used effectively for identifying species and origin of timber are becoming important as well, to monitor legality of timber harvest. The Barcode of Life project attempts to use DNA markers to identify species (see Chapter 9).

Conservation of evolutionary potential is important for the sustainable management of forests, particularly for adapting forests to environmental change (Lefèvre *et al*., 2013), as well as for improvement of valuable traits. This requires a good understanding of the extent and patterns of genetic diversity throughout a species' range. For many species, studies have been conducted on limited numbers of populations, using various molecular markers to elucidate patterns of diversity. Studies are often limited by small sample sizes and the applicability of results is thus limited. The use of different markers for subsequent studies in divergent geographic locations of the same species leads to disparate results that may even be contradictory, with little potential for generating a common understanding.

In many countries, little concrete action has been taken on the basis of most conservation genetic studies, in part because of a gap between the science and the application of conservation knowledge (Knight *et al*., 2008). The data are still largely insufficient to allow testing of whether congruent patterns of spatial genetic diversity exist among species (i.e. zones of genetic endemism and richness; see e.g. Conord, Gurevich and Fady, 2012 for the Mediterranean). This knowledge would have important implications in terms of landscape management and conservation, as forest reserves are ideally localized on the basis of genetic information across all species.

## Tree improvement

**Wood production.** Improvement programmes for wood production have generated knowledge about productivity and quality traits for most tree species that are used extensively in planted forests. The earliest genetic studies on forest trees were designed to quantify variation in traits of commercial value for selection and breeding. Most of the effort has focused on increasing wood volume, both for timber and for pulp and paper, and on improving the form of trees for timber production. Many studies have been reported on genetic parameters associated with wood quality, including strength, density and more recently lignose/cellulose ratio, although these traits have generally been considered to be of secondary importance. Breeding for resistance or tolerance to biotic and abiotic factors tends to be restricted to more specialized research programmes (Yanchuk and Allard, 2009). Hence much information is available for most commercial planted forest species on the complicated growth rate related traits associated with quantity and quality of wood production, but relatively little genetic information has been generated about other traits. This one-sidedness may have negative consequences in efforts to adapt to changing climatic conditions.

**Agricultural purposes.** Fruit-trees and other tree species that are important for food or fodder or that have cultural or religious significance have been domesticated for millennia, without the benefit of scientific genetic knowledge for most of that time. The most widely used method for capturing improvements has been by cloning trees having desirable properties. Unlike commercial timber species, domesticated varieties of trees important for food and other non-wood amenities have been developed for centuries, simultaneously, in many geographic locations. Cross-continental exchange of planting material started early in human history and has intensified since colonial times. For example, in the Americas, intercultural contacts with European settlers some five centuries ago led to an early but systematically underestimated (intentional and accidental) floristic homogenization. Useful plants from the Old World were actively and passively distributed over the New World tropics and subtropics as a consequence of colonial horticultural endeavours (Bennett and Prance, 2000). By the mid-nineteenth century, exotic fruit-trees were fully incorporated into home gardens along the Amazon (Miller and Nair, 2006).

## Taxonomy, phylogeny and phylogeography

Patterns of genetic differentiation and speciation have been studied in order to understand the evolutionary history of species. Petit and Hampe (2006) reviewed the evolutionary consequences of “being a tree”, noting that the high diversity and very high fecundity of most tree species allow for rapid evolution at the micro scale, but that long generation time, large size and other characteristics result in slow macroevolution.

Taxonomic studies rely increasingly on genetic markers (see Chapter 8) to complement or

replace conventional morphological methods to determine taxonomic status and understand phylogenetic relationships. Many tree genera are incompletely described at the species level, in part because of hybridization and introgression among species; an example is the genus *Quercus* in Mexico, which has between 135 and 150 species but the exact number is not known (González-Rodríguez *et al*., 2004). A combination of nuclear markers and morphological traits is employed to differentiate species.

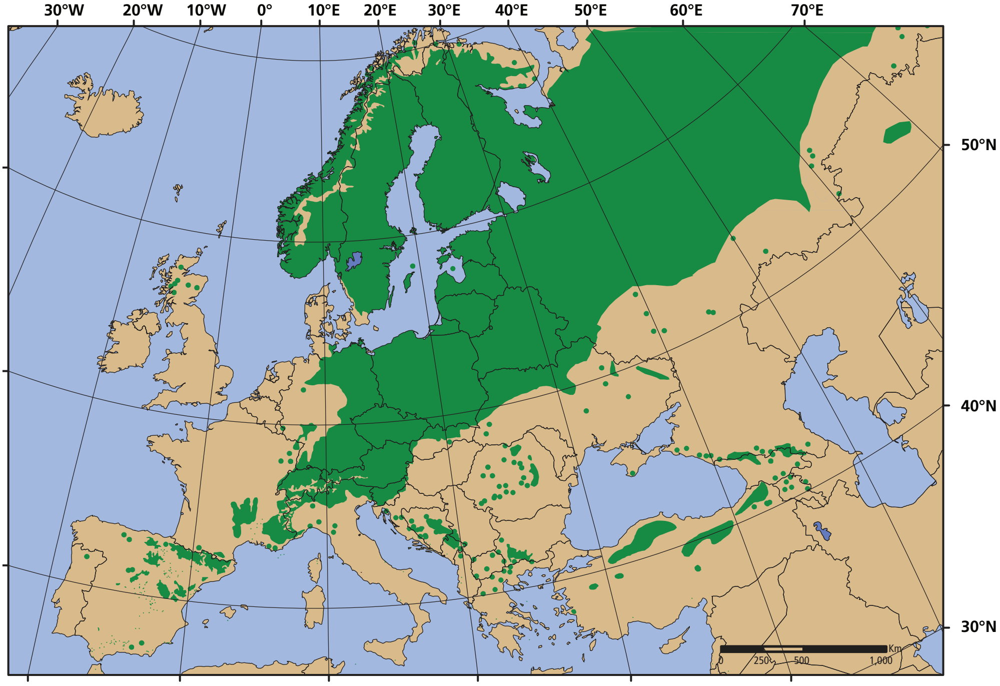
Chloroplast DNA (cpDNA) is the genome of choice for phylogenetic and phylogeographic studies because of the small size of the genome and uniparental inheritance, which make it possible to interpret the spatial pattern of haplotypes as an estimate of past gene flow. Chloroplast DNA is also easily sequenced and assessed for length variation using restriction enzymes. In addition, cpDNA shows neutral differentiation among divergent populations sooner than nuclear alleles. If population divergence has occurred relatively recently, neutral cpDNA variation will be more likely to show the differentiation than nuclear polymorphisms (Hamilton *et al*., 2003). Hamilton *et al*. (2003) examined patterns of cpDNA haplotype variation, searching in particular for evidence of selection acting on several insertion/deletion regions of the chloroplast genome of eight species of Lecythidaceae, which is the Brazil nut family. They found that the rate of evolution was highly variable among regions in the genome, but that the variability seemed to be related to lineage rather than region. They concluded that the insertion/deletion markers and nucleotide variation in the chloroplast genome were selectively neutral and thus should provide unbiased estimates of population parameters.

## Availability of information on genetic resources

The availability of, and access to, quality and up-to-date information on FGR is reported to be poor in many countries. For example, knowledge on species distribution remains inaccurate in the tropics, and distribution maps have been developed for only a small proportion of species. In contrast, more is known for temperate species. In Europe, for instance, the European Forest Genetic Resources Programme (EUFORGEN) has developed 34 species distribution maps (Figure 4.2); they include population-level information which is essential for monitoring the dynamics of the species' genetic resources.

Most country reports highlight the need to promote awareness among decision-makers and the general public of the importance of FGR and their roles in meeting present and future development needs. Lack of information limits the capacity of countries and the international community to integrate FGR management into cross-cutting policies. In spite of the efforts of plant taxonomists and geneticists to characterize and describe forest plant species and species populations, many key questions still need to be answered.

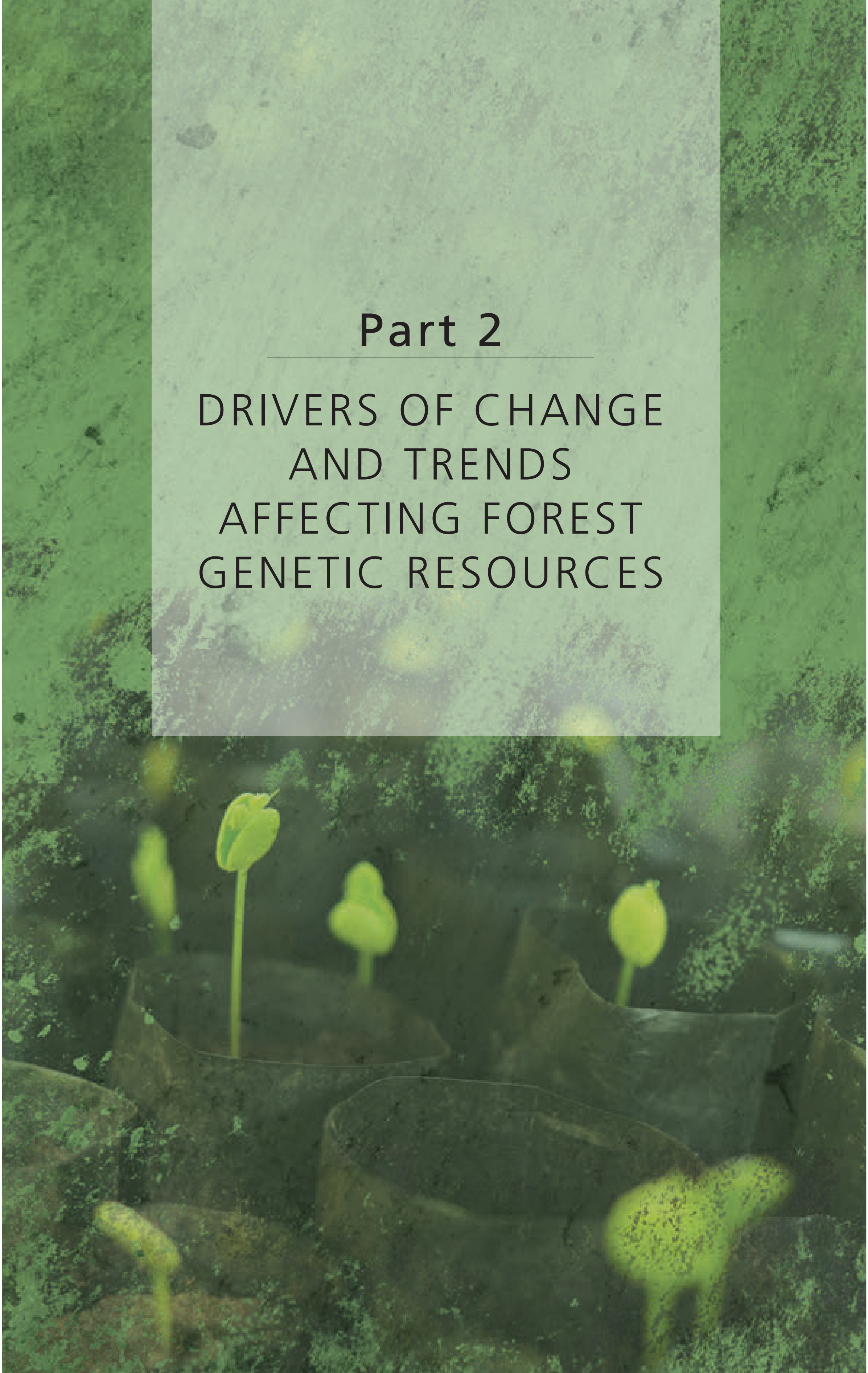
**FIGURE 4.2**
Example of a species distribution map: *Pinus sylvestris* in Europe



*Source*: EUFORGEN, 2009 (by permission).

# Part 2

# DRIVERS OF CHANGE AND TRENDS AFFECTING FOREST GENETIC RESOURCES



## Chapter 5

# Drivers of change

The main drivers of change causing unprecedented threats to FGR in recent times are almost exclusively of human origin. The world's current population of 7.2 billion is projected to reach 9.6 billion by 2050. Whereas population in developed countries is expected to remain largely constant, growth is expected to be particularly dramatic in the world's least developed countries, which are projected to double in size from 898 million inhabitants in 2013 to 1.8 billion in 2050 and to 2.9 billion in 2100 (UN, 2013). Along with population growth, production of energy, food and many other commodities is predicted to increase, with some negative impact on natural resources including forests and forest genetic resources.

Many major drivers of change in forestry are external to the forestry sector. Demographic, economic, technological and climate changes all shape forest development. With the exception of geological events, the categories of threat to species identified by IUCN are residential and commercial development; agriculture and aquaculture; energy production and mining; transportation and service corridors; biological resource use; human intrusions and disturbance; natural system modifications; invasive and other problematic species; pollution; geological events; and climate change and severe weather events.

Major modern-day human impacts on the environment involve massive changes in land-use systems (e.g. conversion of forest to agriculture and other land uses), destruction and fragmentation of natural habitats, air and soil pollution, salinization and soil acidification, climate change, overexploitation of biological resources, homogenization of biota and biodiversity loss. These impacts interact in complex ways and may result in non-additive cumulative effects (Yachi and Loreau, 1999). Threats to FGR that have increased greatly in recent times and could continue to increase in the future include forest cover reduction and degradation, climate change, forest ecosystem modification, spread of invasive and ecosystem-transforming species and interactions of different threat factors.

## Forest conversion and expansion of crop land

The main needs of the world's growing human population that have impact on FGR in native forests are additional land for agriculture and agroforestry production, infrastructure, human settlements, mining, and planted forests for wood, paper and fuel. For example, the demand for wood products for both industrial and domestic uses is expected to increase by 40 percent in the next 20 years (FAO, 2010a).

The growing global demand for land for the production of agricultural commodities has resulted in sometimes irreversible changes to the world's forest cover. The conversion of forest lands to agriculture is one of the major threats to forest genetic resources. Expansion of small-scale permanent agriculture accounts for 60 percent of forest conversion in Africa, while large-scale permanent agriculture involving commodities such as palm oil and soybean represents the major cause of forest conversion in Latin America and Asia (FAO, 2001c). Over the decade 2000–2010, permanent crop area has increased by 15.7

percent globally and by 22 percent in the least developed countries (Figure 5.1). Together croplands and pastures have become one of the largest terrestrial biomes on the planet, rivalling forest cover in extent and occupying about 40 percent of the land surface (World Bank, 2008).

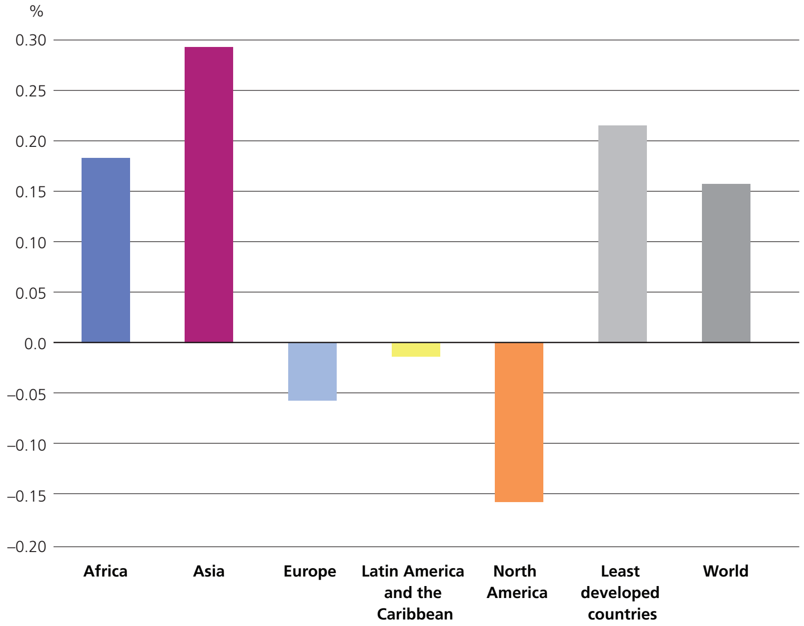
Important drivers of forest ecosystem degradation also include large-scale plantations for timber or paper pulp or for oil-palm (Foley *et al*., 2005; Kongsager and Reenberg, 2012) which have replaced many natural forests and cover 190 million hectares worldwide.

## Demand for energy

Bioenergy, including fuelwood and charcoal, currently represents a major portion of the domestic energy consumption in many developing countries and is one of the main causes of forest degradation in these countries, particularly in the dryland or semi-arid countries in Africa. Fuelwood represents 90 percent of total wood removals in Africa, compared with 47 percent in the world overall (FAO, 2010a). Driven by population growth and the subsequent demand for more domestic energy supply, global fuelwood consumption has increased by 4 percent from 2000 to 2010.

Bioenergy is expected to become an important component of future renewable energy systems, and policies are being developed to facilitate this process. The European Union (EU) currently imports almost half the energy resources it consumes, including liquid biofuels and wood pellets. Already in 2007, many European countries, such as Belgium, Finland, the Netherlands, Sweden and the United Kingdom, imported significant amounts of biomass (between 12 and 43 percent

**FIGURE 5.1**
Changes in area of cropland, 2000–2010



*Source*: Data from FAO, 2013a.

of their total used for energy purposes). The EU is now promoting energy policies that have potentially far-reaching implications for forests and forest use.

## Unsustainable harvesting and use

Many of the country reports provided for this report detail overexploitation and unsustainable harvesting threats to FGR. Overharvesting by itself rarely leads to extinction, but it can seriously erode genetic diversity, and recovery can be very slow for species that occur naturally at low frequency. For narrowly distributed and naturally rare species, overharvesting can directly lead to or threaten extinction. *Thuja sutchuenensis*, for example, a critically endangered, narrowly distributed endemic tree in Chongqing Municipality, China, was driven to the brink of extinction from overharvesting for its precious scented wood; in 1999 it was rediscovered and accorded protection. Chile has identified overexploitation, along with land use change and deforestation, as a major threat for 22 priority tree species (Hechenleitner *et al*., 2005).

Some countries report selective overharvesting, much of it illegal, as a major and increasing problem intertwined with rural poverty, threatening extinction of the highest-value species in the forests – including high-value timbers such as *Dalbergia cochinchinensis* in Southeast Asia, *Dalbergia melanoxylon* in sub-Saharan Africa and *Pterocarpus santalinus* in India; and valuable NWFP species such as *Cryptocarya massoia* (whose bark provides massoia lactones for the food industry) in New Guinea, *Prunus africana* (whose bark is used in treatment of benign prostate hypertrophy), certain *Santalum* and *Osyris* species (sandalwoods, whose heartwood provides essential oils) in India, Indonesia, Timor Leste and the Pacific Islands, and *Taxus contorta* (producing taxol, a chemotherapy drug to treat cancer) in Afghanistan, India and Nepal.

Overharvesting usually concerns highly valuable species such as ebonies, sandalwoods, agarwoods and frankincense, but in areas with high population pressure and poverty, overharvesting may be associated with lower-value products such as fuelwood and charcoal. Even an activity as seemingly innocuous as harvesting for Christmas trees may threaten FGR; in Guatemala, for example, uncontrolled cutting of *Abies guatemalensis* branches for use as Christmas trees is reducing the regenerative capacity of the species, which has now disappeared from some areas (López, 1999). In Tonga, harvesting of *Santalum yasi* saplings for Christmas trees is limiting recruitment and is one of the major threats to the species (Tuisese *et al*., 2000).

Harvesting of wood resources for fuelwood and charcoal is often less discriminatory but can lead to permanent loss of tree species in locally adapted populations, reducing options for future natural or human-mediated recovery from the associated environmental degradation. Somalia, for example, reports deforestation and elimination of ecologically and economically important tree species such as *Acacia* spp. as a result of charcoal production for income generation (including though export); *Boswellia* spp. have also been overexploited for frankincense. In northeastern Thailand, high rates of drug addiction in some villages have resulted in increased charcoal production and unsustainable resin harvesting from dipterocarps and pines in adjacent forests to pay for illicit drugs, threatening the efforts of the Thai Forestry Department to conserve unique lowland populations of *Pinus merkusii.*

One remedy to overharvesting can be the greater involvement of indigenous and local communities in management of forests and FGR, especially if this is backed by appropriate technical support, including improved silvicultural practices to ensure sustainable production of desired products and regeneration of preferred species. Other strategies include better legislative protection, including compliance monitoring, and development of alternative sources of wood and NWFPs such as highly productive plantation systems and improved agroforestry systems.

## Livestock and browse animals

In some regions, grazing by the growing livestock population is a serious threat to many woody forage species and can have a destructive impact on the genetic resources. In Latin America, for example, rapid expansion of cattle ranches accounts for a large portion of forest loss (FAO, 2007a). In the Brazilian Amazon region, ranches cover an area of at least 8.4 million hectares in total (UNEP, 2009). In the Sahelian and other semi-arid countries of West Africa, where the cattle and small ruminant population is estimated to be as high as 60 million and 160 million respectively (SWAC-OECD/ECOWAS, 2008), forest reserves are the main source of fodder for cattle grazing freely during the dry season when animal feed becomes scarce. Furthermore, herders who practice pollarding of fodder trees to feed their animals can put particular tree species in danger. Heavy grazing in forest land can cause a shift from perennial to annual vegetation type; studies have shown up to 50 percent reduction of large woody shrub cover in South Africa from grazing (O'Connor *et al.*, 2011). Other studies (e.g. Olff and Ritchie, 1998), however, mostly on grassland conditions, suggest that grazing can sometimes result in increased species richness. Excluding grazing animals from ecosystems that evolved with grazing has been documented to decrease biodiversity through competitive exclusion of certain plant species (Nuzum, 2005).

Browsing animals, especially introduced goats, have wrought havoc on tree vegetation in many parts of the globe, especially on island communities. *Pinus radiata* is among the most important plantation forestry trees species in the world, but the unique island population on Guadalupe Island, Mexico, was until recently highly threatened with surviving trees being very old and browsing by goats removing any regeneration (Spencer, Eldridge and Matheson, 1999). The goats have now been taken away from the island and the population is being monitored. While the Guadalupe provenance is secured through *ex situ* conservation efforts, a loss of the tree in its natural habitats would have excluded continued evolution and adaptation in the environment that has resulted in highly drought tolerant germplasm.

By 1945 goat predation on Three Kings Island in northern New Zealand had reduced the entire population of *Pennantia baylisiana* to one individual female tree incapable of sexually reproducing itself. In 1985 researchers treated latent pollen with hormones, inducing some seed, including a self-fertile individual; the future of this species has now been secured. In French Polynesia (France), rats have prevented the natural regeneration of *Santalum insulare* by eating more than 99 percent of fruits before their ripening (Meyer and Butaud, 2009).

## Climate change

Since the start of the Industrial Revolution in Europe in the eighteenth century, atmospheric pollution has caused damage to forests. However, its importance as a direct threat to FGR is diminishing, with most damage likely to result from stressed trees being more susceptible to insect pests and diseases. Of greater global concern for FGR are increasing levels of atmospheric $CO_2$ resulting from human activities such as burning of fossil fuels and forest destruction over the past half-century. Deforestation and forest degradation, with the causes described above, account for nearly 20 percent of greenhouse gas emissions.

Elevated levels of $CO_2$ are already contributing to more extreme climatic events, as predicted by the Intergovernmental Panel on Climate Change (IPCC, 2013). Climate alterations and increased occurrence of extreme climatic events are mentioned as a threat to FGR in many of the country reports prepared for this publication. Many Sahelian zone countries in West Africa, for example, cited prolonged drought as a threat. High mortality due to extreme climatic events, in combination with regeneration failure, can result in local population extinction and the loss of FGR, particularly at the receding edge of a species' distribution.

Climate change could alter the frequency and intensity of forest disturbances such as insect outbreaks, invasive species, wildfires, and storms. A greater incidence of intense cyclones, extreme drought, fires, flooding and landslides has been observed in tropical forest ecosystems which have experienced increased temperatures and more frequent and extreme El Niño–Southern Oscillation (ENSO) events. Some climate change models predict substantial dieback in parts of the Amazon and other moist tropical forests, and the resulting loss of carbon sinks and storage would exacerbate global warming (Bernier and Schoene, 2009).

Predictions regarding the impact of climate change on FGR in natural forests, in planted forests and on farms vary. Although some authors (e.g. Hamrick, 2004) consider that many trees have sufficient phenotypic plasticity and genetic diversity at the population level to withstand the negative effects of climate change, others predict severe impacts (e.g. Mátyás, Vendramin and Fady, 2009; Rehfeldt *et al*., 2001). Different positions relate partly to the types of species and environments being considered. The more pessimistic authors often base their views on tropical trees (Dawson *et al*., 2011) or on marginal populations of temperate species (Mátyás, Vendramin and Fady, 2009), while the more optimistic authors are often those discussing temperate and boreal taxa (Lindner *et al*., 2010). Current and future climate change impacts on forests are likely to vary from abrupt negative impacts to more subtle negative and positive impacts in some regions or at particular sites, often only for certain tree species. Many countries urgently require assistance to cope and deal with impacts of climate change on FGR and to promote and use FGR to help with climate change adaptation and mitigation.

## Climate impact on species and ecosystems

Temperature and precipitation are the two main climate drivers for forest ecosystems; any significant changes in either of these will have an impact on species composition and forest cover. Impacts can range from extreme disturbances such as forest fires or pest outbreaks to effects on physiological processes from more subtle changes in temperature. The ability of a tree species to survive the current rapid climate changes will depend on its capacity to adapt quickly to new conditions at existing sites, to survive changing conditions through a high degree of phenotypic plasticity without any genetic change, and/or to migrate to an environment with the desired conditions for that species.

Some forest types are more vulnerable than others to climate change. For example, in tropical forests, small changes in climate are likely to affect the timing and intensity of flowering and seeding events, which would in turn have negative impact on forest biodiversity and ecosystem services. Increased frequency and intensity of extreme events, such as cyclones, may result in shifts in species composition. Mangrove ecosystems are especially vulnerable, with projected sea-level rises posing the greatest threat. Mangroves could potentially move inland to cope with sea-level rise, but such expansion can be blocked either by infrastructure or by the lack of necessary sediment, such as in the reef-based island archipelagos in Melanesia. Temperature stress will also affect the photosynthetic and growth rates of mangroves (McLeod and Salm, 2006). Climate change impacts are expected to be severe in dry, high-temperature regions where trees are at their adaptive limit (e.g. Lindner *et al*., 2010 for Europe) and in confined islands of moist forest that are surrounded by drier land (e.g. moist forests in Australia [Williams, Bolitho and Fox, 2003]).

Forest cover will alter under climate change. The range of some species will expand, whereas that of others will diminish. Changing temperature and precipitation regimes will also cause shifts in forest types. For example, boreal forests are expected to shift towards the poles, with grassland moving into areas formerly occupied by boreal species. There is evidence of the migration of keystone ecosystems at the upland and lowland

treeline of mountainous regions across southern Siberia, Russian Federation (Soja *et al.*, 2007). For temperate forests, range reduction is expected to be more rapid at low elevation and low latitude. At high elevation and high latitude, temperate forest species ranges are expected to expand more than those of boreal forests; as a result the total area of boreal forests will decline. Thuiller *et al*. (2006) have shown that at low latitudes in Europe climate change will have a greater impact on species richness and functional diversity than at high latitudes.

In the subtropical forests of Asia, where key biodiversity hotspots are found, endemic species are predicted to decline, with changes in ecosystem structure and function as a result (FAO, 2010b). Changes in precipitation may be more critical than temperature changes for these species and systems (Dawson *et al*., 2011).

Changes in water availability are a major emerging threat to FGR; they will be a key factor for the survival and growth of forest species. The response to prolonged droughts will vary among tree species and also among different varieties of the same species (Lucier *et al*., 2009). In arid and semi-arid lands, increased duration and severity of drought has increased tree mortality and resulted in degradation and reduced distribution of forest ecosystems, including pinyon pine-juniper woodlands in the southwestern United States of America (Shaw, Steed and DeBlander, 2005) and *Cedrus atlantica* forests in Algeria and Morocco (Bernier and Schoene, 2009). Indirect impacts must also be considered. For example, in Africa, where drought is limiting the output from adjoining agricultural land, many communities with limited economic alternatives are likely to use forests for crop cultivation, grazing and illicit harvesting of wood and other forest products, aggravating the local loss of forest cover (Bernier and Schoene, 2009).

Choat *et al.* (2012) found that of 226 forest tree species from 81 sites worldwide, 70 percent have narrow safety margins in the event of injurious levels of drought stress and therefore could face long-term reductions in productivity and survival if temperature and aridity increase as predicted. While gymnosperms were found to be more tolerant of reduced hydraulic conductivity than angiosperms, safety margins were seen to be largely independent of mean annual precipitation, with all forest biomes equally vulnerable to hydraulic failure and drought-induced forest decline. These findings help to explain why drought and increased heat are resulting in forest dieback across a broad range of forest and woodland types around the world (Allen, 2009). These dieback problems have occurred at a time when increases in temperature have been relatively modest, which does not bode well for forests given future temperature predictions. Under a scenario of a 4°C increase in global temperature, greater mortality rates can be expected as well as significant long-term regional drying in some areas.

Changed hydrological conditions associated with climate change also include increases in severity and duration of flooding, which can kill whole stands of trees. Even inundation-tolerant species, such as *Eucalyptus camaldulensis* and *Cocos nucifera*, are killed by waterlogging if the trees have not been regularly exposed to waterlogging and inundation through their development. Inundation due to sea-level rise is beginning to kill vegetation in coastal areas (see Box 5.1).

In temperate and boreal regions, reduced snow cover, changed timing of snowmelt and shorter frost periods are contributing to forest changes and stresses. Reduced snow cover has been shown to be responsible for the decline of *Xanthocyparis nootkatensis*, a culturally and economically important tree in southeastern Alaska, United States of America, and adjacent areas of British Columbia, Canada. Snow normally protects the vulnerable shallow roots from freezing damage. The decline is affecting about 60 to 70 percent of the 240 000 ha of *X. nootkatensis*. Coastal Alaska is expected to experience persistent periodic cold weather events but less snow in the future, which may support the spread of dieback (USDA Forest Service, Pacific Northwest Research Station, 2012).

Sensitivity to spring temperatures will affect fecundity (Clark *et al*., 2011). In central Spain a decline in cone production in *Pinus pinea* over the past 40 years has been linked to warming, in particular the hotter summers (Mutke, Gordo and Gil, 2005). In angiosperms, changes in the climate could have an impact on seed production; asynchronous timing between flower development and the availability of pollinators could result in low seed production for outbreeding species that depend on animal vectors. Pollinators worldwide are being affected by climate change, and this will likely have a major detrimental impact on breeding systems and seed production, with consequences for forest health and regeneration.

A changing climate also provides the opportunity for some plant species more suited to a wide range of climate conditions to invade new areas (Dukes, 2003). The spread of *Leucaena* spp. and *Eupatorium* spp., for example, is already known to have had adverse impacts on biodiversity in subtropical forests in South Asia. In addition to new species invasions, changing climates will result in altered patterns of gene flow and the hybridization of species and populations. Shifting ecological niches will increase the risk of invasion by more competitive tree species that are more precocious or can move more quickly than the present species. Invasions of new genes via pollen and seed dispersal may disrupt local evolutionary processes, but could also be a welcome source of new adaptive traits (Hoffmann and Sgro, 2011).

### Box 5.1

### Selecting for salt tolerance: one way to address impacts of sea-level rise on coastal forests

In Kiribati, a single king tide can kill established *Artocarpus altilis* (breadfruit) trees. As these trees harbour seabirds such as terns which are used by local fisherman to locate schools of fish, their loss has a major impact on food security and livelihoods.

Given the impacts of sea-level rise in Kiribati, Tuvalu, and other atoll island nations in Oceania, development of salt-tolerant breadfruit is an urgent task. Studies with salt-tolerant non-halophyte trees (Thomson, Morris and Halloran, 1987; references in Marcar *et al*., 1999) have frequently demonstrated considerable genetically based resistance to salinity. Given the substantial genetic diversity in breadfruit, including putative salt tolerance in particular varieties and natural hybrids between *A. altilis* and *Artocarpus mariannensis* (Morton, 1987; Ragone, 1997), it is almost certain that salt-tolerant breadfruit can be selected and further developed – illustrating the need to conserve and make use of genetic diversity in multipurpose tree species.

## Climate impact on insect pests and diseases

Changes in temperature and water availability will also influence the incidence and spread of pests and diseases. For example, unusually warm winters – i.e. the absence of consistently low temperatures over a long period – supported the spread of mountain pine beetle, *Dendroctonus ponderosae*, from an existing outbreak to an attack on some 14 million hectares of montane and boreal forests in North America (see section on insect pests below). Spreading into new areas and attacking pine trees with no resistance, the beetle threatened the genetic diversity of forest populations.

Trees already weakened by climatic stresses are more vulnerable to destruction by insect attack (e.g. bark beetles) (McDowell *et al*., 2008). In Finland, the spread of a virulent fungus, *Heterobasidion parviporum*, favoured by longer harvesting periods, increased storm damage and longer spore production season, is expected to increase root and bud rots in coniferous forests (Burton *et al*., 2010).

A thorough analysis of historical records and adequate knowledge of insect population dynamics is needed before outbreak frequencies can be linked to climate change. The availability of such information has enabled researchers to link drought stress due to climate change to

the extensive damage caused by insects to *Pinus edulis* in the southwestern United States of America (Trotter, Cobb and Whitham, 2008)

Climate change may be facilitating the global spread of harmful forest pests by allowing species moved through international trade to find hospitable habitats (Régnière and Saint-Amant, 2008). Significant evidence regarding insect distributions is accumulating, although the complexity of insect responses to climate factors makes predictions difficult (see Box 5.2).

Useful insects such as pollinators, biological control agents and other plant-associated organisms can be affected by climate change as well.

Knowledge of forest genetic diversity, including pest resistance, will therefore be increasingly important in forest management.

## Changed fire regimes

Forest fires can be a great threat to biodiversity, and climate change may alter their frequency and intensity. In Siberia (Russian Federation), Alaska (United States of America) and Canada, extreme fire years have become more frequent (Soja *et al*., 2007). In recent years, wildfires consumed more than 2.5 million hectares of forest in Alaska, assisted by warm temperatures and drought conditions during early summer (CCSP, 2008). In 2006, fires engulfed more than 4 000 ha in New Caledonia (France), destroying rare fauna in the archipelago's unique tropical forest ecosystems. Other countries reporting forest fires as a threat to FGR included Algeria, Burundi and Ethiopia.

Fire may cause variable effects depending on the fire's intensity and spacial extent. Increased fire frequency could result in the erosion or even elimination of fire-sensitive species from woodlands and forests. In regions that have not regularly experienced wildfires in the past, fire may become the main driver of change, with a rapid transition from fire-sensitive to fire-resistant species.

Severe fire may have the same effect as clearing a forest, especially where fire creates large patchy openings. The pattern and size of such openings in relation to the forest cover influence genetic diversity. Where mortality among burnt species is heavy, it results in reduced population sizes and increased genetic drift. For isolated populations, the migration rates of seed and pollen exchange are therefore affected. Sources of migration could

### Box 5.2
### Predicting impacts of climate change on distribution of forest insect pests

Modelling tools such as BioSIM (Régnière and Saint-Amant, 2008) have been designed to predict the geographic range and performance of insects based on their responses to key climate factors. The basis of BioSIM is the ability of the insect to complete its life cycle under a specific climate with all requirements to sustain that cycle available. The model predicts distributions by mapping climates that provide viable seasonality and overlaying the distribution of resources essential for (or most at risk from) a particular species. Further refinements can be achieved by also considering the survival of that species under extreme climatic conditions. This approach has been applied to three species of importance to North American forests within a climate change scenario of a 1 percent rise per year in atmospheric $CO_2$. One of these species, *Lymantria dispar* (gypsy moth), is prevalent in the United States of America and some parts of Canada; however, its northern limit in Canada is set by adverse climatic conditions. The model established for this species shows that it will be a considerable threat to hardwood forest resources as climate change allows for its expansion further north and west in Canada. It has been estimated that the proportion of forest at risk from this pest will grow from the current 15 percent to more than 75 percent by 2050 (Logan, Régnière and Powell, 2003).

even be cut off, thus reducing the effectiveness of pollinators (Kigomo, 2001).

Adverse fire may directly affect biotic dispersal agents, and this may decrease migration of genes between populations. Migration may increase if the migration vectors are abiotic. A devastating fire may affect traits that could have a direct bearing on fire-resistant species, resulting in direct selection that indiscriminately removes all such genotypes (FAO, 2010a).

The cumulative impact of interacting disturbances can increase fire risk. For example, drought often reduces tree vigour, increasing vulnerability to insect infestations and diseases. Insect infestations and diseases add to the fuel available and therefore increase the opportunity for forest fires, which in turn can support future infestations by weakening tree defence systems (Dale *et al.*, 2001).

## Invasive species

Invasive species, including plants, insect pests and microbial pathogens, are increasingly being identified and noted as major threats to ecosystem integrity and individual species, including trees. The United States of America, for example, reports that 46 percent of all federally listed threatened and endangered species are considered at risk primarily because of competition with or predation by invasive species, sometimes in interaction with other threat factors. The spread and impacts of invasive species are frequently exacerbated by climate change and/or major environmental disturbances.

National assessments, networking, research and collaboration among concerned countries and the International Plant Protection Convention (IPPC) are key strategies to avoid the further spread of invasive alien species.

### Invasive plants

The main invasive plant threat comes from "transformer" plant species which have the capacity to invade natural or slightly disturbed forest associations, becoming the dominant canopy species and completely modifying or displacing entire ecosystems, with the loss of many of the existing species (trees and others). An example is the introduced tropical American tree *Prosopis juliflora* in East Africa, which is taking over large swathes of natural forest and woodlands, with considerable negative impacts on native tree populations (in terms of both species and genetic diversity). It is also damaging local livelihoods in the process (e.g. Mwangi and Swallow, 2005). Another example is the Australasian tree *Melaleuca quinquenervia* in South Florida (United States of America), introduced in the early 1900s and later planted to drain swamps; it has since invaded up to 200 000 ha and transformed various ecosystems in the Florida Everglades, causing major environmental and economic damage (Carter-Finn *et al.*, 2006).

It appears that even minor climatic changes can result in native tree species becoming more invasive, spreading into neighbouring regions and dramatically changing the forest dynamics, structure and species composition. The spread of *Pittosporum undulatum* and *Leptospermum laevigatum* in southeastern Australia, for example, is a portent of future challenges for *in situ* FGR management, as the more extreme climatic changes that are predicted would favour disturbance-adapted pioneer and early secondary tree species.

Island ecosystems are especially vulnerable to invasive species. In just a few decades, *Spathodea campanulata* (African tulip tree), introduced in Fiji as an ornamental in 1936, has taken over large areas of secondary forest and abandoned agricultural fields (Brown and Daigneault, 2014); it has also become invasive in mesic lowland tropical moist forest up to 1 000–1 200 m elevation in much of Oceania, including French Polynesia (Meyer, 2004), Cook Islands (Meyer, 2000), Papua New Guinea and Australia (where it has been declared a pest and its propagation and sale as an ornamental are now prohibited). The tropical American tree *Miconia calvescens* has become one of the world's most invasive species and has completely taken over more

than a quarter of moist tropical forest in Tahiti (France) (Meyer and Florence, 1996). In island countries and territories of Oceania, excessive opening of the forest canopy through intensive timber harvesting, coupled with major cyclones, has greatly favoured the spread of light-loving vines such as *Merremia peltata* and *Mikania scandens*; these vines and creepers have now taken over large swathes of forest ecosystems, thickly draping all trees and shrubs (e.g. Maturin, 2013; Kamusoko, 2014).

### Insect pests

A global review of forest pests and diseases (FAO, 2009) revealed major and increasing threats to forests from insect pests, both native and exotic. Some examples of how exotic pests threaten FGR and the economic and environmental contribution of forests are discussed here, and are mainly derived from the FAO review.

Invasive *Sirex noctilio* (European wood wasp) has affected thousands of hectares of planted pine forests in countries around the globe, including South Africa, South American countries, and Australia. It continues to spread and is now threatening native pine and Douglas fir in North America.

*Heteropsylla cubana* (leucaena psyllid) is a significant pest of *Leucaena leucocephala*, a fast-growing multipurpose tree legume native to Mexico and Central America which has been widely planted throughout the tropics. In the mid-1980s, this insect spread across Asia (FAO, 2001b); the spread of the psyllid was especially rapid because most leucaena plantings consisted of a very narrow, nearly identical genetic base.

*Anoplophora glabripennis* (Asian longhorned beetle) spread in Chinese planted forests as a result of widespread planting of susceptible poplar hybrids (EPPO, 1999) and has been accidentally introduced in North America and Europe. In China more than 200 million infested trees have been removed to control outbreaks. Authorities in the United States of America and Canada have implemented emergency control measures whenever the pest has been detected. Strains of *Populus nigra* resistant to attack by the Asian longhorned beetle have been developed in China, through insertion of a Cry1Ac gene from *Bacillus thuringiensis* (Hu *et al*., 2001).

*Cinara cupressivori* (cypress aphid), originally from Europe (Greece) and the Near East (Islamic Republic of Iran), spread to Africa around 1986. In Kenya it rapidly caused major damage to *Cupressus lusitanica* (cypress) plantations, which constituted half of Kenya's planted forest estate. The cypress aphid killed a total of USD 27.5 million worth of trees in 1991 and was causing a loss in annual growth of around USD 9 million per year (Murphy, Nair and Sharma, 1996). This is one example, of many, of the perils and risks of plantation and farm forestry that is reliant on a single exotic species, especially when grown in monocultures. In Malawi the cypress aphid also attacks and kills the highly endangered conifer and national tree *Widdringtonia nodiflora* (Bayliss *et al*., 2007); genetic resistance has yet to be found.

A devastating outbreak of *Dendroctonus ponderosae* (mountain pine beetle), a bark beetle indigenous to western North America that primarily feeds on *Pinus contorta* var. *latifolia*, began in the 1990s and has affected about 14 million hectares of forest land in western Canada (Nealis and Peter, 2008), killing 50 percent of the standing volume in British Columbia. Increased warming associated with climate change enabled the beetle to expand its range; it spread across a mountain range and into Alberta in 2006, and may eventually cause large-scale destruction to *Pinus banksiana* in boreal forest (Cullingham *et al.*, 2011). The extent to which jackpine might show genetic resistance to mountain pine beetle is unknown, but natural hybrids with lodgepole pine are expected to display some resistance.

*Leptocybe invasa* (blue gum chalcid), probably native to Australia, is a relatively new threat to planted eucalypt forests in Africa; it was first reported in Kenya in 2002 and in South Africa in 2007. It has also been reported in Asia, Europe and the Near East.

The severity and frequency of insect pest outbreaks are projected to increase in concert with extreme climatic factors. China reports increased forest pest outbreaks in 2009 following a major snowstorm in South China and severe widespread drought in 2008 (China country report).

## Pathogens

Cases of virulent introduced pathogenic fungi wreaking havoc on economically and environmentally important tree species are particularly well documented in the Northern Hemisphere (see examples in Box 5.3).

Over the past decade outbreaks of exotic pathogens have caused major damage in forests in the tropics and the Southern Hemisphere. The reported increase in such outbreaks may be attributed to movement of goods and people, together with changing climate and environmental disturbances. An example is *Fusarium circinatum* (pine pitch canker), introduced perhaps originally from Mexico, which has been devastating the native California (United States of America) stands of *Pinus radiata*, with more than 90 percent of the trees likely to succumb to the disease (Devey, Matheson and Gordon, 1999). Pitch canker has recently been found on *P. radiata* in South Africa (where it seriously threatens the future of the country's pine plantation industry, which comprises 670 000 ha and half the country's wood and fibre assets) (Coutinho *et al*., 2007) and on *Pinus* species in Colombia (Steenkamp *et al*., 2012). In areas of the world where pitch canker has spread, management practices will need to be altered and more pitch canker resistant *Pinus* species and provenances will need to be deployed, such as *Pinus tecunumanii* from low-elevation sources and *Pinus maximinoi* in Colombia.

Poplar rust was one of the first major exotic tree diseases to be reported from the Southern Hemisphere. Two species of poplar rust (*Melampsora medusae* and *Melampsora larici-populina*) appeared in Australia in 1972/73 and rapidly spread to New Zealand, devastating poplar plantations. However, considerable genetic variation in resistance to poplar rusts has been found among poplar species and clones (and alternate conifer hosts), and disease impacts can be managed by planting mixtures of more resistant clones. Selection for poplar rust resistance has been complicated, however, by the appearance of different races of rust.

Fungal pathogens including another rust (*Atelocauda digitata*) are a major concern for the productivity of the more than 1 million hectares of *Acacia* plantations in Asia (see Old *et al*., 2000). However, different *Acacia* provenances show considerable variation in susceptibility to disease, which indicates potential for selection of resistant genotypes.

In 2010 a new pathogen, *Puccinia psidii* (myrtle rust or guava rust), originating in South America, was detected in New South Wales, Australia. Most species in the family Myrtaceae – which has more than 2 000 plant species including eucalypts, and which is Australia's dominant plant family – have the potential to become infected to some degree by this rust species (Morin *et al*., 2012). It could alter the composition, function and diversity of many of Australia's eucalypt-dominated forest and woodland ecosystems and could have severe impact on forest industries. Doran, Lea and Bush (2012) have recently identified family- and provenance-level resistance to *Puccinia psidii* in *Backhousia citriodora*, an economically important essential oil producing plant, through wide-ranging provenance, family, and clone trials.

Because forest pathogens are continuously evolving, a combination of management measures is needed to deal with them, including deployment of diverse resistant genetic materials and continuing breeding programmes with access to genetic diversity. The above examples and those in Box 5.3 illustrate how variation in susceptibility to disease can be useful for selection of resistant genotypes, underscoring the importance of genetic diversity, its conservation in native stands, and provenance and family trials in combating threats from pathogens,

especially newly introduced strains and species. Successful examples of breeding for pathogen resistance include resistance to *Mycosphaerella pini* (red band needle blight) in *Pinus radiata* in New Zealand (Carson, 1990) and resistance to *Cronartium ribicola* (white pine blister rust) in *Pinus monticola* in North America (Sniezko, 2006).

## Genetic pollution

A significant but largely unquantified risk to FGR conservation and use is the uncontrolled and undocumented mixing of gene pools of forest tree species. This can occur within species, whereby genetically diversified local populations, which may possess valuable attributes, interbreed with non-local germplasm introduced for planted forest establishment. Hybridization of local and introduced gene pools may reduce local adaptation in subsequent tree generations (Millar and Libby, 1989; Palmberg-Lerche, 1999). Mixing of gene pools can also inadvertently lead to incorporation of undesirable genes, resulting in a diminished economic value for production forests and vastly complicating and increasing the costs of tree breeding in cases where breeders may need to "unscramble the omelette". Interbreeding can also occur when formerly allopatric (geographically isolated)

### Box 5.3
### Some destructive pathogens in Northern Hemisphere forests

*Cryphonectria parasitica* (Asian chestnut blight fungus), accidentally introduced into the United States of America early in the twentieth century, wiped out almost the entire population of *Castanea dentata* (American chestnut) including more than 3 billion trees over 70 million hectares (Cox, 1997); this annihilation was accompanied by the extinction of other species dependent on chestnuts, including ten species of moths. Ironically, early salvation logging may have removed some of the few American chestnut trees that showed resistance to the disease. Programmes have been implemented to backcross surviving American chestnuts with blight-resistant chestnuts from Asia for reintroduction into the former natural range of the American chestnut.

*Ophiostoma* spp. (Dutch elm disease), since its introduction into North America around 1930, has killed more than 95 percent of *Ulmus americana* (American elm), millions of trees. It is estimated that only one in 100 000 trees is naturally resistant. A few recently-cloned resistant individuals in Canada (Shukla *et al.*, 2012), along with newly identified resistant diploids and triploids in the United States of America (Whittemore and Olsen, 2011) and interspecific hybrids derived from crossing with resistant Asian *Ulmus* species, are paving the way for American elms to be reintroduced in North America. In the late 1960s a virulent strain of Dutch elm disease (*Ophiostoma novo-ulmi*) introduced into the United Kingdom wiped out most of the *Ulmus procera* trees, although in the United Kingdom and continental Europe they often survive as suckers and in hedgerows (e.g. Forestry Commission, n.d.) Various selection and breeding programmes with *Ulmus* spp. in Europe, including development of interspecific hybrids, have produced clones that are resistant to the fungus.

Various pathogenic diseases, many only identified or found over the past ten years, are now threatening important tree species in the United Kingdom (Forestry Commission, 2014). A new bacterial bleeding canker, *Pseudomonas syringae* pathovar *aesculi*, which was first detected around 2002, now afflicts 70 percent of *Aesculus hippocastanum* (horse chestnut) trees and is likely to eventually kill them. Chalara dieback, a serious disease caused by the introduced fungus *Hymenoscyphus pseudoalbidus*, first identified in 2012, infects *Fraxinus* species, often resulting in tree death and spreading throughout Europe. Another new bacterial disease, acute oak decline, threatens to wipe out *Quercus* species in the United Kingdom.

related species are brought together. If the taxa are not fully reproductively isolated and share the same flowering times and pollinators, then hybridization is likely; if the resulting progeny are fertile and are not selected against, then the eventual outcome can be loss of a species through assimilation.

Factors that threaten extinction by hybridization, such as habitat destruction, fragmentation and species introductions, are all increasing and often act synergistically (Rhymer and Simberloff, 1996). Outbreeding depression from detrimental gene flow may reduce the fitness of a locally rare species, making it vulnerable to extinction. Alternatively, pollen swamping may result in a rare species' loss of genetic integrity, and it may become assimilated into the gene pool of a more common species (Potts, Barbour and Hingston, 2001).

FAO's International Poplar Commission's Working Party on Poplar and Willow Genetics, Conservation and Improvement has drawn attention to the fact that populations of some native poplar species have been rapidly disappearing because of their spontaneous hybridization with cultivars and/or displacement by agriculture or other land uses (FAO, n.d.). Natural stands of *Populus nigra* have almost disappeared in Europe, and *Populus deltoides* is seriously jeopardized in North America as a result of interbreeding. However, there are few documented examples in the literature in which hybridization has threatened the existence of rare tree species, although presumably this has happened often during angiosperm evolution. The main cited example is *Cercocarpus traskiae*, a rare endemic species on Catalina Island, California, United States of America, which has been reduced to about seven mature pure individuals and which hybridizes with the more abundant *Cercocarpus betuloides* (Rieseberg *et al*., 1989). In Fiji and Tonga, *Santalum yasi* hybridizes freely with the introduced *Santalum album*, producing more vigorous F1 hybrid offspring (Bulai and Nataniela, 2005); this may eventually lead to the disappearance of pure *S. yasi* due to natural selective pressures and the commercial choices of smallholder sandalwood growers (Huish, 2009).

Awareness is increasing in the forestry profession of the risks that hybridization poses to local gene pools. Lebanon, for example, in order to protect the genetic integrity of its national tree (Lebanon cedar, *Cedrus libani*), has taken a ministerial decision that prohibits the import of *Cedrus* germplasm into the country (Lebanon country report). In Australia, Barbour *et al*. (2008) have formulated a framework for managing the risk of gene flow from plantations of non-native *Eucalyptus globulus* into native eucalypt populations in southern areas where *E. globulus* does not occur naturally. This framework could serve as a useful model for other tree genera and species.

## Chapter 6

# Global forest trends affecting forest genetic diversity

## Forest trends

Land-use activities, primarily agricultural expansion and timber extraction, have caused a net loss of about 700 to 1 100 million hectares of forest in the past 300 years (Foley *et al*., 2005). In spite of the notable forest restoration and afforestation activities undertaken to reverse the trend of forest cover loss (5.7 million hectares restored or planted annually), 13 million hectares of forest are still being lost every year. This loss represents a serious threat to habitats, species and genetic diversity.

Sustainable forest management is of major importance for its role in maintaining biological diversity and global ecological functions while enabling adequate use of the products derived from forests to meet growing demand. The Global Forest Resources Assessment 2010 (FRA 2010) (FAO, 2010a) reported on broad progress towards sustainable forest management since 1990 and found that at the global level the situation has remained relatively stable. The 2010 assessment did not include species or population-level indicators suitable for a global comparison of trends over time and therefore did not directly report on FGR. However, biological diversity was addressed through reference to the area of primary forest, areas designated for conservation of biological diversity and area of forest in protected areas.

This section on forest trends reports some of the major findings of FRA 2010 (FAO, 2010a), with notations on impacts and considerations for FGR.

### Forest cover

The world's total forest area is just over 4 billion hectares, with the five most forest-rich countries (the Russian Federation, Brazil, Canada, the United States of America and China) accounting for more than half of the total forest area. Human-mediated forest cover reduction and forest degradation have been among the main causes of negative change in forest genetic resources, including loss of tree species, over the past few hundred years. Loss of forest cover will almost certainly continue to be a problem while the world's population continues to rise.

The rate of loss of forest cover – mainly from conversion of tropical forest to agricultural land – shows signs of decreasing but is still alarmingly high. Around 13 million hectares of forest were converted to other uses or lost through natural causes each year between 2000 and 2010, compared with 16 million hectares per year in the 1990s.

In spite of its high importance, the natural moist tropical forest has continued to diminish rapidly at the global level. Most forest losses in the period 2000–2010 occurred in the regions and countries with more biodiversity-rich tropical forests (Tables 6.1 and 6.2). Brazil and Indonesia, two countries with biodiverse and FGR-rich forests, had the highest net loss of forest in the 1990s but have significantly reduced their rate of loss, which will also entail a slowing in the rate of loss of tree species and populations.

**TABLE 6.1**

Area of primary forest change, 1990–2010

| Region | Area of primary forest (1 000 ha) | | | Annual change (1 000 ha) | | Annual change (%) | |
|---|---|---|---|---|---|---|---|
| | 1990 | 2000 | 2010 | 1990–2000 | 2000–2010 | 1990–2000 | 2000–2010 |
| East and Southern Africa | 7 594 | 7 024 | 6 430 | –57 | –59 | –0.78 | –0.88 |
| North Africa | 15 276 | 14 098 | 13 990 | –118 | –11 | –0.80 | –0.08 |
| West and Central Africa | 37 737 | 32 540 | 27 527 | –520 | –501 | –1.47 | –1.66 |
| East Asia | 28 179 | 26 456 | 25 268 | –172 | –119 | –0.63 | –0.46 |
| South and Southeast Asia | 87 062 | 83 587 | 81 235 | –348 | –235 | –0.41 | 0.29 |
| Western and Central Asia | 2 924 | 3 083 | 3 201 | –16 | 12 | 0.53 | 0.38 |
| Europe | 5 183 | 5 360 | 5 438 | 18 | 8 | 0.34 | 0.14 |
| Caribbean | 207 | 206 | 205 | n.s. | n.s. | –0.07 | –0.02 |
| Central America | 5 766 | 5 226 | 4 482 | –54 | –74 | –0.98 | –1.52 |
| North America | 274 920 | 273 795 | 275 035 | –113 | 124 | –0.04 | 0.05 |
| Oceania | 41 416 | 39 191 | 35 493 | –222 | –370 | –0.55 | –0.99 |
| South America | 684 654 | 653 691 | 624 077 | –3 096 | –2 961 | 0.46 | –0.46 |
| World | 1 190 919 | 1 144 258 | 1 102 382 | –4 666 | –4 188 | –040 | –0.37 |

*Source*: FAO, 2010a.

Note: n.s. = not significant.

**TABLE 6.2**

The ten countries with the largest annual net loss of forest area, 1990–2010

| Country | Net loss of forest area (1 000 ha) | % loss |
|---|---|---|
| Brazil | 2 642 | 0.49 |
| Indonesia | 498 | 0.51 |
| Nigeria | 410 | 3.67 |
| United Republic of Tanzania | 403 | 1.13 |
| Zimbabwe | 327 | 1.88 |
| Democratic Republic of the Congo | 311 | 0.20 |
| Myanmar | 310 | 0.93 |
| Bolivia | 290 | 0.49 |
| Venezuela (Bolivarian Republic of) | 288 | 0.60 |
| Australia | 280 | 0.18 |

*Source*: FAO, 2010a.

Forest loss in tropical areas was relatively stable on a percent basis from the period 1990–2000 to 2000–2010. In West and Central Africa and in South America the rate of forest loss was the same for both periods (0.66 and 0.45 percent per annum, respectively). In East and Southern Africa the rate of forest loss increased from 0.62 to 0.66 percent per annum over the two periods, while annual forest loss in South and Southeast Asia dropped substantially from 0.77 to 0.23 percent. Annual forest loss also declined substantially in Central America, from 1.56 to 1.19 percent.

At the regional level, the changes in the period 2000–2010 were as follows.

- South America suffered the largest net loss of forests – about 4.0 million hectares per year.
- Africa had the next largest loss of forests, 3.4 million hectares annually.
- Oceania also reported a net loss of forest (about 700 000 ha per year),

mainly because of large losses of forests in Australia, where severe drought and forest fires exacerbated the loss of forest during the reporting period.

- The area of forest in North and Central America was estimated as almost the same in 2010 as in 2000.
- The forest area in Europe continued to expand, although at a slower rate (700 000 ha per year) than in the 1990s (900 000 ha per year).
- Asia reported a net gain of forest of more than 2.2 million hectares per year, in contrast with the net loss of some 600 000 ha annually in the 1990s. The gains were primarily due to the large-scale afforestation reported by China.

Both South America and Africa are rich in tree species and FGR, and their high forest losses represent a loss, though poorly documented, of irreplaceable FGR. Meanwhile the gains of forest area in Asia mask a loss of valuable FGR (of both species and especially populations of useful tree species) from shrinking native forests in many countries in South and Southeast Asia.

Forest area was increasing or stable in a number of countries, owing to the establishment of reserves and protected areas, controls on logging and overharvesting, implementation of sustainable forest management, planting of trees and plantations and natural regeneration of abandoned farmland. Countries with constant or increasing forest cover tended to be developed countries with highly developed forest management and administration institutions, although China and India achieved large increases in the decade, mainly through planting. Between 1990 and 2010 China planted more than 1.9 million hectares per year. The United States of America also undertook planting on a large scale (805 000 ha per year).

It is impossible to estimate accurately the genetic loss that is resulting from deforestation and forest degradation, given the generally poor knowledge of forest genetic resources, particularly for tropical forest. It should also be noted that many land-use or forest product extraction practices (e.g. forest grazing, road construction, fuelwood, NWFPs) can degrade forest ecosystems – in particular with regard to their productivity, biomass, stand structure, species composition and genetic diversity – even without changing the forest area (Foley *et al*., 2005; Todd and Hoffman, 1999).

**Primary forests.** Primary forests, defined as "forest of native species where there are no clearly visible indications of human activities and the ecological processes have not been significantly disturbed" (FAO, 2010a), are among the most species-rich, diverse terrestrial ecosystems, i.e. those most rich in FGR. Primary forests make up 36 percent of the global forested area but have been declining by 4.7 million hectares per year during the 1990s and 4.2 million hectares per year between 2000 and 2010 – with a loss of more than 40 million hectares since 2000 (0.37 percent per annum).

Containing an estimated 50 percent or more of all terrestrial biodiversity, primary forests (in particular tropical moist forests) have an essential role in conservation of biodiversity (Gibson *et al*. 2011), and their loss is likely to be accompanied by loss of genetic diversity. There is no substitute for primary forest to maintain tropical biodiversity. Furthermore, the food security, livelihoods and cultural and spiritual identity of many indigenous people are often linked to primary forests (CBD Secretariat, 2009). The pursuit of development can jeopardize their conservation in countries where primary forests constitute a large portion of the forest cover (e.g. 95 percent of total forest cover in Suriname, 92 percent in Brazil, 91 percent in Papua New Guinea, 89 percent in Peru and 65 percent in Gabon) and where forest production, in particular timber, provides an important contribution to the national economy.

**Planted forests.** The area of planted forest has increased over time, amounting to a total of 264 million hectares in 2010, compared with

178 million hectares in 1990. Planted forests currently represent 7 percent of the total forest area, with the highest proportion in Asia (almost 20 percent) (Figure 6.1) and provide an essential contribution to the supply of industrial wood, wood energy and non-wood forest products as well as environmental services including soil and water protection.

It is estimated that less than 400 tree species – still a high number – are used in planted forests. In many countries in the temperate and boreal zone, however, the ten most planted species represent more than 90 percent of the total growing stock; while in tropical countries with high species diversity, they represent less than 20 percent of total growing stock.

Regionally and subregionally there are large differences in the proportion of planted forest consisting of exotic species, from 100 percent in East and Southern Africa to a very low proportion in North America and arid regions (Figure 6.2).

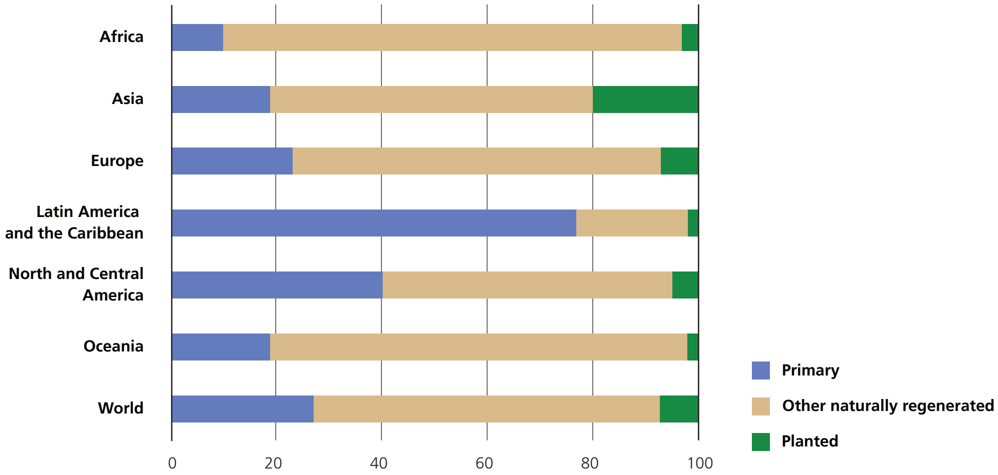
## Conservation of forest biodiversity

In 2010, 12 percent of the world's forest area was designated for conservation (Figure 6.3), while legally established protected areas – including national parks, game reserves, wilderness areas and others – comprise an estimated 13 percent of the world's forests. The main functions of protected areas usually include the conservation of biological diversity, the protection of soil and water resources, and/or the conservation of cultural heritage.

Globally, the area of forest designated primarily for conservation of biodiversity has continued to increase substantially, by 1.92 percent per annum from 2000–2010. This increase is a result of global efforts to conserve biological diversity (e.g. the Aichi Biodiversity Targets under the CBD). However, even if the area of forest designated for conservation of biodiversity is growing, primary forests are unfortunately still increasingly threatened.

**FIGURE 6.1**

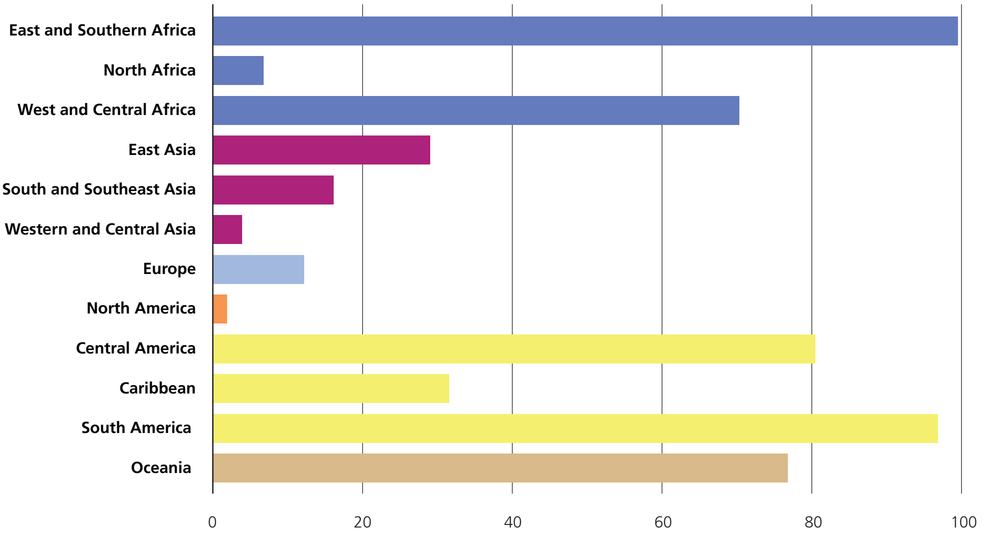
Characteristics of the world's forests in 2010 (%)



*Source*: FAO, 2010a.

**FIGURE 6.2**

Proportion of planted forest area made up of exotic species (%)



*Source*: FAO, 2010a.

Note: In some regions (e.g. North America) native species may be underestimated, because some countries do not report planted forests as plantations, so most of what is reported as plantation is exotic by definition.

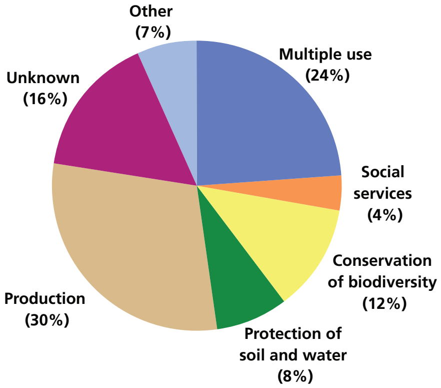
In sum, the results for forest biodiversity conservation were mixed, with the area of primary forest recording one of the largest negative rates (in percentage terms) of all measures. The area of forest designated for conservation of biological diversity increased by about 6.3 million hectares per year during the decade 2000–2010 with a similar increase in the area of forest in protected areas. The area under production forests, considered equally vital for conservation of FGR, has continued to decline at an increasing rate, by about 2 million hectares per year during the 1990s and 3 million hectares per year between 2000 and 2010.

## Trends in ownership

Ownership is a key variable determining forest management options and sustainability. FAO reported that in 2005, 80 percent of the world's forests were public and 18 percent private

**FIGURE 6.3**

Designated functions of forests reported in the Global Forest Resources Assessment 2010



*Source*: FAO, 2010a.

(2 percent other). Of the privately owned forest, 58 percent was owned by individuals, 19 percent was owned by corporations or institutions and 23 percent was community or indigenous forest. Of publicly owned forest, 80 percent is under public administration.

Public ownership remains the predominant ownership category in all regions. In many countries decentralization has been having a large impact on forest management. While forest management is guided by national and international legal instruments, decentralization may allow different subnational administrations within a country (at the community, province or state level) to apply different forest management regulations. Furthermore, the role of local communities and indigenous people in forest and forest ecosystem management is increasingly acknowledged, which is leading to greater integration of their rights in forest management plans. Ensuring the consistency of the regulations at the different levels remains a challenge, especially in seeking to combine the user rights of local and indigenous people and the conservation of endangered species.

## Consequences of forest changes for genetic diversity

The loss of forest cover has dire consequences for forest genetic diversity, loss of ecosystems, loss of species and loss of intraspecific diversity. While globally the rate of forest loss is slowing (FAO, 2010a), the impacts of further forest loss on FGR are increasing proportionally because the losses of forests are affecting a smaller residual base of native forest, are concentrated in more biodiversity-rich forests, and are leading to greater fragmentation, with long-term impacts on associated animal species, gene flow and viability of more fragmented species and populations.

### Loss of ecosystems

Loss of FGR due to disappearance or significant modification of the ecosystems of which they are a constituent is an increasing threat. For much of the twentieth century and until recently, the main threat was from conversion of forest to a different land use, mainly agriculture. Examples of major forest loss include the following:

- Brazil's Atlantic forest has been reduced to 2 to 5 percent of its original extent, according to the country's report.
- Forest cover in Ethiopia has diminished from more than 50 percent in the middle of the twentieth century to around 3 to 11 percent (depending on forest cover definition) at present, with most forest types reduced to small fractions of their former extent, including conversion to more open woodland formations (Ethiopia country report).
- Eastern Australia's moist subtropical lowland forest has been reduced to 7.2 percent of its original extent (Australian Government, Department of the Environment, 2011).
- Many smaller countries, such as Haiti and Samoa, have lost almost their entire lowland tropical forests.

It is estimated that 20 to 33 percent of the Brazilian Amazon's more than 11 000 tree species, especially rare and narrowly distributed endemics, will become extinct because of habitat loss (Hubbell *et al*., 2008); a broadly similar situation can be expected for much of the tropics.

Dramatic breakdown of forest ecosystems and changes in their function and structure are increasingly attributable to climate change and associated extreme events such as uncontrolled wildfires and alien invasive species. Climate change will have particular impact in isolated montane forest ecosystems (including cloud forests) in tropical and subtropical zones (e.g. tropical Central and South America and the Caribbean, East and Central Africa, the Philippines, Malaysia, Indonesia and Papua New Guinea), especially as these forests often have a high proportion of unique endemic associated species which may have no possibility of migrating to other climatically suitable habitats. Foster (2001) has described a scenario of complete replacement of many of the cloud forests with narrow altitude range by lower-altitude ecosystems, as well as the extinction of cloud forests located on high mountain peaks.

Some forest ecosystem changes are associated with changes to keystone animal species. In a recent literature review, Ripple and Beschta (2012) concluded that predation by large mammalian carnivores, notably sympatric grey wolves (*Canis lupus*) and bears (*Ursus* spp.), limits densities of large mammalian herbivores in boreal and temperate forests of North America and Eurasia, with impacts on tree and shrub recruitment. The same authors previously reported that cougars (*Puma concolor*) limit mule deer (*Odocoileus hemionus*) densities, releasing woody plants from browsing and maintaining biodiversity in western North America (Ripple and Beschta, 2008). Large carnivores such as the tiger (*Panthera tigris*) and lion (*Panthera leo*) are increasingly threatened and reducing their natural ranges in many places. Reductions in top-of-the-chain predator populations and changes to other keystone species, such as elephants (*Loxodonta* spp.) in Africa, will result in changes, both major and subtle, to forest and woodland ecosyems and will alter the FGR contained in them.

## Loss of tree species

Scientific consensus is growing regarding the view that a new era of mega species extinction has begun, with current rates of extinction at least three orders of magnitude more than the average rate of extinction in the Earth's geological and biological history (Pimm and Brooks, 1999). In late 2012 the IUCN Red List of Threatened Species (www.iucnredlist.org), widely regarded as the most comprehensive and objective global evaluation of the conservation status of plant and animal species, included 65 518 species, of which 20 219 are threatened with extinction and 795 already extinct. IUCN (2012) reported that of Madagascar's 192 unique palm species, a staggering 159 species are threatened with extinction. Indigenous palm seeds are becoming an important NWFP export product, and this is a contributory threat factor for some species.

Thomas *et al*. (2004) have shown through modelling that between 18 and 35 percent of the world's animal and plant species are on the path or committed to extinction due to climate change, and this figure does not take into account interactions with other threats; these authors have also shown that the threat to survival of species from climate change is much greater than the threat from habitat loss, with some variation depending on the biome under consideration.

Through the Global Trees Campaign and under the auspices of IUCN's Species Survival Commission, conservation status has recently been partially or fully assessed for certain plant groups (including conifers [Coniferae], cycads [families Boweniaceae, Cycadaceae and Zamiaceae], Magnoliaceae, *Acer* spp., *Quercus* spp., palms [Arecaceae] and *Rhododendron* spp.) and certain areas (including Central Asia, Guatemala, Ethiopia, Eritrea and Mexican cloud forests) (see Box 6.1). However, most families and genera comprising mainly tree and woody species have yet to be subjected to comprehensive assessments of their level of endangeredness, which could help determine where best to direct conservation effort and resources.

The number of threatened forest species reported in the country reports is shown in Figure 6.4, by region. These data have different sources and their detail and reliability vary. Developed countries with greater available government resources, but often less species diversity, sometimes maintain their own Red Lists. Sweden, for example, maintains a Red List which includes *Fraxinus excelsior, Tilia platyphyllos, Ulmus glabra, Ulmus laevis* and *Ulmus minor*; the main threats are exotic diseases (Sweden country report). Threat assessments for tree species in developing countries are usually lacking owing to a shortage of trained botanists and conservation biologists and resources to support field surveys. India lists 261 tree and woody species whose genetic diversity is threatened, including 94 species in the highest threat category; the

## Box 6.1
## Conservation status of forest species assessed under the Global Trees Campaign

**Geographic assessments**

In Guatemala, 79 endangered tree species were identified, including 10 critically endangered endemics (Vivero *et al*., 2006).

In the floristically rich cloud forests of Mexico, which are replete with endemics, approximately 60 percent of the 762 tree species in 85 botanical families were assessed as threatened (González-Espinosa *et al*., 2011).

Of 96 tree taxa assessed in Central Asian countries, including Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan, 46 percent (or 44 taxa) were found to be threatened with extinction in the wild. This status was attributed to a combination of overexploitation, desertification, pests and diseases, overgrazing, fires, rural poverty, lack of alternative energy sources and the lack of institutional capacity to protect and regulate forests (Eastwood, Lazkov and Newton, 2009).

A preliminary assessment of 428 endemic and near endemic woody plants in Ethiopia and Eritrea determined that 135 species (including 31 trees) were threatened (Vivero *et al*., 2011).

**Plant group assessments**

A global assessment of 151 species in the family Magnoliaceae found approximately 74 percent (or 112 species) to be threatened (Cicuzza, Newton and Oldfield, 2007).

Approximately 45 percent of *Quercus* species (79 species) are considered endangered of the 176 species for which data were available and sufficient for assessment (Oldfield and Eastwood, 2007).

In assessment of the conservation status of 125 species of maple trees (123 *Acer* spp. and 2 *Dipteronia* spp.) at least 54 taxa (28 percent) were found to be threatened (Gibbs and Chen, 2009).

Of the approximately 1 018 known *Rhododendron* species, mainly woody shrubs, approximately 25 percent (or 316 species) were found to be threatened (Gibbs, Chamberlain and Argent, 2011).

identified threat types are almost all related to forest cover loss, degradation and fragmentation, including combinations and interactions of these threats. However, the taxonomic assessment of many tropical tree genera, including those with important FGR such as *Diospyros, Mangifera, Syzygium* and *Terminalia*, is often incomplete. Furthermore, updated taxonomic information and botanical keys may not be readily available in the countries where the species naturally occur. Available threat assessments, where these have been undertaken, are typically several or many years old and are in need of updating.

The Global Tree Specialist Group, part of the IUCN Species Survival Commission, has identified major challenges for conservation of individual tree species. The group estimates that approximately 8 000 tree species are threatened with extinction, with about 1 000 tree species critically endangered and likely to become extinct unless urgent action is taken (Oldfield, Lusty and MacKinven, 1998; Global Trees Campaign, 2014). Figure 6.5 shows the main threats to 52 endangered tree species in different plant families and geographic regions profiled at the Global Trees Campaign website (globaltrees.org). However, many species are threatened by a combination of threats and interacting threats. These data are from a small sample (about 5 percent of threatened tree species), and overharvesting is likely to be overrepresented because of deep concerns about precious timber tree species.

Overharvesting, including poorly regulated, unregulated and illegal harvesting, is still arguably the most important threat factor for FGR at present, because this activity causes a loss of genetic diversity and populations in those

**FIGURE 6.4**
Number of species and subspecies mentioned as threatened (at various levels) in country reports, by region

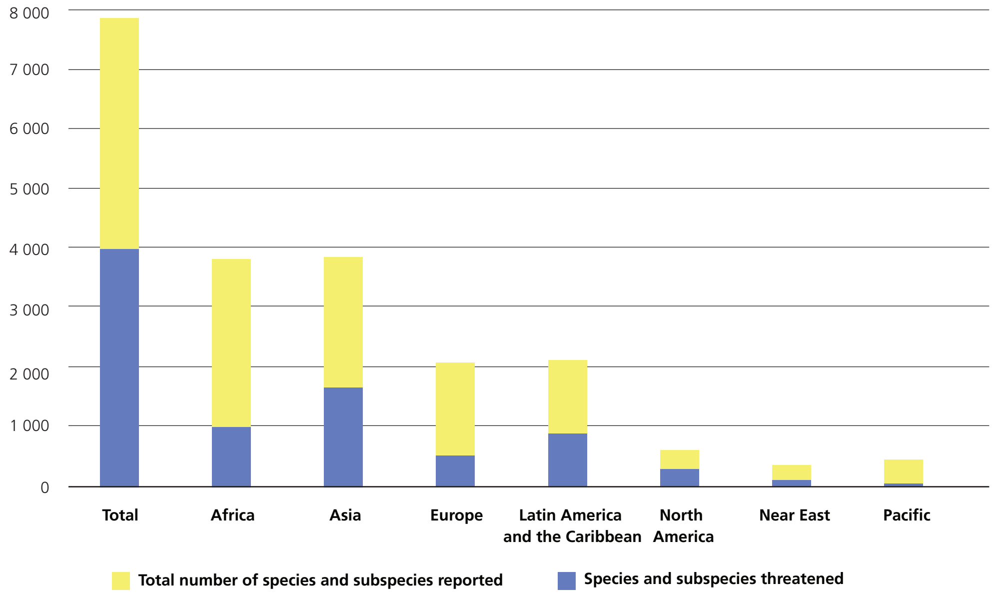
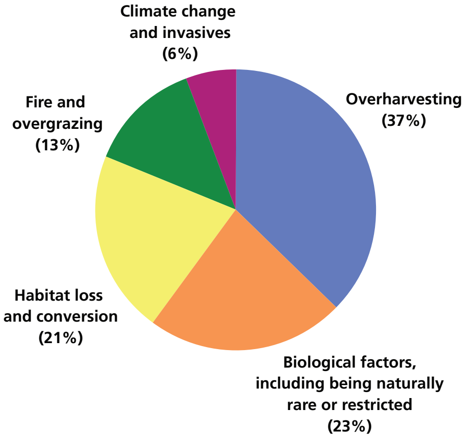


**FIGURE 6.5**
Main threats to 52 endangered tree species profiled by the Global Trees Campaign



*Source*: Global Trees Campaign data at globaltrees.org.

tree species that have the most economic value and utility. Over the next century, climate change and interactions with other threats are likely to become the most important threat for tree species and populations.

## Loss of intraspecific diversity

The loss of intraspecific diversity in economically important tree species has been a major concern of the forestry profession for many decades. Despite the many continuing and long-term threats to FGR, a high (although variable) level of success has been achieved in conserving and using the genetic diversity of many commercially important tree species for timber and paper pulp production. The successes, of which there are many examples, have often been achieved under the auspices of tree breeding programmes in developed countries, increasingly led by private-sector consortia. Genetic resources work on some major tropical timber and NWFP species has also been undertaken by national agencies of tropical developing countries, often with international support. For example, FAO and the Danish International Development Agency (DANIDA) Forest Tree Seed Centre have supported work on *Tectona grandis, Gmelina arborea* and *Azadirachta indica*; ICRAF, work on African agroforestry tree product (AFTP) species; the Tropical Agricultural Research and Higher Education Center (CATIE), work on *Swietenia macrophylla*; Camcore (an international tree breeding organization based in the United States of America), work on tropical American pines; and the Australian Centre for International Agricultural Research (ACIAR) and the Commonwealth Scientific and Industrial Research Organization (CSIRO) Australian Tree Seed Centre, work on *Chukrasia tabularis* and *Casuarina equisetifolia*.

The main threats to intraspecific diversity in tree species are essentially the same as those that cause species extinction (see preceding section). For example, major losses to diversity have occurred for some high-value species that have been selectively and heavily harvested for their timber and NWFPs. Paradoxically, this has meant that some of the most economically useful tree species have been the most genetically depleted.

According to its country report, Ethiopia is rich in FGR, including more than 1 000 woody plant species and two biodiversity hotspots (the Eastern Afromontane hotspot and the Horn of Africa), but the viability of populations of important woody species is threatened by fragmentation (reduced gene flows), coupled with utilization pressures, fire and invasive species which increase the risk of local extinctions.

The loss of entire populations or genetically distinctive provenances (for species exhibiting clinal variation) has both short- and long-term adverse consequences. The short-term consequences include potential major changes to ecosystem function and services for native forests in which these populations or provenances occur, through loss of documented seed sources of known performance. Longer-term consequences include species extinction (for which loss of populations is a well identified precursor) and loss of vital genetic material for selection and tree improvement programmes. For trees introduced into a new environment with a broad genetic base, better-adapted landraces may often evolve in only one or two generations, but the same is not true for recovery of lost diversity. A study on *Pinus resinosa* has indicated that very long periods, possibly on the scale of tens of thousands of years, are required for long-lived, long-generation organisms like trees to recover genetic diversity after it has been lost (Mosseler, Egger and Hughes, 1992).

The loss of intraspecific diversity in economically important species has consequences not only for immediate seed supply for replanting, but also in terms of reduced opportunities for selection and breeding, as often only lower-quality or less desirable phenotypes remain. Dysgenic selection (perpetuation of defective or undesirable genes and traits) is most likely if successive regeneration cycles are derived from only a small residual number of poor-quality phenotypes (Ledig, 1992). Cornelius *et al*. (2005) found only a small (≤5 percent) and rather insignificant maximum negative dysgenic response to a single selective logging–mediated phenotypic selection event in *Swietenia macrophylla*, but for species with more heritable traits (e.g. chemotypes) and/or several to many cycles of selection of superior phenotypes, dysgenic selection is more problematic. *Swietenia mahogani*, native to the Caribbean Islands and southern tip of Florida (United States of America), is the most valuable mahogany timber producing species and has been commercially exploited for more than 500 years. The small residual populations are thought to have undergone dysgenic selection (Styles, 1972). Hybridization with other *Swietenia* species (e.g. with *S. macrophylla* on Cuba) is another threat to the species' genetic integrity and genetic resources.

Box 6.2 lists some examples, from around the globe, of the many hundreds of valuable tree species that have already lost, or are at imminent risk of losing, important intraspecific diversity.

## Box 6.2
## Loss of intraspecific diversity in valuable species: some examples

***Boswellia papyrifera*** is an economically important NWFP tree in Ethiopia and Eritrea but is rapidly declining and predicted to become commercially extinct within the next 15 to 20 years. The decline is related to resin tapping, which reduces reproductive and recruitment potential (Rijkers *et al*., 2006; Eshete *et al*., 2012), and to attack by longhorned beetles, excessive fire and increased grazing pressure. Seedling recruitment is failing because of excessive fire and increased grazing pressures, preventing dying trees from being replaced (Groenendijk *et al*., 2012). Forest reduction and degradation and competition for land use have also been identified as threatening factors (Ethiopia country report).

***Dalbergia cochinchinensis*** has been heavily and selectively overharvested throughout its natural range in Cambodia, the Lao People's Democratic Republic, Thailand and Viet Nam and continues to be cut, often illegally. Its intraspecific variability is highly threatened (Thailand country report). Good seed sources from native stands are scarce, as surviving populations are reduced to scattered and isolated trees of poor phenotypes.

***Endospermum medullosum*** – populations of the fastest-growing trees, which originate from eastern and southeastern Espiritu Santo in Vanuatu (Vutilolo *et al*., 2005), have almost disappeared as a result of land use change, absence of regeneration in coconut plantations and cattle ranches, and harvesting of remnant trees (Corrigan *et al*., 2000; Vanuatu country report). Some efforts to conserve this species in *ex situ* plantings are now under way (Doran *et al*., 2012).

***Erythrophleum fordii*** is a valuable timber tree threatened by overexploitation in China. It now only occurs there in small, fragmented and degraded stands and with greatly diminished genetic diversity (China country report).

***Populus euphratica* and *Populus ilicifolia*** are fast-growing, multipurpose riparian poplars from the Near East, Central Asia, China and Kenya, with a remarkable range of tolerance to edaphic and climatic extremes. However, they are declining and endangered throughout their range by clearance, overharvesting and modification to hydrological regimes (Viart, 1988; Ball, Russo and Thomson, 1996; Cao *et al*., 2012).

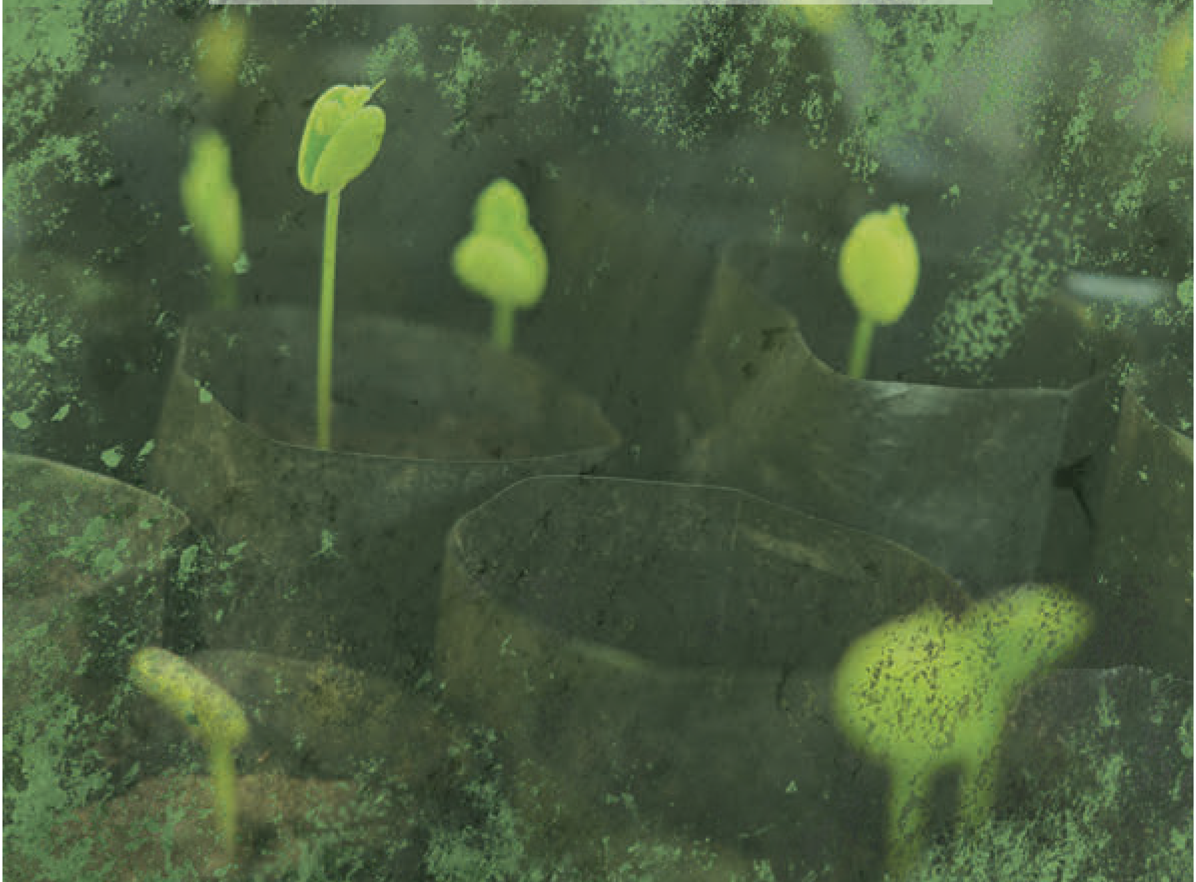
***Prunus africana*** is a keystone afromontane species important for its bark, which is harvested for use in treatment of benign prostatic hypertrophy. The species has been listed by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (Appendix II) since 1995, but almost all native populations in central, eastern and southern Africa are threatened by overharvesting, which often kills the trees, and also by land-use and climate changes. In South Africa, close monitoring and controls may provide a greater level of protection than in other parts of its range (South Africa country report). Populations of *P. africana* on Madagascar, which are morphologically distinct and likely constitute a different taxon, are similarly threatened. They are no longer exported because of previous overharvesting (Madagascar country report).

***Pterocarpus santalinus,*** a highly valuable timber and NWFP species from the state of Andhra Pradesh in India, has been overharvested, especially during the 1950s and 1960s. The species was listed in CITES Appendix II in 1995, but an illegal smuggling trade continues, causing concern for loss of genetic diversity (MacLachlan and Gasson, 2010; India country report).

***Santalum* sp.** – an undescribed species of sandalwood, referred to in the literature as *S. macgregorii* (Brophy *et al*., 2009) – exists in three small populations, each consisting of only a few individuals, in coastal areas of Western Province, Papua New Guinea. It has highly fragrant heartwood with high santalol content and is at high risk of being harvested, which would cause the species to become extinct as no actions are being taken to ensure its natural regeneration or *ex situ* conservation.

# Part 3

# CURRENT AND EMERGING TECHNOLOGIES



## Chapter 7

# Trait-based knowledge of tree genetic resources

Until the advent of biochemical and molecular methods, the only way to estimate genetic values or variation was by measuring phenotypes and using statistical tools to separate genetic effects from environmental influences. Although field studies designed to estimate genetic parameters have declined, such studies are still essential for understanding genetic control of phenotypic traits.

Before the development of genetics as a scientific discipline, trees had been planted for food, wood, shade and religious purposes for thousands of years. Knowledge of trait variation was used in traditional farming and subsistence systems to select, save and/or cultivate valuable individual trees on the basis of phenotypic characteristics. Besides food tree species such as *Citrus sinensis* (orange), *Malus domestica* (apple) and *Olea europaea* (olive), other cultivated tree species of significant importance include *Cinchona lederiana* from Bolivia, which was transported to Europe to combat malaria and then grown in Asia, and *Hevea brasiliensis*, the Pará rubber tree, whose seeds were transported from Brazil to the United Kingdom and then to Asia in the late 1800s. All of these species were subject to selection and breeding on the basis of valuable phenotypic characteristics.

## Indigenous and traditional knowledge

Traditionally living societies generally maintain an intimate relationship with the natural world of their (actual and/or historical) living environments. They are (or were until recently) strongly dependent on natural resources for their livelihoods. Through their intimate relationship with, and dependence on, the natural world, traditional societies have developed extensive knowledge about natural resources, often built up over generations. For such people, trees are among the most important and useful life forms because they are more complex and more multipurpose than herbaceous plants; apart from fulfilling human needs for food, medicine, construction materials and fuel, they provide a wide array of environmental services (Thomas and Van Damme, 2010). The importance of tree species for traditional societies depends to a large extent on the floristic composition of their living environments. For example, Clement (1999) calculated that of the 138 species under cultivation or management at the time of European arrival in Amazonia, 68 percent were trees or woody perennials.

Ethnobiological research on people-plant interactions has traditionally focused mainly on the utilitarian (ethnobotanical) dimension of plant species and far less on ecological aspects. However, studies on traditional ecological knowledge (TEK) of plants have demonstrated deep knowledge of species' habitat preference, phenology, pollination systems, seed dispersers, species associations, intraspecific variation, pests and diseases, environmental services provided and behaviour under different types of management (e.g. Assogbadjo *et al.*, 2008a; Hmimsa, Aumeeruddy-Thomas and Ater, 2012;

Parra, Blanca and Casas, 2012; Fraser *et al*., 2012). Most studies of traditional knowledge about plants at subspecies level have focused on ethnolinguistic and ethnotaxonomic aspects, i.e. the ways traditional societies name and classify plants (Berlin, 1992). Ethnotaxonomical classifications often coincide to a certain extent with corresponding scientific classifications and can provide a first approximation of existing intraspecific variation in plants. Overdifferentiation – splitting a scientific species or subtaxon into two or more traditionally named groups – is primarily encountered with cultivated varieties for which distinctive scientific names are often lacking; such cultivated varieties may be genetically different (Hunn and Brown, 2011) or not (e.g. Assogbadjo *et al*., 2008b).

TEK can provide valuable information to inform scientific research on the ecology, management, intraspecific variation and conservation of tree species, as scientific information is still lacking for many tropical tree species. However, TEK about tree species is being lost more rapidly than the respective scientific knowledge is increasing; thus strengthened efforts to record remaining knowledge are urgently needed. Participatory tree breeding and domestication of tree species is a fairly recent approach which combines TEK about tree use and management with scientific advances in germplasm collection, selection and propagation as well as with market development. Its ultimate goal is to improve people's livelihoods (Dawson *et al*., 2013). TEK can also be a rich source of inspiration for designing biological approaches to tackling current environmental problems such as the development of renewable energy resources (Martin *et al*., 2010) or environmental restoration (Douterlungne, Thomas and Levy-Tacher, 2013).

## Tree and landscape management

Traditional societies are typically positioned at the interface of the natural and cultural worlds. They live in close proximity to natural vegetation from which they extract livelihood goods, and at the same time they engage in different types of plant management. Plant management in traditional societies covers a continuum ranging from gathering and protecting plants in wild populations, to deliberately tolerating plants in human-made habitats (also defined as disturbance habitats), to cultivating domesticates as well as non-domesticates. Of all anthropogenic habitats, home gardens in particular are laboratories where people have experimented with plant genetic resources; they contain a combination of strictly wild plants, camp followers (weeds, which can be trees, e.g. in Amazonia [Balée, 1994]), spared and tolerated plants, and cultivated and domesticated plants. Through ongoing processes of experimentation and innovation, wild plants with desirable traits are gradually brought into the cultural sphere (Bennett, 1992; Miller and Nair, 2006; Clement, 1999; Thomas and Van Damme, 2010).

Useful wild tree species may also enter the cultural sphere when spared during land clearing for human use, as this increases contact intensity between people and trees remaining in the margins of crop fields. Intensity of contact, salience, accessibility and availability of plant species are often correlated with their perceived usefulness to people (Adu-Tutu *et al*., 1979; Byg, Vormisto and Balslev, 2006; Thomas, 2009; Thomas *et al*., 2009; Thomas, Vandebroek and Van Damme, 2009; Turner, 1988). Tree management is not limited to humanized landscapes such as home gardens and swiddens, but occurs also in natural vegetation where certain species may receive protection, e.g. through removal of competing plants or pests to enhance the target plants' chances of survival. More significant, however, is landscape domestication, which was initiated by early human societies all around the world (Chase, 1989; Clement, 1999; Anderson, 2005; Young, 2009; Aumeeruddy-Thomas *et al*., 2012; Sheil *et al*., 2012) and has culminated in the highly artificial land uses of modern society. The impact of longstanding landscape domestication in forest environments is, for example, evidenced by enrichment in useful species (Wiersum, 1997; Shepard and Ramirez, 2011; Levis *et al*., 2012), anthropogenic forests (Balée, 1989) or anthrosols such as black-earth soils containing charcoal and cultural waste from prehistoric burning and settlement, which carry distinctive vegetation as a consequence of their high nutrient content. In Amazonia, black-earth soils are generally associated with forests that are enriched with useful species such as Brazil nut trees (Clement and Junqueira, 2010; Junqueira *et al*., 2011). Longstanding human management often leaves a mark on the geographical distribution of the genetic diversity of trees (Vendramin *et al*., 2008; Shepard and Ramirez, 2011; Thomas *et al*., 2012). Archaeological knowledge about historical tree use and management can provide a valuable entry point to understanding of contemporary patterns in inter- and intraspecific diversity patterns of trees (e.g. Chepstow-Lusty and Jonsson, 2000; Goldstein, Castillo Vera and Pay-Pay, 2012).

### Risk management

Throughout human history, traditional societies have been in the firing line of environmental and climate change. They are aware of the need to monitor environmental change, often through the use of indicator plants; an example is *Barbaceniopsis boliviensis*, a Bolivian Andes plant whose leaves are said to turn yellow as an early warning sign to predict rain (Thomas, 2009). Traditional societies have developed a plethora of risk management strategies to cope with the adverse impacts of environmental fluctuations. Most of the strategies are designed to make opportunistic use of space, natural resources, social relations and time. People tend to invest in a diverse portfolio of options, which lowers vulnerability and increases resilience and stability by ensuring the availability and supply of livelihood goods and services (Frison, Cherfas and Hodgkin, 2011). A popular strategy is to maximize the accessibility and use of different ecosystems in the landscape where people can grow a variety of different plants and/or extract plant and animal resources for their livelihoods (Berkes and Folke, 1994; Ladio and Lozada, 2004; Thomas *et al*., 2009). This explains why indigenous groups are drawn to environments with high ecological variation, such as ecological edges (Turner, Davidson-Hunt and O'Flaherty, 2003). Biological and ecological diversification strategies imply the need for diversified knowledge, not only about the ecological conditions of different environments, but also about a high number of biotic elements, their useful traits and management. Risk strategies based on optimal use of natural resources spread risk in terms of space and resources; crop failure in one ecological zone may be offset by more stable harvest in another, and reduced availability of one biotic resource may be compensated by use of a variety of alternative resources.

Traditional societies often complement their biological and ecological diversification strategies with equally important social risk-management strategies (van Oudenhoven, Mijatovic and Eyzaguirre, 2011) (see Box 7.1). Smith *et al*. (2012) recently suggested that resilience entails a dynamic social process determined in part by the ability of communities to act collectively and solve common problems. Systems that spread risk and innovation in social space, either consciously or unconsciously, simultaneously stimulate further diversification of available resources and provide alternative options in case of unforeseen events (e.g. poor harvest). A good example is the high variation in germplasm commonly seen in home gardens in rural communities, with different tree species, varieties or genotypes generally occurring at low densities and frequencies (Padoch and De Jong, 1991; Ban and Coomes, 2004; Perrault-Archambault and Coomes, 2008; Jarvis *et al*., 2008; Thomas and Van Damme, 2010; Wezel and Ohl, 2005; Hmimsa, Aumeeruddy-Thomas and Ater, 2012). A similar pattern is observed at larger scales, across the home gardens of different villages and in predominantly agricultural landscapes (Dawson *et al*., 2013). For example, Van den Eynden (2004) reported that of 214 edible plants used or known in 42 villages investigated in southern Ecuador, about 60 percent were used in one village only. Guarino and Hoogendijk (2004) postulated that because populations of

many, if not most, species in home gardens are often small, they are prone to genetic drift and rapid genetic divergence or differentiation. This likelihood, together with the experimentation of individual garden owners selecting for particular traits of plant species according to their own interests, may explain the high intraspecific variability found in home gardens. Regardless of the biological and human factors responsible for the high variability of germplasm found in different gardens, it is clear that within the social system uniting different home gardens or villages, social bonds, relations and interactions are crucial in allowing individuals to benefit from the system's diversification strengths. For example, it has been suggested that the number of plant species or varieties found in gardens is positively related to their owners' opportunities for exchange of germplasm through social and kin networks (Ban and Coomes, 2004; Perrault-Archambault and Coomes, 2008).

### Box 7.1
### Adapted social structures underlie resilient societies

The success of some ancient societies can at least partly be related to their social structures. For example, the rise of the pre-Columbian Inca society has been related to its verticality, specialization and reciprocity. Verticality refers to the extraction of resources and production of goods from multiple ecological zones along steep mountainsides, while reciprocity refers to the exchange of these resources and goods for those produced by people inhabiting other ecological zones (Murra, 1975). These characteristics are at the base of Andean people's extraordinary knowledge and use of micro-environments, a great range of technological and agricultural innovations, and formalized systems of reciprocity (e.g. exchange of labour or agricultural produce) (Alberti and Mayer, 1974).

## Preserving traditional knowledge

From the above it is clear that traditional societies are in many cases the creators and keepers of an often remarkably diverse and untapped repository of tree germplasm in varying stages of domestication that is spread out over ecological and social space. Traditional diversification strategies represent a large latent potential which modern society could exploit to address human development needs, not only in terms of tangible resources, but also in terms of social and ecological management and organization.

It should also be noted that traditional knowledge is not evenly distributed across or within indigenous and local communities, but is known to vary with ethnicity, age, gender, social status and numerous other possible factors (e.g. Thomas, 2012). Who holds the knowledge about certain tree species also depends on where they grow in the landscape; for example, home gardens are generally the domain of women, whereas men are often more knowledgeable about trees in the forest. These disparities have important implications when planning research with traditional knowledge holders: It is not only important to identify and work with people that hold the most knowledge on a topic of interest, but also to include as many people as possible in order to be able to access the full spectrum of often complementary bits of knowledge. Another important aspect of traditional knowledge is that it is highly dynamic and adaptive, depending on the context of use. Indeed practical knowledge is kept alive, at least in part, through its use. If the plant is no longer required for a particular use, related knowledge is likely to disappear eventually. Indeed as traditional lifestyles become modernized, people tend to replace traditional knowledge and plant use with modern knowledge and/or practices. Hence, unless deliberate efforts are made to retain knowledge of plant uses that are no longer applied by or relevant for a society, whether through written or oral transmission, the knowledge will be lost.

## Classical tree improvement

Methods from crop and livestock breeding have been adapted to accommodate the peculiarities of forest trees. Unlike agronomic crops and livestock, most forest tree species have not been domesticated, so the starting point for tree breeders is typically different from that of crop or animal breeders. Tree breeders usually begin working with wild populations instead of varieties or breeds. This means that the type of knowledge required and generated through research differs significantly from that required for agricultural species.

In classical tree breeding, desired phenotypes are selected in the wild (plus-tree selection) and propagules are collected; typically seed for progeny testing and scions or cuttings for establishment of seed orchards. Quantitative genetic data are generated from phenotypic measurements taken under uniform environmental conditions in a series of progeny or clonal trials. Statistical analyses are employed to separate genetic from environmental sources of variation in measured traits. The ratio of genetic to phenotypic (including environmental) variation provides a measure of the heritability of the trait, and thus the potential for improvement.

Types of knowledge that may be obtained from field trials associated with tree improvement include:

- genetic variability and heritability of traits related to growth, product quality and quantity, and resistance or tolerance to insect pests, diseases and adverse environmental conditions;
- genetic correlations between traits;
- epigenetic effects;
- genotype × environment interactions;
- trait-specific juvenile-mature correlations;
- gene action (additive, dominance) and in some cases, estimates of numbers of genes involved in traits of interest.

Tree improvement has existed for many hundreds of years. However, tree improvement using genetic theory has been under way for only a little more than a century (Box 7.2), and intensive selection and breeding for wood products, only since the 1930s, beginning in Austria, Denmark, Germany, Italy, the Netherlands and Sweden (Hitt, 1952). Methods for provenance trials to identify the best seed sources and progeny trials to estimate additive genetic variation and heritability of valuable traits were adopted by the mid-twentieth century in Europe, North America (McKeand *et al*., 2007), Australia and New Zealand (Burdon, Carson and Shelbourne, 2008). Thousands of trials were established, leading to rapid improvement of growth rate and stem form and associated broad-scale planting of commercial tree species such as *Picea abies, Picea sitchensis, Pinus contorta, Pinus elliottii, Pseudotsuga menziesii, Pinus pinaster, Pinus radiata* and *Pinus taeda*. Over the course of selection, testing, and breeding for improved traits, a body of quantitative genetic knowledge has been accumulated for the major plantation species.

Knowledge gained from early tree improvement trials led to valuable insights about patterns and extent of genetic variation in forest trees. Early studies in New Zealand and Australia on *Pinus radiata*, for example, demonstrated that although the species' native range was small (Rogers, 2002) and the species did not show much variation or promising traits in the wild, there was sufficient heritable variation among the planted trees to make strong and rapid improvement in traits of commercial importance (Burdon, Carson and Shelbourne, 2008). Genetic gains of as much as 33 percent were reported for volume at age 15 years from the first generation of selection of *Pinus radiata* in New Zealand; furthermore, a literature review revealed the average heritability for stem straightness and for branch angle to be about 0.25 and for branch size to be just over 0.50, all traits that are important for wood quality – results indicating potential for rapid improvement (Wu *et al*., 2007). Although populations in North America are small, they are genetically isolated, and variation is therefore

### Box 7.2
### Research organizations historically active in work on forest genetics

The International Union of Forest Research Organizations (IUFRO) has developed well defined standards for work on FGR through its working groups involving national forest research agencies from many different countries (but predominately from Europe and North America in the first half of the twentieth century). Indeed the IUFRO provenance trials of *Pinus silvestris* initiated more than 100 years ago were at the genesis of international action on FGR.

The work of FAO and its Panel of Experts on Forest Gene Resources, commencing in 1969, has been pivotal in developing a globally shared understanding and appreciation of and modus operandi for FGR conservation and management.

National forest agencies and institutes in developed countries, with backing from their governments, have assisted FGR work in tropical regions of Africa, Asia and Latin America; examples include the Commonwealth Scientific and Industrial Research Organization (CSIRO) Australian Tree Seed Centre, the Danish International Development Agency (DANIDA) Forest Seed Centre, the Centre technique forestier tropical (France) and the Oxford Forestry Research Institute (United Kingdom).

During the early 1990s, forestry research was incorporated into the Consultative Group on International Agricultural Research (CGIAR) with three centres – Bioversity International (formerly the International Plant Genetic Resources Institute), the World Agroforestry Centre (ICRAF, formerly the International Centre for Research in Agroforestry) and the Center for International Forestry Research (CIFOR) – subsequently contributing in significant and complementary ways to FGR research and development.

higher than would be likely if the populations were contiguous.

In spite of the great number of tree species (80 000 to 100 000) and numerous large international efforts to generate genetic data, only a tiny fraction of tree species have been thoroughly studied for breeding purposes, mainly temperate conifers and some *Eucalyptus* species. In addition a limited number of traits have been studied, mainly growth-related traits, focused on increasing production of wood. Considering what has been learned about trait variation in many tree species, it is clear that a huge untapped potential exists for improving product quantity and quality as well as adaptive traits of many tree species. This potential is especially important in light of climate change.

## Provenance trials

Provenance trials were originally conceived more than 250 years ago to identify species-specific sources of planting material that are suitable for different locations (Mátyás, 1994). The main objective was to evaluate which sources had the best performance, usually measured as survival and growth under particular growing conditions, often as the first step in a breeding programme. The first provenance tests were in plantations established in France in 1745–1755 by Duhamel, the Inspector General of the French Navy, to compare *Pinus sylvestris* seed sources from the Baltic region, the present Russian Federation, Central Europe and Scotland (United Kingdom) in the quest for suitable mast material for naval vessels (Langlet, 1971). It was already known that planting material from different sources performed differently at a given planting site. Unfortunately, the results of this pioneering experiment did not provide lasting knowledge because they were not written up and published. Since then, hundreds of thousands of trees have been planted in provenance trials around the world.

Testing provenances involves collecting seed (or other propagules) from populations of trees covering a range of environments and growing them together in experimental field trials (common garden tests); ideally, a series of trials is established to cover the range of environments where the species occurs or may be planted. Although many provenance tests have not been intended to characterize adaptive traits, survival and growth are basic measures of the adaptation of a provenance to the sites where it is planted (Mátyás, 1994). Ying and Yanchuk (2006) argued that height growth is generally a valid surrogate for fitness, noting that this trait responds quickly to changing environmental conditions.

An important use of provenance trial results is the definition of seed zones (or zones of provenance) (Ying and Yanchuk, 2006). Seed zones are geographic areas within which seedlings of the tested species, sourced from anywhere within the zone, can be planted without loss of local adaptation. For a given species, a provenance trial usually includes trees grown from seed collections from ten or ideally more trees at each of several or many geographic locations; however, the planting material may vary from bulk collections from many trees per population to individual tree collections, which would allow combined progeny/provenance testing. Planting sites may be within or outside the species' range. The field trials are usually established following a randomized block design at several locations to test performance under different environmental conditions and to allow assessments of genotype × environment interactions (Sáenz-Romero *et al.*, 2011). Provenance trials provide population-level information intended to identify the sensitivity of seed sources to varying environmental conditions.

Provenance trials can convey knowledge of:

- intraspecific quantitative variation in survival and growth among provenances across variable environmental conditions;
- the degree to which adaptation tracks environmental gradients;
- existence and type of genotype × environment interactions;
- probable responses of different provenances to climate change.

Many provenance trials could yield much more information than is often measured or published; nevertheless, the scientific literature is rich with published results from such trials. Examples from many countries are given in Part 4, Chapter 11.

An early example of this type of research, undertaken in the 1960s and 1970s under the auspices of FAO, was the investigation of provenance variation in *Eucalyptus camaldulensis*, the most widely naturally distributed *Eucalyptus* species and one of the most widely planted trees in the world (nominated by 17 countries as a priority species in their country reports, second only to *Tectona grandis* with 20 priority listings). The research demonstrated the substantial and economically important variation in performance of different provenances or seed sources, depending on their origin and the environmental (climate and soil) conditions under which the different trials were conducted. Series of international provenance trials of *Acacia* spp., *Eucalyptus* spp., *Gmelina arborea, Pinus* spp. and *Tectona grandis*, arid-zone species, and more recently *Azadirachta indica* and *Casuarina* spp. have been remarkably successful, making immense scientific contributions and leading directly to or contributing to major forest plantation developments in the developing tropics. Hundreds of tree species and provenances (including many *Eucalyptus* spp.) were introduced in multi-location arboreta in African countries to assess adaptation and potential use. These arboreta now serve as *ex situ* conservation stands in some countries.

**Evolution of provenance testing.** Globally, provenance testing is often done outside species' native ranges to identify sources of planting material for commercial forestry. Understanding of growth parameters of exotic provenances performing under particular environmental conditions can also be useful in matching provenances of those species to novel conditions resulting from climate change, within the natural range of the species. Thus applying the information from provenance trials, where

a species is exotic, to restoration of harsh sites within the species' natural range is an unplanned potential value of the trials.

During the past two decades, the establishment of new provenance tests has declined because large field trials were generally considered too expensive, slow to produce results and difficult to maintain. The days of collecting large quantities of seed from scores or hundreds of provenances and planting them in dozens of long-term field trials may be finished, with a few exceptions – for example, the project REINFFORCE (IEFC, n.d.) recently established provenance tests along the Atlantic shores of Europe from southern Portugal to northern Scotland (United Kingdom) to test for local adaptation and plasticity under climate change.

New approaches have emerged that provide useful information at lower cost. The United States of America, for example, reported that in the northwest of the country most provenance testing is done through short-term common-garden tests to map genetic variation across the landscape. These tests are carried out in nursery environments where site conditions are uniform, so the observed variation in adaptive traits such as growth rate, phenology, form and cold and drought tolerance across the landscape is known to be due to their genetic composition or epigenetic effects. If the pattern of genetic variation tracks the physiographic or climatic characteristics of the seed-source locations, it provides evidence of natural selection and may be important for adaptation.

Genetic field trials have given way to the sometimes unfulfilled promise of laboratory-based molecular analyses. In recent years it has been increasingly recognized that the knowledge gleaned from provenance trials cannot be substituted by molecular data, and that the gap between molecular and quantitative knowledge is especially important in understanding adaptive traits. A resurgence of interest in field trials is also explained in large part by recognition of their value for predicting responses and designing strategies to counter impacts of climate change, which has led to several attempts to capture data before they are lost as scientists retire. The Center for Forest Provenance Data in Oregon, United States of America, is one such effort (see cenforgen.forestry.oregonstate.edu); it invites researchers to submit and use provenance trial data. Although this initiative is intended to have global reach, to date only researchers from western North America have been taking advantage of the opportunity to house data there. Data have been uploaded from 25 studies on eight North American tree species. In Europe, the European Union (EU) is sponsoring TreeBreedEx (http://treebreedex.eu) and Trees4Future (www.trees4future.eu) as components of a projected virtual EU tree-breeding infrastructure; databases from genetic field tests (not just provenance trials) are a main component. However, there too, few data have been submitted so far.

**Use of provenance trials to predict responses to climate change and restore degraded sites.** As noted above, multilocation provenance trials that have been established in the past to determine appropriate seed sources for production at specific sites can provide information that is highly valuable for predicting responses to climate change. Results of such trials can be coupled with precipitation and temperature data and time series to observe adaptive genetic variation across provenances under specific climate conditions (Sáenz-Romero, Guzmán-Reyna and Rehfeldt, 2006; Schueler, Kapeller and Konrad, 2012). Such analyses are useful for assessment of climate change impact on tree species distributions and productivity in planted forests and agroforestry systems under future climate projections according to global climate models (Sáenz-Romero, Guzmán-Reyna and Rehfeldt, 2006). Collection of existing provenance trial data for a given species will help in carrying out systematic analyses of its vulnerability to climate change in specific geographic areas.

Provenance trial survival and height growth data of subtropical pine species native to Mexico and Central America have been used to validate predicted climate change impact on natural species distributions for 2050 with environmental envelope modelling (EEM) (van Zonneveld *et al*., 2009a). Survival data have been used to calibrate EEM to make more realistic predictions (Benito Garzón *et al*., 2011). EEM can overpredict climate change impact on species' distributions because species can also survive and perform well outside their existing climate niche (van Zonneveld *et al*., 2009a). The EEM estimations for tree species improve considerably when provenance performance data are included in the analyses (Benito Garzón *et al*., 2011). Trait data can be coupled with climate data to develop empirical productivity models to identify the seed sources that perform well for desired traits under expected climate change (Leibing *et al*., 2013).

Provenance trial results have value beyond production forestry. They can be useful in restoration of degraded sites because often the conditions in an area to be restored are substantially different from those of surrounding forest; for example, degraded sites may be more drought prone, may have depleted soil, and may lack some species that would normally be part of a functioning forest ecosystem. Often early successional or pioneer species are needed as a first stage to reclaim a forest site. Provenance trials have been conducted mainly for early to mid-successional species, which tend to be the fastest growing and the most easily cultivated; hence these results are useful if data have been generated on the response of different provenances to diverse environmental conditions. Species whose adaptive traits track environmental conditions closely will have different results in a provenance trial from species that show little variation across large distances. In the first case, applying the results is a simple matter of matching planting sites to trial sites and choosing the provenances that perform best. In the second case, planting material can be chosen from a greater breadth of sources.

Mátyás (1996) noted that although seldom recognized as such, provenance research may be among the most important contributions of forestry to biological sciences. Of course, this is only true in regions where there have been serious efforts to test provenances. In addition, provenance of planting material is legislated for forestry purposes. In restoration projects, however, there is often no legal requirement to use site-appropriate provenances.

Changing climate in combination with other causes of site degradation will likely render much of the area that could benefit from forest ecosystem restoration substantially different from the environment in which local remnant trees became established. Several approaches have been recommended for planning of planting projects that may conserve rare and threatened species (Ledig *et al*., 2010) or simply increase the likelihood that planted material will be adapted to future climatic conditions (Wang, O'Neill and Aitken, 2010; Hamann, Gylander and Chen, 2011; Rehfeldt *et al*. 1999; Beaulieu, Perron and Bousquet, 2004; Saenz-Romero, Guzmán-Reyna and Rehfeldt, 2006); some of these have been tested and are now being employed. Wang, O'Neill and Aitken (2010) claim that an approach called "universal response function", which integrates environmental and genetic variables, is more precise than other approaches in situations in which provenances or test sites are fewer than desirable. Each of the methods described has potential value in the planning phases of restoration projects, for identifying suitable sources of planting material, but only in cases where provenance testing has been carried out.

Perhaps the most valuable knowledge gained from provenance testing is that all species are different in their responses to environmental variation. The United States of America country report notes that in the northwestern region of the country – one of the areas where provenance testing has been the most comprehensive over the past half century and more – all conifers exhibit clinal variation in all or part of their ranges, but the amount and patterns of variation differ for each species. Conifer species sampled in the region also exhibit differences in the geographic

distance on an elevational gradient needed to detect seed source differences, as well as in the climatic distance (number of frost-free days) needed (Table 7.1). Rehfeldt (1994) described *Pinus contorta* and *Pseudotsuga menziesii* as specialists because their populations appear to be adapted to relatively narrow niches. The opposite is true for two generalist species, *Thuja plicata* and *Pinus monticola*. In the southeastern United States, geographic variation is more complex for *Pinus taeda* than for the other southern pines (Schmidtling, 2001). The fact that evidence has been documented for clinal and/or ecotypic variation in all forest tree species examined indicates the importance of matching seed sources to environmental conditions. In most cases, local sources are best adapted to planting sites (Table 7.2), but this may no longer be the rule with climate change. The evidence that patterns and amounts of adaptive variation also differ among all species evaluated implies that there are no model species and no shortcuts. Some form of provenance or genecological testing is needed for all planted tree species.

**TABLE 7.1**
Amount of environmental difference needed to show a genetic difference in some conifers

| Species | Elevation difference to find genetic difference (m) | Frost-free days to find genetic difference | Evolutionary mode |
|---|---|---|---|
| *Pseudotsuga menziesii* | 200 | 18 | Specialist |
| *Pinus contorta* | 220 | 20 | Specialist |
| *Picea engelmannii* | 370 | 33 | Intermediate |
| *Pinus ponderosa* | 420 | 38 | Intermediate |
| *Larix occidentalis* | 450 | 40 | Intermediate |
| *Thuja plicata* | 600 | 54 | Generalist |
| *Pinus monticola* | None | 90 | Generalist |

*Source*: United States country report (from Rehfeldt, 1994).

**TABLE 7.2**
Evidence from reciprocal transplant studies showing local sources as optimal or near optimal

| Family | Genus | Species (reference) |
|---|---|---|
| Betulaceae | *Alnus* | *A. rubra* (Hamann *et al.*, 2000) |
| Cupressaceae | *Chamaecyparis* | *C. thyoides* (Mylecraine *et al*., 2005) |
| Fagaceae | *Quercus* | *Q. rubra* (Sork, Stowe and Hochwender, 1993) |
| Pinaceae | *Abies* | *A. grandis* (Xie and Ying, 1993) |
| Pinaceae | *Pinus* | *P. contorta* (Ying and Hunt, 1987; Ying and Liang, 1994; Xie and Ying, 1995; Wu and Ying, 2004)<br>*P. lambertiana* (Harry, Jenkinson and Kinloch, 1983)<br>*P. ponderosa* (Squillace and Silen, 1962; Wright, 2007)<br>*P. taeda* (Frank, 1951; Wakeley, 1944) |

*Source*: United States country report (from Johnson *et al*., 2010).

### Challenges in classical tree improvement

According to the country reports, more than 700 tree species worldwide are subject to tree improvement, mostly including provenance and/or progeny testing. The results of such tests provide valuable information to determine sources of planting material that are adapted for a particular site and the range within which reproductive material of these species can be moved without loss of adaptation. In many cases the full potential of this knowledge is not realized because:

- provenance trials have not been maintained and measurements have stopped after an initial assessment;
- measurement data that have been collected have not been thoroughly analysed;
- results are not readily available (published or entered in an electronic database);
- data are lost as scientists retire.

A concerted effort must be made to locate and use existing information about the species that have been tested.

## Participatory tree domestication

People began selecting and planting trees for their own purposes thousands of years ago, as they did with other useful species. However, impeded by long generation times and the highly outcrossing mating system of many tree species, they made little progress towards domestication. More recently scientists began working with local people in what is known as participatory domestication. This collaborative approach was initially developed in Central Africa with a focus on domesticating fruit- and nut-tree species valuable to local people (Leakey *et al*., 2005). The objective is to bring together local knowledge and objectives with scientific knowledge and theory to speed the process of improvement of specific traits for particular uses (Tchoundjeu *et al*., 2012). The World Agroforestry Centre (ICRAF) has compiled principles and methods for agroforestry domestication, in large part involving local participation (Dawson *et al*., 2012).

The participatory domestication approach in Central Africa differs from the tree improvement methods described above in that multiple species are typically targeted for improvement at the same time. The multispecies approach is less risky for the participating small producers than banking on a single species (Tchoundjeu *et al*., 2012). Progress for a given species is likely to be slower than for commercially planted species because the effort is less concentrated and the range of traits of interest is sometimes greater. The typical production method for improved stock is cloning, either by grafting or rooting cuttings, which allows selection for multiple traits at the same time (Leakey, 2004).

Most examples of participatory domestication are in the tropics. In the past two decades the number of tree species discussed in the literature on agroforestry domestication has increased from about 10 to 50 (Leakey *et al*., 2012). Much of the recent progress in domestication has combined local and scientific knowledge. Small-scale village nurseries have proliferated in West and Central Africa, in particular, and have become on-farm enterprises and de facto applied experimental sites where knowledge about cultivation practices is acquired for a range of tree species.

# Chapter 8

# Modern advances

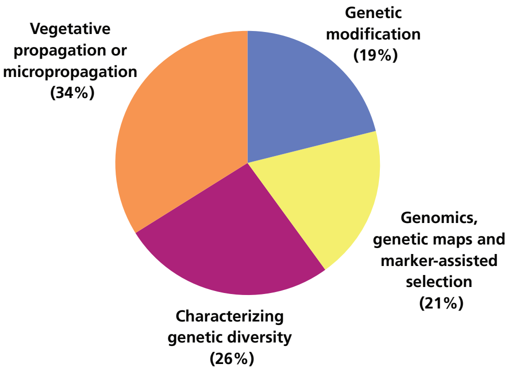
An array of biotechnological tools are contributing to knowledge of forest genetic resources in naturally regenerated and planted forests.

For naturally regenerated forest, molecular markers and genomics are providing important knowledge on genetic variation within and between species populations. Biotechnology further provides important insights into the nature of the entire tropical forest ecosystem, including the relationship between forest trees and the soil microbial communities with which they interact.

For planted forest, depending on the level of management intensity and genetic material used, the biotechnology tools can range from tissue culture in vegetative propagation to molecular markers, quantitative trait locus analysis, whole-genome sequencing and genetic modification. These tools are currently applied for a range of purposes and involve a varied number of species. The rapid development of tools (e.g. molecular markers) for analysing the genetic variability of forest trees has enabled scientists to better understand the effects of silvicultural practices on the long-term evolution of the genetic diversity of forest trees (Carnus, 2006).

An FAO assessment of biotechnology in forestry (2004) found that major forest biotechnology activities had been reported for 142 genera in over 80 countries, with activities relatively evenly spread among major categories (Figure 8.1). Of the over 700 tree species reported by countries as subject to tree improvement programmes, 241 species were included in biotechnology research.

**FIGURE 8.1**
Major categories of forest biotechnology activities



*Source*: FAO, 2004.

## Population genetics based on molecular markers

The use of terpenes and especially allozymes opened new avenues for understanding the population genetics of forest trees, beginning in the 1960s (Mitton *et al*., 1979; Guries and Ledig, 1978). Allozyme analyses were instrumental in accumulating knowledge on relative amounts and patterns of genetic diversity, gene flow, inbreeding levels and mating systems for many tree species (see for example, Hamrick *et al*., 1991; Hamrick, Godt and Sherman-Broyles, 1992). Isozyme analyses have been carried out for most temperate and many (although far from most) tropical species, allowing researchers to test theory and predictions based on the Hardy-Weinberg principle (i.e. that allelic and genotypic frequencies remain constant in the absence of evolutionary influences) with real data. Allozyme markers are also useful in the conservation of genetic diversity of forest trees, for example in designing sampling for conservation, in quantifying distribution and amount of genetic variability among and within populations, and in monitoring changes (reviewed in Millar and Westfall, 1992).

Many studies have been carried out in Europe and North America, and fewer in the tropics, to elucidate the genetic structure of tree populations. Isozyme analysis of temperate conifers in Mexico, for example, showed that relict *Picea* populations were genetically depauperate, as theory would predict on the basis of their isolation and small size (Ledig *et al*., 1997, 2000; Ledig, Hodgskiss and Jacob-Cervantes, 2002). Ledig and Conkle (1983) demonstrated that *Pinus torreyana*, which occurs in two small populations in the western United States of America, had the lowest genetic diversity of any tree species that had been studied; no difference was detected within populations, but several alleles were found only in one of the two populations. They identified the likely cause to be genetic drift. Hamrick *et al*. (1991) and Hamrick, Godt and Sherman-Broyles (1992) demonstrated relationships between life history traits and amount and distribution of genetic diversity. Duminil *et al*. (2007) have since demonstrated that positive correlations among life history traits and genetic parameters have to be interpreted with caution when phylogenetic relationships are not taken into account; nevertheless, the work of Hamrick and colleagues helped to move application of population genetics for forest trees from pure theory to evidence-based hypotheses about patterns of genetic diversity, and it is still useful in this regard.

Allozymes are usually considered to be neutral in population genetic analyses, but many of the enzymes are crucial for metabolic processes, and the variants are not neutral in all circumstances. Mitton (1997) described situations in which variants of particular "housekeeping" enzymes apparently resulted in selective advantages, particularly for heterozygous individuals of a number of species. Such effects were found to be small but significant in a number of studies (Bush and Smouse, 1992). DNA markers, which have a stronger claim to neutrality, gradually replaced allozymes because they provide direct information on genetic variation; the number of markers available can be orders of magnitude greater than for allozymes, the results may be more repeatable, and samples are more easily handled because DNA is more durable than protein. Although initially the use of DNA markers was expensive, prone to error and time consuming, during the past 25 years their use has dominated population genetic analyses.

Early DNA molecular markers used for forest trees and especially in tree breeding, such as restriction fragment length polymorphism (RFLP) and random amplified polymorphism DNA (RAPD), had distinct advantages over allozymes, for example in the vastly greater number of potential markers (Neale and Williams, 1991; Neale *et al*., 1992); however, problems such as low repeatability of results led to adoption of other approaches. As more informative but also more expensive approaches were developed, microsatellites (simple sequence repeats [SSRs]) became the most frequent markers used in population genetic studies.

Chloroplast DNA markers have been particularly useful in elucidating genetic structure of populations. Reviewing the use of organelles compared with nuclear markers, mainly SSRs, in evaluating population structure of plants (for 138 species, including 37 conifers), Petit *et al*. (2005) determined that pollen is generally more

**TABLE 8.1**
Indicative studies of tropical tree species using molecular markers since 1990

| Region | DNA analyses (No. of species) | Isozyme studies (No. of species) | No. of studies |
|---|---|---|---|
| Asia | 51 | 22 | 172 |
| Africa | 39[a] | 3 | 114 |
| Latin America and the Caribbean | 63 | 19 | 239 |
| Oceania (Australia) | 24 | 7 | 87 |

[a] Includes exotics.

important than seed in gene flow and that although nuclear marker variability is lower in gymnosperms than angiosperms, the opposite is true for maternally inherited organelle markers. For the proportion of total diversity among versus within populations, no correlation was found between nuclear and maternally inherited markers.

Because tropical tree species have been studied less than temperate species, much less is known about their population genetic structure and diversity. Within the tropics, some regions have had much more attention than others. In Latin America and the Caribbean, the most well covered tropical region (in part because of several major European projects during the 1990s), at least 239 studies have focused on 63 tree species since 1990 (Table 8.1). Asia is next with at least 172 studies on about 50 species (including DNA and isozyme studies). In Africa, 114 studies have reported on the genetic diversity of about 40 tree species including a few exotics.

The number and scope of the studies on tropical forest trees vary greatly by species. Some relatively important species have been subject to many studies; for example, at least 21 molecular studies have been conducted on *Araucaria angustifolia* in Latin America and the Caribbean, and at least 15 studies on *Acacia mangium* in Asia. However for most species, even those that have been the subject of at least one molecular study, little information is available.

Approaches, techniques and sample sizes vary widely, from single population studies to distribution-wide surveys, with markers varying from a few allozymes to genome scale.

## Marker-based understanding of population genetic processes

Molecular markers have been used to quantify genetic diversity and its partitioning between and within populations. They have also been used to understand population genetic processes that influence or determine levels and patterns of genetic diversity, particularly gene flow, genetic drift and mating systems. The following are some general results regarding genetic processes derived from marker studies.

- Gene flow is more influenced by pollen than by seed (Petit *et al*., 2005).
- Gene flow covers long distances in northern and temperate forests where most species are wind pollinated (Petit and Hampe, 2006).
- Fragmentation can actually lead to greater gene flow among remnant populations and breakdown of genetic structure (Young, Boyle and Brown, 1996), although the extent varies depending on the population densities of isolated fragments (Ismail *et al*., 2012).
- Gene flow varies with pollinator energy in tropical species but frequently extends over several kilometres (Petit and Hampe, 2006).
- Most forest trees are strongly outcrossed (Petit and Hampe, 2006).
- Mating systems can adapt to accommodate pollen availability (Lowe *et al*., 2005).

- Many tree species naturally have large effective population sizes (Petit and Hampe, 2006).
- Genetic drift was detected in small populations that had been isolated for many generations (Ledig *et al.*, 1997).

This general knowledge and related species-specific information that could only be obtained through marker analyses has been valuable for testing hypotheses based on population genetic theory and for informing management and conservation decisions. However, because of the relative ease and availability of these markers, they have often been overinterpreted (Holderegger, Kamm and Gugerli, 2006). In general, neutral markers do not provide reliable information about genetic variation that is subject to selection, and they have contributed little to the understanding of natural selection and adaptation (González-Martínez, Krutovsky and Neale, 2006). The need for markers that could be used beyond selectively neutral processes led to the development of quantitative trait locus (QTL) detection and mapping and later to genomic resources from candidate genes, transcriptomes and now whole genomes.

## Genomic advances

Gene discovery begins with construction of maps, and this has been more challenging for forest trees than for agricultural crops because of the large size of the genome (especially for gymnosperms), the high heterozygosity of most species, the longevity of trees and their intolerance to inbreeding which prevents creation of highly homozygous lines. The history of genetic mapping for forest trees began with RFLP, then RAPD and amplified fragment length polymorphism (AFLP) markers, all of which were less than ideal, in part because of their poor reproducibility (Neale and Kremer, 2011). The discovery and development of SSR markers improved the reproducibility problem, but their development was too expensive for broad application for mapping purposes. Single-nucleotide polymorphism (SNP) markers, combined with high-throughput technology (using robotics, automated machines and computers for simultaneous processing of many samples), have made highly saturated genetic maps possible, however, and rapid progress has been made during the past decade. SNP frequency is high in forest trees, providing unlimited numbers of markers with no reproducibility problems and at ever-decreasing cost, so this marker is increasingly the first choice for many applications.

In genomics as in other genetic technologies, trees lag behind key agronomic crops, and tropical tree species have tended to receive less attention than temperate ones (see e.g. Neale and Kremer, 2011; Gailing *et al.*, 2009; Grattapaglia *et al.*, 2009). However, the number of scientists taking on the challenge of applying the latest technologies to trees is growing. Neale and Kremer (2011) noted that despite drawbacks associated with long generation times, large genomes, lack of well characterized mutants for reverse genetic methods, and low funding, forest biology is now well positioned to make rapid strides. Gailing *et al*. (2009) argued that in using genomic approaches to understanding the genetic basis of adaptation, forest trees have some distinct advantages over other plant species because they generally have high diversity within populations that are still wild, and forest tree populations are subject to natural selection.

Genomic advances have opened doors to understanding the molecular biology of trees. Next-generation high-throughput sequencing technologies, in particular, have made the sequencing and understanding of the large and complex genomes of tree species an affordable possibility. Significant accomplishments include draft genome sequences for several tree species, most recently *Picea abies* (Nystedt *et al*., 2013) and *Picea glauca* (Birol *et al.*, 2013), the first conifers for which such data have been published. *Populus trichocarpa* was the first tree for which the entire genome sequence was published (Tuskan *et al.*, 2006); its provision of an important reference genetic map has contributed to its status as a model species. Myburg *et al*. (2011) published the *Eucalyptus grandis* draft sequence.

Other tree species for which entire genome sequencing is under way or nearly completed, with completed drafts, include *Azadirachta indica, Carica papaya, Castanea mollissima, Citrus sinensis, Coffea canephora, Larix siberica, Malus domestica* (Velasco *et al*., 2010), *Pinus taeda* (Neale and Kremer, 2011), *Pinus lambertiana, Pinus pinaster, Pinus sylvestris*, other *Populus* spp., *Prunus persica, Pseudotsuga menziesii, Quercus robur, Salix purpurea* and *Theobroma cacao* (Argout *et al*., 2011). Despite the complexity and size of conifer genomes, their high economic value and the investment in such species for commercial forestry has led to significant sequencing efforts. Important commodity tree crops, including fruit-trees, have received significant attention.

The main factor influencing the choice of species for sequencing is undoubtedly their economic value and the importance of identifying genes for important traits for marker-facilitated selection, which will reduce time and cost in tree improvement programmes. However, there are many knowledge spin-offs. Pavy *et al*. (2013) noted that the availability of large SNP databases allows investigation of polymorphism patterns in genetically distant species to examine evolutionary pathways. For example, Nystedt *et al*. (2013) obtained evidence that the large genome of conifers is probably not due to a relatively recent whole-genome duplication event, but is instead the result of gradual and continuing genome expansion over time via the steady accumulation of long-terminal repeat transposable elements that are not eliminated, as they are in angiosperms. They found that whole-genome duplication probably predated the divergence between angiosperms and gymnosperms. This is an example of the knowledge that can be gained through sequencing of whole genomes.

## Knowledge of the genetic basis of adaptive traits, productive traits and resistance to pests and diseases

As a result of the combination of rapid advances and rapidly decreasing costs, genetic maps, markers and candidate gene sequences have become available for a range of species, allowing for investigation of complex questions and the application of these tools to practical problems in breeding programmes (Hamanishi and Campbell, 2011).

Much of what is known about genes that are important for adaptive, productive and resistance traits was discovered prior to full genome sequencing, based on genome-wide analysis techniques such as microarray analysis (Hamanishi and Campbell, 2011). Genome-wide techniques can reveal global gene expression patterns and thus are important for identifying groups of genes that respond to specific stimuli, such as drought. Early microarray experiments used sets of expressed sequence tags (ESTs) from specific tissues from *Populus* or *Pinus* species to understand gene expression patterns (Sterky *et al*., 1998; Hertzberg *et al*., 2001; Heath *et al*., 2002) and identify candidate genes involved in wood formation and drought tolerance.

For most trees, candidate genes are identified by transferring information from model species for which gene function has been elucidated or by carrying out gene expression studies (González-Martínez, Krutovsky and Neale, 2006). Another approach is to carry out neutrality tests on population nucleotide sequence data for individual genes or groups of genes. Deviation from neutrality may indicate selection. This approach has been used to identify genes associated with stress tolerance and disease resistance.

Next-generation high-throughput sequencing can shed light on epigenetic effects, which have profound multigenerational impacts on plant responses to environmental stimuli such as drought or cold (Hamanishi and Campbell, 2011). *Populus* trees vary in their epigenetic effects, which occur when methylation turns genes off or on under stress conditions. Using combinations of EST and SNP markers will help to elucidate the mechanisms by which DNA methylation influences gene expression under stress conditions.

Grattapaglia *et al*. (2009) noted (and it is still true) that although recent advances have

greatly increased the understanding of complex, interacting mechanisms, it is not yet practical to apply genomic tools to increase productivity and growth because of the number of component traits, each of which is genetically variable.

## Combining molecular tools with tree improvement: marker-assisted selection

The first applications of molecular genetic information in tree improvement were for other purposes than identifying genes responsible for traits of interest. Early uses of genetic fingerprinting with molecular markers used in tree improvement programmes included:

- measuring genetic diversity of breeding population accessions between indigenous provenances and naturalized landrace origins;
- testing paternity contributions to offspring grown in field tests;
- verifying genetic identity during vegetative propagation.

As genetic mapping became possible with molecular markers, interest arose in linking quantitative traits with markers, launching numerous QTL projects. For a variety of reasons – including the rapid decay of linkage disequilibrium, which requires close association between markers and genes for traits of interest (Neale and Kremer, 2011) – QTLs did not provide the expected insights as quickly as hoped. Attention turned to other approaches, including association genetics and diversity arrays technology (DArT). These approaches are discussed in this section.

As genomic tools have become increasingly accessible, in terms of both ease of application and cost, the bottleneck in linking traits to the growing knowledge of forest tree genomes has shifted to the cost and time required for sampling in the field and phenotyping. There is still a need to measure the range of phenotypic variation in traits of interest in order to link the genomic markers to phenotypic expression.

### Quantitative trait loci

Quantitatively inherited traits are controlled by many genes, and most phenotypic traits of interest in forest trees fall into this category. Each gene controls a relatively small amount of variance in a quantitatively inherited trait (Brown *et al*., 2003); such genes are known as quantitative trait loci. Over the past two decades much effort has gone into identifying linkages between various molecular markers and QTLs by determining the number and location of chromosome regions affecting variation in a trait and finding statistically significant associations between markers closely associated with the chromosome regions and quantitative phenotypic traits in a segregating population (Brown *et al*., 2003). Mapping QTLs allows elucidation of the genetic structure of complex traits for application to marker-assisted selection in well studied breeding populations of tree species that are undergoing genetic improvement. The main focus of QTL analysis has been on growth traits, which are the main target of breeding programmes but have relatively low heritability and are controlled by multiple genes (Grattapaglia *et al*., 2009).

QTL mapping requires highly marker-saturated linkage maps and phenotypic measurements of all pedigreed individuals in large segregating populations (González-Martínez, Krutovsky and Neale, 2006). Such maps have been successful in showing the existence of loci accounting for between 5 and 15 percent of observed variance (Guevara *et al*., 2005), in spite of significant challenges such as the instability of associations across different environments. In long-lived organisms the expression of QTL is likely to change on a seasonal or yearly basis. Factors influencing the ability to detect QTLs include sample size, genetic background, environment and interactions among quantitative gene loci (Brown *et al*., 2003).

QTL mapping has been used to generate genetic maps for many forest trees, and many QTLs have been identified for drought-related traits (Hamanishi and Campbell, 2011). Yet although this knowledge is useful for tree breeding, progress is slow because of the time required for identifying genes in species with limited genomic sequence availability.

Echt *et al*. (2011) combined SSR markers with previously mapped expressed sequence tag polymorphism (ESTP) and RFLP markers to produce a map of the loblolly pine genome that is useful for a variety of population genetic and germplasm management applications. In addition, the mapped markers can facilitate understanding of the evolution of candidate adaptive trait genes that require unambiguous identification of parental and clonal genotypes.

## Association genetics approaches

Association mapping was developed to overcome problems with QTL mapping experiments. It uses linkage disequilibrium mapping to understand the genetic basis of complex traits, relying on the association between complex traits and chromosome regions containing genetic markers.

Unlike QTL mapping, searching for loci using association genetic approaches does not depend on pedigreed families. Association genetics uses linkage disequilibrium between a phenotypic trait and markers, and it can be applied for any large sample of a natural segregating population (Ingvarsson and Street, 2011). It requires many more markers than have typically been used in QTL mapping, but the rapid development of sequencing has made it possible; the hundreds of thousands of SNP markers needed for association mapping can be generated rapidly and relatively inexpensively from any species. The bottlenecks now are related to the fieldwork required, first to collect enough samples to ensure that associations are robust and second to phenotype the sampled populations. Ideally, replicated field trials will provide the most precise phenotype information, but time and cost constitute serious impediments.

Association genetics may start with candidate genes or a genome-wide approach. Using candidate genes as markers, individual alleles can be found that are involved in controlling traits. Neale and Kremer (2011) summarized association genetic studies using candidate genes for stem growth, wood quality, pest resistance, bud phenology, cold hardiness and drought tolerance in six genera of forest trees including two conifers and four angiosperms. Gonzalez-Martinez, Krutovsky and Neale (2006) tested 18 candidate genes for association with drought tolerance in *Pinus taeda* using this approach; all but two were found to be selectively neutral. A drawback of using the candidate gene approach is that as with QTLs, individual associations between markers and traits account for only very small proportions of the genetic variation.

An association mapping approach that has the potential to be very useful for tree breeding strategies in the future is the whole-genome scan (Hamanishi and Campbell, 2011). For example, in *Picea glauca*, Namroud *et al*. (2008) identified SNPs in expressed genes and used them as genetic markers for mapping purposes to identify potential associations between local adaptation of candidate genes and phenotypic attributes of populations. This approach can be used for identifying genes under potential selection for drought tolerance and other adaptive traits in non-model tree species.

## DArT methods

Intragenus species transferability of markers is highly desirable, and new methodology known as diversity arrays technology (DArT) offers exciting prospects for rapid genome-wide screening of thousands of polymorphisms (Petroli *et al*., 2012) across related species. Because the markers are gene based, they are useful for genomic selection and can dramatically enhance breeding and improvement of forest trees that have been subject to intensive genomic study (Grattapaglia and Kirst, 2008).

Among uses that Steane *et al*. (2011) noted for DArT markers in *Eucalyptus* spp. (see Box 8.1) are species differentiation, identification of interspecific hybrids, and resolution of biogeographic disjunctions within species.

### Box 8.1
### Use of genomic tools in *Eucalyptus* spp.

Some of the most rapid advances in application of genomic tools to breeding are focused on *Eucalyptus* species. Faria *et al*. (2010) reported development of 20 microsatellite markers from ESTs which are fully transferable across six *Eucalyptus* species. They predicted that the usefulness of the markers would extend to all 300+ species in the subgenus, and they noted that the markers provide excellent resolution and potential for use in breeding.

Steane *et al*. (2011) reported the use of several *Eucalyptus* species to create more than 8 000 DArT markers which were used for high-resolution population genetic and phylogenetic studies.

Resende *et al*. (2012a) used more than 3 000 DArT markers to evaluate the efficiency and accuracy of genomic selection in two unrelated *Eucalyptus* breeding populations; they reported that for growth and wood quality traits they were able to match accuracies attained by conventional phenotypic selection. However, they cautioned that in spite of the potential for the approach to revolutionize tree improvement, experimental support is required, and in the short term it is likely that predictive models will be population specific. Resende *et al*. (2012b) applied the same approach to *Pinus taeda* populations across multiple ages and found high accuracies across environments within a given breeding zone, but not when models generated at early ages were used to predict phenotype at age six.

## Genetic modification

Genetic modification (GM) of forest trees poses challenges both biologically and in terms of public acceptance and policy. Walter and Menzies (2010) reported that activities related to genetic modification of forest trees are taking place in at least 35 countries, and 16 of them have field trials which are generally small and of short duration. The first genetically modified tree, a poplar, was produced more than 25 years ago (Fillatti *et al*., 1987).

Gene transfer is being tested in many forest species undergoing intensive breeding activities; Carnus *et al*. (2006) reported 24 tree species involved in GM experimental plantations around the world. Species frequently mentioned are *Eucalyptus* spp., *Picea abies, Pinus radiata, Pinus sylvestris* and *Populus* spp. However, the number of tree species that have been successfully transformed remains low, especially among conifers, and transgenic plants have only been recovered from a small proportion of the genotypes in which this has been attempted (Meilan, Huang and Pilate, 2010). Traits targeted by transgenic experiments include pest, herbicide and abiotic stress resistance, hormone regulation, lignin and cell wall biosynthesis and growth (McDonnell *et al*., 2010). Among forest tree species, by far the most numerous transgenic experiments have been conducted on *Populus* species and hybrids.

Except for a few hundred hectares of genetically modified *Populus* species planted in China, no commercial planting has been reported. However, genetic modification protocols have been developed and tested for traits such as stem shape, herbicide resistance, flowering characteristics, lignin content and insect and fungal resistance in many commercially important planted tree species (McDonnell *et al*., 2010) (Table 8.2).

Although most genetic modification is done with the aim of increasing or improving wood production, it can also be a tool for conservation, for example in the case of *Castanea dentata* (American chestnut). Barakat *et al*. (2009) compared canker transcriptomes from *C. dentata* and *Castanea mollissima* (Chinese chestnut) to identify candidate genes that may be involved in resistance to *Cryphonectria parasitica* (chestnut blight). They identified several candidate genes for resistance and gained a better understanding of the resistance pathway in Chinese chestnut.

**TABLE 8.2**
Number of published successful transgenic experiments achieving gene expression or overexpression in transgenic cells (number of genes used in the various experiments in parentheses, where relevant), by tree species or genus and by modification objective

| Species/genus | Pest resistance | Herbicide resistance | Abiotic stress resistance | Hormone regulation | Lignin | Cell wall biosynthesis | Growth |
|---|---|---|---|---|---|---|---|
| *Populus* spp. and hybrids | 8 (>5) | 11 (9) | 11 (10) | 9 (7) | 26 (10) | 6 (6) | 8 (7) |
| *Pinus taeda* | 1 | | 1 | | 1 | | |
| *Pinus radiata* | 1 | 1 | | | 1 | | |
| *Picea glauca* | 2 (2) | | | | | | |
| *Eucalyptus camaldulensis* | | 1 | 1 | | 1 | | |
| *Eucalyptus grandis × urophylla* | | | 1 | | | | |
| *Picea abies* | | 1 | | | 1 | | |
| *Larix decidua* | | 1 | | | | | |
| *Larix leptoeuropaea* | | | 1 | | | | |
| *Pinus strobus* | | | 1 | | | | |

*Source*: Summarized from McDonnell *et al*., 2010.

Transgenic trees are likely to be planted within crossing distance of wild populations of the same species. Robledo-Arnuncio, González-Martínez and Smouse (2010) concluded that it is highly probable that transgenes from genetically modified trees would move into conventional forest because of the efficiency of dispersal systems over the long lifetime of tree species. Concerns about genetically modified forest trees dispersing pollen or seed, which will spread transgenic, selectively advantageous propagules into natural populations, has led to a strong focus on sterility mechanisms. Attaining a stable form of both male and female sterility in transgenic trees before releasing them is not a trivial problem. Researchers have encountered significant obstacles in the search for sterility, but this work has led to expanded knowledge of the genetic control of reproductive functions and floral genomics (reviewed by Brunner *et al*., 2010). However, when transformations are intended to keep a species in the ecosystem (by introducing a gene conferring resistance to chestnut blight, for example), the objective is actually to disperse the new genes into the native population.

## Chapter 9

# Application of genetic knowledge in forest conservation

Population genetic knowledge is important to inform conservation actions. For example, understanding the distribution of genetic diversity among and within populations and the degree to which migration occurs between populations is necessary for prioritizing populations for conservation. Many studies have been conducted to understand mating systems and gene flow (migration and drift) patterns of forest tree species. The initial focus was on Europe, North America and Australia, but more recently the number of studies targeting tropical species has steadily increased. There is still considerable disequilibrium among continents, however, with more study of tropical American species (e.g. Ward *et al*., 2005) than of African and Asian ones. In any case, the percentage of studied species is still very low in relation to the high levels of tree species endemism in tropical regions.

As one of many examples of the growing work on gene flow within and among populations of neotropical species, Fuchs and Hamrick (2011) found that isolated remnant populations of the endangered tropical tree *Guaiacum sanctum* (Zygophyllaceae) maintained high genetic diversity because of long-distance gene flow, which indicates that the species has potential to adapt and expand populations if suitable habitat is available.

Considering that level of heterozygosity may be related to fitness, conservation strategies should be responsive to the heterozygosity of targeted populations or species. Spielman *et al.* (2004) conducted a meta-analysis to compare the heterozygosity of threatened species with that of their nearest non-threatened relative. They found that for paired groups of 15 gymnosperm species and 6 angiosperms, heterozygosity was lower in 67 and 81 percent of the threatened species, respectively. Overall, the difference in heterozygosity between the threatened and non-threatened species was on average 35 percent for both gymnosperms and angiosperms.

Genetic interventions may contribute to *in situ* conservation, for example, reintroduction of lost alleles or gene infusion for genetically depauperate at-risk populations, or breeding to introduce resistance to pests or diseases and allow reintroduction of species to parts of their range where they have been eliminated.

Conservation actions when species are threatened by invasive insects or disease require particular genetic information, such as range-wide population structure including distribution of genetic diversity within and among populations, occurrence of rare alleles and levels of inbreeding. For example, Potter *et al*. (2012) studied *Tsuga canadensis*, a North American conifer that is threatened throughout much of its range by an introduced adelgid, to inform an *ex situ* conservation strategy. They used microsatellite markers to identify locations of glacial refugia which are of interest because they typically have high genetic diversity. The study confirmed a negative relationship between population isolation and diversity; and a positive relationship between diversity and population size. This information will be used to refine seed collection areas to ensure that the patterns of genetic diversity in the landscape are represented in the collections, and that areas with high genetic diversity and unique or rare alleles will be included.

Research by Fady *et al*. (2008) on the impact of natural and anthropomorphic factors on populations of *Cedrus libani*, a species of the eastern Mediterranean mountains that has long been influenced by human activities, determined that Lebanon and Turkey constitute two genetically isolated groups where gene flow patterns are widely divergent. Whereas gene flow connects populations in Turkey, differentiation is strong in Lebanon and populations there experience significant genetic drift. Using a combination of chloroplast DNA markers and allozymes, they showed that human impact does not easily translate into an identifiable genetic imprint, although they could identify priority populations for conservation and appropriate source populations for assisted gene flow.

Azevedo *et al*. (2007) reported on the population genetic structure of an Amazonian tree species, *Manilkara huberi*, which is endangered because of overexploitation for its high-value wood. Based on seven microsatellite loci, they examined its mating system and patterns and structure of genetic diversity, to guide conservation and management of the species. *Manilkara huberi* has limited pollen flow and a highly structured spatial genetic pattern. The researchers reported evidence for genetic isolation of populations, indicating that further fragmentation of the species' distribution may result in loss of subpopulations and their associated genetic variability. This means that at least several large populations should be maintained to conserve the evolutionary potential of the species. The authors estimated, on the basis of population genetic parameters, that in order to maintain an effective population size of 500, seed should be collected from more than 175 maternal trees.

The above examples are but a few of the many studies carried out over the past three decades using molecular markers to identify conservation priorities. Such thorough studies cannot be carried out for all species that are at risk from increasing land pressures, overexploitation, climate change and other causes, but lessons learned in one species can be applied more broadly.

Genomic approaches will be relevant for conservation and sustainable management of natural populations of trees in the near future. For example, the emerging potential to conduct association studies in a well defined ecological and evolutionary context, where correlations can be estimated between phenotypes and genotypes at a fine scale (Neale and Kremer, 2011), will facilitate identification of populations having high conservation value.

## Combining spatial analysis with genetic markers to prioritize conservation

An understanding of spatial patterns of tree species genetic diversity can maximize the effectiveness of *in situ* conservation strategies (Petit, El Mousadik and Pons, 1998). Areas of high genetic diversity should be targets for *in situ* conservation, as they are considered more likely to contain interesting materials for use and genetic improvement. The recent development of new powerful molecular tools that reveal many genome-wide polymorphisms has created novel opportunities for assessing genetic diversity. The potential is especially great when these markers can be linked to key adaptive traits and are employed in combination with geospatial methods of geographic and environmental analysis (e.g. Escudero, Iriondo and Torres, 2003; Manel *et al*., 2003; Holderegger *et al*., 2010; Chan, Brown and Yoder, 2011). New methods are now available for prioritizing populations and geographic areas for *in situ* conservation and for monitoring genetic diversity over time and space, and their use can improve *in situ* conservation.

Geospatial analysis of genetic diversity has been undertaken for a wide range of tree species that depend largely on *in situ* conservation for maintenance of their genetic resources. Among recent examples, a geographic grid-based gap analysis for *Picea abies* in Austria was used to identify new genetic conservation units – areas managed specifically for dynamic *in situ* conservation of genetic diversity, maintaining the natural evolutionary processes – to complement the coverage of mitochondrial and nuclear molecular marker variation as well as the adaptive genetic diversity in the current network of conservation units (Schueler, Kapeller and Konrad, 2012). In another recent case study, *Prunus africana* populations were prioritized at continental scale on the basis of nuclear and chloroplast microsatellites, combined with climate clustering as a proxy for adaptive variation (Vinceti *et al*., 2013).

One effective method to describe genetic diversity in the geographic space is circular neighbourhood-type analysis. This approach is especially effective when working with georeferenced individuals rather than with populations (van Zonneveld *et al*., 2012). It has been used to identify genetic diversity hotspots for the *in situ* conservation of a number of important tree species, including the high-value timber species *Cedrela balansae* in northern Argentina (Soldati *et al*., 2013), *Theobroma cacao* (cacao) in its Latin American centres of origin and domestication (Thomas *et al*., 2012), the fruit-tree *Annona cherimola* (cherimoya) in the Andes (van Zonneveld *et al*., 2012) and *Irvingia gabonensis* (bush mango) and *Irvingia tenuinucleata* in Central Africa (Lowe *et al*., 2000).

In addition to these large-scale studies to map genetic diversity, many other studies have assessed geographic patterns of genetic diversity at a smaller scale. Most have been carried out in temperate and boreal zones, and more studies are required in the biodiversity-rich tropical regions (Pautasso, 2009). However, the number of molecular studies is increasing, even in the tropics. The results can be used in meta-analyses to detect overall geographic patterns of genetic diversity for species with similar life history traits or other analogies (Conord, Gurevich and Fady, 2012); they can also be extrapolated to provide conservation recommendations for other tree species that share common ecological features but for which no genetic studies have been carried out.

One approach that can be used to extrapolate patterns from these analyses and to prioritize areas for maximum capture of tree genetic resources is to identify Pleistocene refugia and converging postglacial migration routes. These areas harbour high interspecific and intraspecific diversity (Petit *et al*., 2003). Georeferenced observation points from herbaria and gene banks can be used to predict Pleistocene species distributions on the basis of past climate data (Waltari *et al*., 2007). Such data are freely available from the website of the Paleoclimate Modelling Intercomparison Project Phase II (www.pmip2.cnrs-gif.fr), although they still need to be downscaled. Georeferenced plant data and climate models are increasingly available through online platforms such as the Global Biodiversity Information Facility (www.gbif.org) and WorldClim (www.worldclim.org), respectively. These data, where available and when they are of reasonable quality, can be fed into environmental envelope models to predict past species distributions and reconstruct potential Pleistocene refugia (Waltari *et al*., 2007; Thomas *et al*., 2012). However, it should be noted that species diversity and genetic diversity are not always congruent and that broad-scale patterns of species diversity and endemism cannot always accurately predict areas of high or threateningly low genetic diversity (Conord, Gurevich and Fady, 2012).

## Research on climate change and forest genetic resources

Predictions of impacts of climate change on forest populations and species have galvanized a great deal of research. The impact of specific climatic changes on tree species will vary with biological,

genetic and distributional properties of the species and of populations within the species. When confronted with significant climatic changes, populations of native tree species face three possible outcomes (Aitken *et al*., 2008): They may be extirpated, with resulting loss of unique genes or gene combinations; they may survive in place, as a result of phenotypic plasticity, adaptation or a combination of the two; or they may migrate following the changing climate to establish in new locations having climatic conditions for which they are adapted. However, migration by seed is likely to be too slow for many tree species if climate change is rapid. Trees, given their long generation time, are of particular concern.

Examples of impacts of already changing climate on tree species and their genetic resources are adding up but are still not readily available in the published literature. Based on available data and deduction, climate change is likely to have impacts on FGR through several processes which may include: loss of populations and their unique genetic variation as a result of extreme climatic events and regeneration failure, especially at the receding end of distributions; more severe pest and disease attack in some areas; altered fecundity of some tree species; pollination failure because of asynchronicity between flowers and pollinators or loss of pollinators; decline or loss of fire-sensitive species because of increased fire frequency; changes in competitive relationships resulting in new species invasions and potential hybridization (Loo *et al*., 2011) (see Chapter 5).

Past climate-driven demographic events have left some signatures in the genomes of species. Such signatures can be traced back using molecular markers. Phylogeographic methods have thus made it possible to retrace the impact of past climate changes on the evolutionary demographic history of plants (Hewitt, 2004; Heuertz *et al*., 2006; Lowe *et al*., 2010a; Petit *et al*., 2002). Modelling of the impact of past climate changes on species diversity provides useful information to predict the future evolution of species.

Spatial modelling using geographic information system (GIS) mapping tools is increasingly used to examine vulnerability of genetic resources to impacts of climate change. For example, van Zonneveld *et al*. (2014) modelled the expected impacts of climate change on populations of *Annona cherimola*, a species of the Andean foothills in Latin America, and mapped their genetic diversity (van Zonneveld *et al*., 2012) to assess vulnerability of the populations. Vinceti *et al*. (2013) carried out a similar analysis for *Prunus africana*, a widely distributed but ecologically restricted species found in all of the Afromontane regions. On the basis of climate models, they predicted that by 2050, the climate will no longer be suitable for the species over about half of its current distribution.

The major challenge facing conservation genetics is the linkage of traits that are important for adaptation to changing climates with molecular markers. Technologies that are being developed for breeding and improvement are relevant in this regard, particularly the whole-genome association genetic mapping approaches; these approaches do not require pedigrees, but they still require more knowledge of ecological and phenotypic variation than is currently available for most species of conservation concern, especially in the tropics.

## Genetic technologies for reducing illegal logging

Unsustainable and illegal logging is a driver of deforestation and forest degradation worldwide. Commercial timber extraction and logging activities account for more than 70 percent of forest degradation in Latin America and the Caribbean and in Asia (Kissinger, Herold and De Sy, 2012). It is estimated that more than 50 percent of wood exported from the Amazon, Central Africa, Southeast Asia and the Russian Federation is illegally harvested, resulting in annual losses of revenues and assets valuing between USD 10 billion and 15 billion (Goncalves *et al*., 2012). Timber-producing countries will continue to lose valuable resources and income until such unsustainable and illegal practices are stopped.

Examples of common practices associated with illegal logging are false declaration of:

- species if harvested wood is from an endangered species or a species excluded from legal harvest in a particular country or region;
- country of origin when harvest of a particular species is allowed in one country but not another;
- timber that has been harvested outside of a concession or inside a protected area.

New policy instruments in Europe, the United States of America and Australia prohibit the sale of illegally harvested wood and wood products and require operators to provide proof of the identity of the species traded and the origin of their products. Accurate species identification and tracking of the geographic origin of timber along the chain of custody are therefore necessary to control the flow of illegal wood and wood products. However, there is a mismatch between the legislated requirements and the capacity of importers to comply fully because existing methods for documenting species identity (wood anatomy and chemistry) and origin (mostly paper-based documentation, tagging) are insufficient, ambiguous and easily falsifiable.

Advances over the past decade have made possible the use of new technologies, based on DNA markers, to provide timber companies and timber traders a high level of accuracy in identifying timber species and origin. DNA provides a scientific, truly independent and infallible platform to distinguish species, validate the chain-of-custody documentation and eliminate fraud.

Significant efforts during the past ten years have been focused on extracting DNA from wood samples; it is now feasible to use DNA markers to complement existing tools, both to identify species and to track the origin of timber along the supply chain (Lowe and Cross, 2011) (Table 9.1). Information obtained from studies carried out

**TABLE 9.1**

Examples of the use of DNA and markers to control illegal logging

| Level of verification | Species | Range | References |
|---|---|---|---|
| Species identity | Multiple species from the Meliaceae family | Worldwide | Höltken *et al.*, 2012 |
| Declared region or country of origin | *Cedrela odorata* | Neotropics | Cavers *et al.*, 2013 |
| | *Neobalanocarpus heimii* | Peninsular Malaysia | Tnah *et al.*, 2009; Tnah *et al.*, 2010 |
| | *Swietenia macrophylla* | Americas | Degen *et al.*, 2013; Lemes *et al.*, 2003; Novick *et al.*, 2003; Lemes *et al.*, 2010 |
| | *Brosimum alicastrum* | Central America | Poelchau and Hamrick, 2013 |
| | *Carapa guianensis, Carapa surinamensis* | Amazonia | Scotti-Saintagne *et al.*, 2013 |
| | *Shorea* spp. | Southeast Asia | Tsumura *et al.*, 2011 |
| | *Milicia excelsa* | Central Africa | Daïnou *et al.*, 2010; Bizoux *et al.*, 2009 |
| | *Pterocarpus officinalis* | Caribbean | Muller *et al.*, 2009 |
| | *Quercus* spp. | Europe | Deguilloux, Pemonge and Petit, 2004 |
| Declared concession of origin | *Entandrophragma cylindricum* | Cameroon | Jolivet and Degen, 2012 |
| Individual log tracking | *Intsia palembanica* | Papua New Guinea, Indonesia | Lowe *et al.*, 2010b |

in the development of timber tracking methods also feed into the growing body of molecular knowledge of forest trees.

The development of DNA technology offers great opportunities for management of forest genetic resources, including:

- better enforcement of forest laws and regulations by improved verification and monitoring procedures;
- the development of genetic (and isotopic) reference databases for tracking traded timber species;
- improved tools to control the trade of species protected by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and species that could be confused with them;
- transfer of expertise and capacity building in timber producer and timber transit countries.

## Species identification

For species that are difficult to distinguish by comparing morphological or wood anatomical traits, genetic differentiation remains the most efficient method for species identification.

The Barcode of Life project (www.barcodeoflife.org) (Stockle and Hebert, 2008) uses DNA sequences that vary among but not within species to differentiate species. The concept has been more useful for fauna than flora, however; plants require two or more sequences for confident identification to the genus or species level.

Barcodes using the two core sequences *matK* and *rbcL* are expected to distinguish at least 50 percent of plant species. For a broad selection of plant species, the addition of the nuclear ribosomal DNA internal transcribed spacer (ITS) sequence increases this proportion to about 80 percent (Hollingsworth, 2011). If needed, additional specific sequences may be used to increase the resolution and likelihood of correct identification for timber species. However, for the highly degraded DNA of timber, the genetic species identification needs to be based on short DNA sequences of less than 200 base pairs. Thus the application of DNA barcoding to timber needs further development (Höltken *et al*., 2012).

Core barcodes have been developed for only about half of the 800 commercial timber species. Some species for which conventional barcodes (i.e. commonly used target DNA sequences) have been developed are represented in the Barcode of Life database by few individuals sampled from just a part of the distribution range. For such species, the intraspecific variation and the effect of geographical scale of sampling on DNA barcoding are still problematic (Bergsten *et al*., 2012; Lou and Golding, 2012). Additional sequences are used (e.g. for the mahogany family [Muellner, Schaefer and Lahaye, 2011]) when the core barcodes are not universal, have bad sequence quality and lack discriminatory power (Hollingsworth, 2011).

## Tracking of origin

For control of illegal logging, the ability to determine the origin of wood is as important as the identification of species. If spatial genetic structuring is strong, the geographic origin of a log may be determined with a high degree of precision (to within less than 10 km). An alternative approach is to obtain wood samples from each standing tree prior to harvest, which makes it possible to track individual logs by matching fingerprints, if necessary, at any point along the supply chain (Lowe, 2010b). A genetic inventory of high-value trees before felling will not only be a first step in a chain-of-custody security system, but will also help avoid felling of the wrong tree species.

Several studies (e.g. Craft, Owens and Ashley, 2007; Tnah *et al*., 2009; Degen *et al*., 2013; Jolivet and Degen, 2012) have demonstrated the efficiency of DNA technology in differentiating trees coming from different locations. Genetic reference maps to trace the origin of timber are, or soon will be, available for about 50 species for at least a portion of their natural range (see example in Figure 9.1).

With the new-generation sequencing techniques, progress in molecular marker development for many species is advancing quickly and costs are decreasing. The most immediate need is widespread sampling to cover the range of as many timber species as possible to have a complete and robust tracking system.

## Forensic testing and analysis

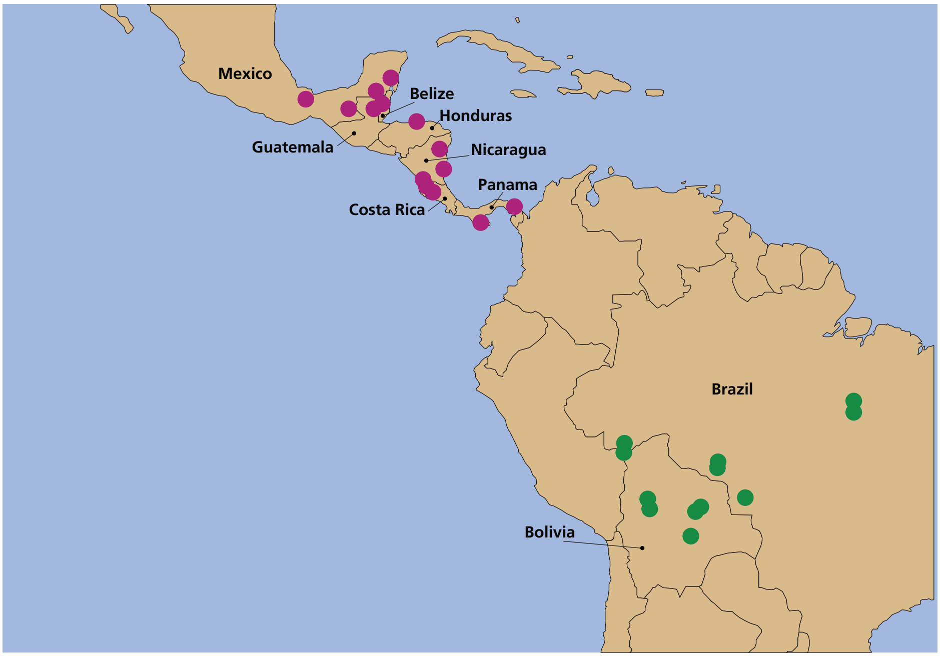
The Global Timber Tracking Network (www.globaltimbertrackingnetwork.org) led by Bioversity International is working with scientists and other stakeholders to define international standards for genetic labs that will conduct forensic testing. The network is creating a reference database of DNA fingerprints for traded species to help identify species and track the origin of wood and wood products along the supply chain.

The practical application of forensic DNA analysis in the timber trade requires adaptation so the methods will work with wood and wood product samples that have degraded or low-quantity DNA. In many timber producing countries where the risk of illegal logging is high, law enforcement agencies and national laboratories are poorly equipped to enforce forest laws before wood and wood products are shipped overseas. Therefore the laboratory procedures must also be simplified for use in small laboratories, without the need for sequencing or capillary electrophoresis techniques.

This simplification is possible with the use of polymerase chain reaction (PCR) RFLPs after SNP detection and has been successfully developed for

**FIGURE 9.1**

Genetic reference map for *Swietenia macrophylla* (mahogany) in Latin America



species protected by CITES (Höltken *et al*., 2012), but it remains to be done for many commercial species.

Capacity building in timber-producing countries, including training in molecular techniques and ensuring availability of basic laboratory equipment, is essential to foster routine use of DNA as a forensic tool.

Existing data are available mainly for timber species traded in the global market. But timber from illegal logging activities is also used within producing countries. For example, 85 percent of the timber production in Brazil is for domestic consumption. Therefore it is important to invest also in developing national capacity for regional and local species (those that are not traded internationally), to reduce illegal logging within countries. In general, the level of knowledge is lower for such species, and data needed to track wood origin are lacking.

# Part 4

# STATE OF FOREST GENETIC RESOURCES CONSERVATION AND MANAGEMENT

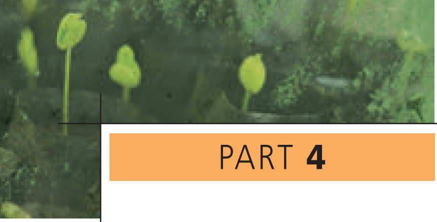
## Chapter 10

# How countries manage and conserve their forest genetic resources

The national reports describe a vast array of actions by countries to recognize, understand, document, manage, and conserve their FGR against a backdrop of diverse biological, environmental, geographic, economic, political, administrative, social and cultural contexts. Strategies addressed in the country reports fall into two main categories. First, there are the strategies that countries develop at the national level which set broad overarching directions for the conservation and management of FGR. This is the level at which national agendas are harmonized with regional and international objectives, and opportunities are identified for coordination and integration among the various sectors within government, the economy and the community that have impact on or influence FGR conservation and management. Second, there are the technical strategies or approaches that are used to achieve FGR conservation and management. These may involve *in situ*, *ex situ*, and *circa situm* conservation, sustainable forest management and community/participatory approaches to conservation and management of FGR. Comprehensive and mutually reinforcing strategies need to be employed across the entire range of activities relevant to FGR conservation and management and may be implemented by the public sector, private sector or community sector, or any combination of these. Public-sector strategies include the use of regulations and/or incentives.

Strategies for FGR conservation and management may include policy and legislation, research, sustainable forest management, private-sector planted-forest development, community management of FGR and establishment of genetic conservation reserves. For certain planted species, breeding and tree improvement are central to FGR conservation, to improve the performance of selected species or forests for economic, social, community, environmental, conservation or other purposes; for species that are not planted, including many providing high-value timber, management in wild populations is essential. Countries adopt a suite of different strategies or approaches that best suit their particular conservation and management needs, consistent with the resources available, their own development goals and the requirements of their economies, communities and particular biogeographical and socio-economic contexts. Countries also noted many and diverse activities that contribute to maintaining FGR even when FGR conservation is not consciously or explicitly identified as the goal.

Rates of progress have depended on political understanding and will and on the resources made available. Collectively the reported actions describe a developing global movement towards the conscious stewardship and sustainable use of these precious resources, as well as the protection and maintenance of the evolutionary processes that have produced this irreplaceable legacy. The country reports represent a vital contribution to global understanding and appreciation of FGR, and the identified strategic priorities will help guide future international action, led by FAO with



guidance from its Panel of Experts on Forest Gene Resources since 1969 (Palmberg-Lerche, 2007).

## Features of effective and comprehensive FGR conservation and management systems

Influences on the effectiveness of a country's FGR conservation and management include the level of economic development, the nature of the forest resource (natural, managed natural or planted forest), the nature of the forest industry, patterns of forest use, patterns of landownership, the type and quality of governance applied to the management of forests, biodiversity assets and natural resources more generally, and the resources available to undertake the task – economic, technical, institutional and logistical. The country reports reveal a number of contextual features and characteristics that influence and shape a country's system of FGR conservation and management; the most important are shown in Box 10.1.

European and North American countries, with well established formal institutions for natural resource management and conservation, carry out and implement the most detailed planning. A number of key functions and features would constitute an effective system for conservation and management of FGR, as follows:

- a national strategy for FGR conservation and management, with a process for review and updating;
- national strategies in other related and relevant areas (e.g. biodiversity, forestry, agriculture, land use, planning, economic development) incorporating goals and objectives of international agreements, including the Millennium Development Goals (MDGs), the Convention on Biological Diversity (CBD) and the World Trade Organization (WTO), harmonized with the FGR conservation and management strategy;
- participation in international agreements that affect FGR conservation and management;
- legislation enacting the FGR strategy and international obligations;
- a national programme for FGR conservation and management to implement the strategy, with adequately funded subprogrammes, including a process for identification and prioritization of assets, analysis of constraints and barriers to effective FGR conservation and management, and the identification of issues, areas, approaches and programmes likely most efficiently to deliver improvement in FGR conservation and management;
- administrative infrastructure and capacity to implement and administer the strategy and programmes, with appropriate budgetary allocations;
- country-wide, comprehensive inventory of FGR assets in naturally regenerated and planted forests and in trees outside forests including agroforestry systems, and in dedicated FGR programmes and facilities, including assessment of threats to FGR and trends in the status of genetic variability;
- a process for prioritization of assets identified in the inventory, consistent with the national FGR conservation and management strategy, national development goals and international agreements;
- established principles and practices for monitoring, evaluating, reporting, and improving activities and programmes;
- coordination, including integration and harmonization of strategies, programmes, administrations and sectors with relevance to FGR conservation and management including forestry, agriculture, biodiversity conservation, national development, industry, research and education;
- participation in regional and international FGR networks and donor programmes;
- consultation with all relevant actors and sectors of the economy and community in identification of priorities and development

## BOX 10.1
## Contextual features that influence a country's system of FGR conservation and management

**Biogeography**

- Biological resources – the nature of the forest genetic resources, for example, species, breeding systems, patterns and levels of diversity, and type, location, and distribution of forests, trees, species and diversity

**Economy, industry and population**

- Human population – size, density, growth trajectory, income, and distribution and location with respect to FGR
- Level of economic development – infrastructure, income, poverty level, industrial versus rural development models, maturity and diversity of economy
- Economic importance of the forestry sector and demand for forest products (wood products and NWFPs) – population, income, level of economic development, standards of living, expectations, preferences, use patterns
- Nature of the formal forestry sector – level of development, type and level of investment, planted versus natural forests, scale of activities (industrial versus local production)
- Involvement of the private sector – research, breeding, planted forest development, use and management of natural forests
- Nature of land-based industries including agriculture and forestry – product types, methods, mechanization

**Political system, policy framework and administration**

- Political system – centrally planned or democratic market economies, relative strength of the State, provincial, local and community governments, governance systems
- Legislative and policy systems – maturity, complexity, efficiency, level of integration
- Development goals and trajectories – urbanization, industrialization, type of industries and economic activities desired, employment
- Biodiversity and natural resource management legislation and policy
- Administrative system – maturity of natural resource management agencies, degree of complexity, efficiency, transparency, accountability
- Attitudes towards forests and forest conservation, protection of biodiversity and natural resource management among politicians, policy-makers, administrators, the private sector, communities, individuals, media, and educators
- Patterns of landownership – size of holding, public, private and communal/traditional ownership
- System of land use planning and allocation to different uses, extent to which the State is willing and can regulate activities and use of non-State-owned lands

**Research and education**

- Education and training system – availability and quality of education for various aspects of FGR conservation and management, development of expertise
- Forest research capacity – number and quality of public, academic and private research institutes and the level of resources available to them in key areas of FGR conservation and management

**Society and community**

- Community traditions, customary law relating to resource use and conservation

of FGR conservation and management strategies and programmes;
- use of a number of mutually reinforcing approaches for the FGR conservation and management strategy, programmes and implementation.

## Approaches to FGR conservation in relation to biodiversity conservation strategies

Landscape-level biodiversity conservation focuses on conserving the whole spectrum of biological diversity *in situ*, from genes to organisms through to ecological processes, and this simultaneously helps maintain and protect the variability of trees and forests within those conserved areas. Global activities to conserve biodiversity through protected areas and implementation of the sustainable forest management principles catalysed by the 1992 Convention on Biodiversity (CBD) make an immense contribution to the conservation of genetic diversity in trees and other woody species, including species of potential importance or those that are lesser known or unknown and undescribed. Several countries (e.g. Estonia) acknowledge the contribution of these activities, supported by the 1994 Montréal Process[3] and Forest Europe.

While forest research programmes in a number of countries focus on an ecosystem approach, several countries note important differences in their approaches to conservation of biological diversity and of FGR (summarized in Box 10.2). For example, biodiversity conservation policy emphasizes ecosystem and habitat protection rather than focusing on individual species. Canada, for example, reports that biodiversity programmes tend to focus on interspecific variation, while for FGR conservation and management, “changes below the species level can be critical for ensuring that the adaptive potential of the species is maintained… this is particularly important when considering threats such as climate change, invasive pests and pathogens, and the ability of species to adapt to these changing conditions”. The introduction of external genetic material into forests is one way to confer adaptability to climate change; this practice has not been widely considered in biodiversity conservation outside of enriching genetically impoverished inbred populations of threatened species. Furthermore, breeding and genetic improvement programmes in FGR conservation and management generally focus on particular economically important traits, which is much less common in habitat-oriented biodiversity conservation. For breeding and deployment of improved stock for commercial forestry, genetic variability in some traits will need to be deliberately reduced to achieve a consistency in genetic makeup and phenotypic expression of the desired characters, while for biodiversity conservation the emphasis is on maintaining processes (particularly evolutionary processes) likely to favour maximum diversity. The management requirements and regulations for strict protected areas (e.g. conservation reserves) may preclude some essential FGR conservation and management activities. FGR conservation has generally not played an explicit part in countries’ nature conservation measures, and in management plans for strict nature conservation areas it is usually not possible to include genetic aspects.

Several countries remark that to ensure adequate attention to FGR conservation and management in law, policy, budgetary allocations and management, it is important to communicate the specific requirements of FGR conservation and management (where these differ from standard biodiversity conservation activities) to legislators, policy-makers, managers and communities involved in biodiversity conservation and forest and land management.

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[3] The Montréal Process countries are Argentina, Australia, Canada, Chile, China, Japan, Mexico, New Zealand, the Republic of Korea, the Russian Federation, the United States of America and Uruguay. These countries contain 83 percent of the world’s temperate and boreal forests, 49 percent of the world’s forests and 33 percent of the world’s population, and they are the source of 40 percent of the world’s wood production.

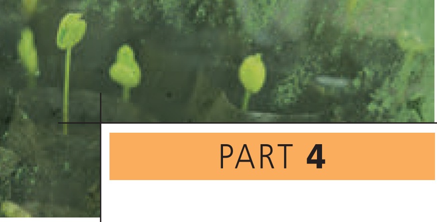
The maintenance of genetic and species diversity implicit in FGR conservation complements the habitat and ecosystem protection of biodiversity conservation. A high degree of integration and coordination between the two activities, in terms of strategies and programmes, is essential. Mutual advancement and reinforcement of FGR in biodiversity conservation can be promoted by strengthening their alignment in legislation, policy, budgets and programme support and by coordinating complementary activities.

The CBD (UN, 1992) notes in article 8(c) that countries are required to "regulate or manage biological resources important for the conservation of biological diversity whether within or outside protected areas, with a view to ensuring their conservation and sustainable use…". This requirement highlights the need to strengthen the contribution of primary forests and protected areas to *in situ* conservation of FGR. FGR conservation and management objectives need to be explicitly incorporated into national biodiversity conservation strategies and action plans, and opportunities for complementarities between FGR and biodiversity conservation need to be identified and explored.

Box 10.2

### Summary: how FGR conservation approaches differ from usual biodiversity conservation approaches

- Activities for *in situ* conservation of FGR can be integrated into biodiversity conservation strategies. Most of the differences are in *ex situ* conservation and genetic improvement programmes. FGR conservation focuses on intraspecific diversity in a smaller number of economically important or threatened tree species. The use of living gene banks such as planted gene conservation stands is greater in FGR conservation and management; biodiversity conservation focuses more on *in situ* approaches.
- For FGR some *in situ* conservation requirements may be satisfied by conservation of a small number of individuals of the target species in a small area; this contrasts with the ecosystem, habitat and landscape-scale protection approach of most biodiversity conservation efforts.
- Genetic improvement for commercial and productive outcomes is a major component of FGR conservation and management, employing a wide range of technical and financial resources in activities such as breeding and provenance and progeny trials, in which the private sector has a significant role. Conservation of biological diversity is largely a public-sector activity, as it involves public goods for which markets are as yet poorly developed and much of the natural biological estate is on public lands – although interest in harnessing private-sector finance for biodiversity conservation is increasing, including through NGOs such as the Nature Conservancy and Conservation International.
- *Circa situm* conservation is generally regarded as having a greater role in FGR conservation and management than in usual biodiversity conservation. Forest remnants in cleared agricultural landscapes may be extremely important as breeding stock. For example, in parts of Thailand where teak has been almost completely cleared for agriculture, remnant trees may contain important genetic variability adapted to local landscapes. Biodiversity conservation, however, is increasingly focused on landscape approaches and on reducing fragmentation by linking protected areas with vegetation corridors through agricultural landscapes.



## National strategies and programmes for FGR conservation and management

The strategies for FGR conservation and management considered in this chapter are those that address conservation, improvement or breeding from the biological, ecogeographical or technical points of view. The country reports also describe strategies for the setting of policy objectives, directions, approaches and agendas in the development of high-level public policy; that type of strategy is addressed in Chapter 16.

Planning, information and technical input requirements for effective national FGR conservation and management programmes include:

- inventory and characterization of priority species' FGR (national, provincial, population, species or group of species, ecogeographic surveys and traditional knowledge) based on technical standards and protocols;
- information management systems, including databases and GIS for inventory and monitoring;
- prioritization for conservation and management of FGR assets falling within the programme scope, including identification of populations at the limit of their range (see next section);
- *in situ* FGR conservation and management, including strategies to identify and promote FGR conservation in primary forests and protected areas;
- *circa situm* FGR conservation and management, including identification of options and potentials and development of methodologies for improved on-farm management;
- sustainable forest management approaches to maintain FGR while optimizing production of goods and services;
- community-based, participatory approaches to sustainable forest management and FGR conservation and management, including technical support for management by indigenous and local communities;
- *ex situ* FGR conservation and management, including review of options and promotion of feasible *ex situ* strategies and technologies as a back-up or complement to other approaches;
- incorporation of gene conservation objectives into breeding and genetic improvement programmes;
- development of national seed programmes to enhance their role in dissemination of genetically appropriate and improved germplasm;
- roles for genetically appropriate and climatically adapted germplasm in replanting and forest restoration programmes, including for predicted new climates;
- review and promotion of appropriate biotechnologies for FGR conservation and management;
- regional and international networks to conserve diversity in priority FGR species and to provide access to germplasm for important planted exotics.

## Prioritizing species for FGR conservation and management

Priority setting is fundamental to effective FGR conservation and management. The types of value for which FGR require conservation and management at national and local levels must first be identified and prioritized, taking into account international agreements that countries have signed and ratified. The process for developing national FGR strategies provides the context for identifying and prioritizing value and then for prioritizing species. Prioritizing FGR assets for conservation, management and improvement facilitates allocation of scarce resources to the most important assets and programmes.

Country reports list 2 260 tree species that are considered national priorities for FGR conservation and management. They also identify the uses of the main trees managed for human utility, including those providing environmental services.

The prioritization is generally consistent with the guidance set out in Article 7 of the CBD (UN, 1992) for information and monitoring, which specifies "components of biological diversity important for its conservation and sustainable use, paying particular attention to those requiring urgent conservation measures and those which offer the greatest potential for sustainable use". The country reports usually demonstrate a greater interest in economic outcomes than conservation.

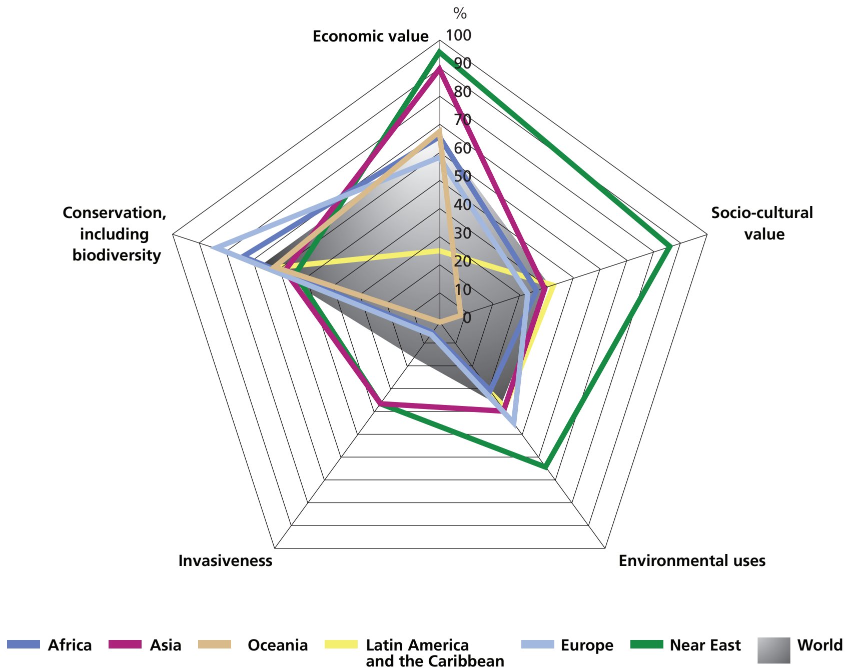
## Economic value

Countries cite economic value (including value of timber, pulp, food, wood energy, and NWFPs) as one of the main reasons for nominating species for priority for FGR conservation and management; economic value accounts for two-thirds of species nominations, equivalent in importance to conservation (see below) (Figure 10.1). However, as the figure shows, some regional differences are observed.

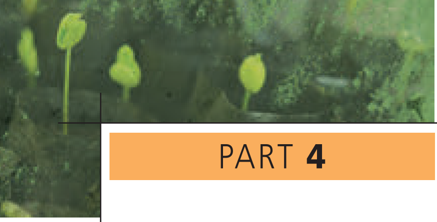
Countries emphasize tree species suitable for development of forest industries and planted forests in their priority listings. Most of these species are well researched, widely planted, globalized, industrial forestry species whose wide appeal lies largely in their proved and documented ability to perform in a variety of environmental conditions, the high level of genetic and performance information available and the relative ease of obtaining germplasm. Among the most widely used and prioritized

**FIGURE 10.1**

Reasons for nominating species for priority for FGR conservation and management (percentage of species nominations)



Note: North American countries did not report on reasons for prioritizing species.



species are *Eucalyptus* and *Pinus* species (Figure 10.2). Increasingly planted high-value tropical trees include *Tectona grandis* (teak), *Swietenia* spp. and *Khaya* spp. (mahogany), *Azadirachta indica* (neem), *Dalbergia* spp. and *Pterocarpus* spp. (rosewoods), *Santalum* spp. (sandalwood) and *Aquilaria* spp.and *Gyrinops* spp. (agarwood). Among 1 451 species used in plantations whose origin was identified, 85 percent were exotic and only 15 percent native, demonstrating the paramount importance of exotic, widely planted, economically important "global" forestry species. However, the native species may be underestimated, because some countries, e.g. Canada, do not report planted forests as plantations, so most of what they report as plantation is exotic by definition. In nominating priority species, many countries cite objectives such as meeting local demand for timber, wood products and food, import replacement, facilitating the development of forest industries, fostering exports, providing employment, and providing alternatives to unsustainable or illegal forest harvesting by rural communities and others.

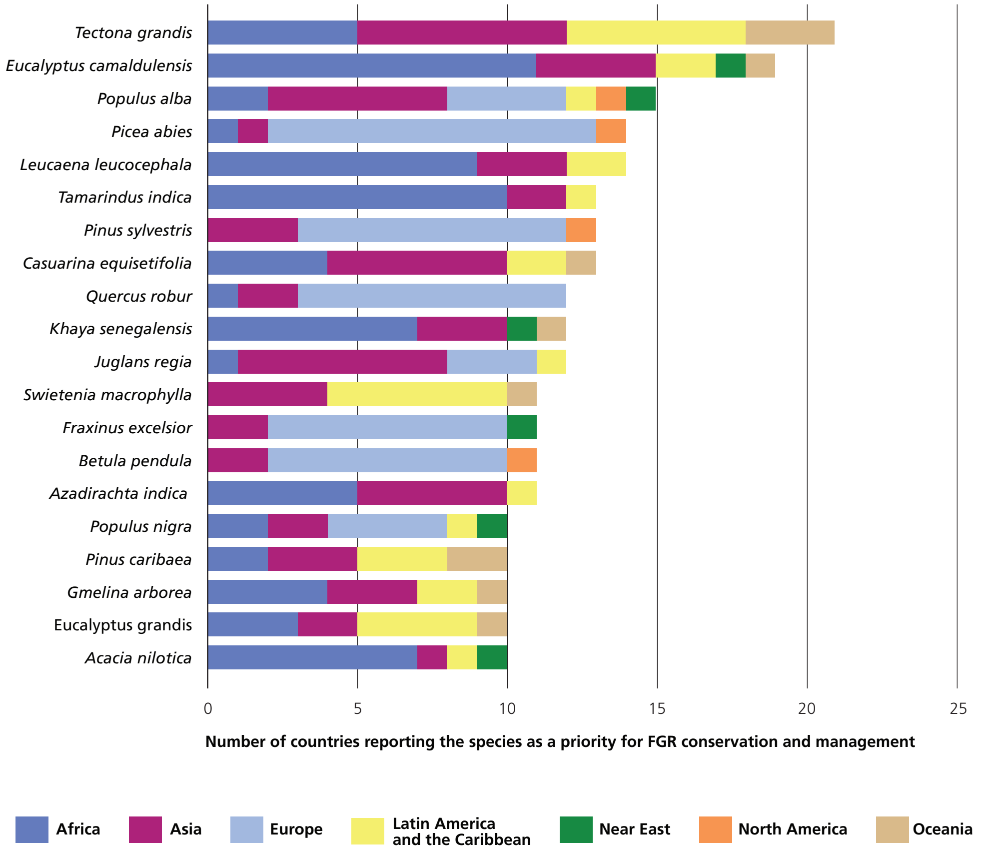
Countries tend to prioritize species with uses and potential applications recognized in their formal economy and forest sector. India, for example, notes that in prioritizing species for *ex situ* conservation, "the efforts must be proportional to the present knowledge on the utility of the species". However, a heavy emphasis on a small number of exotic commercial species important to the formal forest sector entails a risk of overlooking and underestimating the contribution of many native tree species to national well-being, particularly in rural communities. Where a focus on priority species is at the expense of exploring the potential of local trees and conserving their genetic variability, there is a risk of losing opportunities for development of highly adapted, productive trees that are also important ecosystem components. Several country reports list a myriad of tree species used for a multitude of purposes in rural areas, often by many millions of people. The United Republic of Tanzania, for example, notes that a focus on "charismatic" species may draw conservation and development effort away from less recognized indigenous species which help maintain ecosystems and also display excellent growth characteristics.

In some instances a discontinuity is seen between the economic species nominated by a country for priority in FGR conservation and management and the country's reported pattern of use of trees and forests. For example, wood energy (fuelwood or charcoal) is a primary forest value in many developing countries, particularly in Africa, and is also recorded in Europe. However, the importance of these uses is not reflected in the country lists of priority species for FGR conservation and management.

An illustration of the tendency to emphasize commercial timber and planted forest establishment at the expense of other uses and values is reported by Ghana. Energy use now dominates demand for wood products in the country: Wood provides 86 percent of urban energy and more than 95 percent of energy consumption in rural areas, and it accounts for 91 percent of roundwood consumption. However, previous forest policy emphasized high-value timber species, leading to the establishment of timber plantations that do not address the wood energy demand. To date, 260 000 ha of planted forest have been established under various government-led programmes. *Cedrela odorata, Gmelina arborea* and *Tectona grandis* constitute 90 percent of the total plantings.

Thus in some countries there appear to be opportunities for closer alignment of species prioritized for FGR conservation and management with patterns of existing domestic demand. In prioritizing species it is important for countries to address a wide range of needs in both the informal and formal sectors. It is also important to harmonize FGR strategies with other national objectives such as development goals – potentially through more direct and wider consultation and participation of communities in setting priorities for FGR.

**FIGURE 10.2**
Most common priority species, by region

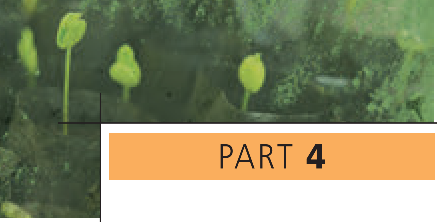


## Conservation and environmental value

As mentioned above, in country tabulations of priority species nominations, conservation purposes (biodiversity, threatened species, endemic species, genetic conservation, scientific value) account for about 66 percent of the nominations (Figure 10.1).

Environmental uses, including soil and water protection, soil fertility and watershed management, account for 37 percent of species nominations for priority. A number of countries include aesthetic, cultural and religious values in the category of "environmental uses".

The vast majority of species used for environmental purposes are native (84 percent) – a contrast with the prioritized economic species, of which 85 percent are exotic. Some of the most frequently reported species used for environmental purposes include *Pinus sylvestris, Alnus glutinosa, Quercus* spp., *Betula pendula, Fraxinus excelsior*, *Ulmus glabra* and *Populus alba* mainly in temperate regions, *Tamarindus indica,*



*Leucaena leucocephala* and *Faidherbia albida* in tropical regions and *Albizia lebbeck, Cupressus sempervirens* and *Casuarina equisetifolia* in both temperate and tropical regions.

It is clear that these figures grossly underestimate both the contribution of forests to environmental services and the number of tree species contributing.

Assessment of the rate of genetic erosion and vulnerabilities of different species, subspecies, varieties and populations is important for determining their priority for conservation and management. Countries vary greatly in the number of tree species under threat (see Figure 6.4 in Part 2). Canada's analysis of criteria of rarity, habitat under threat from alternative uses, decrease in range and lack of viable seed sources determined that, although extinction risk is very low at the species level, populations of 52 percent of all Canadian tree species require some form of *in situ* or *ex situ* conservation. Biodiverse countries experiencing high rates of forest loss – e.g. Brazil, Ecuador, Ethiopia, Indonesia, Madagascar, Papua New Guinea, the Philippines and the United Republic of Tanzania – also often report the presence of large numbers of threatened species.

## Social and cultural value

Social, cultural, recreational, ornamental and gardening purposes are cited as the reasons for 41 percent of species nominations for priority listing (Figure 10.1). Traditional medicinal uses are included in this category. Social values may be especially important in certain countries. For example, sacred and religious values are reported as important in Burkina Faso, Ghana, India and Zimbabwe. Most of the species in this category are native, reflecting the close cultural affinities for native species that people develop over millennia, which help to shape national and cultural identity.

## Invasive species

Invasive tree species pose a significant threat to the integrity and conservation of FGR, mainly through their capacity to transform ecosystems. Small island ecosystems are especially at risk. Understanding the genetic makeup and variability of invasive trees and shrubs can be crucial to developing effective control and management strategies.

About 500 species were nominated as a priority for management (mainly by African and European countries) because of their invasiveness, with implications for FGR conservation and management. Most invasive tree species have been introduced for ornamental purposes, although several species introduced in afforestation or as plantation species have become seriously invasive. Examples include *Prosopis juliflora* in several countries and *Acacia mearnsii, Acacia melanoxylon, Pinus patula* and *Populus canescens* in Zimbabwe. The priority given to these species in FGR management highlights the need to consider the potential invasiveness of species promoted for planting and to ensure that this risk is minimized.

## Chapter 11

# Characterization of genetic variability and monitoring of change

Countries recognize that for effective conservation and management, it is essential to understand and describe their FGR at both broad (geographic) and fine (among and within forest tree species) scales. Countries characterize genetic variability for two main purposes. The first is conservation planning and management, including sustainable forest management, for which it may be necessary to:

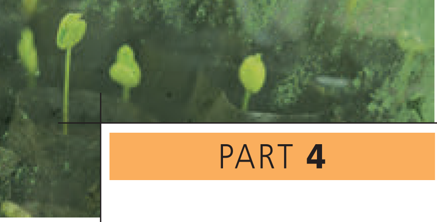
- identify areas, forests, species or populations with high levels of variability for genetic conservation (*in situ* or *ex situ*) and/or those whose variability is at risk;
- identify populations or individuals with rare alleles for conservation (*in situ* or *ex situ*) or with high levels of variability for enriching genetically depauperate populations;
- characterize the variability within areas, forests, populations or stands to guide forest management and silvicultural practice;
- characterize relationships between genetic variability and environmental parameters to establish "genecological" or seed-transfer zones within which transfer of genetic materials is considered most appropriate;
- monitor the trend in genetic variability in species, populations or particular areas or stands, for example in response to silvicultural and harvesting regimes, environmental changes or threats, in order to help guide conservation and management.

The second purpose is breeding and improvement, for which it may be necessary to:

- identify species and populations with the greatest potential for commercial development;
- characterize desirable productive, service or adaptive traits in priority species and relatives for further development;
- identify individual trees with desirable characteristics for breeding and improvement;
- identify genetic markers, develop linkage maps and ascribe function to genes, especially for characters conferring adaptive advantage or otherwise desirable traits;
- identify stands and individuals for provision of propagation materials (seeds and vegetative materials).

Article 7 of the CBD (UN, 1992) details priorities for information and data collection; it requires the identification and monitoring of components of biological diversity important for its conservation and sustainable use, as well as processes and activities that have impact on this value.

Recognition of the economic and ecological importance of genetic variability in tree species has steadily increased during the past 60 years and has driven efforts to study, characterize and document such variation (described in Chapter 7). A number of methods are available for characterizing genetic variability, both quantitative and molecular. Approaches used by countries for characterizing variability include investigation of morphological characteristics and the use of various biochemical and DNA markers through field-based studies, provenance and progeny trials, and laboratory-



based investigations. Use of these methods varies according to the nature of the country's genetic resources, whether the information sought is at the interspecific or intraspecific level, the country's priorities and objectives (conservation, management, improvement), the resources and technology available for the task, the degree of advancement of the country's FGR conservation and management system and the organization undertaking the work. For example, documentation of raw FGR in large protected areas may require taxonomic surveys to provide a broad assessment of variability at the interspecific level, while for detailed conservation planning or breeding programmes, information about the genetic variability between and among populations, provenances or progeny may be sought, involving investigation at the molecular level. Measurement of a variety of parameters is often needed to provide the information necessary for conservation and management of species and their genetic resources.

The different methods of characterization require different levels and types of resources, including funding, technical expertise, equipment, facilities and even land, and they are deployed by different countries in a manner consistent with the technical, financial and personnel resources available. Most methods of characterizing genetic variability require substantial commitment of resources, and as the number of tree species and populations to study is considered impossibly high, priority must be assigned to a limited number of the most important or model species. High-value, widely planted commercial species are generally accorded the highest priority, as the economic benefits from improvement can be substantial: Countries rated commercial value as the most important factor in prioritizing species, as discussed in Chapter 10. Economic returns from improvement programmes also make it possible to allocate significant resources to the characterization of the variability of high-value species – including field investigation, provenance and progeny trials and investigation of end-product quality considerations (e.g. timber and pulping properties, charcoal-making properties, fodder properties, fruit and nut nutrient content for edible species, medicinal properties and essential oil profiles).

The focus on economically important species has produced a great depth of information on genetic variability, and its influence on expression of desirable characteristics, for high-value globalized species and hybrids such as *Acacia mangium, Acacia nilotica, Cunninghamia lanceolata, Eucalyptus* spp. (*E. camaldulensis, E. grandis* and *E. globulus*), *Hevea brasiliensis, Pseudotsuga menziesii, Pinus* spp. (*P. caribaea, P. elliottii, P. massoniana, P. patula, P. radiata, P. sylvestris* and *P. taeda*), *Populus* spp. and hybrids and *Tectona grandis*, which are among the 30 most widely planted trees in the world (Carle, Ball and del Lungo, 2009). Most of the species that have been studied in depth are planted mainly as exotics (see Chapter 10). Historically, countries have expended less effort on characterizing their indigenous FGR, except in cases where the species are of high economic value and widely planted (e.g. *Cunninghamia lanceolata, Pinus massoniana* and *Pinus tabuliformis* in China and *Pinus taeda* and *Pseudotsuga menziesii* in North America) or are threatened and the subject of conservation management interest.

Where appropriate, countries make use of existing information sources for their FGR programmes. For example, some countries with advanced FGR conservation and management systems had not undertaken systematic or special inventories of FGR, rather making use of existing inventories and databases of forest and biological resources.

Rare and threatened species requiring conservation are also considered to have high priority for characterization of variability. They have been the focus of genetic investigations, especially those tree species that are also commercially valuable (e.g. *Eucalyptus benthamii* in Australia, *Baillonella toxisperma* in Gabon and *Dalbergia cochinchinensis* in Thailand).

Assessment of genetic variability has a vital role in conservation planning and guides decision-making and management. Germany, for example, remarks, "…knowledge will be used in decisions on natural and artificial regeneration of forest stands, in the provenance controls of forest reproductive material and in the choice of gene conservation forests".

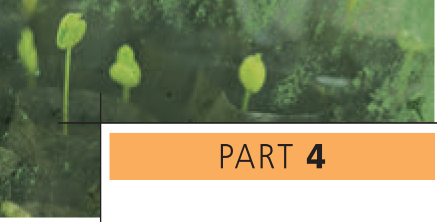
## Characterizing interspecific variability

Characterization of diversity at the species level is a key element and priority for FGR conservation and management. It involves the identification of tree species and mapping of their distributions through nationwide inventories. Environmental and biogeographic information is also important for understanding and interpreting morphological differences. Characterization of interspecific diversity requires botanical, taxonomic and biogeographic expertise, field survey, and GIS and data management systems for mapping, recording, storing and sharing information. Much of the genetic characterization at this level is captured through biological and forestry inventories undertaken in the course of other resource management activities such as biodiversity conservation and forest management. Such surveys often fail to capture and document the extensive genetic resources held in *circa situm* environments. ICRAF and national partners in Africa have documented information for important agroforestry tree product (AFTP) species through participatory rural surveys (e.g. Leakey, Schreckenberg and Tchoundjeu, 2003), and CSIRO's South Pacific Regional Initiative on Forest Genetic Resources (SPRIG) has done likewise in five island nations of Oceania (e.g. Thaman *et al*., 2000).

Countries with well established biological and natural resource management administrations and infrastructure, including herbaria and well trained taxonomists, have better knowledge of their tree species diversity and distribution than countries with fewer resources, which have a greater need for further characterization at the species level. Completion of biological inventories including tree species resources is more challenging for countries with extensive areas of highly diverse tree flora distributed over a wide range of heterogeneous environments, particularly if forests are inaccessible and poorly known or if conflict in or near forest areas raises security challenges.

Interspecific diversity reported by countries varies greatly, from as few as 20 to almost 8 000 species, with major implications for FGR conservation and management systems. Countries with more species will generally have greater reserves of genetic variability, and the task of documentation and characterization is therefore more difficult. Country reports suggest that developed countries with lower interspecific variability generally have detailed knowledge of a higher proportion of their indigenous tree species, especially where these species are important commercially.

Where botanical inventories are lacking, the area of forest or vegetation cover may be used as an approximate surrogate measure of genetic variability. As many countries do not have detailed information on variation among and within species, and are unlikely to have it in the near future, forested area is often used as a primary measure of diversity of FGR and as a means of monitoring their trajectory or trends (see also Chapter 6). For example, Ghana quotes the loss of most of its dry semi-deciduous forest as representing a serious threat to the genetic diversity of the woody species contained within it. Many countries, including Ethiopia, Indonesia, Madagascar and Thailand, report risk from significant deforestation rates. Madagascar lost 4.5 percent of its forest cover between 2000 and 2010 (FAO, 2010a) and reports a risk that "many forest species may disappear forever, without ever being discovered". Ethiopia recognizes that "the most important threats to genetic diversity come from deforestation and forest fragmentation, which can result in total loss



of genetic information and disturbance in the genetic structure".

Where area of forest cover is used as a surrogate for diversity, estimates of species richness and distribution per unit of area are required to establish the relationship between forest or tree loss and the loss of diversity that this represents. Ground truthing of GIS data may assist in this process.

For countries that lack comprehensive inventories of their forest species, completion of inventories is a high priority. For example, the Madagascar country report states that it is indispensable to complete knowledge of the forests and the species they contain by undertaking new floristic inventories across the country. For assessing changes in forest cover, the use of GIS is vital and constitutes one of the most important methods for broadly characterizing genetic variability, particularly in the context of less wealthy, biodiverse nations subject to high levels of forest loss and degradation. International donor and partner assistance in forest inventories can have an important role in assessing diversity and monitoring forest changes.

## Characterizing intraspecific variation

Environmental heterogeneity, breeding systems, the degree of biogeographic isolation from other populations or individuals, and the species evolutionary history all influence the pattern and level of intraspecific variation (see section on species diversity in Chapter 1). Its characterization and documentation is widely appreciated as a central component of conservation and management of individual species, including breeding for economic, genetic conservation and environmental applications; identifying provenances and seed-transfer or genecological zones; and enabling selection of germplasm best adapted to local conditions for use in planting programmes.

Reporting countries recognize that a thorough understanding of intraspecific variation is fundamental to the sustainable management of FGR, including in forests managed for multiple purposes; it is particularly important for forest types, species and populations containing valuable genetic resources of narrow or limited distribution which need to be monitored at the intraspecific level. Despite the great value of knowledge of intraspecific genetic variability, the United States of America notes that, with current resourcing, there are "too many tree species" to assess genetic variability effectively at this level. China has genetic information on 100 species, a very high number compared to many other countries, but these represent only about 5 percent of the country's tree flora – highlighting the need to prioritize species for further investigation.

As plantation forestry in most parts of the world is focused on improvement of a small number of highly productive commercial species, genetic characterization has similarly focused on these species. For example, considerable information is available on the variability of the most commercially important species in four of the most widely planted genera globally: *Acacia, Eucalyptus, Populus* and *Pinus*. Efforts to characterize species that are less widely planted but important locally or in naturally regenerated forests are lagging and in urgent need of study.

Sharing of information on intraspecific variability is essential for effective FGR conservation and management, and is particularly important for developing countries that lack the resources to undertake studies on the exotic species on which some countries' forestry industries depend. Several key international networks, for example for the genera *Eucalyptus, Pinus, Populus, Salix* and *Tectona* and for *Azadirachta indica* (neem), *Bambusa* spp. (bamboo) and *Calamus* spp. (rattan), are reported by developing countries as being particularly important for knowledge sharing. Of like importance is the publication of public-good FGR research in accessible formats, such as in free or open-access online journals and websites.

Methods used by countries to assess intraspecific genetic variation include well established techniques such as identification of morphological differences in the field; provenance testing; progeny testing; genecological studies to examine the variation of adaptive traits (i.e. those that are likely to impart an adaptive advantage) across the landscape, which may assist in delineating appropriate seed-transfer zones; and increasingly laboratory-based approaches based on biochemical and DNA markers. Each method has its particular applications and advantages in different country contexts and applications. Of the examples for which testing methods were cited in country reports, DNA markers were used for 58 percent of the species, biochemical markers for 38 percent, and studies of morphological characteristics for 4 percent.

Individual species vary greatly in degree of variability for different traits, both within and between populations. A species' biogeographical and genecological distribution may be simple or complex, and it may overlap provincial and national boundaries, which means that efforts to characterize the species may require cooperation between agencies in different jurisdictions and/or countries.

Countries' approaches to intraspecific characterization are described briefly here.

## Use of morphological traits

Morphological evaluation or phenotypic selection is one of the main characterization methods used by developing countries, even though its use is not recorded often in tabulations of countries' characterization methods.

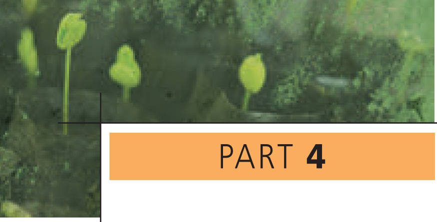
Morphological characters that may be assessed include bole form, branching pattern, height, wood and leaf characteristics and growth traits, as well as structures that show limited phenotypic variation, particularly reproductive parts such as seeds and fruits. The low cost and ease of morphological assessment relative to laboratory-based approaches has led to its widespread application. However, observed differences cannot be attributed to genetic differences with certainty until further testing is undertaken, most commonly through provenance and/or progeny testing (see below), increasingly coupled with molecular marker studies.

Phenotypically based selections and characters of trees in wild stands typically have very low heritabilities, especially for those traits showing continuous variation. Nevertheless, selected individual trees or seed stands showing superior expression of desired traits ("plus trees") are widely used for propagation materials for provenance, progeny or other trials and to produce seed or nursery stock for production plantings.

Morphological assessment is sometimes also used to identify variants and guide selection of more diverse plant materials for conservation management when establishing *ex situ* genetic conservation stands for threatened species. However, random sampling of gene pools, involving a large number of selections (e.g. >30 trees) of widely spaced and presumably unrelated individuals, is generally preferred for both provenance trials and conservation measures. The first step in many traditional breeding programmes is to assess morphological and growth traits on same-aged plants growing under common environmental conditions, so that differences can be attributed to genetic effects rather than environmental variability, yielding higher heritabilities.

## Provenance, progeny and clonal testing

Provenance testing involves growing trees selected from different locations (provenances) in the same field environment so that observed variation among populations or individuals can be attributed to genetic differences. These approaches have a long history and continue to be used widely in tree breeding and improvement programmes (see Chapter 7). The country reports tabulated species/provenance trials, often extensive, which have been undertaken. However, many of these trials are in progress or



not yet mature, have not been reported or are not readily available in the published scientific literature.

The results of provenance tests are typically only valid after half of the projected rotation age, and some characteristics of interest may not express themselves for many years. Accordingly provenance testing is time consuming and rather expensive and may be subject to high levels of risk associated with natural disasters such as drought, fire, cyclones, and social, political and economic disruption. However, as provenance testing does not require high levels of technical infrastructure or facilities, it is used widely in tropical countries, where trees often have fast growth rates and shorter rotation periods, meaning that valid selections may be obtained as soon as five to ten years after planting for short-rotation species.

Provenance testing, including genotype × environment interaction studies and reciprocal transplant trials, help identify provenances adapted to particular environmental conditions, including climate, drought and fire – an increasingly important task given the predicted climate changes which are already having observable effects. Many molecular marker tests, in contrast, help evaluate genetic differences or similarities but cannot necessarily be used to identify genes conferring adaptive or productive advantage. Several countries give a priority to research to identify provenances better adapted to new climate change-induced conditions. More generally, the United States of America notes:

> "Long-term provenance trials test different provenance collections over a variety of planting locations, and… in addition to documenting intraspecies variation, can provide reliable information for determining the limits of seed movement and discern which seed sources are suitable for planting locations because they evaluate seed sources over a long period of time... the wealth of provenance trials have demonstrated intraspecific variation for practically all timber species…."

Genecology studies use provenance testing or environmental surrogates to examine the variation in adaptive characteristics related to traits such as growth rate, phenology, form, cold and drought tolerance across a landscape gradient to delineate seed-transfer zones. This approach has been used to define seed-transfer zones for conifers in the southeastern and northwestern United States, for teak and *Pinus merkusii* in Thailand and for forest tree species in Denmark. It allows the best-adapted plant materials to be matched with appropriate locations and environmental conditions.

**Trials in temperate regions.** Large and well documented provenance testing efforts include the International Union of Forest Research Organizations (IUFRO) *Picea abies* provenance trial established in 1968, which comprised 1 100 provenances collected from throughout the range of the species and planted at 20 locations in 13 countries (Krutzsch, 1974).

Similarly, Russian provenance trials were established with *Pinus sylvestris* from 1974 to 1976 throughout the former Soviet Union, including 113 provenances at 33 planting sites (Shutyaev and Giertych, 1997).

Canada reports 988 provenance tests, comprising 7 573 provenances, that have been established for at least 41 forest tree species and hybrids. Extensive provenance testing has been carried out for 34 native species and at least seven exotics, mostly conifers. In recognition of their wide planting in reforestation programmes, six native species have been extensively tested both nationally and subnationally: *Picea glauca, Picea mariana, Pinus banksiana, Pinus contorta* var. *latifolia, Pseudotsuga menziesii* var. *menziesii* and *Tsuga heterophylla*.

In the 1950s, an ambitious programme with *Pinus resinosa* sent seed to other parts of North America and Europe for testing, in addition to establishing many experiments in Ontario. The programme was abandoned when it became apparent that genetic variation in *Pinus resinosa* was lower than in most other conifers (Stiell, 1994). In eastern Canada the primary focus for early exploration and testing was *Picea* spp.; range-wide provenance trials were established for *P. glauca, P. mariana* and *P. rubens*. Provenance trials including native and exotic Larix species were also established in eastern Canada. *Pinus contorta* provenance trials established in Canada in 1974 in the province of British Columbia and in Yukon Territory included 140 provenances from throughout the species' range in western North America, tested at 62 locations (Wang *et al*., 2006; Wang, O'Neill and Aitken, 2010).

A test in the southern United States of America in 1926 included four provenances of *Pinus taeda* (Rogers and Ledig, 1996). Wakeley (1955) also initiated a large study of geographic variation of four southern *Pinus* species (*P. taeda, P. elliottii, P. palustris* and *P. echinata*), which were planted in 66 test plantations across the southeastern United States in 1951. This study set the stage for most of the later genetics work with these species (Zobel, 2005).

In Germany, provenance testing is being carried out for 34 tree species, including several North American species, by multiple Länder (states) and institutions. Germany has used this approach since as long ago as the second half of the nineteenth century; the first German provenance test for *Pinus sylvestris* was established in 1879.

Bulgaria has 57 provenance trials, focused on 38 tree species.

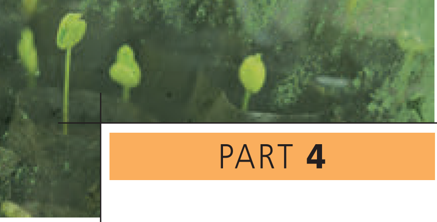
**Trials in other regions.** While provenances of many tree species that are planted for wood production in Europe, North America and Australia have been well studied, often both within and outside their natural ranges, in general fewer species native to the tropics have been studied and information from existing trials is not easy to find. In addition, many tropical tree species have recalcitrant seeds and flower sparsely; these characteristics are a constraint to testing because it is difficult to accumulate the materials to establish a provenance test in a single planting season. The following are some of the known provenance trials in Africa and Asia.

In West Africa, 25 provenances from throughout the range of the multipurpose species *Parkia biglobosa* were established in 1995 at two test locations in Burkina Faso that receive contrasting amounts of mean rainfall (Ouedraogo *et al*., 2012). Results are now available to guide selection of planting material for locations in Burkina Faso. Provenance trials have also been used to test for resistance of *Milicia excelsa* to a *Phytolyma* psyllid (Ofori, Cobbinah and Appiah-Kwarteng, 2001).

Provenance trials on indigenous species have also been set up for *Aucoumea klaineana*; 13 representative provenances from throughout the species distribution were planted in 1967 in M'Voum reserve, Gabon. In the Republic of the Congo and in Côte d'Ivoire, provenances of *Terminalia superba* were established to select the more productive lineages for plantations. Some provenance trials have recently been set up for *Baillonella toxisperma, Distemonanthus benthamianus* and *Erythrophleum suaveolens/E. ivorense* in different forest gaps in Gabon and Cameroon on each side of the Equator (J.-L. Doucet, personal communication). Provenances come from different populations from each part of the climatic hinge (seasonal inversion line) in Cameroon, Gabon and the Republic of the Congo.

The country reports mention provenance trials with at least eight other species in West Africa: *Acacia senegalensis, Adansonia digitata, Allanblackia parviflora, Khaya senegalensis, Tamarinda indica, Terminalia ivoriensis, Triplochiton scleroxylon* and *Vitellaria paradoxa*.

Other regions of Africa report fewer tested native species. Substantial effort has been expended on testing provenances and developing tree improvement programmes in southern Africa, but most of the plantation species are exotics. In Madagascar, provenance trials have been undertaken for important and promising forest plantation species, mainly exotics: Acacia spp., *Cupressus lusitanica, Eucalyptus* spp., *Khaya madagascariensis, Liquidambar styraciflua, Pinus*



spp. and *Tectona grandis.* Zimbabwe's provenance testing programmes for indigenous species date back to the 1980s, and also form the basis of the country's *ex situ* conservation programme.

In Asia, country reports indicate that about 12 native species have been evaluated at the provenance and or progeny level in Southeast Asia, 17 in South Asia and 12 in China, Japan and the Republic of Korea. Central Asian countries provided little information about provenances, but *Haloxylon aphyllum* sources have been tested and drought- and pest-resistant variants have been identified. *Abies sibirica* has been tested in Kazakhstan.

China commenced provenance trials in the early 1980s and has now conducted trials for more than 70 important planted species, including the following as well as various key exotic species: *Betula platyphylla, Cunninghamia lanceolata, Larix gmelinii, Larix principis-rupprechtii, Picea koraiensis, Pinus armandii, Pinus koraiensis, Pinus massoniana, Pinus tabuliformis, Pinus yunnanensis, Platycladus orientalis, Populus tomentosa, Sassafras tzumu, Taiwania cryptomerioides* and *Ulmus pumila*.

## Molecular markers

Molecular marker approaches employ laboratory-based techniques to identify and describe genetic variation. Greatly reduced costs of gene sequencing and increases in computer processing speed and power have led to a proliferation of DNA studies, including whole genome sequencing and rapid progress in identifying the location and function of specific genes.

Entire genomes are now being sequenced for both angiosperms (including the important commercial forest trees *Populus trichocarpa* and *Eucalyptus grandis*; four fruit-tree species, *Carica papaya, Citrus sinensis, Malus domestica* and *Prunus persica*; and the most primitive angiosperm, *Amborella trichopoda*) and gymnosperms (*Larix sibirica, Picea abies, Picea glauca, Pinus lambertiana, Pinus pinaster, Pinus sylvestris, Pinus taeda* and *Pseudotsuga menziesii*). The sequencing of coniferous genomes, which are typically an order of magnitude larger than those of other organisms, has only been made possible through the introduction of new sequencing technologies and dramatic reduction in costs[4] and has been facilitated by collaboration among different laboratories and research groups.

These sequencing studies are complemented by gene mapping studies and elucidation of gene function and expression for traits such as growth, wood properties and response to biotic and abiotic stresses in seven economically important tree genera: *Castanea, Eucalyptus, Picea, Pinus, Populus, Pseudotsuga* and *Quercus* (Neale and Kremer 2011). Novel approaches have been developed to link markers to important traits, with genomic and marker-assisted selection close to being realized in several tree species. Molecular geneticists are increasingly realizing that they will not be able to use the rapidly expanding gene-level information without whole-organism information from the field.

Isozyme and/or allozyme markers were widely used as molecular markers up to the 1990s to evaluate genetic diversity and breeding systems in trees, including for examination of variation within and between populations, using over 20 enzyme systems; the earliest research was mainly focused on high-priority plantation genera and species for production of timber and pulp, such as *Eucalyptus, Pinus* and *Populus* species. However, since the advent of more informative, accessible and cost-effective DNA-based approaches, including direct DNA sequencing, single nucleotide polymorphisms and microsatellites (see Chapter 8), these isozyme studies have fallen out of favour, although they are still useful for some purposes. For example, isozyme markers still have a role in low-cost assessment of diversity and breeding systems.

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[4] Sequencing costs have declined from more than USD 5 000 per raw megabase of DNA sequence in 2001 to about USD 0.05 in 2014, with the most dramatic decline having occurred since 2007 (National Human Genome Research Institute, 2014).

The country reports reflect the trend noted by Mexico that, apart from field testing using quantitative means, "molecular markers have been the most popular [method of characterizing intraspecific variability] for forest species [in] the last ten years". Of 409 reported uses of markers to evaluate intraspecific variation, 58 percent were DNA markers, compared to 38 percent for biochemical markers. The use of morphological markers was reported in only 4 percent of evaluations. Of the analyses using biochemical markers, 65 percent were in Europe and 21 percent in Asia; while 46 percent of the evaluations using DNA markers were in Asia and 44 percent in Europe. Only 3 percent of DNA marker uses were in Africa, possibly reflecting the limited resources available for applying these techniques.

Enzyme electrophoresis and neutral DNA markers (RAPD) have been used in Burkina Faso; species characterized using these methods or simple description of morphological characters include *Acacia senegal, Adansonia digitata, Borassus aethiopium, Parkia biglobosa, Sclerocarya birrea, Tamarindus indica* and *Vitellaria paradoxa* subsp. *paradoxa*.

While quantitative techniques are still the dominant method used to produce improved germplasm for most commercial forest species, molecular techniques have promise for rapid identification of genetic variability. These methods can circumvent the long time periods and risks involved in provenance and progeny testing, which are a constraint on the development and production of improved germplasm for general use. Germany points out that the time available to develop climate change-adapted planting stock is extremely limited, highlighting the importance of developing techniques that can deliver results more quickly than traditional methods.

Although molecular methods are highly effective in identifying variability and evaluating similarity or differences between individuals or populations, many of these techniques use neutral markers, i.e. markers with which the genetic variation identified does not necessarily confer an adaptive advantage or contribute to improvements in productivity, performance or utility. Many countries involved in research at this level identify development of molecular markers for adaptive and productive traits as a high and urgent priority. For example, Germany states: "It is essential that future international research projects also provide more information about the genetic variation to adaptation-relevant gene loci. This would provide important information on the adaptation potentials of tree populations."

Developing countries with limited resources face constraints in using molecular markers, including cost (as noted by Zimbabwe, for example) and lack of expertise, equipment and facilities. Nonetheless, it is recognized that these techniques offer great potential. Ghana, for example, identifies development of expertise in biotechnological approaches and upgrading of existing facilities as key capacity requirements for advancing its characterization agenda. Further, many developing countries already use these techniques, even if to a limited extent. Cooperative arrangements with international or regional partners and donors could provide opportunities for molecular characterization by developing countries or assist in the development of in-country facilities and expertise.

In some countries, research facilities with the capacity to undertake these studies may be located in universities, agricultural institutes, research organizations or the private sector, i.e. outside the institutions charged with FGR conservation and management. In these cases effective collaboration can deliver mutually beneficial outcomes. In the United States of America, for example, much breeding and improvement work involving molecular research takes place through cooperative arrangements among universities, public land management agencies and private companies. Burkina Faso outsources its characterizations based on molecular markers through partnership with universities in Denmark, France, the Netherlands and the United Kingdom. Germany notes that some government departments offer consulting services in FGR characterization; adoption of this approach more widely could make it possible to procure skills, expertise and access to facilities on an "as needed" basis.

On the other hand, development of these capacities within countries can offer advantages, both in facilitating the integration of national strategic priorities for FGR with research capacity and function, and in allowing the country to pursue its own FGR conservation and management interests without having to accommodate external demands.

Ethiopia notes that it has facilities engaged in molecular characterization of agricultural crops but no dedicated facilities for such research on FGR; in the few intraspecific studies of trees, molecular characterization (using inter-simple sequence repeats [ISSRs], AFLP and chloroplast microsatellites) has been outsourced internationally. This example suggests the potential benefits from coordination and cooperation in areas of common interest and underscores the importance of integrating FGR objectives with strategies and programmes in related fields through harmonization at the national level.

## Analytic methods

The national reports rarely refer to the methods used to analyse the data collected in studies using the techniques described above. However, China and Mexico detail the analytic methods used in evaluation of their FGR data.

In analyses of interpopulation variation, China reported the use of variance components, genetic distance and phenotypic differentiation coefficients. Intrapopulation variation has been evaluated using standard deviation, coefficient of variation, variance and Shannon information index. Common parameters used for isozyme and DNA analyses include allele frequencies and their distribution, variance of genotypic frequencies, average number of alleles per loci, effective number of alleles, percentage of polymorphic loci, Wright's inbreeding coefficient and Nei's diversity index, Shannon information index, coefficient of genetic differentiation and genetic distance.

In studies of the variability of Mexican tree species, genetic diversity was inferred through calculation of expected heterozygosity, observed heterozygosity, number of alleles per locus and percentage of polymorphic loci.

## Characters investigated in studies of intraspecific genetic variability

As noted earlier, investigations of variability for commercial plantation forestry (focused on economic characters such as growth rate, wood characteristics or industrial processing qualities) differ somewhat from those carried out in the design of effective genetic conservation programmes (focusing on level and distribution of variability within a species). Provenance and progeny testing may, however, be used to establish variability in conservation management, for example when selecting materials of threatened species for *circa situm* conservation measures. Characterization of variability that can contribute to adaptation and survival under future environmental regimes (involving climate change, human modification of landscapes and spread of invasive species), athough recognized as crucial by some countries, needs further work.

Countries reported the individual characters that were assessed in the course of evaluating genetic variability. Of the 27 characters reported as used in 692 characterizations, the most studied are shown in Table 11.1; around 15 other characters were evaluated less often. These data indicate that purely morphological characters remain widely used in the evaluation of variability, despite the increasing focus on molecular markers. They also highlight the importance that countries place on identifying trees and genotypes for breeding for pest and disease resistance. For example, Ghana notes that although its intraspecific evaluation programme is limited, "all objectives and priorities for understanding intraspecific variation are geared towards identification of planting stocks resistant

**TABLE 11.1**

Characters most frequently assessed in 692 evaluations of genetic variability reported by countries

| Character | Type of character | % of total evaluations assessing this character |
|---|---|---|
| Characters least subject to phenotypic variation, i.e. seed, fruits, cones and pods | Morphological | 17.5 |
| Disease and pest resistance | Adaptive/productive | 13 |
| Leaf anatomy | Morphological | 7 |
| Bole/stem diameter | Productive | 7 |
| Growth rate | Productive | 5.5 |
| Biomass/fodder productivity | Productive | 5 |
| Height | Productive | 5.5 |
| Drought resistance | Adaptive/productive | 5 |
| Phenology | Adaptive | 5 |
| Bark | Morphological | 5 |
| Chemistry/exudates | Biochemical | 3 |

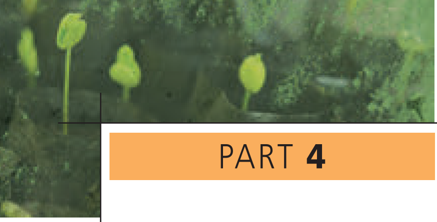
to insect and disease infestation under forest plantation conditions”.

Mexico notes that the variables and measures used in evaluating genetic diversity are indicators that are often used to represent and infer the general variability of target organisms. This process relies on assumptions about the relationship between the variation observed in the variables tested and the variation in the target character or organism under study. Several countries observe the need for continued research on the methods for characterizing diversity. As mentioned above, for example, Germany places priority on identifying molecular markers for adaptive characters (e.g. drought tolerance, fire and wind resistance and pest and disease resistance) and productive characters (e.g. growth rate, form and wood processing qualities).

Identification of markers for adaptive traits is considered especially significant with respect to climate change, which is widely recognized in country reports as the major challenge to the integrity of forest ecosystems and the survival of individual tree species. A number of countries point to the need to identify breeding stock for both productive and environmental purposes that is better adapted to the expected conditions, for example with respect to phenological responses (reproductive phenology and deciduousness) or drought, fire, pest or disease resistance. Germany stresses the high priority for identifying markers for characters that confer the ability to survive under the altered climate regimes predicted by climate models, to facilitate the selection of climate change-adapted plant materials.

## Monitoring of forest genetic resources

Monitoring the state and trends of a country’s genetic resources is an essential requirement for effective FGR conservation and management and decision-making. Monitoring assists in identifying the extent, severity, location and nature of genetic erosion of species and forests as well as in evaluating conservation and management actions. Article 7 of the CBD (UN, 1992) requires signatory countries to “monitor, through sampling and other techniques, the components of biological diversity… paying particular attention to those requiring urgent conservation measures and those which offer the greatest



potential for sustainable use". The rapid rate of forest loss, high levels of genetic erosion and impending impacts of climate change highlight the urgency of establishing effective monitoring programmes.

A number of countries recognize in their reports the need for an effective forest genetic resources monitoring and evaluation system as required by the CBD. Canada notes that monitoring of inter- and intraspecific variation is a priority for tracking FGR status of species including threat status, vulnerability and level of genetic erosion. For such monitoring, Canada notes the need for continuing investment in field and laboratory personnel and information management, as well as a need to ensure consistency across jurisdictions.

As it is impossible to measure the genetic variation and to monitor changes in all or most tree species, two approaches may be applied. The first involves measuring and monitoring the genetic variability in only the highest priority or model species. Germany, for example, monitors genetic variation of five species in response to forest management regimes and silvicultural practices. The second approach involves identifying and monitoring surrogates for FGR – for example, particular species or populations, or the area of forest or tree cover, in combination with GIS, ground truthing, biogeographical interpretation and monitoring of species-rich area. Effective monitoring of genetic variability will often require the use and assessment of several measures in combination.

The current level of FGR monitoring varies enormously among countries. For example, Thailand has a network of 1 285 permanent plots as part of its national forest resources monitoring information system; sampling commenced in 2008 and is expected to provide valuable input for updating information on forest cover, genetic resources and deforestation. Thailand also has a strategic framework for surveys and database establishment for biodiversity and FGR in protected areas. At the other end of spectrum, Solomon Islands currently has no system in place to monitor or report on FGR erosion.

Monitoring needs to be a requirement of all FGR conservation and management programmes and must be included in national FGR strategies with endorsement at the national level helping to secure budget allocations. Several countries point out the need for increased and consistent monitoring and for its harmonization across jurisdictions, regions and national boundaries. Cooperative administrative arrangements, where they exist, can provide a vehicle for integrating this FGR conservation and management function across jurisdictions. For example, European countries are currently negotiating a European forest convention addressing sustainable forest management, which may provide a suitable avenue for harmonization.

Developed countries with well established national forest inventories and monitoring systems, such as Finland and Germany, are better placed to document and describe changes in FGR than most developing countries. However, genetic monitoring of forests is at a very early stage, with so far only a small number of pilot studies (e.g. in Germany and in the framework of EUFORGEN). It is expected that forest genetic diversity can be better maintained through prevention of overcutting and forest loss; through the application of silvicultural techniques favouring multipurpose mixed hardwood stands established from a wider genetic base over monospecific coniferous plantings; and through an increase in forest area, including the targeted introduction of rare tree species into natural forest ecosystems. However, more monitoring and repeat inventories are needed to confirm such assumptions.

Developed, temperate and boreal zone countries may be able to maintain and expand forest cover and genetic variability more easily because they tend to have fewer tree species, more effective forest administration and less un-regulated harvesting than developing countries. They nonetheless offer examples of how it is possible to maintain and expand FGR, for instance through sustainable forest management, silvicultural techniques and policy mechanisms such as incentives for sustainable management of FGR.

## Differences among countries and regions in characterization of FGR

As already noted, knowledge of genetic variability varies widely among countries. From the country reports, the degree to which FGR have been characterized and the methods employed appear to vary with:

- the level of economic development and resources available for characterization (financial, technical, institutional and personnel);
- the level of development of organizations dealing with conservation and forestry and of associated information and management systems;
- the importance of the forest sector in the economy, and the methods of production and forest management (e.g. dependence on planted forests versus naturally regenerated forests);
- the nature and structure of the forest industry, i.e. the production profile with respect to output types and the extent of development of private-sector capacity in genetic improvement;
- the degree of engagement with regional and international networks;
- the support and contribution of international donors;
- which organization in the country has prime responsibility for conservation and management of FGR;
- the involvement and input of relevant research organizations, including institutes and universities;
- the presence or absence of supporting legislation and regulatory frameworks that give value to FGR conservation and management;
- the presence or absence of a national FGR strategy or programme;
- the area of natural forest remaining, the degree of diversity within the country's flora and the heterogeneity of its genecological zones;
- the number of priority tree species identified for conservation and management.

Developing countries thus face several challenges causing them to lag behind developed countries in characterization of genetic variability. First, developing countries, particularly in tropical or subtropical areas, often have much higher levels of tree species diversity and FGR variability, and these countries (especially the 17 megadiverse countries) require greater survey effort to document their FGR, i.e. to identify and map distribution of species, to identify areas of high interspecies diversity and to investigate genecological relationships. Second, developing countries generally have fewer resources available for survey, characterization and data management. Third, developing countries generally experience much higher rates of uncontrolled forest clearing, meaning they have a greater requirement for inventories of FGR variability at the species level. Fourth, tropical developing countries rely heavily on the use of exotic species for plantation development, for which extensive characterization work has already been undertaken but for which access to germplasm remains critical for future breeding and improvement. Given the resource constraints in these countries, remote sensing (coupled with an appropriate level of ground truthing and GIS) is an extremely important tool for assessment and monitoring.

## Chapter 12

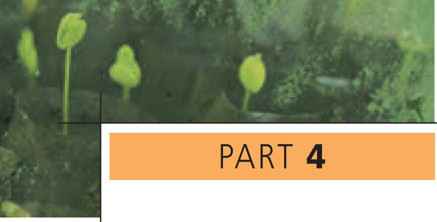
# *In situ* FGR conservation and management

*In situ* conservation of FGR is often considered to be the core activity of FGR conservation and management, as it maintains the existing natural pool of genetic variability while at the same time permitting natural selection processes to operate. It also maintains the typically wide range of variation required for effective selection for breeding and genetic improvement of trees with high commercial or service value. Thailand recounts the challenges of successful long-term *in situ* conservation in reference to an initiative begun with assistance from the Danish Government during the 1970s:

> "The natural stands [of *Pinus merkusii*], especially in the northeast of Thailand, have been heavily exploited by local communities, primarily as a source of resin and fuelwood. In addition, many good stands are fragmented and declining as a result of the widespread conversion of forest to farmland and frequent fires. The lowland stands that showed the best performance in provenance trials are even threatened with extinction; [conserving] genetic variation within the species by selecting a number of populations from different parts of the distribution area will serve as a source for protection, management and maintenance of genetic resources by providing a basis for future selection and breeding activities as well as for seed sources with a broad genetic base."

*In situ* conservation is often considered the first course of action in conservation of both FGR and other forms of biodiversity; alternative methods such as *ex situ* measures are normally only considered when it has been established that *in situ* conservation is not feasible, or when species are at serious risk of extinction in the wild, or for safety duplication purposes. Advantages of *in situ* conservation are that it permits conservation of ecological, aesthetic, ethical and cultural value at the same time, and that large amounts of FGR may be efficiently conserved through simultaneous conservation of the diversity of multiple species. In indigenous production forests where sustainable forest management is practised and FGR variability is maintained, *in situ* conservation is fully compatible with harvesting of timber and forest products. The security of conservation tenure and the type and level of management are major factors in determining conservation outcomes for *in situ* FGR.

*In situ* conservation ensures that in the absence of catastrophe and genetic bottlenecks, the genetic variability contained in the target species is maintained at a high level and serves as the foundation on which selection pressures can direct adaptation to new conditions. *In situ* conservation therefore allows for the genetic variation contained in a population or species to change over time; European countries therefore refer to it as dynamic. *Ex situ* conservation, in contrast, is predominantly static, preserving a



"snapshot" of the variability present at the time of conservation of the germplasm.

Although most *in situ* conservation assets are managed as open, dynamic breeding systems, a small number may be subjected to controlled pollination or other reproductive manipulations for specific breeding outcomes.

*In situ* conservation involves a wide range of activities, and every *in situ* programme will include a combination of these. Measures mentioned in country reports include:

- a process for prioritizing areas, species and populations for *in situ* conservation action;
- research to understand the nature and distribution of genetic variability within the area, species or population and to identify threats to this variability and management actions to protect it – for example, determining the location and number of populations and individuals and the area of reserve required to maintain variability at the desired level – to guide conservation programme design;
- protection of an area containing target or priority FGR (species, population or individual) through its dedication as a protected area or reserve, with restrictions on activities that threaten FGR;
- legislation and/or regulations enabling conservation of the area or species, including control of access and use, for example by gazetting or listing it on an official "threatened" list;
- enforcement of legislation and regulations and corresponding action to control threatening activities;
- preparation of a management plan for a forest or species, involving control of activities that degrade its genetic resources (e.g. by managing access, use and harvesting) and maintenance of the conditions necessary for its survival and regeneration (e.g. by maintaining ecological processes, controlling invasive plants and animals, managing wildfire and maintaining pollinators and dispersers);
- preparation and implementation of a sustainable forest management plan that ensures that genetic variability is not diminished in areas subject to harvesting and use;
- promotion of the participation of forest users and adjoining communities in sustainable forest management including access and benefit sharing, e.g. through incentive payments for stewardship or employment based on activities undertaken in accordance with sustainable forest management principles;
- education and awareness raising for forest-using communities and industries, regarding appropriate uses and activities and practices that minimize impacts on FGR;
- preparation and/or implementation of guidelines or codes of practice governing activities that may be permitted in reserves or areas providing FGR benefits, to minimize impacts on variability – for example, a code of forest practice or guidelines for reduced-impact logging or for harvesting of fuelwood or NWFPs;
- provision of alternative livelihood opportunities for forest users who may be displaced or disadvantaged by change in land use (for example rural, traditional or subsistence communities that rely on forest products for fuel, housing materials, food, medicines and income), including forest plantation or better forest management to counter any shortfalls in supply of forest products.

In their country reports, different countries interpret *in situ* conservation of forest genetic resources in different ways, which complicates interpretation. Countries report conservation *in situ* in a wide range of forest reserve categories and ownership types, ranging from strictly protected areas to forests used for wild harvest and timber production to private property. The strict definition of *in situ* conservation of genetic resources implies reserves established specifically for conserving genetic diversity of targeted tree species. Many European countries have such reserves and report on this basis. The Russian Federation, for example, has designated 205 501 hectares as genetic reserves for 21 tree species.

Ownership of natural forest lands influences a country's approach to *in situ* conservation of FGR; the ability to make land-use decisions depends largely on whether the land is under public, private or communal ownership. In Finland the area of privately owned forests is 15 million hectares, more than double the area of publicly owned forests; while in Canada, which has 10 percent of the world's forest area, only 7 percent of the forest land is privately owned. Where significant forested areas are publicly owned, the State can create protected areas and reserves for *in situ* conservation of FGR, consistent with national strategies and priorities. Governments are generally less able to influence land use and protect FGR on the private estate. Regulations governing protection of FGR on private land are more effective in countries where State power is strongest, administration is effective, incentives are available and community support for conservation is well accepted.

The numbers of species and subspecies conserved *in situ* and *ex situ*, by region, according to the country reports, are presented in Figure 12.1. (*Ex situ* conservation is covered in Chapter 13.) It is important to note that the figures reflect the different reporting approaches taken by the countries. For example, most of the tree species in North America are represented in protected areas, but the areas are not designated specifically for genetic conservation so the reported number is low.

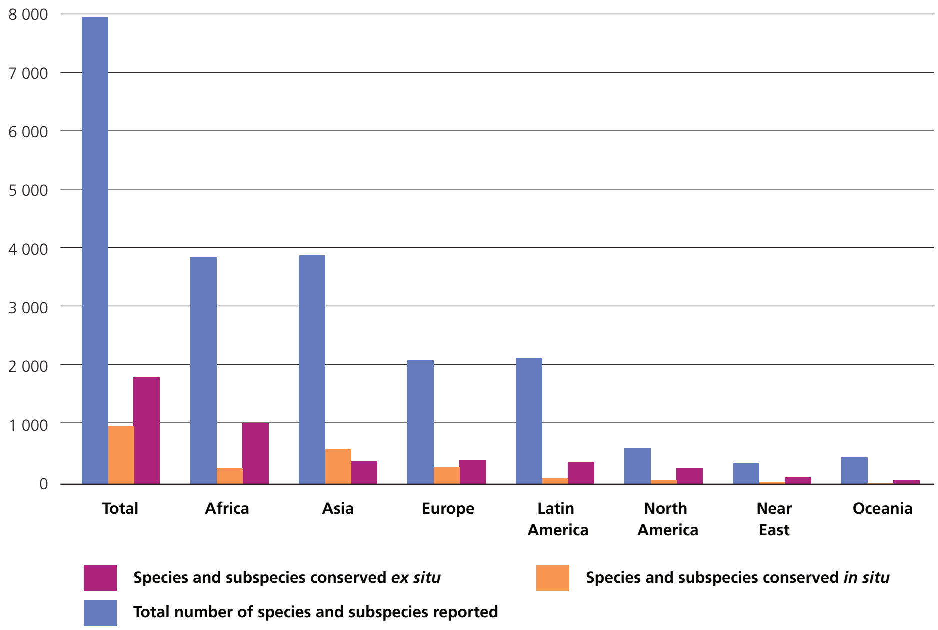
Although country reports detail the vast areas and amounts of FGR conserved *in situ* in protected areas and other public lands, many countries note that they have few if any formal, designated *in situ* conservation reserves for priority species. For example, India points out that nearly 16 million hectares are conserved in protected areas (almost 5 percent of the land area) but lists only 18 481 ha in dedicated reserves for *in situ* conservation of target species.

Countries that do not have such reserves may still have effective *in situ* conservation of FGR. In British Columbia, Canada, for example, secure *in situ* protection is in place for most species across much of their natural distribution. Genetic gap analysis shows that all tree species are represented with adequate population size in existing protected areas; however, across the species' ranges gaps remain in some of the biogeoclimatic zones (Krakowski *et al*., 2009; Chourmouzis *et al*., 2009). Some countries that do not have reserves designated strictly for conservation of FGR report *in situ* conservation in protected areas designated for a variety of purposes, but without the benefit of genetic gap analysis it is not possible to know the degree to which genetic resources are protected.

Integration of FGR objectives into a wide range of land-use designations and regulations governing the use and management of forested land should be considered for both public and private land. Where legislation and regulation relating to reserves providing *in situ* conservation are inadequate, Germany suggests increasing the legislative backing for FGR conservation management actions by including the protection purpose "conservation and sustainable utilization of forest genetic resources" in the relevant legal provisions for designated *in situ* gene conservation assets. This could be extended to other public land reserve categories and designations providing *in situ* conservation benefits.

A further example of the need to address specifically the requirements of *in situ* FGR conservation is provided by the many countries that list their natural or near-natural seed stands and seed production areas as *in situ* conservation areas and reserves. While seed stands clearly have *in situ* conservation value, several countries note

**FIGURE 12.1**
Number of species and subspecies conserved *in situ* and *ex situ*, by region



Note: Numbers for Europe are deceptively high because the region includes a number of territories in tropical regions.

that they are rarely selected by a formal *in situ* conservation programme designed to provide *in situ* FGR conservation outcomes. Their value as *in situ* conservation resources for priority species may be correspondingly limited. This again demonstrates the need for addressing the particular requirements of *in situ* FGR conservation and integrating them more widely into management practices for all categories of forested lands. However, for countries lacking the resources for identification and management of formal *in situ* conservation reserves, seed stands are vital components of their *in situ* conservation efforts.

## Protected areas

Protected areas provide significant *in situ* conservation in most countries. For the past 20 years, protected areas have mainly been created for biodiversity conservation to meet country obligations under the CBD (UN, 1992), which states: "…the fundamental requirement for the conservation of biological diversity is the *in situ* conservation of ecosystems and natural habitats and the maintenance and recovery of viable populations of species in their natural surroundings". The contribution of the CBD to the conservation of forest genetic resources is inestimable.s

Brazil, with 286 million hectares of permanent, public forest estate, reports that protected areas play a central part in *in situ* conservation. In Canada 9.8 percent of the land area is protected. China reports that 149 million hectares or 15 percent of the country is managed as some form of nature reserve providing *in situ* conservation of FGR. Seychelles notes that 48 percent of its land is protected area.

To assess the contribution of protected areas to *in situ* FGR conservation, countries were asked whether they had evaluated the genetic conservation of tree species within their protected areas. A standard response was to list the number of species and threatened species and to detail any specific programmes for priority species. In general, little information is available on the actual FGR benefits of protected areas in relation to populations, genecological zones represented and intraspecific diversity conserved. This is indicative of the immense difficulty of obtaining the detailed information required to evaluate the effectiveness of *in situ* FGR conservation when a country has many hundreds or even thousands of tree species distributed over vast areas.

Solomon Islands, with 80 percent forest cover amounting to 2.24 million hectares, has a tiny fraction of forest (0.017 percent) under formal protection in two locations. The country report notes that the lack of protected areas is of concern given that logging is occurring at four times the sustainable rate with serious impacts on FGR:

> "The latest update on logging concession areas provides evidence of forest cover loss on logged-over areas which [is] also associated with significant loss of natural and ecological value…. Some endemic forest species that are unable to adapt to new environments face possible extinction…. While most agree that the creation of a conservation estate would be in the national interest there is no functioning institutional framework for its advocacy, creation or management. Even if such a framework existed then there would be problems in funding it. For these reasons none of the conservation areas identified… have been reserved and in fact many have already been logged."

The country report from Brazil expresses the value of the protected area approach to conservation of FGR as follows:

> "*In situ* conservation of genetic resources is the most effective strategy, especially when the main goal is the conservation of entire communities of tree species, as in the Brazilian tropical forests. In these cases, trees of other species than the target ones must be included in the genetic conservation scheme, as well as their pollinators, seed dispersers and predators… The conservation of forest genetic resources in Brazil involves a large-scale *in situ* scheme, and for that purpose a national-scale strategy had to be implemented. [This involved] the creation of a significant amount of conservation units, as well spread over the national territory as possible, synchronized with a national strategy for biological diversity."

Similarly, India notes that "when the whole habitat or ecosystems are protected, whole plant genetic resources also enjoy the protection."

*In situ* conservation of FGR in forests under some form of protection involves diverse designations and categories associated with widely differing regulatory regimes. The wide range of protected area designations providing FGR conservation value includes dedicated FGR conservation reserves, protected areas, nature reserves, protection forests, national parks, game management areas, bird sanctuaries, Ramsar Sites, scenic parks, ecoparks, forest reserves, watersheds, mangrove forests and United Nations Educational, Scientific and Cultural Organization (UNESCO) Biosphere Reserves. International Union for Conservation of Nature (IUCN) protected area categories are useful in standardizing country reserve categories, and some countries adapt their designations to allow comparison with IUCN categories. Although the designations vary significantly among countries, systems tend to be shared in regions with historical and political affinities. Brazil lists 12 categories of protected area providing *in situ* conservation benefits. Canada notes that it has "numerous categories of protected areas established by multiple organizations at the federal and jurisdictional levels and through non-governmental organizations that either directly or indirectly have the intent to conserve tree species *in situ*."

Regulations governing permitted activities and guiding management vary widely and differ in the extent to which they are compatible with and/or facilitate *in situ* conservation of FGR. Thailand notes that its forest reserves provide *in situ* conservation benefits for FGR, but the laws and regulations governing them are less strict than those of protected areas. In addition, in many countries large areas have been legally designated as protected areas but the legislation has little or no enforcement. This situation often coincides with outdated inventory of tree species and populations (or no inventory at all). In such situations a tally of the extent of protected areas does not provide much useful information regarding the species currently found within the protected areas or the effectiveness of the *in situ* conservation of FGR.

In many countries the multiplicity of designations and regulations presents a significant challenge for harmonization and coordination of *in situ* conservation objectives and requirements. Closer integration of the requirements for *in situ* FGR conservation with those for biodiversity conservation and with those of other reserve and public land categories, including productive designations, could achieve significant synergies.

An important point regarding the protected area approach for *in situ* conservation of FGR is that although countries named a wide range of protected areas, reserves and land categories as their primary *in situ* conservation initiatives, most of these areas were not designated or selected for the conservation of priority FGR and did not have management plans specific to their particular needs. While landscape-scale biodiversity conservation as currently practised fulfils many requirements of *in situ* conservation of FGR, failure to consider the particular needs of formal *in situ* FGR conservation protocols will inevitably result in losses of genetic variability, especially for those species that depend most on ecological disturbance. Canada's country report points out that although programmes for the protection and management of threatened species also provide *in situ* FGR conservation, they do not necessarily address "silent" extinctions which are "associated with loss of genetically distinct populations, or loss of locally adapted gene complexes, [which] are not considered in [threatened species] legislation, yet may have devastating consequences for tree species faced with increasing environmental change". It is therefore important to integrate requirements for *in situ* conservation of FGR into the full range of a country's biodiversity conservation initiatives, to maximize outcomes for both.

## *In situ* conservation outside protected areas

Most *in situ* conservation of FGR takes place outside protected areas on a range of public, private and traditionally owned lands, especially in multiple-use forests and forests primarily designated for wood production.

Forests on public land used for production of timber or other forest products may provide major *in situ* conservation benefits, depending on the intensity of use and the management approach: Forests under sustainable management regimes that take full account of FGR management principles and practices will help conserve FGR, while forests that are heavily exploited and/or subject to uncontrolled extraction will not. Sustainably managed natural production and multiple-use forests are central to the *in situ* FGR conservation efforts of a number of countries, especially where native tree species are also major commercial timbers.

Private and communally owned and managed forest land may also provide important *in situ* conservation of FGR, especially where important FGR occur outside of protected areas. For example, Brazil's landscape-scale *in situ* programme is guided by the identification of Priority Areas, and many of these fall outside the public estate. In some biomes, such as Mata Atlantica, Pantanal and Pampa, almost all the Priority Areas and almost all the important genetic resources occur on private land. In these cases conservation of FGR relies on the actions of private landholders.

The conservation regulations applied to private and customary lands vary. In Zimbabwe, for example, different categories of private and communal landownership are subject to different laws and levels of control. Government regulation ranges from strong to practically non-existent both within and among countries.

Achieving *in situ* FGR conservation on private and customary land can be problematic, as it may be difficult to secure long-term or permanent conservation tenure over the land and to achieve an adequate level of FGR conservation management. Securing *in situ* conservation of FGR in these contexts may involve a combination of regulations, sustainable forest management, education, provision of income and employment opportunities from sustainable forest-based industries, and incentives to reward landholders for stewardship of FGR. *Ex situ* conservation will often be required in cases where FGR assets are outside publicly protected and managed areas.

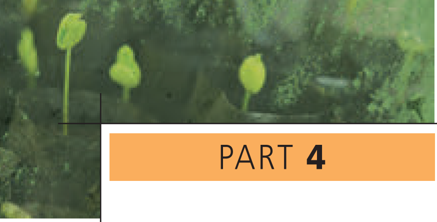
## On private land

Large areas of private forest land are held under strict conservation tenure and management regimes; examples include land under conservation covenants held by NGOs such as the Nature Conservancy; land managed according to sustainable forest management principles or dedicated as reserves; and other private land subject to conservation management or vegetation retention regulations.

The following example from Sweden, where over 75 percent of productive forest is privately owned, demonstrates the potential of private ownership for achieving *in situ* FGR conservation outcomes:

> "Sveaskog, the largest forest company in Sweden, owns 3.3 million hectares of productive forest land, which is 14 percent of Sweden's total productive forest land. Sveaskog´s nature conservation strategy includes the ambition to focus on conservation on 20 percent of the company´s productive forest land; 650 000 ha are assigned to nature conservation using production forests, nature conservation forests and ecoparks."

The use of legislation and regulation to control land use and activities leading to losses of FGR have been noted above. However, while legislation and regulation are important, they are limited in their effectiveness, particularly in the private estate. Many countries note that regulation has failed to control activities leading to forest clearance. Under the Brazilian Forest Code, forest in the private estate, if located along rivers or on hills or slopes, must be preserved as permanent protection areas; in addition, minimum percentages must be maintained under native vegetation (as legal reserves) depending on the biome: 80 percent of rural properties in forest areas in the Legal Amazon; 35 percent of rural properties in savannah areas in the Legal Amazon; 20 percent of rural properties in forest or under other vegetation in other regions; and 20 percent in native grasslands in any region. Legal reserves may be harvested for timber and other products under sustainable forest management plans. Permanent protection areas and legal reserves cover 12 and 30 percent of Brazil, respectively – twice the area of designated protected areas on public land. However, 42 percent of the permanent protection areas



and 16.5 percent of the legal reserves have been subject to illegal deforestation, as have 3 percent of protected areas and indigenous lands, and the extent to which the sustainable forest management plans are adhered to is unknown.

To counteract illegal clearance of FGR on private land and encourage protection and active conservation management of FGR, some countries (e.g. Brazil, Finland and Sweden) offer incentives and stewardship payments. In the United States of America, where 57 percent of forests are under private ownership (with regional variation), 37 million hectares in the private estate are protected through voluntary conservation covenants entered into by individuals, land trusts and NGOs; these arrangements significantly supplement the public reserve system. Such voluntary private land conservation initiatives are oriented towards the protection of areas, taxa (species, varieties) and ecological processes. Their contribution to *in situ* conservation of FGR would be substantially enhanced if FGR conservation and management objectives were incorporated in reserve selection criteria and subsequent management.

### On community or customary lands

Indigenous or traditional ownership, use rights and management may have a significant role in conservation and management of *in situ* FGR in many countries. For example in Canada, aboriginal people own or control around 3 million hectares of forested land and play a major part in the management of FGR; other countries where indigenous peoples feature importantly in ownership, use and management of FGR include India and Brazil. Customary tenure dominates landownership profiles in many countries in Oceania and parts of Africa. In Zambia, for example, 46 million hectares (61 percent of the country's area) are under traditional ownership.

Solomon Islands reports the difficulties of FGR conservation on customary lands:

> "In the Solomons any moves to limit a landowning group's ability to dispose of its forests as they see fit would be regarded by them as interfering with their rights of private ownership. The Land and Titles Act and other statutes, including the proposed new Forests Act, have mechanisms that provide for the State to impose limits on the use of private land; however where this is in the national interest the understanding is that the owners will be compensated for any rights foregone. In the current economic conditions the State is in no position to make such compensation."

Where lands under indigenous or customary ownership and/or management are managed under sustainable forest management principles, e.g. as protected areas or under customary regimes consistent with FGR conservation, they can provide significant *in situ* conservation benefits. In Vanuatu, all forests are under customary ownership, with benefits flowing from the direct involvement of landowners in forest use and reforestation. Shortcomings, however, include the convoluted arrangements required for approving government management plans and disruptions from landownership disputes.

## Formal *in situ* FGR conservation programmes

In well protected areas with effective habitat conservation enforcement there may be a need for management actions to maintain genetic resources that are not allowed by protected area legislation. In such cases conservation of genetic resources of tree species must be an explicit objective of conservation areas.

The first step in preparing an *in situ* conservation programme is to specify and clearly define the conservation objectives to be achieved. Breeding programmes aimed at improving a species' commercial or environmental value may seek to conserve adaptive, productive and quality traits (e.g. growth rate or form, pest and disease resistance and adaptation to climatic extremes) in populations or stands identified for conservation. Programmes designed to maintain genetic variability for biodiversity conservation purposes (e.g. threatened species management) or general conservation of FGR will seek to preserve the widest range of variation possible with the available resources. Many countries stress the importance of maintaining the widest genetic base possible through *in situ* and dynamic conservation measures to facilitate adaptation to climate change for all forestry and tree planting programmes, whatever their objectives.

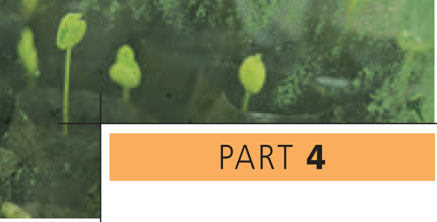
In contrast to the multispecies landscape-scale protected area approach to *in situ* conservation, dedicated programmes for *in situ* conservation of the genetic diversity of priority trees require specific provisions. Finland, for example, notes that "valuable genetic resources exist also in strict nature conservation areas, but these areas are not considered to be part of the gene conservation programme" because of differences in management approach.

A dedicated programme for FGR conservation of a priority species may specify the proportion of variability to be preserved, the number of trees to be protected, the area required for conservation, and which populations need to be represented. The most variability can generally be preserved by maintaining a selection of genetically representative populations, although some loss of low-frequency or rare alleles may occur (as reported by the United States of America). To maintain rare alleles it is necessary to conserve additional populations and/or many more trees over a wider area, and the additional expense may be difficult to justify. Measures to protect the population's variability and viability by managing threats and ensuring regeneration of the stand must also be specified (e.g. disturbance regimes such as fire management).

Knowledge required for a scientifically sound FGR conservation programme for a particular species includes the targeted species' pattern of genetic variability, including variability within and between populations across the species' range; its distribution; its ecological and regenerative requirements; its physiological tolerances; its genecological zones; its reproductive biology; and associated pollinators, dispersers and symbionts. The Thailand report states that "genetic resources must be selected mainly based on the available knowledge of spatial patterns of genetic variation…. The combination of marker-aided population genetic analysis and information about adaptive and quantitative traits as well as forest ecosystems would allow comprehensive conservation programmes for individual species in each forest type". While some countries have sufficiently detailed information to guide *in situ* conservation planning for priority species, concern is widely expressed about the lack of genetic or other pertinent information for most species, with some countries having little information on which to base *in situ* conservation programmes. Even well-off countries note the impracticality of surveying all populations of all tree species; for poorer countries with high levels of tree diversity distributed over wide areas the task is impossible with current technologies.

Ideally, priority species must first be thoroughly investigated for genetic and ecological diversity; then genecological zones need to be identified and delineated, with conserved populations selected to represent the full suite of genecological zones across the entire range, resources permitting. Thailand's conservation of *Pinus merkusii*, for example, includes all eight identified genecological zones; similarly, the country's *in situ* conservation programme for teak covers all five genecological zones identified in 15 locations on the basis of topography, climate and vegetation. China describes a similar process for designing *in situ* FGR conservation for priority species: "The number of populations or stands of target species, the size of area and effective number of trees for *in situ* conservation were determined according to the result of genetic diversity analysis, combined with data obtained from field surveys."

Where detailed knowledge is lacking, general guidelines based on established principles may be used to design *in situ* conservation programmes (e.g. FAO 1993; FAO, DFSC and IPGRI, 2001).



Parameters that may be considered in the preparation of such guidelines include:

- breeding system – e.g. obligate outcrossing versus self-fertility; vegetative propagation; animal vector versus wind pollination (with the latter assumed to have a more even distribution of alleles);
- range – localized or widespread, disjunct or continuous (level of fragmentation), edge of range;
- isolating factors – greater or less breeding isolation between populations;
- environment – homogeneous versus heterogeneous environmental factors (e.g. geology, soils, aspect, moisture, climate);
- population size – small in number and limited in area versus numerous and extensive;
- level of natural variability occurring within the species and its populations – high or low diversity within and among populations;
- patterns of distribution – e.g. clustered versus dispersed, continuous versus disjunct.

Guidelines for establishing *in situ* conservation reserves for particular species have been prepared in some countries and regions. For example, China has developed technical standards and codes for *in situ* conservation sites; these address selection of species, number of populations, area, number of trees and management requirements.

The European Information System on Forest Genetic Resources (EUFGIS) provides information for use in defining the minimum number of individuals required for *in situ* conservation of a species in European countries. Regional guidelines are particularly useful for shared species and environmental conditions, and where conservation and management priorities are similar. The use of the EUFGIS guidelines is demonstrated by the following description of minimum *in situ* conservation programme requirements from Sweden's country report:

> "Five hundred trees per gene conservation unit are sufficient for species with large and continuous populations which are extensively used in forestry. These species are subjected to extensive forest tree breeding and import of forest reproductive material. In Sweden, *Pinus sylvestris, Picea abies* and perhaps also *Betula pendula* and *Betula pubescens* belong to this category.
>
> "Fifty trees per gene conservation unit are sufficient for species with populations of varying size and structures and with no or limited use in forestry. In Sweden, several tree species such as *Acer platanoides, … Fagus sylvatica, Fraxinus excelsior, Populus tremula, … Quercus robur, Salix caprea* … and *Ulmus glabra* likely belong to this category.
>
> "Fifteen trees per gene conservation unit are sufficient for species with (very) small and isolated populations, which may be situated at the edge of the species geographic distribution area. These species may be red-listed or their populations may have recently decreased owing to forest damage. In Sweden, for instance, *Acer campestre, Carpinus betulus, Juniperus communis, Prunus avium* and *Ulmus minor* belong to this category of tree species."

Also in Europe, EUFORGEN (www.euforgen.org) has developed technical guidelines for FGR conservation and use for 36 tree species and species groups. EUFORGEN has facilitated the development of gene conservation reserves in many countries. EUFORGEN's standards for effective *in situ* conservation include periodic monitoring of the FGR contained within the reserves. The information collected through monitoring will be extremely useful for understanding factors that influence the effectiveness of conservation.

Finland also lists some general rules:

> "A basic requirement for a gene reserve forest is that it is of local origin and has been either naturally regenerated or regenerated artificially with the original

> local seed source. The general objective is that a gene reserve forest of a wind-pollinated species should cover an area of at least 100 ha, in order to secure sufficient pollination within the stand, but smaller units have been approved in particular for birch species. The *in situ* units for rare broadleaves are much smaller as a rule."

The Thailand report offers these guidelines for outcrossing species: "After the genetic variation within and among populations of any species has been investigated, the most variable populations with relatively high outcrossing rates (for outcrossing species) should be chosen as the sources for gene conservation."

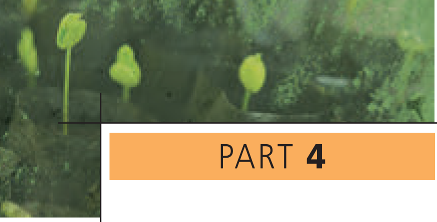
Although general principles can be used to design *in situ* conservation programmes, guidelines are best prepared with reference to the species and conditions existing in the particular country or region. Guidelines may already exist, or at least a high level of information may be available, for well studied genera and species. Regional associations or networks focused on particular taxa may provide opportunities to update and/or prepare guidelines. To facilitate *in situ* conservation, the preparation of guidelines should be considered for countries, regions, genera and species that lack them; the work of EUFGIS and EUFORGEN provides a useful model for other regions.

Dedicated FGR conservation programmes for priority species, whether based on detailed species knowledge or guidelines, generally seek the most efficient design to conserve the optimal amount of genetic variability, for example through identifying the number and location of populations, the number of individuals and the area required to conserve the most genetic variation in the target species. The guidelines of FAO, DFSC and IPGRI (2001) suggest, for example, that between 150 and 500 interbreeding individuals are required for each population to be conserved *in situ*.

To establish, manage and monitor *in situ* conservation units at the fine scale necessary is resource intensive and expensive. Accordingly, *in situ* conservation programmes strive to conserve the minimum number of individuals and populations and the smallest possible area consistent with the conservation outcomes sought. Thailand's *in situ* conservation of *Pinus merkusii* includes two reserves of 100 and 960 ha; Denmark conserves 56 species on 2 880 ha of genetic conservation reserves; and the average size of *in situ* conservation units in Bulgaria is 6.3 to 6.8 ha for conifers and hardwoods. While these reserves meet the genetic requirements for *in situ* conservation, it must be noted that reserves of limited size and individuals will rarely if ever be adequate alone to conserve the full range of ecological and evolutionary processes needed for the long-term viability of the population. To remain viable, conserved populations need to be embedded in a healthy landscape matrix that includes the pollinators, seed dispersers, microbial associations, and myriad of other organisms and processes that comprise a viable ecosystem. The matrix and its ecological processes must be properly managed together with the designated *in situ* conservation units.

Consistent with this approach, target conservation populations of priority species are almost always located in existing designated protected areas, forest reserves or production forests. These areas may be subject to further specialized conservation and management measures such as monitoring, stricter control of use or access or stimulation of regeneration. Therefore a landscape-scale approach to conservation of FGR that addresses ecological processes must be implemented together with management of smaller, well sited and dedicated reserves for priority tree species.

The provision of biological corridors to facilitate gene flow may help reduce risks of inbreeding and genetic drift in situations where *in situ* conservation units are functionally and reproductively isolated. Examples include the Greater Mekong Subregion Core Environment



Programme and Biodiversity Conservation Corridors Initiative and plans to link fragmented landscapes in Australia and Sri Lanka. In situations where FGR *in situ* conservation value is extremely high and the conservation of reproductively isolated, small populations is considered essential, then population viability analysis is needed to assess the feasibility of such conservation and to inform management options for it.

### Selecting areas for *in situ* FGR conservation

Countries use a variety of approaches to identify and prioritize areas for *in situ* FGR conservation. The importance of the landscape-scale, protected-area approach to *in situ* FGR conservation has been noted above; areas may be selected as a means of preserving the entire range of species contained within them (including trees) as well as ecological processes and many other functions. Conserving large areas of forest in reserves serves well in the absence of detailed genetic information on priority species. Criteria for selecting areas may include high levels of tree species diversity; the presence of tree species with a high level of endemism or threatened status; a high threat level for the particular forest association/vegetation community; the ability to support ecological processes; and the viability of populations and processes.

Brazil reports that since its FGR conservation involves a large-scale *in situ* scheme (as described above), "a national-scale strategy had to be implemented". An extensive country-wide survey identified 3 190 priority areas for biodiversity conservation and sustainable use, using the criteria of representativeness, environmental persistence and vulnerability.

Ethiopia has defined 58 National Priority Forest Areas and five classes of vegetation containing priority species; in conjunction with other protected areas, these are the basis for the *in situ* conservation programme, which covers about 14 percent of the country's area. Ethiopia's Forest Genetic Resources Conservation Strategy sets general criteria for establishment of *in situ* conservation sites, including:

- the number of priority species in the forest;
- the presence of unique, endangered and endemic species within the population;
- the accessibility of the forest;
- the degree or threat of forest disturbance;
- the species richness of the site or population;
- the attitude of the local people or community towards conservation.

The Republic of Korea has a vast system of 432 FGR reserves covering a total area of 126 868 ha. These are areas warranting special conservation measures. They are classified in seven categories: primeval forest, rare plant natural habitat, rare forest type, useful plant original habitat, alpine plant area, wetland forest and valley stream, and natural ecosystem conservation.

Zimbabwe uses the level of threat to the genetic diversity of economic species as a criterion for establishing "strict natural reserves", which are areas containing "commercially harvestable indigenous hardwoods whose genetic integrity could potentially be altered by overexploitation".

To identify areas where genetic diversity may be eroding most seriously, the United States of America assesses range contractions among forest species as a surrogate for genetic loss. The northeastern region (from the mid-Atlantic to New England) shows the greatest loss of forest-associated vascular plants. Sweden also notes the importance of range criteria for conservation, especially with respect to adaptation to climate change in situations where there is clinal variation along a climate gradient, e.g. latitude, altitude, aspect and rainfall. Gap studies and analyses are used to identify FGR that are not adequately conserved through existing measures, to identify vulnerabilities and to guide conservation and management decision-making.

The distribution of natural forests serving as repositories of FGR may vary significantly across a country. The most extensive forest clearing has occurred in areas of longest settlement, highest population density and highest agricultural productivity, such as Brazil's Atlantic Forest biome. In Thailand, as well, much of the teak resources have been lost to agriculture. The high rates of clearing in agricultural areas result in the loss of species and the associated variability adapted to these highly productive areas, suggesting that a high priority should be placed on the conservation of any remnant FGR remaining in sites of high productivity and fertility. While highly degraded, overexploited forests in rural areas may provide opportunities for replacement with more productive planted forests (as pointed out by Ghana), it is important to consider the current and future value of the forests as potential sources of genetic variability for conservation, and not to overlook the development of improved varieties for use and planting in these areas.

## Priority species for *in situ* conservation

While the process of prioritizing species for *in situ* conservation is consistent with prioritization of species for conservation and management of FGR in general (discussed in Chapter 10), several particulars are worth noting.

Many countries list priority species for *in situ* conservation in their reports; they add up to 743 species globally. The main reasons for this prioritization are shown in Figure 12.2, although species are sometimes prioritized for *in situ* conservation for several reasons simultaneously. For example, *Dalbergia cochinchinensis* is prioritized in Thailand for both its commercial value and its threat status.

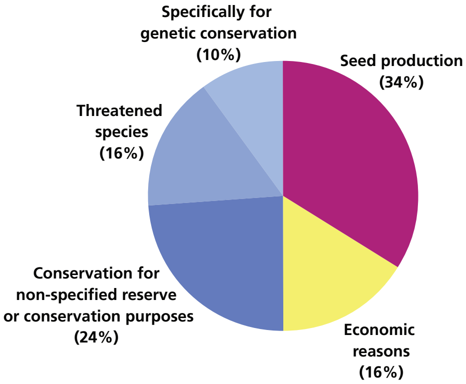
It is interesting to note the discrepancy between the relatively small number of tree species nominated for *in situ* conservation and the protected-area approach that many countries report as their primary means of conserving FGR *in situ*. The number of species and populations maintained in protected areas and other forested lands far outweighs those in dedicated *in situ* conservation programmes for priority species. This is likely to be due to:

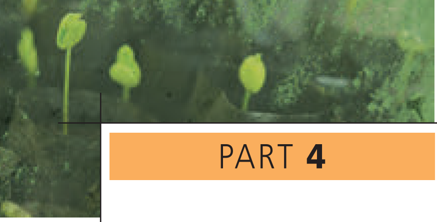
- the high cost and difficulties of undertaking the research, planning, implementation and management of dedicated *in situ* conservation programmes for priority species;
- the lack of information available for priority species on which to base dedicated *in situ* conservation programmes;
- the efficiency of the protected area approach (which is the only option for countries lacking the resources for dedicated *in situ* FGR programmes) in conserving the FGR of a wide range of species and ecological processes simultaneously.

As an example, Sweden states it "has hitherto very few *in situ* genetic resources for the approximately 30 native forest trees to enter into the EUFGIS Portal. Obviously, there is a clear need to improve the *in situ* conservation of forest genetic resources in Sweden." On the other hand, Sweden has 4.7 million hectares in nature reserves

**FIGURE 12.2**

Reasons cited by countries for conserving species *in situ*





and national parks which provide at least some level of *in situ* FGR conservation.

Only 16 percent of priority species for *in situ* conservation were nominated for economic reasons, contrasting with 46 percent of priority species for FGR conservation and management in general (see Chapter 10). This difference can be attributed to the fact that 85 percent of the species reported as used in plantation forestry globally are exotic species and are therefore ineligible for *in situ* conservation in the countries where they are widely planted as exotics. These globally important, exotic industrial plantation forestry species are usually well documented and conserved through *in situ* FGR programmes in their countries of origin (as well as in *ex situ* FGR conservation programmes around the world). In this regard countries widely acknowledge the leadership and coordination by FAO since the 1960s, coupled with the work of internationally active agencies and programmes such as the DANIDA Forest Seed Centre (DFSC), CIRAD-Forêt (the forest arm of the French Agricultural Research Centre for International Development) and its predecessors, CSIRO's Australian Tree Seed Centre, Camcore (a non-profit, international tree breeding organization established by North Carolina State University, United States of America) and donor programmes of Australia, Canada, the United States of America and several European countries.

Naturally, in countries where commercial species are indigenous they have been nominated for *in situ* FGR conservation; for example, in Thailand both *Tectona grandis* and *Dalbergia cochinchinensis* are the subject of *in situ* FGR conservation programmes to ensure that high-quality genetic material is available for improvement. In Germany, important commercial species account for 70 percent of designated *in situ* conservation stands (*Fagus sylvatica*, 37 percent; *Quercus robur* and *Quercus petraea*, 15 percent; *Picea abies*, 11 percent; and *Pinus sylvestris*, 7 percent); 29 other tree species account for 22 percent of *in situ* conservation stands, with shrubs accounting for the remaining 8 percent.

In several reports it is apparent that indigenous tree flora have been poorly investigated for their economic and productive potential; the United Republic of Tanzania, for example, notes: "the [indigenous] gene pool has more to offer…". This lack of research is partly being rectified by ICRAF and its national partners and by others such as the Australia-funded South Pacific Regional Initiative on Forest Genetic Resources (SPRIG) project. From 1996 to 2005, SPRIG assisted several countries in Oceania in research, conservation and development of their indigenous species; this effort has resulted in much greater planting of native species such as *Santalum* species in Fiji and Vanuatu, *Endospermum medullosum* in Vanuatu and *Terminalia richii* in Samoa.

While 50 percent of the responses cite conservation as the reason for nominating priority species for *in situ* FGR conservation, only 10 percent specifically mention gene conservation, while 16 percent cite conservation of threatened species. It appears that some countries correlate threatened species conservation with *in situ* FGR conservation, whereas one seldom implies the other. Improved understanding and promotion of the methodology for formal *in situ* FGR conservation is required to increase its application.

Seed production purposes account for 34 percent of priority species nominations for *in situ* conservation. However, as noted above, selection criteria for *in situ* seed production stands may differ from those used for *in situ* conservation of FGR; for example, ease of access may influence seed-stand selection but is not generally a consideration in formal *in situ* FGR conservation programmes; and the conservation of populations growing in marginal and extreme environments and/or uncommon alleles may be considerations for *in situ* FGR conservation of a species but are less important for seed stands providing germplasm for commercial forestry.

A further point is that priority species nominations only reflect existing knowledge of economic value and threatened status; where the potential economic value or the threat status is unknown, species are neither nominated nor dealt with as priorities. Landscape-scale approaches such as protected areas and sustainable management of multiple-use forests, on the other hand, provide the benefit of maintaining a large number of species and populations regardless of the level of knowledge, and for this reason are more appropriate where species information is scant or lacking.

Nevertheless, it is essential to prioritize species for *in situ* conservation, because the ecosystem conservation approach alone is unlikely to fulfil the particular requirements of dedicated *in situ* FGR conservation programmes. Both coarse-grain, landscape scale and fine-grain, species-specific *in situ* FGR programme approaches are required and must be treated as complementary.

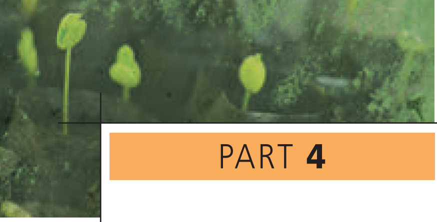
Some country reports describe the criteria used to set species priorities for *in situ* conservation of FGR. In China, "priority species for *in situ* conservation are determined by the existing quantity of the species, the socio-economic value and the depletion of FGR", while Thailand's three priorities are: "species with socio-economic importance, both commercial importance and importance for maintaining ecosystem functions and services; species with higher levels of genetic diversity; and species with populations at risk or under threat from any cause, e.g. critically endangered, endangered or vulnerable species".

## Management of *in situ* FGR conservation areas

*In situ* conservation of FGR involves more than legislating for a protected area. Populations conserved *in situ* constitute part of an ecosystem, which must be managed to maintain both intra- and interspecific diversity at appropriate levels over time. Country reports, particularly from developing countries, note serious losses of FGR resulting from inadequate management, lack of oversight and failure to enforce regulations in protected areas, conservation reserves and dedicated FGR *in situ* conservation stands; these areas accordingly suffer from illegal logging and harvesting, mining, clearing, poaching, growth of invasive species and damage from unmanaged wildlife, uncontrolled wildfire and pests and diseases, often amplified through interactions with climate change. The negative impacts sometimes occur in the last remaining natural stands of high-value timber species (e.g. *Tectona grandis* and *Dalbergia cochinchinensis* stands in Thailand) or threatened or otherwise significant species with extremely valuable genetic resources.

Countries all note the paramount importance of managing *in situ* FGR conservation sites to ensure the maintenance of the genetic resources, species and ecological processes contained therein. The Islamic Republic of Iran remarks the requirement for "management plans to monitor the changes in target populations over time and ensure their continued survival". Approaches identified and implemented by countries include improved and strengthened forest management; better legislation and regulation; more effective enforcement; preparation of management plans and guidelines; better funding; inventories including conservation trajectories of threatened species and vegetation communities; expertise; community education; incentives for improved management of FGR; and means of generating financial returns from sustainable management such as creation and management of wildlife parks, development of game-based tourism and sustainable harvest and marketing of forest products by local communities.

Canada notes the need for better understanding of the risks faced by individual species and of how to manage them – requiring research on species' vulnerability, sensitivity and adaptive capacity; on their habitat, physiology, phenology, and biotic interactions; on their exposure to and ability to respond to threats such as climate change, for example by adapting in place or migrating; and on at-risk ecosystems.



Several countries note the importance of maintaining genetic fitness and regeneration of conserved stands. Sri Lanka notes that for outbreeding species, large areas of contiguous forest are required to avoid loss of diversity through genetic drift and inbreeding. Sri Lanka also notes the value of re-establishing "gene corridors" to reduce the risks to fragmented, isolated populations, and proposes conversion or enrichment of monoculture plantations surrounding isolated natural forest patches using mixed indigenous species with appropriate levels of variability.

Many countries identify well considered and comprehensive management plans for *in situ* FGR conservation areas as essential. Thailand, for example, reports that after selection of natural stands in different zones, "conservation measures and management options were proposed specifically for each zone based on the available information on its population size, legal protection, social aspects, commercial interest, and management costs". Thailand notes that for teak, a "conservation plan comprising a number of activities [has] been recommended: field survey and selection of the populations; demarcation and protection; monitoring; and management guidelines". Thailand also observes the need to ensure that regeneration occurs in the conserved stands: "Silvicultural practices and management are essential to promote the natural regeneration of the existing conservation areas." It may be necessary to research the particular regeneration requirements of threatened species.

This subject is addressed in more detail in the section on sustainable forest management, below.

## Forest restoration and FGR

Many significant FGR assets, including threatened, high-value timber and NWFP species and forests with high genetic diversity, have been seriously degraded through failure to regulate extraction and prevent overharvesting. These areas must be brought under management and rehabilitated at the earliest opportunity to prevent further decline and to improve their condition, viability and economic utility. This view is consistent with CBD Article 8(f) (UN, 1992) which refers to the need to "rehabilitate and restore degraded ecosystems and promote the recovery of threatened species… through the development and implementation of plans or other management strategies". Reafforestation and restoration initiatives are needed especially urgently in low forest cover countries (i.e. those with less than 10 percent forest cover). As recognized by China, knowledge of species requirements and *in situ* restoration techniques for endangered populations is essential. In the Islamic Republic of Iran, degraded forests are restored through plantation of native pioneer species; "the main objective of rehabilitation is to achieve ecosystem sustainability in forest area and increased biological diversity". Ghana undertakes restoration of degraded "convalescent forests" by ceasing exploitation and undertaking management.

In northeastern Thailand, a framework species selection approach was adopted to identify a small number of local tree species for revegetation from more than 350 local tree species, so as to most efficiently restore forest cover and catalyse return of biodiversity and regeneration of hundreds of other tree species (Elliott *et al.*, 2003).

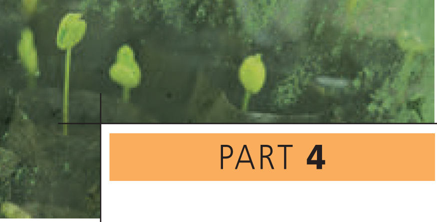
Enrichment planting, whereby threatened tree species are propagated from local germplasm and reintroduced into areas in which they have become depleted, is an important element of *in situ* conservation consistent with Article 8(f) of the CBD. Reintroduction into the wild subjects the species to natural selection, allowing the continuation of evolutionary processes. It is vital to ensure that an appropriately high level of genetic diversity is represented in enrichment plantings. Zimbabwe notes that some species believed to be extinct in the wild are conserved in *ex situ* and *circa situm* contexts (e.g. home gardens) and could potentially be reintroduced back into natural settings. Ghana uses artificially propagated stock to enrich forests that have been depleted by overexploitation and lack adequate natural regeneration. Denmark has re-established the previously locally extinct *Pinus sylvestris* to its former range in the country, using germplasm from adjacent countries. These examples demonstrate the value of adopting multiple, integrated and complementary approaches to FGR conservation, successfully combining *in situ*, *ex situ* and *circa situm* conservation and site management.

Enrichment and reintroduction plantings require a supply of plant materials, and for some species with particular reproductive requirements, including a number of threatened species, propagation may be difficult. China notes the importance of developing propagation techniques for threatened species, especially those that are resistant to standard techniques, for *in situ* enrichment plantings as well as for *ex situ* and *circa situm* conservation; research may be required to identify the best and most efficient propagation techniques for less well known species. Ethiopia notes a need to promote tissue culture for mass propagation, which may assist *in situ* enrichment plantings.

## Opportunities from climate change initiatives: restoration and connectivity for *in situ* FGR

Several countries note opportunities for simultaneous conservation of FGR, reduction of carbon emissions and income generation through REDD+ (reducing emissions from deforestation and forest degradation in developing countries, including the role of conservation, sustainable management of forests and enhancement of forest carbon stocks). A number of country reports refer to programmes for planting and regenerating trees over extensive areas as a means of sequestering atmospheric carbon and mitigating climate change. With thoughtful planning, these programmes may also offer significant opportunities to improve the viability of fragmented landscapes suffering reproductive isolation and genetic erosion, and to restore local vegetation to its former range. The following are some programmes cited in the country reports.

- India’s National Mission for a Green India, under the National Action Plan on Climate Change, aims “to double India’s afforested areas by 2020, adding an additional 10 million hectares”. India’s Sustainable Landscapes programme is another example.
- Indonesia notes, “40 REDD+ pilot or demonstration projects across Indonesia [are] being implemented for ecosystem restoration concessions for carbon sequestration and emission reduction… [and a] massive campaign programme to plant 1 billion trees nationwide annually [has been] launched for greening Indonesia”.
- In Australia, federal and state governments and NGOs (e.g. Bush Heritage Australia, Greening Australia and Landcare Australia) are supporting multipurpose, biodiverse and carbon-sequestration planting programmes that also restore and promote ecological and evolutionary processes by reconnecting fragmented landscapes. With appropriate selection of species and planting materials, these programmes could provide significant FGR conservation benefits, for example by using locally sourced planting stock and incorporating depleted or threatened species or genetic variability.
- In the Niger, a programme for farmer-managed natural regeneration has restored over 5 million hectares of barren land into productive agroforests through protection of tree coppice and seedling regrowth, simultaneously sequestering vast amounts of carbon and restoring degraded FGR assets and farm productivity and resilience (Tougiani, Guero and Rinaudo, 2009). This programme has also given farmers the confidence to protect trees, and it respects



the integrity and value of trees as the property of the landowner.

Where these plantings involve reintroduction of trees grown from local, genecologically appropriate genetic sources back into their former range, they are referred to as "*inter situ*" plantings, meaning that germplasm is collected and re-established in field trials or planted forests located within the same geographical area, which allows it to continue to undergo natural selection under prevailing climatic conditions. There plantings have particular benefits when they extend into or connect with existing natural vegetation, reducing fragmentation, increasing gene flow, supporting ecological processes and increasing the viability of remnant forest patches or isolated FGR assets. At the same time, these plantings may be used to provide a range of timber and NWFPs and may offer employment to rural and traditional communities, especially where access to forests is reduced through conservation management.

## *In situ* conservation through sustainable forest management

As mentioned above, most *in situ* conservation of FGR takes place outside protected areas, especially in multiple-use forests and forests primarily designated for wood production. It is vital that these forests be managed through sustainable forest management (SFM) principles and practices. While almost all extant forests and trees provide some level of *in situ* conservation of FGR, these benefits may be quickly lost or diminished through forest destruction or degradation. Countries employ numerous SFM strategies, approaches, initiatives and programmes to ensure that adverse impacts on FGR are minimized while forest productivity and other uses and services are maintained if not enhanced. These include certification schemes for sustainable forest operations, identifying and protecting stands of high conservation value, promoting the use of indigenous species, ensuring that natural and artificially regenerated stands contain sufficient genetic variability and

### Box 12.1
### Community and participatory management

Reporting countries identify a suite of causes of deforestation related to the failure of conservation management to address indigenous or traditional ownership, knowledge and practices of forest use and management, including:

- uncontrolled access to protected areas and *in situ* FGR conservation sites by neighbouring rural communities seeking fuel, food, housing materials and other forest products;
- a decrease in the value placed on trees and sustainable forest management owing to the loss of traditional or indigenous knowledge about the uses of forest foods and plants and traditional management systems;
- a poverty-driven increase in use pressure, amplified by climate change and resulting in encroachment of agriculture and pastoralism on forest lands;
- conflict caused by loss of access to forests designated as protected areas, resulting in loss of informal control over illegal harvesting and uncontrolled and unsustainable use.

Community or participatory management – which involves harnessing traditional valuation and knowledge of the use of traditional forest trees – is increasingly used to address such causes of deforestation and genetic erosion. In Madagascar, for example, local communities are increasingly directly involved in management and use of natural forests through licensing and agreed management and harvesting plans.

promoting community participation in forest management, thereby maintaining traditional valuation, knowledge and management of forests (Box 12.1). Some SFM certification schemes also promote replacement of monocultures with mixed species plantations, although it should be noted that in certain situations this may reduce the conservation of FGR at the landscape level, as highly productive short-rotation monocultures can remove harvesting pressures from indigenous forests.

Secure *in situ* conservation of FGR requires security of appropriate tenure over the area, for example through gazettal as a protected area, conservation reserve or production forest permanently subject to FGR-appropriate SFM. It also requires continuing application of dynamic management regimes that address and maintain genetic diversity of the tree species. The importance of SFM is illustrated by the observation that forests subject to harvesting and use under SFM conserve FGR more effectively than protected areas that are poorly managed, uncontrolled or subject to threats such as illegal incursions, unsustainable harvesting, wildfire, grazing or invasive species.

Prior to the modern era and its unprecedented population growth, many forests under traditional and customary management were used sustainably. Forest management has been progressively developed and institutionalized over the past three centuries; it was described in German forestry texts as early as 1713 and introduced in central Europe in 1742. SFM is now widely recognized in many national policies and programmes and in international processes such as the CBD (e.g. Aichi Biodiversity Targets 5 and 7) and the Non-Legally Binding Instrument on All Types of Forests (NLBI) (UN, 2008) as a means of achieving conservation outcomes simultaneously with multiple productive uses. The requirement for the sustainable use of forests is enshrined in CBD Articles 8(c) (*in situ* conservation) and 10 (sustainable use of components of biological diversity) (UN, 1992).

### Box 12.2
### Global Objectives of the Non-Legally Binding Instrument on All Types of Forests

**Global Objective 1:** Reverse the loss of forest cover worldwide through sustainable forest management, including protection, restoration, afforestation and reforestation, and increase efforts to prevent forest degradation.

**Global Objective 2**: Enhance forest-based economic, social and environmental benefits, including by improving the livelihoods of forest-dependent people.

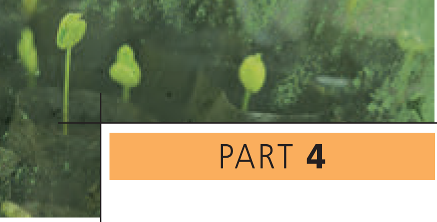
**Global Objective 3:** Increase significantly the area of protected forests worldwide and other areas of sustainably managed forests, as well as the proportion of forest products from sustainably managed forests.

**Global Objective 4**: Reverse the decline in official development assistance for sustainable forest management and mobilize significantly increased, new and additional financial resources from all sources for the implementation of sustainable forest management.

*Source*: UN, 2008.

As defined in the NLBI, "sustainable forest management, as a dynamic and evolving concept, aims to maintain and enhance the economic, social and environmental values of all types of forests, for the benefit of present and future generations" (UN, 2008). FGR conservation and management are crucial to the achievement of these aims and need to be explicitly recognized and steadfastly incorporated into SFM. The NLBI sets out general objectives for SFM (Box 12.2) which are also relevant to *in situ* FGR conservation.

SFM applies to all activities and uses of forests and trees, both extractive (e.g. harvesting of



## Box 12.3
## Addressing genetic resources in sustainable forest management plans

FGR conservation and management are primary components of SFM and must be incorporated in SFM plans. Information is required on the genetic resources and associated evolutionary processes and on how these are affected by use. Appropriate SFM approaches must then be selected to minimize negative impacts. An example might be to adopt a system for valuing FGR and to provide payments or other rewards for FGR stewardship or conservation.

Written plans provide objectives and benchmarks against which outcomes and performance can be measured, thus facilitating accountability. Plans are vital for monitoring, auditing, evaluation and improvement and provide a documented frame of reference for future adaptive management of FGR.

Some countries comment that lack of funding, organizational capacity, political support and/or jurisdiction over forests under customary or private tenure makes it difficult to implement FGR conservation and management through their SFM plans. Adequate finance is vital, whether allocated from government budgets or raised from forestry activities (e.g. licence or royalty payments). Capacity building for incorporation of FGR concerns in SFM programmes is essential but is often lacking in developing countries. Some countries (e.g. the Islamic Republic of Iran) report support to community participation in the preparation of SFM plans to facilitate sustainable outcomes.

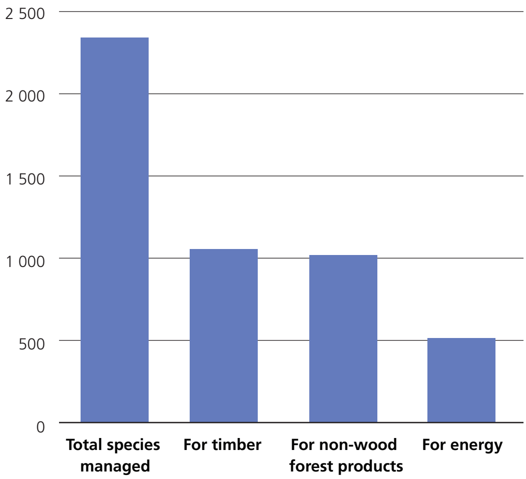
timber and NWFPs) and non-extractive (e.g. forest-based tourism). To achieve effective *in situ* conservation of FGR, SFM plans incorporating FGR goals and objectives need to be prepared and implemented for all forests subject to use (Box 12.3).

Production forestry remains a major focus of SFM (Figure 12.3). FRA 2010 reports that 39 percent of the world's forests are primarily used for production of wood and NWFPs; an additional 24 percent are designated for multiple uses that usually include the production of wood and/or NWFPs (FAO, 2010a). The proportion of natural forests subject to timber harvesting varies greatly among regions and countries. While a few countries ban harvesting in natural forests or limit it to small areas, other countries maintain large areas of natural forest for production (notably in Europe and Africa) or multiple use which often has timber production as a major objective (e.g. in North America). In Indonesia, 60 percent of total forest area is managed as production forest. Germany manages most of its forests jointly for production forestry and conservation.

While protected areas make an essential contribution to FGR, they comprise less than 13 percent of forests worldwide (see Chapter 6). Productive uses may occur in various categories of protected areas. Many countries' protected areas include multiple land use designations that allow for a range of uses and activities, such as limited timber extraction, harvesting of NWFPs, grazing, hunting and tourism. A number of countries also note that protected areas are subject to encroachment and illegal occupation. SFM involves both ensuring that approved activities within protected areas are conducted in such a way as to minimize impacts on the genetic resources, and preventing (or, if prevention is not possible, at least reducing) uncontrolled, illegal uses.

Forest management, as sometimes currently practised, may not always adequately address the requirements of *in situ* conservation of FGR, for example in situations where maximizing timber production is emphasized at the expense of genetic and ecological outcomes, which are important components of SFM. It is essential

**FIGURE 12.3**
Number of species mentioned as actively managed in country reports, by main management objective



to ensure that SFM protocols address the requirements for conservation of FGR, both for major commercial timber species and for other forest tree species whose continued presence and variability may be affected by timber extraction, especially those providing NWFPs. Nonetheless, for countries where forests are currently harvested with inadequate controls and at unsustainable rates, applying the basic forest management principle of sustainable yield can contribute significantly to FGR conservation.

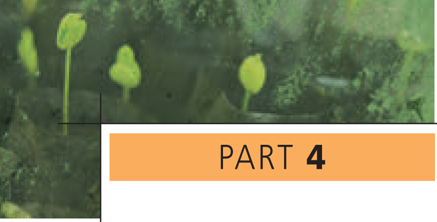
China expresses the concern that population growth, increasing wealth and consumer demand for timber and wood products will result in a significant shortfall between national demand and supply, and the same may hold for other fast-growing economies in Asia such as India and Thailand. Some traditional timber-exporting countries in Africa (e.g. Ghana) have experienced major declines in exports and may eventually become net importers of wood products. The long-term challenge of meeting rising global demand for wood products will necessitate adoption of SFM, including *in situ* conservation of FGR, in all forms of production forestry. Demand for NWFPs and environmental services of forests is also increasing; with proper management to avoid rapid depletion of the resources, these uses can usually be fully compatible with FGR conservation. SFM plans require regular updating to meet new circumstances including changes in demand and production for diverse NWFPs (e.g. cork, honey, mushrooms, wild game, essential oils and bamboo) and environmental services (e.g. biodiversity conservation, carbon sequestration and restoration of degraded soils).

Customary management practices are often consistent with sustainable management of FGR. When nearby impoverished communities are excluded from protected forests that they previously lived in and used following customary and sustainable management regimes, the result is often uncontrolled harvesting and use. Where SFM makes productive uses possible with minimal impact on the environment, including FGR and associated processes, it may be appropriate to permit productive activities in protected areas or conservation reserves. Providing controlled access and shared management responsibilities to communities under appropriate SFM plans can reduce negative impacts on FGR and even provide positive conservation benefits. For example, involving neighbouring communities in informal surveillance can help reduce illegal and detrimental activities.

The following sections outline SFM approaches and initiatives that contribute to the maintenance of genetic variability and evolutionary processes.

## Reducing use and harvest pressure on natural forests

The application of SFM to increase the production of timber and NWFPs from natural forests can reduce the harvest pressure on other forests conserved for biodiversity and FGR purposes and free up production forest for other uses. SFM can deliver increased timber production from



the same or reduced area of natural production forest. Indeed, a number of countries report slight increases in forest area, increment of forests and/or standing volume of timber in production forests through the application of SFM principles and associated legislation, including for FGR. Sweden's standing wood volume, for example, has increased by 86 percent over the past 90 years, with the annual increase in standing volume doubling over the same period. Although the forest area in Finland has remained constant, the volume of timber is 40 percent greater than 50 years ago, and 45 percent more volume is added annually than is harvested. Standing volume has also increased in Germany. The United States of America reports an increase in timber production with a fairly constant forest base and increasing standing volume.

Sustainable increases in timber and NWFP production may be achieved through the application of SFM practices such as selected seed sources and improved genetic materials, altering rotation length, species-specific minimum-diameter cutting limits, enrichment plantings of preferred timber species, thinning operations, retention of mother or seed trees, retention of preferred NWFP species during clearing, and applying the principle of sustainable yield, where the amount harvested does not exceed the annual increment.

To increase production from existing natural forests through better management, Ghana has prioritized increasing investment in natural forest management to relieve the utilization pressures on forests that have FGR and conservation value. Sweden remarks that more intensive forestry to increase forest growth requires an increased effort in gene conservation to balance production and environmental objectives. In Japan, national forests that are not protection forests are also managed sustainably through long-term regional forest management plans and contribute to FGR conservation.

Another strategy is to increase the area of forest available for productive uses and FGR conservation through planting and facilitation of regeneration. A number of countries recorded large annual net gains in forest area between 1990 and 2010 (FAO, 2010a) (see Chapter 6). In some cases, especially in Asia, these gains were the result of deliberate reforestation programmes, while in southern Europe and the United States of America the gains may be attributed in large part to natural regeneration on abandoned, marginal agricultural lands. Solomon Islands identifies an urgent need to rehabilitate harvested areas that have failed to regenerate, as a step to restoring the productivity of such areas. This strategy may extend to increasing farm and landscape plantings and expanding planted forest areas to meet the demand for forest products and services to avoid adding to the use pressures on natural forests; these plantings may include tree species and populations under pressure *in situ*, thereby providing *circa situm* FGR conservation benefits.

Increasing planting to reduce pressure on natural forests is an important adjunct to SFM strategies. Ghana proposes intensive planted forest development for this purpose. Indonesia is one of several countries adopting this strategy: "To reduce pressure from natural forest exploitation, the Ministry of Forests has increased permits for industrial plantation forest from 4.5 million hectares in 2000 to 8.97 million hectares in 2010." Myanmar, Solomon Islands and Vanuatu similarly identify this approach as vital to reducing unsustainable harvesting of natural forests, including particular high-value species. Plantations enable Brazil to be extremely efficient at producing pulpwood for manufacture of paper. Its 1.1 million hectares of pulpwood plantations represent just 0.2 percent of the country's area. Brazil states that the wood harvested from 100 000 ha produces 1 million tonnes of pulp annually in Brazil, while in Scandinavia and the Iberian Peninsula, 720 000 and 300 000 ha, respectively, would be necessary to obtain the same amount.

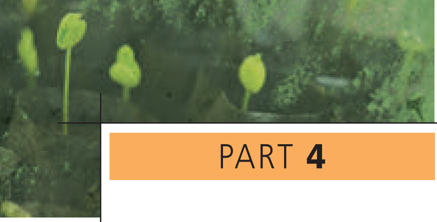
From an FGR conservation and management and long-term sustainability viewpoint, it is essential that existing, genetically diverse natural forests not be replaced with monocultures of limited genetic variation. In many locations, abandoned or marginal agricultural land may be suitable for planted forest establishment, thereby avoiding loss of natural forest. Other strategic measures adopted by countries to facilitate planting include provision of low-interest loans for planting programmes (particularly of multipurpose tree species) and for forest-related cooperatives; and ensuring that land for planted forest establishment is affordable.

Application of sustainable yield principles can contribute to sustainable forest management and to conservation and management of FGR. Implementation of sustainable yield principles requires guidelines, inventory and FGR survey, planning and effective administration. In Solomon Islands – where roundwood accounts for over 70 percent of export earnings, provides 18 percent of total government revenue and is a major source of income and employment in rural areas as well as for landowners – unsustainable extraction threatens to deplete the resource substantially by 2018, which could have destabilizing effects on the economy and society. Institution of a sustained yield regime would be a critical step in improving forest management and would provide the basis for conservation of FGR. In Vanuatu, sustainable forest management is enshrined in the constitution and backed by a Forestry Act, National Forest Policy and Codes of Logging Practice, but its implementation is hampered by lack of land use planning, out-of-date forest inventory, inadequate government resources and a gross imbalance between extraction and reforestation.

Another important approach in relieving harvesting pressure on natural forests is to establish alternative uses and income generation opportunities for forests, such as ecotourism, conservation, water provision and environmental protection. Seychelles has incorporated this strategy and the alternative uses into high-level government policies and programmes to ensure that they are adequately addressed at the field level. This approach is consistent with Part V, Paragraph 6(j) of the NLBI (UN, 2008), which suggests encouragement of "recognition of the range of values derived from goods and services provided by all types of forests and trees outside forests, as well as ways to reflect such values in the marketplace, consistent with relevant national legislation and policies". Markets for alternative goods and services may already be available through mechanisms such as forest certification schemes, stewardship payments, payments for carbon sequestration or credits for biodiversity, land or environmental management.

A number of countries seek to provide alternative goods and services to replace natural forest products – for example, alternative energy sources to lessen the demand for fuelwood and charcoal, which often contributes to unsustainable harvesting. Seychelles reports that "the demand for fuelwood appears to be rapidly dwindling due to rural electrification and expanding use of kerosene also in the rural areas". Zambia proposes rural electrification and more efficient technology for burning wood and charcoal as strategies for reducing the demand for charcoal, which is at present partially responsible for loss of FGR. The Philippines mentions efforts to extend the life of construction materials to reduce the requirement for wood for repairs and replacement. Countries with less pressure on the forests and/or an expanding production forest estate, on the other hand, may promote the use of wood because it has a lower negative environmental impact than other products (e.g. Norway).

Value addition to forest products is increasingly used as a strategy to counter unsustainable high-volume/low-return forestry based on extraction and export of roundwood. Gabon has prohibited roundwood exports since 2009 to encourage domestic processing, while Papua New Guinea and Solomon Islands have developed domestic processing targets and projects to add value to



logs in order to provide greater employment and increase financial returns to the population as well as government revenues. Solomon Islands has a policy that 20 percent of timber logged under licence must undergo further processing, implemented as a condition of logging licences, to facilitate value addition.

### Zoning: identifying and protecting important areas for increased protection and management

As with more targeted *in situ* conservation approaches, SFM for maintenance of FGR requires that key tree populations or areas containing priority or threatened tree species or other essential elements for maintaining FGR be identified, demarcated and given extra protection and appropriate management. This approach is practised by many countries, including Finland, which identifies and protects valuable habitat areas within production and other forests; and Thailand, which in 1989 gazetted National Forest Reserves as three zones (conservation, economic and agricultural). Nonetheless, some countries (e.g. the Philippines) report failure to protect significant areas for conservation of FGR and biodiversity once they are identified, even when protocols have been set out in codes of practice and other programmes, because of administrative failure, lack of political will or inadequate funding.

A number of countries apply land-use planning to allocate production forestry and plantation expansion activities to areas where they will deliver the maximum benefits with the least impacts, as well as to identify areas suitable for agricultural expansion. It is essential that conservation of FGR be taken into account during land-use planning.

### Multiple-use approach to production forests

Adopting an explicitly multiple-use approach to production forests facilitates the incorporation of FGR conservation and management objectives into their management. Multiple uses may include timber and NWFP harvesting, conservation of genetic resources and biodiversity, catchment management and water provision, environmental protection, $CO_2$ sequestration and recreation. The various uses must be compatible, i.e. no use should have negative impact on the others in the area. In many cases management for multiple uses is not only complementary to, but may also assist, FGR conservation and management. For example, Seychelles reports that allowing honey production in protected areas helps prevent damaging fires as beekeepers protect their hives and nectar sources. Germany's multiple-use forest management approach is particularly directed towards simultaneous production and genetic and biodiversity conservation, based on "protection through utilization". FGR conservation in multiple-use forests requires detailed information about the genetic resources and the requisites for their management requirements, as well as high organizational capacity.

FGR conservation can also be integrated with plantation management, for example through protection of forest buffers along watercourses or planting of corridors of native forest species to link retained natural forests and minimize fragmentation. Indonesia notes that elimination of regeneration on new plantation sites prior to planting results in failure to meet FGR conservation objectives. By contrast, establishment of mahogany through enrichment planting in logged-over forest in Fiji has allowed regeneration and continued growth of many native tree and understory species, including species important for FGR conservation such as *Endospermum macrophyllum* and *Atuna racemosa*.

### "Close-to-nature" forestry practices

Adopting management techniques that rely on or mimic natural forest processes is an important SFM approach. Natural regeneration of harvested blocks is one such approach: The countries reporting on regeneration methods for this report predominantly regenerate their commonly used species using natural regeneration (61 percent, as compared with 30 percent regenerated through planted forest establishment). Natural regeneration can be lower in countries with forest production based on indigenous species; in Canada, for example, about 32.8 percent of logged forest is regenerated naturally.

European countries are increasingly applying "close-to-nature" approaches to forest management that emphasize natural regeneration, and the approach is also under investigation elsewhere. Denmark's 2002 National Forest Programme recommends adoption of the close-to-nature approach, and the Forest Act of 2004 provides the legal framework for this transition. Germany proposes that close-to-nature forestry is the most effective approach for simultaneous forest production and conservation; the country's report notes that "[owing] to the strict legal provisions and largely practised close-to-nature forestry, overexploitation and clear-cutting are no real threat to the state of the forests' genetic diversity in Germany".

## Codes of practice

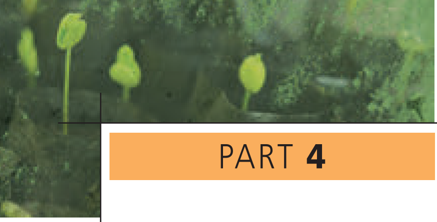
Codes of practice provide guidance for conducting operations according to SFM principles and, where relevant, for complying with government legislation or regulations. They may apply to the operations of State, parastatal and private companies or individuals engaged in forest use on public land, and their use may extend through legislation to timber extraction activities on private land. They may be imposed as a condition of access to public forest resources or government licences for their use, thereby forming part of the regulatory system, or they may be developed by forest industry for voluntary use. Some codes may be developed as part of certification schemes or to demonstrate best practices in the marketplace. It is vital that codes of practice for SFM incorporate measures to ensure the maintenance of FGR and the ecological processes that support them. In Australia, for example, several state jurisdictions have codes of practice governing forest operations on both private and public land; these include provisions for maintaining ecological assets and conserving non-target species.

For codes of practice to be successful in promoting SFM and FGR conservation and management, effective forest and natural resource administrations are required. Mechanisms must be in place to ensure compliance, such as enforcement of penalties for breaches, implementation of provisions for damage, lodgement and potential forfeiture of bonds, fines, cancellation of licences or permits to operate or denial of access to the forest resource. Furthermore, the compliance of forest operators must be monitored. Codes must have legislative or legal backing to be enforceable.

Some countries report instances of failure to implement SFM and FGR conservation and management protocols contained in codes of practice because of lack of funding or human resources, insufficient administrative and technical capacities or lack of jurisdiction over important forest resources requiring conservation. The effectiveness of codes of practice in the private forest estate may depend on the government having jurisdiction over forest protection activities and harvesting on private land, for example through granting of permits. Where codes of practice exist for activities that can have impact on FGR but lie beyond the normal purview of forest operations, these codes must also address the requirements of FGR conservation and management. Harmonizing a national FGR strategy with relevant cross-sectoral programmes will facilitate the integration of FGR concerns into codes of practice for related activities.

## Harvesting

To conserve and manage FGR effectively, sustainable harvesting regimes must address the genetic characteristics of any species, including but not limited to target or priority species, that could potentially suffer negative impact from harvesting, as well as associated evolutionary and ecological processes. Areas to be conserved for their FGR value must be identified and,



if necessary, protected from harvesting. The harvesting intensity and techniques must minimize impact on non-target species, and the harvesting and regeneration practices must ensure that the genetic variability of the target species is retained as much as possible. Monitoring the impacts of forest utilization and applying appropriate management are essential elements of SFM.

A number of countries note negative impacts of unsustainable harvesting regimes and techniques on their FGR, most significantly the depletion or extermination of the target species and/or others. The Islamic Republic of Iran reports a research programme to investigate damaging silvicultural practices, while some countries (e.g. Papua New Guinea, Solomon Islands, the Sudan, Thailand and Viet Nam) have banned harvesting of selected endangered and economically important timber tree species.

## Maintaining germplasm variability in regenerated production-forest stands

Ensuring that harvested stands are regenerated adequately and contain sufficient variability for adaptation and continued evolution is crucial to SFM for FGR conservation and management. This is particularly important for countries with significant forest industries that rely heavily on natural forest and with limited strictly protected areas. Most commercial timber tree species regenerate naturally and maintain sufficient variability as long as enough trees contribute to the reproductive materials used for stand regeneration.

Regeneration must be monitored and may need to be supplemented with artificial seeding or planting if stocking rates are inadequate. Where artificial regeneration is the preferred method of restocking, then genetically diverse germplasm is essential. For example, Germany mandates the minimum number of seed trees to be used; with the large number of seed stands available and the system of private certification of germplasm suppliers, “sufficient amounts of reproductive material with high genetic diversity are available for artificial regeneration of most provenances”. Germany also notes that incorporating non-commercial tree species into natural regeneration regimes and cultivating “adapted populations with great genetic diversity” are particularly beneficial for *in situ* conservation.

In order to maintain the variability of germplasm in the 15 percent of production forests in Canada that are artificially regenerated, the country’s criteria and indicators for SFM state that:

> “Under Criterion 1, biological diversity, Indicator 1.3.1, genetic diversity of reforestation seed lot, addresses the variation of genes within a species by ensuring that seed used to regenerate harvested areas has sufficient genetic diversity to respond to changing environmental conditions… The genetic diversity of seed used for reforestation is a result of both the number of areas where seed is collected and the parental composition of those areas. Most of the seed used in reforestation programmes across Canada is collected from natural stands where the number of parent trees is typically in the hundreds to thousands. This seed likely has genetic variation that is representative of the natural populations where it was collected. [However] in some jurisdictions, a significant portion of the seed for reforestation… comes from seed orchards.”

Ideally seed is collected beforehand from the area to be harvested and regenerated. However, where this is not possible, germplasm of local provenance or from the same genecological zone may be used to maintain variability and ensure that the stock is well adapted to local conditions. Guidelines based on knowledge of the target (or closely related) species may be used to guide collection and use of germplasm for artificial regeneration to maximize variability in situations where genetic variation patterns are known partially or not at all. Germany points out the need to monitor the genetic impacts of its silvicultural practices on its priority species, and is developing a methodology to facilitate this monitoring. Early work suggests that losses to date are not excessive. Solomon Islands notes a failure of natural regeneration and a failure to undertake remedial measures, which comprise a threat to the survival of the country's forests, FGR, and sustainable forest industry.

Countries increasingly recognize the need to provide higher genetic variability (both more species and greater intraspecific diversity) in production forestry, especially for traits associated with adaptability to changing climatic and environmental conditions. Some countries have identified this as a priority for their breeding and forest management programmes; and some seek to incorporate variability that can confer adaptation to climate change into germplasm used for regeneration of harvested areas as well as different types of planted forest.

## Using local species

Country reports indicate that there is a global trend of increasing use of indigenous tree species for afforestation and environmental services. The use of locally indigenous tree species in plantings for timber production, fuelwood and afforestation can assist in maintaining genetic variation, especially where planting stock is developed from genecologically appropriate and genetically variable germplasm and management regimes do not excessively deplete variability in non-target species. The use of indigenous species as an alternative to commonly planted exotics can yield major FGR benefits. Nonetheless, consideration must be given to reducing the risk of loss of local genetic variability which can occur if genetic material from improved indigenous species enters local populations of the same or hybridizing species.

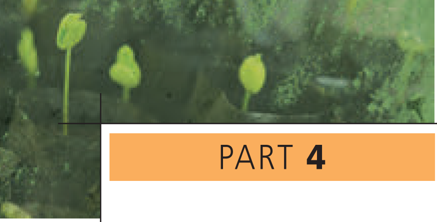
Using local tree species has the added benefit of raising awareness of their value. The United Republic of Tanzania recommends further use of its valuable, high-performing indigenous species such as *Antiaris usambarensis* and *Khaya anthotheca*, whose growth rates "compare closely with [those of] industrial plantation species raised in the country", in afforestation programmes. However, where high-performing exotic species yield a more valuable crop than local species with minimal impact on FGR, their use may not only be commercially preferable but can also lower pressures on a country's natural forests. This approach may form part of a high-level policy and strategy for SFM that addresses FGR conservation and management.

## Increasing variability in establishment of planted forests

As reported by Indonesia, land preparation for forest plantation or agroforestry in cleared forest areas often involves removal of all residual species and regrowth. Instead, partial retention of advanced growth and natural regeneration, especially of economically valuable local tree species, can assist in maintaining diversity with minimal economic losses.

Several countries are considering or have undertaken conversion of monoculture plantations to mixed-species plantings to increase variability for a variety of reasons, for example to provide opportunities for adaptation to climate change or to increase genetic connectivity among isolated remnants. Germany notes that climate change may necessitate the transformation of pure spruce stands in many parts of the country to mixed stands of putatively adapted tree species. Mixed-species plantations serving multiple purposes are increasingly finding favour, for example under initiatives for reafforestation in the Islamic Republic of Iran.

Other practices to minimize losses of FGR during planted forest development may include documenting and conserving *ex situ* any threatened local FGR, avoiding conversion of natural forest to planted forest, and ensuring genetic diversity within planted stock across a range of adaptive traits while maintaining uniformity for desired production and quality traits.



### Certification: increasing market share for sustainably produced products

Forest certification schemes specify management protocols that are in accordance with accepted SFM principles. To obtain certification, organizations involved in forest management and harvesting, whether public or private, must provide proof of compliance with the protocols and undergo regular auditing to ensure ongoing compliance. Certification of a product may confer a marketing advantage. This approach to SFM is consistent with the NLBI, Part V, Paragraph 6(x), which encourages "the private sector, civil society organizations and forest owners to develop, promote and implement… voluntary instruments, such as voluntary certification systems or other appropriate mechanisms, through which to develop and promote forest products from sustainably managed forests…" (UN, 2008).

Principle 9 of the predominant certification system, the Forest Stewardship Council (FSC), is "Maintenance of high conservation value forests". The standards specify that management activities in high conservation value forests must maintain or enhance the attributes that define them.

## Chapter 13

# *Ex situ* conservation

Internationally, governments and non-governmental agencies and organizations have made strong commitments to *ex situ* conservation. The CBD Global Strategy for Plant Conservation 2011-2020 promotes efforts at all levels – local, national, regional and global – to understand, conserve and use sustainably the world's immense wealth of plant diversity while promoting awareness and building the necessary capacities. The 2011-2020 strategy includes 16 outcome-oriented global targets for 2020; Target 8 specifically addresses *ex situ* conservation: "At least 75 percent of threatened plant species in *ex situ* collections, preferably in the country of origin, and at least 20 percent available for recovery and restoration programmes" (CBD, 2013).

Global infrastructure commitments can be best depicted by, for example, the Svalbard Global Seed Vault in Norway, which was built in 2007 to provide insurance against the loss of germplasm from seed banks as well as a refuge for seed in the case of long-term regional or global crisis (Global Crop Diversity Trust, 2013), and the Millennium Seed Bank Partnership of the Royal Botanic Gardens, Kew, United Kingdom (see Box 3.3 in Part 1), which both store tree seed.

Increased emphasis in recent years on expanding collections in botanical gardens, especially in China and other highly diverse countries, has contributed significantly to knowledge of cultivation of tropical tree species, particularly endemics. The global network Botanical Gardens Conservation International (BGCI) has a mission "to ensure the world-wide conservation of threatened plants, the continued existence of which are intrinsically linked to global issues including poverty, human well-being and climate change" (BGCI, 2013). The BGCI network currently has 700 members in approximately 118 countries. BGCI supports *ex situ* conservation through many of its activities, in particular the establishment of regional networks that strengthen and support botanical gardens such as the African Botanic Gardens Network (ABGN).

Based on data obtained from the country reports, the total number of species conserved *ex situ* is 1 800. The number of species conserved by region is shown in Table 13.1; see Figure 12.1 in Chapter 12 for a comparison with species conserved *in situ*. Many of these are in botanical gardens. Some 95 percent of the species are native in the countries where they are conserved; 8 percent are exotic. (The total exceeds 100 percent because some species are present both in countries where they are native and in countries where they have been introduced.) In all regions the majority of species conserved *ex situ* are native species.

**TABLE 13.1**

Species conserved *ex situ*, by region

| Region | No. of species |
|---|---|
| Africa | 1 025 |
| Asia | 389 |
| Europe | 401 |
| Latin America and the Caribbean | 372 |
| Near East | 102 |
| North America | 265 |
| Oceania | 57 |

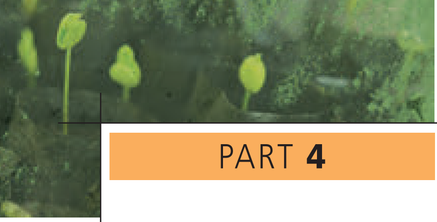


**TABLE 13.2**
Genera of global priority that are conserved *ex situ*

| Genus | No. of species conserved |
|---|---|
| *Pinus* | 65 |
| *Eucalyptus* | 28 |
| *Albizia* | 24 |
| *Acer* | 15 |
| *Quercus* | 13 |
| *Acacia* | 10 |
| *Terminalia* | 10 |

Of the 2 260 species listed as priorities in country reports (see Chapter 10), 626 are represented in some form of *ex situ* conservation, and 135 of them are conserved in more than one country.

Considering genera of global priority, *Pinus* has the largest number of species conserved *ex situ* (Table 13.2). Globally the total number of accessions reported is 159 579, and for some species there are multiple accessions. Most accessions are as field collections, including clone banks and provenance trials; far fewer are in seed or *in vitro* collections.

## *Ex situ* conservation activities by region

### Africa

*Ex situ* conservation in African countries is primarily achieved through arboreta and botanical gardens, but other means such as provenance trials, plantations, seed orchards and seed banks are also used.

Short- and long-term storage of germplasm is not available in all African countries, and where that capability exists the capacity varies. Burkina Faso has one of the most operational seed centres, established in 1983, which serves as a seed bank for medium- and long-term storage; it is a partner in the Millennium Seed Bank Partnership, focusing on research, seed and herbarium specimen collection and conservation of duplicates from its collections. Burundi has capacity for medium- and long-term cold storage of seed. Madagascar has one seed bank, functional since 1986, which collects seed from rare, threatened and valuable tree species. Morocco has four facilities for production and storage of tree germplasm; these facilities are equipped for conditioning, conserving, organizing and managing seed lots. Tunisia has two gene banks; the largest has the capacity to store 200 000 accessions. The Zimbabwe Tree Seed Centre has approximately 23 000 accessions. Burkina Faso and Cameroon have infrastructure for storage but report that frequent power outages and lack of funds for maintenance present major challenges. In Malawi, the Millennium Seed Bank assists in backing up the *ex situ* conservation collections.

The tree species conserved in African countries include indigenous and exotic species from many genera and families. The main genera conserved and propagated for multiple reasons are *Acacia* spp., *Eucalyptus* spp. and *Pinus* spp. Some countries (e.g. Benin and Burundi) report that they conserve species valued for medicinal uses. Mauritania’s main driver for *ex situ* conservation is utility for mitigating the impacts of desertification and restoring degraded ecosystems.

In addition to traditional *ex situ* conservation methods such as seed and live field collections of all kinds, Burkina Faso, Cameroon, Ethiopia, Gabon, Kenya, South Africa and Zimbabwe report that they have genetic improvement programmes to select plus trees for different purposes including seed orchards. Others (Ghana and the United Republic of Tanzania) note that their improvement programmes are moribund or in decline because of lack of funding. In many sub-Saharan African countries, ICRAF has partnered with national government agencies, universities and others to implement domestication and improvement programmes for indigenous multipurpose tree species (see Chapter 14).

A few countries, including European countries and some developing countries (e.g. Algeria), have tried *in vitro* propagation methods such as somatic embryogenesis and axillary bud inductions for some of their priority species.

Limitations and constraints are numerous, primarily lack of monetary and human resources, proper equipment or facilities for effective storage and management of germplasm for short- and long-term safekeeping. Another commonly reported limitation is a lack of technical knowledge and training for the proper management of *ex situ* conservation programmes, for example relating to reproduction, propagation and storage, data logging and management strategies. Future priorities reported by many African countries include the development of a national strategy and research programmes for the management of *ex situ* conservation and nomination of priority FGR; and identification of ways to fund, develop, and maintain proper infrastructure and collections for the safekeeping of FGR.

**Species conserved.** Two African countries, Ethiopia and Burkina Faso, report details pertaining to species conserved *ex situ*. Both countries have *ex situ* conservation collections for native *Acacia* spp. and *Tamarindus indica* and for exotic *Eucalyptus* spp. (*Eucalyptus globulus* in Ethiopia and *Eucalyptus camaldulensis* in Burkina Faso).

In Burkina Faso, six native species (*Acacia nilotica* var. *adansonii, Acacia senegal, Faidherbia albida, Khaya senegalensis, Parkia biglobosa* and *Tamarindus indica*) and four exotics (*Eucalyptus camaldulensis, Leucaena leucocephala, Prosopis chilensis* and *Prosopis juliflora*) are conserved in field collections, including clone banks, and in seed collections. The native species with the largest number of field stands and accessions are *P. biglobosa* and *F. albida. Eucalyptus camaldulensis* is represented by 101 clones in two clone banks.

In Ethiopia, 92 native species and one exotic are conserved in multiple field and seed bank collections. The accessions from all native species include one or more field stand and *ex situ* seed bank collections. *Phytolaca dodecandra* is the native species with the largest number of collections – 59 accessions over 19 field stands and 59 accessions represented in three seed banks. Five native species are represented by more than 20 accessions over multiple field stands: *Acacia etbaica, Cordia africana, Morinaga stenopetala, Oxytenanthera abyssinica* and *Phytolaca dodecandra*. The only exotic species conserved *ex situ, Eucalyptus globulus*, is represented by ten accessions available from one stand; these ten accessions are also conserved in one seed bank.

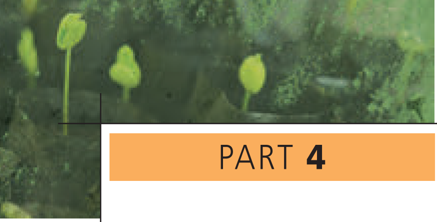
## Asia

Reported *ex situ* conservation activities in Asia include provenance trials, seed orchards, clonal repositories, botanical gardens and arboreta, and seed and pollen gene banks targeting multiple native and exotic species.

Community-based *ex situ* conservation programmes are emerging in a number of countries in the region. For example, in Nepal the government has endeavoured to shift responsibility for managing seed orchards to local communities by providing a mechanism through which the communities receive direct benefits from the resources. However, adequate benefits have not yet been generated, reportedly because of poor market linkages.

As recorded by Kyrgyzstan, studies under Bioversity International, the United Nations Environment Programme (UNEP) and the Global Environment Facility (GEF) are establishing demonstration sites and forest reserves in Central Asian countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan) and conserving wild fruit-tree species in accordance with State legislation. These efforts aim to support local farmers through on-farm *ex situ* conservation and use of local tree species, primarily fruit- and nut-trees.

Commonly reported constraints include a lack of resources to support *ex situ* conservation activities, especially limited infrastructure and lack of trained personnel. Country priorities for future *ex situ* conservation activities include the



development of national cooperatives to promote FGR conservation and to enhance countries' self-sufficiency with regard to seed supply.

**Species conserved.** In Asia, no significant trends were evident among countries concerning which native species were conserved *ex situ*. In both India and Nepal *Dalbergia sisso*, a deciduous rosewood tree, is a main species for *ex situ* conservation in field collections (e.g. provenance and progeny trials). A few Central Asian countries have *ex situ* collections that focus on agroforestry species. For example, Kazakhstan's largest *ex situ* collection is for *Malus sieversii*, the primary wild ancestor to most cultivars of domestic apples, and Uzbekistan's largest collections are for nut-bearing trees, *Juglans regia* and *Pistacia vera*.

In China, field collections for *ex situ* conservation include progeny and provenance tests for native and exotic tree species. Four native tree species (*Cunninghamia lanceolata, Larix olgensis, Pinus massoniana* and *Pinus sylvestris* var. *mongolica*) are conserved in over 1 200 accessions in one or more stands for each species as well as in extensive clone banks. Of 16 native tree species stored in seed banks, six (*Melia azedarach, Pinus bungeana, Pinus massoniana, Pinus sylvestris* var. *mongolica, Pinus tabulaeformis* and *Sophora japonica*) each have over 1 000 accessions. For exotic species, from 62 to 646 accessions are held for each of ten species (nine *Eucalyptus* species and *Tectona grandis*) in field stands.

India has numerous species in *ex situ* conservation field collections. Most are native (e.g. *Acacia nilotica, Azadirachta indica, Dalbergia sissoo, Tectona grandis* and bamboos), but India also has a few extensive collections of exotic species. For example, 3 122 accessions of *Acacia auriculiformis* are conserved in field stands and 4 548 accessions of *Hevea brasiliensis* in clone banks. India's *ex situ* germplasm storage collections also focus primarily on native species, and these collections are less extensive than the *ex situ* field banks. The largest seed storage collection is for a native species, *Prosopis cineraria*, with 453 accessions, while the largest *in vitro* collection is for an exotic species, *Jatropha curcas*, with 145 accessions.

Japan's *ex situ* conservation activities are for native species and focus primarily on clone banks and seed storage. Collections for some species are extensive: 7 812 clones in field collections and 2 298 seed accessions of *Cryptomeria japonica*; 2 452 field clones and 1 515 seed accessions of *Chamaecyparis obtusa*; and 2 450 accessions in clone banks and 508 seed accessions of *Larix kaempferi*.

In Kazakhstan, seven native species (*Aflatunia ulmifolis, Alnus glutinosa, Berberis karkaralensis, Corylus avellana, Juniperus seravschanica, Malus sieversii* and *Quercus robur*) are conserved *ex situ* in field collections, and *ex situ* seed stores are also kept for these species.

Nepal identifies 36 native species under some form of *ex situ* conservation. Of these, 24 species are in field stands and 14 species are maintained in *in vitro* collections. No *ex situ* seed collections are reported for any of the 36 species. Under *ex situ* field collections, *Dalbergia sissoo* has seven stands, while *Cinnamomum tamala* and *Leucaena leucocephala* each have three stands. The remainder of the species have two or one stands per species.

Sri Lanka's *ex situ* collections focus on field collections for exotic species such as *Eucalyptus grandis, Eucalyptus microcorys, Khaya senegalensis* and *Tectona grandis. Tectona grandis* has the largest number of field collections, including 200 accessions in five stands. Sri Lanka reports no *ex situ* collections for native tree species.

Uzbekistan has four native species in *ex situ* field collections (*Amygdalus* spp., *Haloxylon aphyllum, Juglans regia* and *Pistacia vera*) and has no other *ex situ* collections.

## Europe

European countries report a range of *ex situ* conservation activities; some countries have extensive activities (including provenance trials, seed orchards, clonal repositories, botanical gardens and arboreta, and seed and pollen gene banks) while others have none. Some European countries (e.g. Bulgaria and Sweden) note that *ex situ* conservation is of secondary importance compared to *in situ* conservation because it is a static approach and therefore does not provide for adaptation to a changing environment.

Northern European countries identify a need for long-term seed storage, as seed years are scarce at northern latitudes and high altitudes. In Norway, for example, the Nordic Genetic Resource Centre (NordGen), a meeting place for researchers, managers and practitioners from Nordic countries working on forest genetics, seeds, plants and regeneration methods, is assessing the possibility of using the Svalbard Global Seed Vault in Norway as a long-term seed storage option for forest seed banking activities.

Cyprus is considering the establishment of a national seed banks for forest species.

*Ex situ* conservation priorities identified by European countries include the conservation of rare and endangered species, populations that are genetically unique, and species of ecological and economic importance. Many European countries report that *ex situ* conservation activities have been negatively affected by the fiscal and economic slump of recent years.

**Species conserved.** Significant diversity is seen in the native species conserved *ex situ* in the 15 European countries reporting data. A number of countries have large accessions of *Pinus sylvestris*, to a lesser extent *Picea abies*, and many hardwoods including *Quercus* spp. and *Populus* spp. In seven countries, *Pseudotsuga menziesii* is a common exotic species conserved *ex situ*.

Bulgaria has identified 36 native and exotic tree species conserved *ex situ* primarily in field collections and in a few seed bank accessions. The largest *ex situ* field stands for native species are for *Quercus petraea, Q. frainetto* and *Fagus sylvatica,* each with at least 49 accessions, while *Populus* spp. and *Pinus sylvestris* have the largest number of field stands and accessions. For exotic species, *Pseudotsuga menziesii* has the largest number of accessions, with 55 accessions in one field stand. Seed is stored *ex situ* for two species (*Picea abies* and *Pinus sylvestris)*.

Cyprus reports that the majority of *ex situ* collections are for stored seed; seed is stored for 16 native species, mostly trees, and the number of accessions ranges from 3 to 15. The largest accession is of *Astragalus macrocarpus* subsp. *lefkarensis*, a small shrub present in evergreen mixed forests (IUCN, 2013).

In Denmark, *ex situ* conservation is in the form of seed storage, with accessions of ten tree species. *Abies nordmanniana* has the largest number of accessions, followed by the native species *Pinus sylvestris* and the exotic species *Pseudotsuga menziesii.*

Estonia's *ex situ* conservation activities are also in the form of seed storage, with two native species, *Populus tremula* and *Populus tremula* f. *gigas*, and the exotic species *Populus* × *wettsteinii* having multiple accessions.

Finland has *ex situ* field collections for eight native tree species (*Acer platanoides, Fraxinus excelsior, Juniperus communis, Quercus robur, Sorbus aucuparia, Tilia cordata, Ulmus glabra* and *Ulmus laevis)*. Germany has 58 species represented in *ex situ* field collections, with the largest collections for the native species *Taxus baccata, Picea abies* and *Fagus sylvatica* and for the exotic species *Pseudotsuga menziesii*.

Hungary has large *ex situ* field collections for 23 species, mostly native. The largest collections are for *Populus nigra* and *Picea abies*, with over 1 000 accessions each, then *Castanea sativa*, followed by species such as *Ulmus laevis, Ulmus minor* and *Ulmus pumila*, each with over 300 accessions.

Ireland has 11 species conserved *ex situ*, primarily in field collections; only one species, *Pinus sylvestris*, is native. The collections for this species are extensive: 52 stands, 619 accessions and three clone banks with a total of 562 clones, as well as 100 *in vitro* and 75 seed accessions.

Most of the Netherlands' *ex situ* collections are in clone banks, with 59 native species represented. The largest collections are for *Crataegus monogyna* and *Juniperus communis*, with 333 and 284 clones, respectively.

Norway has approximately 19 species in *ex situ* collections, of which eight are native. Most of the collections are field stands or long-term trials. Two native species are conserved in clone banks (*Picea abies* and *Pinus sylvestris*). Norway has a large number of field collections for *Picea abies*, with 260 stands or trials and 6 000 accessions.

In Poland, 33 species are conserved *ex situ*, the majority native. Seed storage is the main form of *ex situ* conservation; the largest collection of 4 764 accessions is for *Pinus sylvestris*, followed by 836 accessions for *Picea abies*.

Spain has *ex situ* collections, primarily in the form of clone banks, for approximately 27 species, of which most are native species. The largest collection is for four native species (*Populus tremula, P. nigra, Ulmus minor* and *U. glabra*). Spain also has *ex situ* seed collections for five native species (*Arbutus canariensis, Pinus pinaster, P. pinea, Pinus uncinata* and *Populus alba*).

Sweden's reported *ex situ* conservation collections are primarily field collections; species include *Alnus glutinosa, Betula pendula, Fagus sylvatica* and *Quercus robur*. Sweden also has seed collections for a few species and a few clone banks.

In Ukraine, *ex situ* collections comprise field collections, which include a few clone banks for native and exotic species. The largest collection is for *Pinus sylvestris*, with 95 stands representing 1 148 accessions and 38 clone banks with 1 092 accessions. The next largest collection is for *Quercus robur*, with 30 stands representing 539 accessions and 16 clone banks with 540 accessions.

The Russian Federation has extensive *ex situ* tree seed collections. The Russian Forest Seed Warehouse in Pishkino, Moscow Region, for example, currently stores 10 tonnes of seed, focusing on *Larix* spp., *Picea* spp. and *Pinus* spp.

### Latin America and the Caribbean

Argentina, Brazil, Chile, Costa Rica, Ecuador, Mexico and Peru have similar *ex situ* conservation activities; all have multiple seed banks, botanical gardens or arboreta and seed orchards, and most have the capacity for germplasm storage in other forms such as DNA, pollen and cryopreserved tissue. Germplasm sources range from non-native commercial species with economic impact to native species with unique medicinal and other uses. Gene banks have been set up as networks within some countries and are therefore controlled mainly at local level. All of the countries have storage infrastructure – facilities, technology and equipment.

Mexico has 54 forest gene banks with temporary to medium-term storage; their objective is to supply nurseries for government reforestation programmes, but some are used for conservation. Mexico is working with 74 tree species, mostly native and equally divided between conifers and hardwoods. Conservation activities in field collections and clone and seed banks are conducted for 55 native and 12 exotic species. Seed banks hold over 6 900 accessions from 36 species; the number of accessions per species ranges from 1 to 3 665. Mexico has 57 arboreta and botanical gardens which harbour germplasm for scientific research; nutritional, medicinal and ornamental uses; and conservation of at-risk species.

Most countries with *ex situ* conservation programmes have identified priorities to guide their respective programmes. These include conserving and improving FGR important to the country, contributing to their sustainable use and promoting the value of FGR conservation among scientists and the general population. *Ex situ* conservation of a species entails determining an appropriate representative sample of the species based on geographic or genetic variation, and identifying the future uses of the material (e.g. in breeding, planting, research and development, and conservation programmes).

The countries in the region report similar constraints, including a lack of permanent financing for long-term projects. The knowledge and in-depth research needed to characterize the material being conserved are often lacking. Thus a critical area of research that needs to be addressed is the nature of recalcitrant seed and protocols for handling seeds of species with this storage behaviour. Countries also cited a need to have clear strategies and policies for conservation.

**Species conserved.** Only Costa Rica, Ecuador and Mexico report on the species in *ex situ* collections.

In Costa Rica, four native species and one of uncertain origin are conserved *ex situ* in field collections. The four species, of which three are native (*Dipteryx panamensis, Sacloglottis* sp. and *Schlerolobium* sp.) and one is of uncertain origin (*Himenolobium parahybum*), are represented in 26 accessions in field stands. *Sacloglottis* sp. and *Himenolobium parahybum* have the most accessions, 12 and 9 respectively. *Swietenia macrophylla*, a native species, is the only species present in clone banks, with 600 clones established.

Ecuador has 114 species conserved *ex situ*, all in field collections; 64 of these species are native, 49 are exotic and one is of uncertain origin. The total number of accessions for all species is approximately 166, in multiple field stands. Multiple species are conserved in three genera: *Eucalyptus* (17 species), *Acacia* (13 species) and *Erythrina* (6 species).

Only one species, *Swietenia macrophylla*, is conserved *ex situ* in all three reporting countries. This species, a commercially important mahogany, is native to these countries and is identified by IUCN as vulnerable (IUCN 1998).

In Mexico, extensive effort is directed to the genus *Pinus* (26 species and seven varieties); over 320 accessions of *Pinus greggii* var. *greggii* and *P. patula* are held in 28 field stands, while just over 1 000 accessions of *P. greggii* and *P. patula* are represented in 16 clone banks. Considerable effort has been expended in establishing field stands of other species such as *Calophyllum brasiliensis, Cedrela odorata, Cupressus guadalupensis, Eucalyptus grandis, Eucalyptus urophylla, Guaciacum coulteri* and *Platymiscum lasiocarpum*, with almost 3 500 accessions represented in 39 stands. Of these species, *E. grandis* and *E. urophylla* have 1 300 accessions in five clone banks. The most represented species in seed banks are *Pinus patula* and *Toona ciliata*, with 700 and 3 665 accessions respectively.

## Near East

The reporting countries from the Near East (Egypt, Islamic Republic of Iran, Iraq, Jordan, Lebanon, the Sudan and Yemen) cite similar priorities and constraints in *ex situ* FGR conservation. All want to establish, enhance or continue scientific research and education on aspects of FGR conservation such as propagation of trees and protocols for storing seed. The countries report a clear need to improve their infrastructure and technical capacity with respect to provenance tests, seed orchards, arboreta, gene banks and seed centres. They also cite a need to promote partnerships with forest-neighbouring communities to manage the resources and improve livelihoods.

Lack of funding, trained personnel, research and equipment are reported as constraints. Climate change is expected to have severe impact on this region given the current stage of desertification. Habitat degradation and depletion from logging, grazing and fuelwood harvesting highlights the importance of protecting the forest through establishment of reserves, botanical gardens and arboreta. National policy to support and create a strategy for FGR conservation and management is urgently needed in most countries in the region. Some countries (e.g. Iraq and Jordan) report the lack of capacity to develop comprehensive GIS surveys to identify areas and species that require conservation or protective management measures.

Wild relatives of fruit-tree crops are widespread in the Near East but have been neglected in terms of *ex situ* conservation, and little is known about their distributions (Table 13.3).

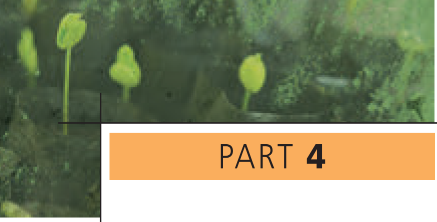


**TABLE 13.3**
Wild relatives of fruit-tree crop species reported by Jordan as present but understudied in terms of *ex situ* conservation

| Tree crop | Neglected wild relatives |
|---|---|
| Almond | *Amygdalus* spp.<br>(5 species and many interspecific hybrids) |
| Apple | *Malus* spp. |
| Cherry | *Cerasuse microcarpa* |
| Olive | *Olea europea* subsp. *oleaster* |
| Pear | *Pyrus syriaca* |
| Pistachio | *Pistacia* spp. |

**Species conserved.** The Islamic Republic of Iran, the only country in the region reporting data on species in *ex situ* collections, lists 18 *Populus* species conserved in clone banks with a total of 258 clones. *Populus* × *euramericana* of uncertain origin and *Populus nigra,* a species native to the Islamic Republic of Iran, have the most clones established, 59 and 91 respectively.

## North America

Canada conserves FGR *ex situ* in trials, plantations and clone banks; 28 native and five exotic species are established in over 510 field sites, and 14 native and one exotic species are represented in 37 clone banks (excluding provenance trials and clone banks for breeding programmes). Five seed banks – one national and four provincial – hold 15 000 accessions representing 75 species (all native except one).

Conservation activities in the United States of America are conducted for many species that are native not to the continental United States but rather to its tropical islands; 48 of the 57 listed species are native to the state of Hawaii or the territories of Puerto Rico and the United States Virgin Islands. The United States has multiple *ex situ* field and seed collections, predominately for native species. *Ex situ* conservation activities are conducted for 77 species of trees and shrubs by over 80 arboreta and botanic gardens, and national and regional seed banks store over 120 000 seedlots from over 250 species. Over 200 tree and shrub species are conserved *ex situ* in seed collections of the United States Department of Agriculture (USDA) Forest Service and Agricultural Research Service. Conifers are the best conserved, since they have large reforestation programmes. The USDA Forest Service maintains family seedlots for 44 reforestation species, totalling over 80 000 families. Breeding cooperatives in the United States maintain large breeding population sizes (in the hundreds) for each of their breeding zones, and their hundreds of progeny trials represent hundreds of field sites providing gene conservation as a secondary objective.

Future priorities include conservation and deployment strategies for mitigation of climate change impacts; prioritization of species identified at the federal and provincial levels and those at risk from invasive alien species; a focus on non-commercial coniferous and deciduous species; gap analyses to optimize sampling; and promotion of the sustainable use of forest genetic resources.

**Species conserved.** In Canada, key conifer species with 550 to 770 accessions in clone banks are *Picea glauca, P. glauca* × *engelmannii* and *Pinus contorta* var. *latifolia*. For five hardwood species (*Fraxinus pennsylvanica, Prunus virginiana* var. *virginiana, Quercus macrocarpa, Sherpherdia argentea* and *Symphoricarpus occidentalis*), the number of accessions in clone banks ranges from 1 900 to 6 600. In seed banks, 1 000 accessions each are held for *Picea glauca, P. glauca* × *engelmannii* and *Pinus contorta* var. *latifolia*.

The three most predominant species in *ex situ* conservation in the United States of America are *Pinus lambertiana* with over 26 000 family collections, *Pseudotsuga menziesii* with over 20 000 family collections, and *Pinus ponderosa* with over 13 000 family collections.

## Oceania

*Ex situ* conservation activities have been conducted for about 60 species in the countries of Oceania that submitted reports: Australia, Cook Islands, Fiji, France (represented by three territories – French Polynesia, New Caledonia and Wallis and Futuna), Papua New Guinea, Solomon Islands and Vanuatu. The conservation activities include species and provenance trials, clonal seed orchards, seed production areas, clone banks and cryogenic storage. In 2011, the Secretariat of the Pacific Community developed the Pacific Islands Tree Seed Centre to help research, conserve and disseminate seeds of socio-economically important tree species for its 22 member countries and territories.

Australia has more than 1 000 species conserved *ex situ* in seed banks and field plantings (clonal archives, seed orchards, arboreta). The Australian Seed Bank Partnership (www.seedpartnership.org.au), which developed from the Millennium Seed Bank Partnership, has a mission to safeguard Australia's plant populations and communities through a national network of conservation seed banks. This partnership unites the expertise of 14 institutions, including universities, herbaria, botanic gardens, NGOs and environmental agencies. The Threatened Flora Seed Centre of the Western Australian Department of Environment and Conservation (one of the members of the partnership), established to safeguard a geographically diverse range of seeds from threatened plant species, has successfully stored seeds from three-quarters of Western Australia's threatened plant species – many of them trees and other woody species. The centre has also reintroduced more than 50 threatened species back into the wild. CSIRO's Australian Tree Seed Centre maintains a national *ex situ* seed collection of more than 900 tree species, while the Southern Tree Breeding Association contributes significantly to *ex situ* conservation through provenance and progeny trials for multiple tree species.

New Caledonia (France) has developed a small number of clonal archives and seed orchards of unique endemic species of Araucariaceae.

Papua New Guinea has a national tree seed centre that stores seed for research, reforestation and export.

Solomon Islands reports that 30 000 plant specimens transferred from its National Herbarium to Fiji during civil unrest in 1999–2000 have not yet been returned.

Constraints for *ex situ* conservation in the region include limitations in, or lack of, research, national policies and strategies, funding, facilities, public education and training for staff, as well as land tenure issues. Future priorities identified in the country reports include staff training, involvement and engagement of rural communities; funding commitments; external collaboration with funding agencies; assessment of the state of endangered species; development and upgrading of facilities; and expansion of collections and field trials.

**Species conserved.** Only Australia and Papua New Guinea report data on species under *ex situ* conservation. In Australia, well represented genera and species include eucalypts in the genera *Angophora, Corymbia* and *Eucalyptus* (900 species in seed banks and arboreta), *Acacia auriculiformis* (780 accessions in seed banks), *Araucaria cunninghamii* (800 clones and 400 families planted in field), *Khaya senegalensis* (150 clones and 80 provenances in seed banks) and *Pinus radiata* (916 clones and 772 seed accessions).

In Papua New Guinea, 200 field stands containing 107 accessions have been established for five native species (*Acacia crassicarpa, Acacia mangium, Araucaria cunninghamii, Araucaria hunsteinii* and *Eucalyptus deglupta*) and one exotic species (*Tectona grandis*). Seven clone banks contain 114 clones of these species.

## Chapter 14

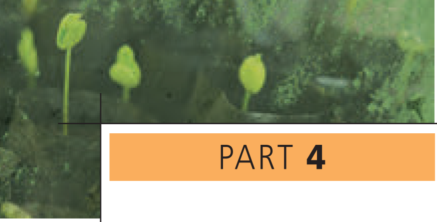
# Genetic improvement and breeding programmes

Tree breeding programmes have the potential to improve the production of planted forests and trees in a sustainable way and are necessary to meet growing global demand for forest products and services. More extensive development of forest industries based on planted forests using diverse, improved tree germplasm has the potential to meet a large proportion of the world's wood requirements and relieve pressures on natural forests. For example, timber plantations growing at 10 to 20 $m^3$ per hectare per year and covering an area equivalent to 2.5 to 5 percent of the world's forests would be capable of producing 2 billion cubic metres, meeting much of the expected global demand for roundwood projected for 2030 (Carle and Holmgren, 2008).

At the national level, ongoing tree breeding is needed to support planted forest development to help meet the export and local demands for forest products. This is especially the case in countries where harvesting in natural forests is occurring at unsustainable rates or is highly restricted or banned, and in those countries where natural production forests are limited in area and/or low yielding. Tree breeding is also essential to address new challenges associated with climate change and emerging pests and diseases.

Trees have been the subject of informal selection, breeding and movement for centuries if not millennia, with traditional domestication efforts mainly focused on edible fruit- and nut-trees. Informally improved trees have contributed in a significant way to livelihoods in many countries, although the benefit attributable to improvement is difficult to quantify. The past two to three decades have seen growing interest in domestication and less intensive improvement programmes for a wider range of multipurpose and food-tree species, often of native origin. For example, Brazil describes a successful programme in which wild races of *Bactris gasipaes* (peach palm) were bred and distributed to over 80 percent of the Latin American farms that grow this high-value product. ICRAF's tree domestication programmes with national partners in sub-Saharan Africa, Southeast Asia and Latin America focus on improvement of agroforestry tree products (AFTPs) such as charcoal, fodder, fruits and nuts, oils and medicines.

For much of the second half of the twentieth century, tree breeding and genetic improvement focused on species for commercial production of timber and pulpwood, and on improving a relatively small number of traits that would maximize economic gains (including growth rate, volume, form, processing and product quality). The focus on commercial species was related to the high costs involved in undertaking a comprehensive breeding rogramme, the specialist expertise needed, and the typically long periods before benefits are realized (of the order of several decades in cooler climates). The productivity gains and increased commercial returns of plantations established with improved germplasm, however, more than compensated for the high costs involved in tree breeding programmes.



In recent decades government agencies and the private sector have subjected a wider range of tree species to domestication and formal breeding programmes to produce myriad goods including timber, pulp, fuelwood, fruit, nuts, oils, traditional medicines, dyes, resins, thatch, and other NWFPs, and to provide forest service functions. In addition, tree breeding efforts are increasingly focused on adaptability-related traits, for adaptation to predicted new climate regimes; for resistance to drought, fire, pests and diseases (see FAO, 2013c); and for use in forest restoration programmes. These breeding programmes are primarily initiated by public agencies. The United States of America reports several programmes of tree breeding for conservation and forest restoration; for example, to reintroduce species eliminated by disease, breeding programmes seek to confer disease resistance from selected wild individuals (see section on North American tree improvement activities below). In breeding for resistance, valuable knowledge is gained about the behaviour of introduced diseases and insect pests and about genetic options for control (Schlarbaum *et al*., 1997; Loo, 2009). Within identified genecological zones, inclusion of the broadest available range of genetic variability in direct-seeded or planting stock maximizes the opportunity for a species to reoccupy its former range, perform vital ecological services, and adapt for the future.

The change in the scope and role of tree selection and breeding programmes is a response to several factors, including:

- the scale and unpredictability of environmental change (including climate change, especially extreme climate events and interactions with pests and diseases);
- new demands and requirements for trees for food and nutritional security, environmental restoration and carbon sequestration to mitigate climate change.

It is increasingly recognized that selected improved tree germplasm needs to be generated and deployed with multiple objectives in mind, including human food, biofuels and environmental and ecological purposes. Adaptation characteristics that will be more sought after in some breeding programmes include improved drought resistance, resistance to and recovery from fire, and an ability to withstand hurricane-force winds at all stages during the development and life of a planted forest. It is further anticipated that the introduction of more diverse (in both inter- and intraspecific terms) and *a priori* better-adapted genetic material will increasingly be required in both natural and planted forests, because the rapid rate of climate change may exceed the ability of indigenous tree species and populations to respond to change through natural selection and/or migration.

Sweden notes that the success of ongoing and future breeding activities will in large part depend on the natural variability of FGR contained in wild populations and in existing breeding programmes and plantations; this underscores the importance of FGR conservation. Breeding programmes can also contribute to *ex situ* conservation; the United States of America remarks that “breeding programmes, by default, have *ex situ* conservation plantings in their seed orchards [and] progeny tests in addition to any seed stores”. However, breeding activities by themselves cannot be regarded as secure form of long-term *ex situ* conservation, since the facilities may be abandoned once the testing or breeding programme has been completed.

Almost ten years ago FAO reported that “The scale of forest genetics and tree improvement in the tropics is entirely inadequate, both in geographical distribution and species coverage, and bears no relation to its potential value and importance” (FAO, 2005b). This situation has not substantially changed, although native species are being gradually brought into improvement programmes in all regions.

## Improvement approaches

Successful and efficient tree breeding requires genetic characterization, whether through the use of growth and morphological characterizations (principally through field trials) or through the use of molecular markers and DNA characterization, as discussed in Chapter 11. The improvement process, described in Chapter 7, typically involves seed collection of a large number of individuals from native stands. Collection may be range wide for exotic tree species or more geographically focused to match climate and/or soil or if superior sources have already been identified. Seed collection is followed by provenance and progeny trials, from which phenotypic selections of plus trees are made and/or breeding values determined, followed by breeding, crossing and/or selection programmes based on different strategies depending on species, breeding objectives and resources available.

In tropical regions, *Eucalyptus* spp., *Tectona grandis* and several other species have been subjected to intensive selection and breeding and are now primarily clonally propagated. *Eucalyptus* breeding programmes in the tropics often focus on producing high-value hybrid clones either between species or between highly selected lines. The commercially important temperate eucalypt species are usually managed as seedling-based, pure species breeding populations, as clonal forestry is difficult in most temperate eucalypts. Most teak field trials are clonal because of the low seed production and the difficulty of conducting controlled crosses.

Increasingly sophisticated approaches and technologies are being applied to tree breeding to generate faster rates of gain, for example more statistically powerful trial and mating designs; combined index-based selection taking into account the economic weight, heritabilities and covariances of different traits; prediction of breeding values based on best linear unbiased prediction; improved management of breeding populations and maintenance of sublines to reduce risks of inbreeding; and promotion of earlier flowering and seed production. The complementary use of molecular markers and quantitative data is an important emerging trend (see Chapter 8).

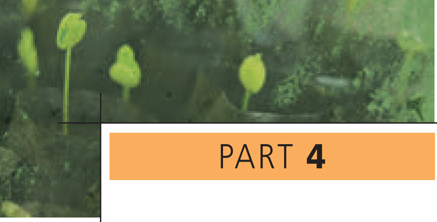
Hybrid breeding, involving interspecific hybrids and wide provenance crosses, is used in many countries to produce trees with superior productive capabilities (through heterosis) and also to introduce genes for disease resistance. Examples include eucalypt hybrids, *Larix* and *Populus* hybrids, *Pinus* hybrids and increasingly hybrids for diverse tree genera such as *Acacia, Casuarina, Fraxinus, Liriodendron, Prosopis* and *Santalum*.

As noted in Chapter 8, at the global level, relatively few attempts have been made to develop genetically modified or transgenic trees, mainly because of community concerns and associated legal restrictions and impediments to their development and use in Europe, the United States of America and elsewhere. In China transgenic poplars have been produced through incorporation of genes for insect resistance into hybrid poplars.

Some 15 years ago the FAO Panel of Experts on Forest Gene Resources (FAO, 1999b, 2001a) noted with concern the widening gap between science and practice, stressing that successful application of scientific knowledge was at risk if the science was too advanced to be understood and implemented at the operational level. This is increasingly the case today, with entire genomes now being sequenced for trees. Many developing countries lack skilled tree breeders who can understand and use the information generated by forest geneticists and ensure its application in practical, large-scale research, breeding and planting programmes.

## Administration and coordination of breeding and improvement programmes

Tree improvement is undertaken by different types of organizations in different countries. In Finland and Norway – countries with a major/and or diversified forest sector and market economy – national tree breeding programmes are funded by the government as a public service. In Germany, the government-funded forest research units of the states (Länder) are the main actors in forest tree breeding. In other countries breeding is undertaken by private forestry interests and independent academic and research institutions.



The benefits of tree improvement programmes accrue over very long periods; thus to realize these benefits, national and local security is vital, as is a favourable investment environment and stable global and national economies with assured demand for forest products. National governments have essential roles in these areas. Where tree improvement programmes are publicly funded, broad political support is necessary to ensure that they reach fruition and are either maintained by the government or adopted by the private sector. For a private company to engage in improvement work, it must have a sufficient planting programme to justify the required long-term investment. Private companies and others need to be able to protect the intellectual property resulting from their breeding work, through patents and plant variety rights. As reported by Germany, however, patents do not play a significant role for FGR. Legally binding and firm agreements for benefit sharing are necessary (see section on benefit sharing in Chapter 15).

Coordination and documentation of tree breeding efforts are important at the national level. Brazil, for example, reports that the Instituto de Pesquisas e Estudos Florestais (Forestry Science and Research Institute, IPEF), associated with the University of São Paulo, "is leading an effort to 'rescue' most of the information scattered all over the country regarding genetic improvement programmes for *Eucalyptus*, pine and other exotic tree species" – programmes that have been carried out since the 1970s.

Collaborative tree breeding programmes are most well developed in North America. The United States of America, for example, has 43 cooperative breeding programmes working with 31 species. Camcore, a tree breeding organization based in the United States, also operates internationally. Collaboration is also strong for commercial species in Australia and New Zealand. With the decline of public funding, where private companies once participated in coordinated national programmes, they may now be likely to participate in breeding cooperatives.

In most countries, full realization of the benefits of tree improvement will require national information systems and better coordination among all actors – among and within government agencies and departments (especially departments of forestry, agriculture and environment), research institutes and universities and the private sector. A national FGR strategy has a paramount role in coordinating these actors; furthermore, national FGR strategies need to be coordinated with strategies in forestry, agriculture and development.

It is evident from several country reports that governments tend to allocate more resources to breeding of conventional agricultural crops than to breeding of forest trees. With few exceptions, tree breeding is administratively separate from agricultural breeding. However, forest foods and tree crops are extremely important for many people around the world, often providing vital nutrition and sustenance when other crops fail because of drought, other environmental stress or sociopolitical disruption. A number of countries in Central Asia and the Near East harbour progenitors or wild relatives of important food-tree species, and these are vital FGR for food security. Closer cooperation between agriculture and forestry might thus provide opportunities for breeding improved trees for a wide range of uses, particularly on farms and in rural communities, to alleviate rural poverty and hunger and to increase food security. There is considerable scope for greater collaboration among individual tree farmers practising improvement for edible fruit and nut bearing trees, through better networking and sharing of germplasm, information, technologies and other resources.

A major avenue for international collaboration in tree improvement is through sharing of genetic resources, especially for those species whose distributions cut across national boundaries. In certain situations it may also be possible to contract out tree improvement activities to other countries (breeding cooperatives and/or companies), as long as genotype × environment interactions are demonstrated to be limited. A country must have a high level of confidence to entrust the development of its unique genetic resources to another country, because of perceived or real risks of losing control of the process and not receiving a fair share of the benefits flowing from improvement. This underscores the vital role of agreements that are firm, enforceable and fair between parties engaging in such arrangements (see section on benefit sharing in Chapter 15).

## Prioritizing uses, traits and species for improvement

The selection of traits and species for improvement should reflect the demand for forest products, the needs of their users and the country's rural communities, and the goals set out in the national development and forestry strategies and of course the national FGR strategy. Where countries lack these documents or the objectives are not explicit, these decisions may be made within government departments or research and tree improvement institutes. Changes in demand for forest products must also be considered; China notes the importance of responding to market signals. The extremely long time frame of breeding programmes can be problematic, however, when it comes to responding to changes in demand for forest products and services. To respond to the increasing demand for wood as a sustainable energy source to mitigate climate change, for example, Germany has developed intensive improvement programmes to breed trees for energy production, with a particular focus on rapidly growing species harvested on short rotation.

With shrinking public funding for breeding programmes, private companies are increasingly pursuing their own research priorities; the private sector tends to be guided by potential for commercial gain and is not bound by tests of public benefit in its selection of traits and species for improvement.

Many countries import improved genetic materials for evaluation and further breeding, which may involve adapting them to local conditions. At least 25 North American tree species have been introduced, tested and improved in other countries for commercial use (Rogers and Ledig, 1996) (see example in Box 14.1). Imported materials are usually exotic species but may include species indigenous to the importing country (particularly if the species is widely distributed).

A relatively small number of commercially important plantation species, e.g. acacias, eucalypts, pines, poplars and teak, are used widely around the globe and are the focus of many breeding programmes internationally (Figure 14.1).

### Box 14.1

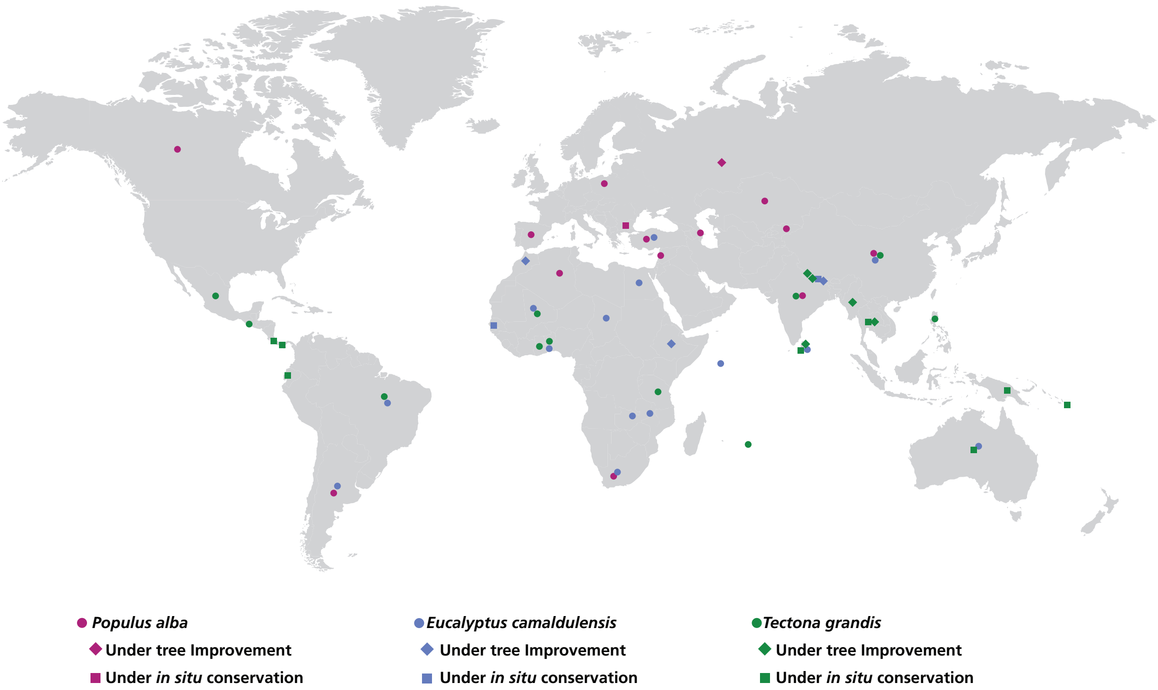
### *Pinus radiata* – a species improved outside its native range

The North American species *Pinus radiata* occurs only as five small populations in its natural range. It has not been planted commercially in North America but has become a highly important timber species in other countries (Cope, 1993). In its native range it is used for ornamental purposes, erosion control and fuelwood, but it is not considered to have commercial value for timber because of its typical poor crown form.

*Pinus radiata* was first introduced into Australia for ornamental plantings around 1857 (Wu *et al*., 2007), and its rapid growth led to its use in planted forests beginning in the 1920s. Through selection and breeding programmes in countries where the species has been introduced, its productivity and stem and crown form have been significantly improved. Indeed *P. radiata* has become one of the most widely planted pine species for timber.

**FIGURE 14.1**

Most common species in tree improvement and conservation programmes worldwide



Environmental parameters changing in response to climate change will require planting stock adapted to new conditions. Several countries observe that their breeding programmes will increasingly need to focus on survivability, drought and fire resistance, and resistance to pests and diseases that may become more prevalent under climate change. Breeding for adaptation to climate change is increasingly considered a high priority.

Many developing countries have not yet properly explored their indigenous tree flora for domestication and improvement; the United Republic of Tanzania, for example, reports that indigenous species have generally been neglected in favour of tried and tested exotic species (as cited in Chapters 10 and 12). Likewise, Seychelles has an extremely rich endemic tree flora, with many excellent timber species that have not been investigated for their forestry potential; the country has focused instead on importing exotic species. Many developing countries contain large areas of natural forest providing extensive reservoirs of tree genetic diversity with potential for development for human use. National forest agencies are increasingly keen to explore such diversity through domestication and improvement of local or indigenous tree species. International donors and research partners are also increasingly supporting this approach, desiring to promote indigenous species that are already adapted and well known by local communities and to contribute to biodiversity conservation objectives while avoiding risks associated with possible invasive behaviour of exotic species.

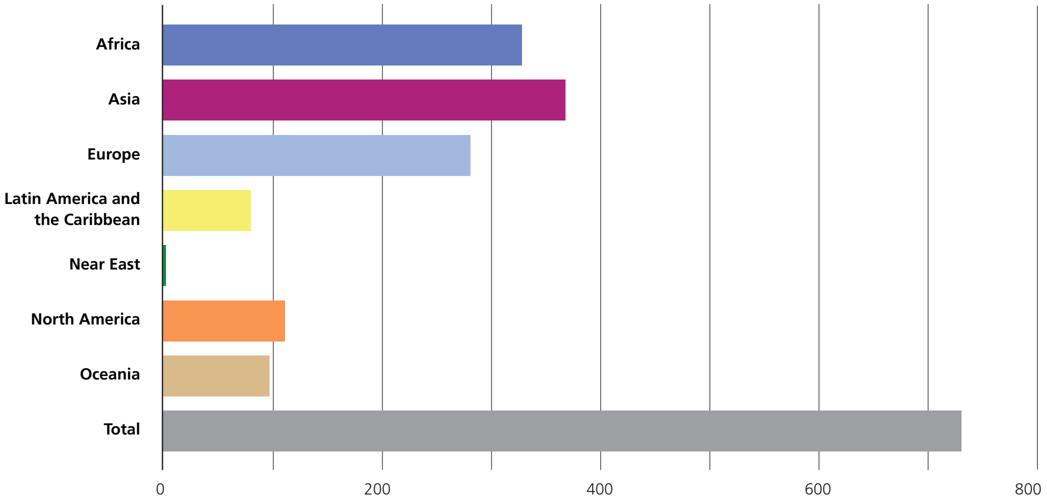
Domestication and improvement programmes can deliver long-term economic and other benefits and when appropriately designed can help to ensure conservation of genetic diversity. However, smaller countries often lack the resources or capacity to conduct their own domestication and improvement programmes even for important local tree species. Some countries have limited or no local forest industries and rely instead on imports or minor local harvesting to meet their needs. Cyprus, for example, has no forest industry because of low growth rates; its forests are conserved for environmental protection. Countries lacking improvement programmes include almost all of the 52 small island developing States (SIDS) in the Caribbean, Indian and Pacific Oceans – although some SIDS in Oceania have or have had collaborative tree improvement or domestication programmes, e.g. with CIRAD-Forêt, CSIRO/ACIAR and the Australian SPRIG project. Seychelles, with its small population and limited resources in terms of expertise, infrastructure and financial support, has no breeding programme for trees but rather conducts "adaptive screening" of imported materials (e.g. mango and avocado). Several other countries without domestication or breeding programmes import improved material, generally high-performing, high-value exotic industrial forestry species for which germplasm is readily available.

## The state of tree improvement and species priorities by region

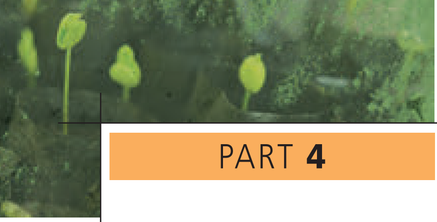
More than 700 species are the subject of improvement efforts around the world (Figure 14.2). Improvement programmes described in the country reports are presented here.

**FIGURE 14.2**

Number of species and subspecies in improvement programmes, by region



Note: Numbers for Europe may be high owing to the inclusion of a number of territories in tropical regions.



## Africa

Tree improvement has a long history in some African countries, including Kenya, Morocco, South Africa and Zimbabwe. One of the world's earliest breeding programmes for a broadleaved tree was for *Acacia mearnsii* in South Africa; it was initiated more than 60 years ago (Dunlop *et al.*, 2003).

The objectives of African programmes were initially to improve tannin yields, growth and gummosis resistance, then to improve wood properties and most recently to breed for sterility in future plantations to reduce invasiveness risk (with a 2015 target). A number of the earliest tree improvement activities were undertaken with the assistance of the United Kingdom (official development assistance and the Oxford Forestry Institute) and France (Centre technique forestier tropical [CTFT]); these programmes mainly focused on exotic timber species to be developed for industrial forestry plantations. *Eucalyptus* and *Pinus* species dominated, and still do today.

Tree improvement typically requires sustained support and often considerable capital injections; consequently some improvement programmes initiated in Africa many decades ago with European support are no longer operational, while smaller countries such as Burundi and Seychelles have no tree improvement programmes. Zimbabwe's tree improvement programmes for exotic industrial species, which had delivered impressive gains (e.g. cumulative volume gain of up to 45 percent in third-generation selections of *Pinus patula* over the original wild material), are being reactivated owing to improved economic circumstances.

Most tree improvement programmes in Africa use traditional and modern breeding approaches involving provenance testing, plus-tree selection, family and/or progeny trials, open pollination and/or hand cross-pollination, recurrent selection and multiple breeding populations and breeding indexes for multiple-trait improvement.

Over the past two decades many sub-Saharan African countries have increased their focus on improving many and diverse local multipurpose species, often traditional food trees. These programmes often involve collaboration between national agencies and ICRAF and may involve local communities in a participatory process of selection and breeding.

Some species under improvement in more than one African country are as follows.

- Eleven African countries have improvement programmes for *Eucalyptus* species, notably *E. camaldulensis* and *E. grandis* in eight and seven countries respectively, as well as *E. globulus, E. tereticornis* and *E. urophylla*.
- *Pinus* improvement is reported in eight countries; the main species are *P. caribaea, P. elliottii, P. oocarpa, P. brutia* and *P. halepensis*.
- Other exotic timber-producing species undergoing improvement in several African countries include *Tectona grandis, Cupressus* spp., *Acacia auriculiformis, Azadirachta indica* and *Grevillea robusta*.
- Native timber trees under improvement in more than one country include *Khaya* spp., *Milicia excelsa* and *Terminalia superba*.
- Multipurpose and NWFP trees (including those providing food and medicinal products) under improvement in more than one country include *Acacia senegal, Adansonia digitata, Detarium* spp., *Irvingia gabonensis, Parkia biglobosa, Sclerocarya birrea, Tamarindus indica, Vitellaria paradoxa* and *Ziziphus mauritiana*.

## Asia

The Asia region has a great diversity of tree improvement programmes and species for improvement which vary depending on the subregion, level of development and other factors. China, India, Japan and Thailand have well developed and comprehensive improvement programmes.

China has a vast tree improvement programme including more than 100 mainly native species, principally being improved for wood production. An example is the improvement of the native conifer *Cunninghamia lanceolata* which has involved trials of more than 200 provenances in nine regions and resulted in an average gain in wood production of 16 percent. China reports:

> "Significant gains have been achieved due to the use of genetically improved plant materials in plantations, achieving an average growth gain of 10 to 30 percent for timber trees and an average yield gain of 15 to 68 percent for fruit-trees. … The average growth gain of improved timber trees was more than 10 percent, and the average yield gain of improved economic trees was more than 15 percent."

India has ongoing programmes to improve more than 140 species, mainly native. However, most plantations are established with *Acacia* spp., *Casuarina* spp., *Cedrus deodara, Eucalyptus* spp., *Gmelina arborea, Grevillea robusta, Pinus roxburghii, Pinus wallichiana, Shorea robusta* and *Tectona grandis*. While the focus for most species in improvement programmes is wood production, a substantial number of species are bred for fuel production, multiple uses and NWFPs.

Japan's tree breeding programmes commenced more than 60 ago and aim to increase productivity and sawn timber quality for the major planted native conifers: *Abies sachalinensis, Chamaecyparis obtusa, Cryptomeria japonica, Larix kaempferi* and *Picea glehni.* The largest programme is for *C. japonica,* with breeding conducted in four regions and based on 500 to 1 000 selected individuals per region.

The Republic of Korea's tree improvement activities have mainly focused on plus-tree selection (2 724 trees of 28 species) and seed-orchard development (59 species, including 16 gymnosperms covering 734 ha). The main focus has been on native species, particularly the major planted species, *Pinus densiflora* (now into the second generation of improvement), *Pinus koraiensis* and *P. thunbergia*.

Thailand also has a long and successful history of tree breeding developed through collaboration with Denmark (the DANIDA Forest Seed Centre) for improvement of teak and pines. Over the past three decades Thailand has also collaborated with Australia (the CSIRO Australian Tree Seed Centre) for improvement of *Acacia, Casuarina, Chukrasia* and *Eucalyptus* species. Major improvement effort has been on the two main planted timber trees, teak (*Tectona grandis*) and *Eucalyptus camaldulensis.* Improvement of the latter species, and its hybrids, has involved improving form and growth rates, then disease resistance and most recently pulpwood traits, increasingly with involvement of the private sector and clonal registration.

*Eucalyptus* is an important genus for improvement in the region, with programmes reported in eight countries involving many species including *E. camaldulensis, E. globulus, E. pellita, E. tereticornis* and *E. urophylla*.

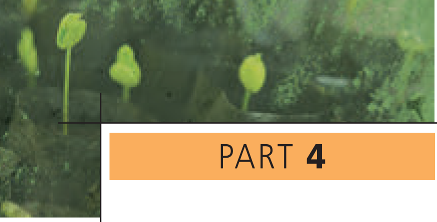
*Pinus* species are also widely planted in Asia, with more than ten different species undergoing improvement in seven Asian countries.

*Tectona grandis* improvement is being undertaken in seven countries in the region, including three in which it is native (India, Myanmar and Thailand).

Other species undergoing improvement in several Asian countries include:

- several high-value timber species in the genera *Pterocarpus* and *Dalbergia*, undergoing improvement in five and three countries, respectively;
- *Gmelina arborea* and *Acacia* species (especially *A. auriculiformis, A. mangium* and their hybrid), important industrial plantation timber species that are in improvement programmes in four countries each;
- mainly Asian timber and NWFP species: *Albizia* spp., *Azadirachta indica, Casuarina* spp., *Magnolia* spp., *Phyllanthus emblica* and *Santalum album*.

*Populus* species and hybrids are being improved in China, India and Kazakhstan, both for wood and for bioenergy. *Populus euphratica* has notable climatic and ecological amplitude which



is increasingly being exploited for restoration programmes. In China and Uzbekistan certain salt-tolerant *Haloxylon* species are also being improved for restoration plantings.

Improvement programmes in Central Asia are often focused on fruit- and nut-trees and their wild relatives in the genera *Juglans, Malus, Pistacia, Prunus* and *Pyrus*.

## Europe

With the exception of Switzerland, all reporting European countries have tree improvement programmes, although in some cases they are limited or only recently initiated. Northern European countries have the most advanced breeding programmes; the most comprehensive programmes are detailed by Finland, France, Germany and Sweden. These activities are mainly for timber and pulpwood species. The main species undergoing improvement in Northern and Central Europe are *Pinus sylvestris* and *Picea abies*; 11 or more countries report programmes for each of these conifers. According to country reports, at least 25 other native conifer and broadleaf species are subject to improvement, but some of the species are in the beginning stages of selection and breeding. Most of the efforts are on improving productivity, wood quality and environmental adaptation, particularly in view of climate change. Only a few European countries mention breeding for pest resistance; the Netherlands, for example, notes that in addition to selection for adaptation to site conditions, considering survival and bud burst, trees are also selected for resistance to pests and diseases.

Several European countries have breeding programmes for Christmas trees and other NWFPs. In addition to improving trees for timber and pulp, almost half the countries in the region report improvement programmes for tree species used for energy. Genotypes of several species are also being tested in the Netherlands for non-forestry purposes such as their performance as roadside trees. The existence of breeding programmes focusing on such a diverse range of species and traits implies a substantial body of knowledge about genetic variation and heritability.

In Finland, breeding is managed by the Finnish Forest Research Institute. Activities are carried out in six regions and focus on improving productivity, wood quality and improved climatic adaptation in the two main native timber species, *Pinus sylvestris* and *Picea abies*. Together these two species comprise over 90 percent of Finland's annual reforestation area.

The Russian Federation adopted State programmes and guidelines on forest improvement through breeding from the 1960s to the 1980s. The Central Research Institute of Forest Genetics and Breeding was established in 1971 and has subsequently directed the country's breeding and genetic studies and coordinated the work carried out by research institutions in different regions of the country. Provenance trials (mean age of 40 years) and many years of research have contributed to a broad body of knowledge. Pine trees, in particular *Pinus sibirica*, have been selected and bred for resin productivity and nut yield.

Sweden's comprehensive breeding programmes involve intensive plus-tree selection in collaboration with forest owners, large-scale controlled crossings and evaluations, with 7 to 24 breeding populations for each major species. The large impact of the tree improvement work is indicated by the projected annual increase of 10 million cubic metres of wood from planted improved germplasm of *Picea abies* and *Pinus sylvestris*.

Other coniferous species included in breeding programmes in at least two or three countries in Europe include *Larix* spp. (five countries), the North American species *Pseudotsuga menziesii* (six countries), *Abies* spp., *Cedrus* spp. and *Taxus baccata.* Species in many broadleaf genera are also being improved in several countries, mainly for increased timber production but also for bioenergy and environmental services. *Betula* spp. (mainly *B. pendula*), *Fagus* spp. (mainly *F. sylvatica*), *Populus* spp. (especially interspecific hybrids) and *Quercus* spp. (mainly *Q. petraea*), each in six countries; *Prunus avium* in five countries; and *Alnus glutinosa, Fraxinus excelsior*, *Juglans regia* and *Ulmus* spp., each in four countries.

A different suite of species is under improvement in Mediterranean countries, including more drought-tolerant trees in the genus *Pinus* (*P. brutia, P. halepensis* and *P. pinaster*) and *Quercus suber.*

Most of the tree species included in breeding programmes in Europe are native to Europe and to the countries where breeding efforts are under way; however, about one-third of the tree species under improvement are exotic in the reporting countries. In some cases these species originated from North America or other parts of Europe. Knowledge gained about the performance of these species outside their native range may also be useful within their native range, particularly in matching seed sources to novel environmental conditions.

France's tree improvement programmes include long-distance interspecific hybrids in three genera, *Larix* (hybrids between European and Japanese species), *Populus* (hybrids between European and North American species), and *Juglans* (hybrids between European and North American species); these activities highlight the continuing importance of germplasm exchange for tree improvement programmes in the Northern Hemisphere.

Apart from these activities in the region, it should also be noted that the contributions of the DANIDA Forest Seed Centre in Denmark and of donors, tree breeders and geneticists in European countries (especially Finland, France, Germany and the United Kingdom) have greatly assisted development of tree improvement programmes throughout the developing tropics over the past 40 years.

## Latin America and the Caribbean

Well developed tree improvement programmes are found throughout Latin America, especially for species in the industrial plantation genera *Eucalyptus* and *Pinus*. Several smaller countries do not have improvement programmes and may rely on importation of improved genetic materials, for example for species in the genera *Eucalyptus, Pinus* and *Tectona*.

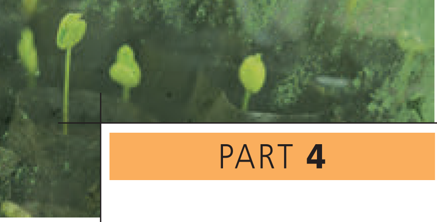
Brazil's improvement programme for *Eucalyptus* species, based on considerable species and provenance selection work, family evaluation and hybrid development, is especially noteworthy. This work has resulted in some of the fastest-growing plantation trees in the world: Individual clones of *E. urophylla* × *E. grandis* grow more than 100 m$^3$ per hectare per year.

Genetic improvement programmes underpin Brazil's 5 million hectare eucalypt plantation industry, and the commercial benefits of this improved material are immense:

> "Brazil is … one of the main pulp and paper producers in the world and a sector reference in terms of sustainable pulpwood production, which is 100 percent harvested from planted forests, mainly eucalyptus and pine. The productivity of these planted forests is the highest among all pulp producers in the market, with an annual average growth of 41 m$^3$ per hectare per year for eucalyptus and 35 m$^3$ per hectare per year for pine plantations. This is the result of 30 years of a successful research development and transfer process in a country where the climate is very favourable and private research institutes work… integrated with researchers in universities to generate genetically improved material and advanced silvicultural treatments."

Several other countries in the region also have *Eucalyptus* improvement programmes, not only for *E. grandis* and *E. urophylla* but also for *E. camaldulensis, E. globulus, E. nitens, E. tereticornis* and hybrid combinations as well as for several other eucalypt species such as *Corymbia maculata* in Peru and *Eucalyptus dunnii* in Argentina.

Several Central and South American countries have major improvement programmes for *Pinus* species. The largest programme is for *Pinus*



*radiata* in Chile, initiated over 40 years ago and now into its third or fourth generation, involving more than 1 300 trials (including other *Pinus* species, notably *P. ponderosa*). Argentina's pine breeding efforts are focused on the two main planted species, *P. elliottii* and *P. taeda,* and their hybrids. Germplasm collected in Guatemala from several *Pinus* spp. (*P. caribaea* var. *hondurensis, P. maximinoi, P. oocarpa* and *P. tecunumanii*) has been subjected to breeding by Camcore outside Guatemala; this material and associated information are now being used for pine breeding in Guatemala.

For species in other genera, the main focus in tropical Latin America has been on fast-growing exotic timber trees such as *Acacia mangium, Gmelina arborea, Grevillea robusta, Hevea brasiliensis* (in Mexico), *Tectona grandis* and *Terminalia* spp. Some countries (Argentina, Chile) also have improvement programmes for *Populus* species and hybrids; *Salix* and *Populus* species are tested for pulp and paper. Some Latin American countries employ only exotic tree species for commercial production. In such cases, breeding programmes are designed to increase the adaptedness of selected genotypes to local environmental conditions and improve their productivity.

A more recent trend has been the development of improvement programmes for diverse native species. A host of tropical American timber species now feature in improvement programmes in Costa Rica, Ecuador, Guatemala and Peru. These include: *Alchorneoides hieronyma, Alnus acuminata, Cabralea canjerana, Calycophyllum spruceanum, Cedrelinga cateniformis, Cordia alliodora, Dipteryx panamensis, Guazuma crinita, Jacaranda copaia, Ochroma pyramidale, Parkia multijuga, Roseodendron donnell-smithii, Schyzolobium* spp., *Swietenia macrophylla, Terminalia* spp. (including *T. amazonica*), *Virola* spp. and *Vochysia* spp. (including *V. guatemalensis*). Mexico's tree improvement programmes (which are substantial but mainly in the early stages) are based on the country's high forest biodiversity and focus mainly on native timber species: *Cedrela odorata, Cupressus lusitanica, Jatropha platyphylla,* six *Pinus* species (*P. douglasiana, P. greggii, P. leiophylla, P. oocarpa, P. patula* and *P. pseudostrobus*), *Swietenia macrophylla* and *Taxus globosa*. In Chile four *Nothofagus* species and *Laurelia sempervirens* are undergoing improvement, while in Argentina the focus for improvement of native timber species is again *Nothofagus* spp. (*N. nervosa* and *N. obliqua*) as well as *Prosopis* spp. (*P. chilensis* and *P. flexuosa*), the latter not only for timber but also for recovery of degraded lands.

In Brazil and Peru one focus has been on indigenous fruit-trees – especially in the families Myrtaceae (e.g. *Acca* spp., *Campomanesia* spp., *Eugenia* spp., *Myrcianthes* spp., *Myrciaria dubia* and *Psidium* spp.) and Arecaceae (e.g. *Bactris gasipaes* and *Butia* spp.) – but also including legumes (e.g. *Caesalpinia spinosa* and *Inga* spp.), custard apples (e.g. *Rollinia* spp.) and stone fruits *(Prunus serotina*).

Mexico reports the following uses of tree species that are undergoing improvement: food, essential oils, forage, gums and resins, Christmas trees, medicines, conservation and restoration.

## Near East

Tree breeding in the Near East region has been limited, which is surprising given the need and potential to improve environmental adaptability to arid environments. In the Islamic Republic of Iran improvement work is being conducted on *Fagus orientalis, Populus nigra* and its hybrids and *Quercus castanifolia* for various product traits (for timber, pulp and NWFP uses) and for resistance to environmental stresses such as drought and salinity.

Other species under improvement in the Near East include local acacias (*Acacia senegal, Acacia nilotica, Faidherbia albida*) and the exotics *Eucalyptus camaldulensis* for wood production and *Jatropha curcas* for biofuel.

## North America

North America has a long history of tree improvement (see Box 14.2) and highly developed programmes. Approximately 85 species are under some form of tree improvement at various stages. However, the most intensive breeding efforts have focused on just a few species, notably *Pinus taeda* and *Psuedotsuga menziezii*.

Canada has major active tree improvement and breeding programmes in nine of its ten provinces covering 40 species (of which 33 are native) in 13 genera and hybrid *Larix* and *Populus*. Key target species for improvement are native conifers for timber and pulp production including *Callitropis nootkatensis, Larix* spp., *Pinus* spp. (*P. banksiana, P. contorta* and P. *strobus*), *Picea* spp. (P. *glauca, P. mariana* and *P. sitchensis*), *Thuja plicata* and *Tsuga heterophylla*. First-generation programmes comprise more than 50 000 plus trees selected predominantly from the natural forest. Second-generation programmes are in place for 13 species, and breeding populations contain more than 9 000 selections from progeny tests and other tests. Third-generation selections have been made for *Pseudotsuga menziesii*.

## Box 14.2
## Early tree breeding programmes in Canada and the United States of America

Tree breeding programmes in North America began generating knowledge about a range of timber species in the mid-1900s. Exploration, testing and breeding of *Pseudotsuga menziesii* began in the 1950s in British Columbia, Canada (Orr-Ewing, 1962). Beginning in 1958, a breeding population was established with more than 200 *Pseudotsuga menziesii* sources from throughout its range in Canada and the United States of America as well as Mexico. The objective was to provide as wide a gene pool as possible for a breeding programme (Orr-Ewing, 1973). Samples of the other five *Pseudotsuga* species were established in the collection as well.

Early efforts in the United States also focused on *Pseudotsuga menziesii.* The first seed source studies were initiated in the northwest in 1912 in Wind River Experimental Forest, southern Oregon (Duffield, 1959); the tree improvement programmes began in the 1960s. Because of the topography and associated high environmental variation over short geographic distances, many small breeding programmes were initiated in North America. By the 1980s there were 125 separate breeding programmes for *Pseudotsuga menziesii* in Oregon and Washington in the United States and British Columbia in Canada (Johnson, 2000).

Species covered in subsequent testing and tree improvement projects in the Pacific Northwest of both countries include *Larix occidentalis, Picea* spp., *Pinus contorta, Pinus ponderosa, Thuja plicata* and *Tsuga heterophylla,* and to some degree *Chamaecyparis lawsoniana, Pinus lambertiana* and *Pinus monticola*.

Elsewhere in the United States, the foundation for tree improvement was laid in the 1920s and 1930s. The Placerville Institute of Forest Genetics in California was initiated in 1925 to improve forest growth through breeding. This private research institute was first focused on pines, and 49 *Pinus* species from many countries were planted in 1926. The most complete pine arboretum in the world was established there in 1931. In 1935, the institute was donated to the United States Forest Service, and it has been an important knowledge base for forest genetics research since that time (US Forest Service, n.d.).

In the early 1950s a tree improvement programme was initiated in eastern Texas, focusing on drought resistance and wood properties (Zobel, 2005). Tree improvement cooperatives were established in Texas in 1952, Florida in 1954 and North Carolina in 1956, and programmes developed rapidly during the rest of the century.

Before 1960, no genetically improved seed was available and all seedlings for planting were produced from seed collected in the forest, with little control over quality (Dorman, 1974). By the mid-1970s, much of the seed used for tree planting in the southern United States was from genetically improved seed orchards.

The United States of America has an exceptionally well developed tree improvement programme with at least 150 public or cooperative breeding programmes representing over 70 species. However, more than 50 percent of the improved seedlings are just two *Pinus* species: *P. elliotti* and *P. taeda* (McKeand et *al*., 2007).

Some 66 of the country's breeding programmes involve 14 *Pinus* species; those appearing most frequently (in from four to eleven programmes each) are *P. elliottii, P. palustris, P. ponderosa, P. rigida, P. strobus* and *P. taeda*). Other coniferous species with many improvement programmes (three to seven each) include *Abies* spp., *Larix* spp., *Picea* spp. and *Pseudotsuga menziesii*.

Among broadleaves, the most breeding effort is focused on *Quercus* spp. (18 programmes for seven species, including six programmes on *Q. rubra*) and *Juglans* spp. (a total of 12 programmes for *J. cinerea* and *J. nigra*).

Many breeding programmes are part of the United States Department of Agriculture (USDA) Forest Service or are based in universities, which often lead the cooperative breeding programmes. These tree improvement programmes involve traditional techniques, often pioneered in the United States, and the whole array of modern breeding approaches and biotechnologies, including genetic engineering. Some of the most advanced tree improvement programmes are in the United States; for example, Neale and Ingvarsson (2008) reported that more than 11.5 million progeny from more than 41 000 parent trees had been tested in just four conifer programmes, of which two were in the third generation of testing and breeding at the time of their report.

The United States also has breeding programmes focused on conservation and forest restoration for several species. For example, *Castanea dentata* and *Ulmus americana* have both been severely depleted by introduced diseases – chestnut blight and Dutch elm disease, respectively (see Box 5.3 in Chapter 5). In each case the primary breeding objective is to develop disease-resistant genotypes. Wild individuals resistant to these diseases are identified, selected, and used in breeding programmes to introduce the genes conferring resistance.

## Oceania

In Australia, tree improvement and propagation programmes are highly developed and variously undertaken and managed by government agencies (CSIRO and State departments), forest industries and/or cooperatives (e.g. the Southern Tree Breeding Association). These improvement programmes mostly rely on traditional methods of selection, breeding, improvement and propagation. Molecular markers are being developed and associated with traits of interest to accelerate selection of preferred varieties. Species currently under improvement include:

- native species for timber, poles and pulpwood, especially eucalypts (23 species of *Corymbia* and *Eucalyptus* and various hybrid combinations), native conifers (*Araucaria cunninghamii*), acacias (*A. crassicarpa* and *A. mangium*) and *Grevillea robusta*;
- essential oil species: *Backhousia citriodora, Eucalyptus polybractea* and other oil mallees, *Melaleuca alternifolia* and *Santalum album*;
- exotic timber trees: *Khaya senegalensis, Pinus* species (*P. brutia, P. caribaea* var. *hondurensis, P. elliottii, P. pinaster* and *P. radiata*) and *Tectona grandis*.

The larger island nations and territories in the region have established tree improvement programmes, often with assistance from Australian institutions (CSIRO and universities) and donors, and in the case of New Caledonia (France) from French institutes (CTFT and CIRAD). The species under improvement vary but are mainly highly valuable timbers such as the exotic *Swietenia macrophllya* in Fiji, native sandalwoods in Fiji, New Caledonia and Vanuatu, and multipurpose nut- and timber trees such as *Canarium* spp. and *Terminalia catappa* in Solomon Islands and Vanuatu. Fast-growing industrial species under improvement include *Ochroma* *pyramidale* (balsa) in Papua New Guinea and *Pinus caribaea* var. *hondurensis* in Fiji and New Caledonia.

A worthy example is the spectacular improvement of *Tectona grandis* that has taken place in Solomon Islands in a short period through intensive screening of teak stands in the early 1990s, grafting of 50 selected phenotypes and use of seed from this clonal archive for production purposes. This teak material is now being widely used globally, including through selections supplied to Malaysia.

Solomon Islands reports that through the Australia-funded SPRIG project, improvement activities have extended to promising indigenous timber species including *Cordia subcordata, Gmelina moluccana, Pterocarpus indicus, Terminalia catappa* and *Vitex cofassus*. In Papua New Guinea, collaboration with international and regional agencies and donor support (e.g. an ACIAR funded collaborative project between the Papua New Guinea Forest Research Institute [PNGFRI] and CSIRO) have been vital for seed collection, provenance trials, seed orchards and tree improvement.

## International collaboration and donor programmes for tree improvement

International collaboration includes networks, commercial exchange, partnership with academic and research institutes and donor assistance. Donor programmes may assist establishment of improvement programmes within a country; this support may be especially beneficial where improvement is targeted at rural communities and others whom the private sector may not serve adequately.

Regional coordination and cooperation is especially vital where species and biogeographic and genecological zones are shared. Many countries note the central role of international species networks (for poplars, teak, neem and casuarina) coordinated by FAO and IUFRO. Several countries acknowledge the vital role of Camcore in the development of improved exotic plantation species through the sharing of germplasm. Camcore has been a leader in establishing trials and generating data on conifers from Central America, with an initial focus on *Pinus* species that were of interest for planting in other regions. Examples include *P. caribea, P. patula* and P. *tecunumanii* (Dvorak, Donahue and Hodge, 1996). Many of the trials, which also serve *ex situ* conservation, are located in tropical or subtropical countries. The knowledge gained from these testing efforts is now also useful in selecting provenances or families for planting in the species' natural range.

## A cautionary note: potential threats to FGR from breeding and improvement programmes

While the benefits of commercial genetic improvement programmes are profound and vital for meeting the ever-increasing global demand for forest products, breeding programmes also have potential to affect FGR in a negative way if they are not managed well. The most significant issue is the loss of genetic variation in improved tree stock which is then widely distributed, potentially around the globe. Sweden notes that "forest tree breeding may in the long run result in decreased genetic variation in the production forest. Even though single stands may have somewhat higher genetic variation, genetic diversity will likely on the landscape level be lower than in conspecific natural populations."

Clonal plantation forestry is regarded as the most genetically impoverished industrial forest option, especially where the entire plantation is derived from only one or a very small number of clones. Concentration on one or a few economically important trees in plantations (as in Ghana, where 90 percent of plantations comprise only three species) can also contribute to loss of FGR. Lack of diversity, especially through clonal forestry, also exposes both planted and natural forests to pest and disease epidemics, as the homogenous feedstock provides an opportunity for pests and pathogens to become specialized and dramatically increase in numbers.

## Chapter 15

# Germplasm delivery and deployment

The production, distribution and deployment of germplasm and planting materials are critical to the continued global supply of FGR-derived goods, to the development of forest industries and to programmes for FGR, biodiversity conservation and environmental restoration. It is estimated that planted forests account for 7 percent of the world's forest area yet produce over 50 percent of the world's industrial timber (FAO, 2010a); further forest plantings, particularly using improved germplasm, will help satisfy burgeoning global demand while reducing harvest pressure on natural forests. As noted by China in its country report, "the ultimate goal of FGR conservation is to utilize these resources, and to bring economic, ecological and social benefits"; the United States of America similarly remarks "if germplasm is not readily available for use, resources expended to preserve it will be wasted".

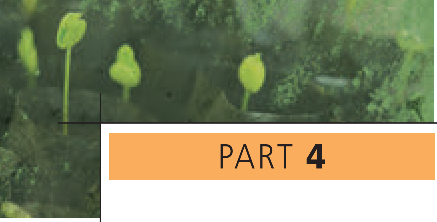
## Uses of germplasm and plant materials

Genetically appropriate germplasm is used as a base for propagating planting materials for the wide range of uses of planted forests and on-farm and other *circa situm* plantings, including timber and pulp, agroforestry products, fodder, food and fuel. The deployment of germplasm with appropriate levels of variability is also an essential component of many FGR and biodiversity conservation programmes, as well as in environmental restoration programmes, research and development. Germplasm is transferred and exchanged within and between countries not only for planting, but also for propagation, research, genetic improvement, breeding, and conservation of FGR.

### Improved or unimproved germplasm

The germplasm and plant materials produced for deployment may be either genetically improved or not. For productive purposes, improved material from genetic improvement and selection programmes enables the delivery of larger amounts of desired benefits with fewer inputs, or better growth under less favourable environmental conditions. Programmes for FGR and biodiversity conservation and for environmental restoration may also benefit from intervention and breeding to enrich genetically impoverished remnants, or to introduce characteristics vital to the survival of threatened species; an example is the introduction of resistance to chestnut blight into North American chestnut (see section on North American improvement programmes in Chapter 14). By contrast, many programmes aimed at conservation of FGR require the inclusion of materials representing the fullest range of local genetic variability (while excluding importing germplasm from more distant provenances or other seed-transfer or genecological zones).

Plant materials used for commercial and utility plantings and plantations are largely derived from high-quality, improved, source-identifed seed and plant materials. In Chile, for example, about 95 percent of planted forests of exotic species are derived from improved material, while less than 2 percent of natural forests have some degree of genetic improvement. For the private sector, the



use of improved planting material is driven by the need to obtain an adequate return on investment by obtaining the highest yield for the lowest cost.

Countries with well developed genetic improvement programmes generally have relatively well developed methods of distributing and deploying their improved materials, whether in the private or public sector.

### Forms of germplasm

The form in which planting materials are delivered to end-users depends on the purpose of the planting programme, the characteristics of the germplasm, the nature of the planting situation, the method of propagation most suited to the species, the capacity for production of plant materials, and the capacity of the people or organization undertaking the planting.

The country reports indicate that material available for transfer, both within and between countries, is strongly dominated by seed (66 percent of the total). Seed is generally the most convenient and safest form for germplasm transfer; however, for some species seed is not suitable for collection, storage, propagation and/or distribution. Reasons include inaccessibility of collecting materials, intermittent seed production, lag time between improvement and seed production, difficulties in ensuring that progeny are true to type, limited storability (recalcitrant seeds), and lack of knowledge on propagation methods. Macro vegetative propagation methods (cuttings and micro cuttings) are commonly used for producing clones, and micropropagation techniques (tissue culture) are increasingly applied, although the cost and technical requirements of micropropagation are prohibitive for some countries. Nonetheless, industrial-scale production by micropropagation is being undertaken for some species of commercial interest or for large restoration purposes despite the high costs.

The predominance of seed as the most available form of germplasm suggests that distribution, deployment and perhaps even research and improvement may be skewed towards species that produce orthodox seed that can be transferred most conveniently and reliably – perhaps at the expense of other potentially useful species or species that require conservation.

## Demand for germplasm and planting materials

Countries vary greatly in the amount of germplasm and planting materials deployed, ranging from negligible (e.g. in many SIDS) to extremely high in countries with major planting programmes such as Brazil, China and Indonesia. Brazil, for example, planted 330 000 ha per year between 2005 and 2010 and has a huge demand for planting stock. Some countries note a paucity of information on demand for germplasm, although projected increases in demand for wood products invariably imply an increase in requirements and a shortfall in supply at current stocking and planting rates. National programmes requiring planting stock include planting programmes for forestry production, combating desertification, landscape-scale climate change adaptation and mitigation, environmental restoration and forest restoration in the wake of major infrastructure projects.

The approach to management of a country's production forests in large part determines the demand for germplasm and planting materials; for example, a forest industry based on plantings will deploy more germplasm and plants than one reliant on naturally regenerated forests. Several countries, especially in Asia (e.g. Samoa, Sri Lanka and Thailand), refrain completely or in large degree from harvesting their natural forests, deriving local timber from planted sources. In these countries, the demand for adapted and improved germplasm and planting materials is relatively high. Many countries, particularly in temperate and boreal regions, adopt hybrid management models involving a mixture of artificial and natural regeneration of natural forests as well as planted forests. For example, in Canada – the world's second largest exporter of wood products in 2012, behind China (Natural Resources Canada, 2013) – 349 000 ha of land were planted in 2011 and another 11 000 ha were seeded. In other countries, the availability of low-cost, high-quality timber resources in natural forests has served as a disincentive to invest in development of improved germplasm and planted forests; these countries have lower demand for germplasm and planting materials.

## Actors involved in production, distribution and deployment

In many countries vast amounts of tree seed and seedlings are produced from seed stands, seed orchards, nurseries and other facilities on public forest or land, with public-sector agencies and seed centres key in the exchange, delivery and deployment of germplasm. In some contexts the private sector is preeminent, generating large amounts of germplasm and plant materials for use in corporate plantation forestry. In most developing countries and some developed countries, small-scale seed collectors and producers, including community or village-level entities and individual landholders or farmers, also have important roles, producing tree germplasm and planting stock for their own use or for sale.

### Public sector

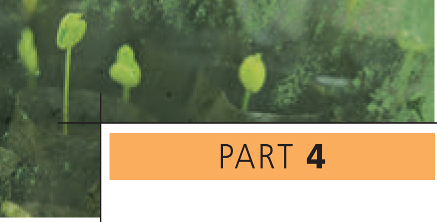
Public departments, agencies and corporations with remits in forestry, conservation and natural resource and land management may have a central role in the production, distribution and deployment of FGR materials. Country reports detail the involvement of the public sector in these activities for purposes of:

- conservation of FGR, including genetic diversity in threatened or potentially threatened species;
- research and tree improvement by local, national and international organizations (both public and private);
- supplying planting materials to government agencies, corporations, NGOs and individuals;
- forest plantation development on public land;
- environmental restoration programmes;
- advancing national development and other policy goals – e.g. poverty alleviation, food security, climate change mitigation, biodiversity conservation, environmental protection and both small- and large-scale industry development.

Public-sector involvement is thus consistent with the view expressed in China's report that the "collection and conservation of FGR is a basic, long-term, public welfare and strategic work". Public-sector involvement – including the ownership of forest resources and land used for collection of germplasm, the creation of seed orchards and the establishment of plantations – is especially important in developing countries where markets are poorly developed or do not function effectively (whether because of the type of political and economic system; the inability of commercial operators to generate income or capture rewards from the activity; the lack of regulatory, legal and financial infrastructure; or the lack of capital).

Foremost among the public agencies involved in germplasm delivery and deployment are the national tree seed centres (NTSCs) or their equivalents, which in many countries serve as primary agents for the collection, storage and distribution of forest tree germplasm to government forest and conservation agencies and to the private sector (including nurseries, forestry companies, NGOs, communities and farmers). NTSCs are also typically involved in regional and international transfer and exchange of germplasm. In addition, NTSCs may have central roles in *ex situ* conservation and improvement of FGR.

A number of countries report that public nursery facilities, either associated with NTSCs or attached to other public bodies, are significant producers of plant materials. NTSCs and public nurseries may also generate funds through local, regional or international sale of germplasm or plants, consultations and/or supply of contracted services to the private sector. For example, Madagascar's National Tree Seed Centre sells



60 percent of its production to the private sector and NGOs, and the rest to government agencies. Countries reporting that NTSCs currently have a major role in germplasm delivery and deployment include Australia, Burkina Faso, Ethiopia, Kenya, Madagascar, Nepal, Papua New Guinea, Sri Lanka and Zimbabwe. Guatemala's NTSC, on the other hand, cannot produce germplasm for commercial purposes under existing legislation, and many countries (including much of Africa and most SIDS) report that their NTSCs have inadequate facilities and support. Countries often report the need to increase the productive capacity of tree seed centres to meet existing and projected demand for germplasm.

Many public agricultural agencies have longstanding involvement in the production and distribution of improved plant materials – particularly in countries where native FGR include many progenitors of widely used fruit and nut trees, as in Western and Central Asia, or where food- or crop-bearing trees are important as cash crops or as contributors to food security. In some countries these agencies also develop and propagate trees to be used in agricultural applications, and they may also have a major role in the *ex situ* conservation of FGR. In some countries with meagre resources, these activities provide at least some level of *ex situ* conservation, storage and distribution of forest germplasm.

The public sector also has a vital role in developing policy governing germplasm development and deployment, for example:

- enacting laws and regulations governing germplasm collection, delivery and deployment;
- developing, implementing and enforcing standards, guidelines and protocols;
- mandating and overseeing certification schemes for the production, movement and exchange of forest germplasm and planting materials;
- facilitating and regulating private-sector involvement in FGR delivery and deployment, including facilitating and participating in organizations and associations concerned with germplasm delivery and deployment.

Finally, the public sector often has a role in increasing adoption of improved germplasm. In many countries the public bodies undertaking breeding and improvement, such as the NTSCs, research institutions and forest and agriculture departments, undertake activities in promotion, distribution, education and extension to ensure the deployment of their improved materials.

### Private sector

The private sector – including companies, from local to multinational; small-scale, village and community enterprises; farmers and landowners – is increasingly the primary actor in germplasm delivery and deployment. Private producers propagate and deploy vast amounts of germplasm and plant materials, generally for their own use or to supply contracts. In some instances the materials may be developed for sale on the open market; if the species are rare or threatened (e.g. some ornamental plants), their commercialization can have both positive and negative implications.

Private-sector participation in germplasm delivery and deployment can complement public efforts where the public sector has limited funding, political will, institutional capacity or remit or where it has difficulties engaging with market processes. Where markets operate effectively, the private sector can respond efficiently to market signals and demand for goods and services. Larger, particularly multinational, companies may have access to capital, technology and expertise that may be unavailable in developing countries; if managed appropriately, their activities can help advance national forestry, FGR conservation and other development agendas.

The private sector exercises a major influence on germplasm delivery and deployment through landownership. In many countries private corporations, small enterprises, communities, villages, families and individuals own or control significant proportions of the total land area.

Private land may be used for establishment of forest plantings of various kinds, in pursuit of commercial, environmental or biodiversity conservation outcomes. In other situations the private sector may access public land for collection of germplasm and establishment of plantations (e.g. in Australia and Indonesia). The landownership pattern helps determine the balance between public and private involvement in germplasm delivery and deployment and the manner in which these activities are conducted.

The private sector also contributes to uptake of improved germplasm. In cases where private enterprises undertake improvement and breeding activities for sale, they have significant financial incentive to promote the use of their products.

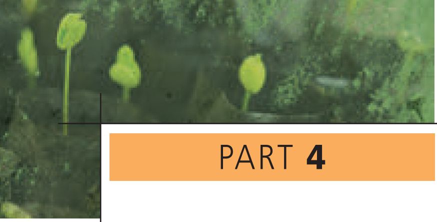
The following issues concerning private-sector involvement in germplasm delivery and deployment are gleaned from the country reports.

- The private sector must be responsive to market demand. However, where demand is internationally driven, private-sector activities may not always be consistent with national strategies or programmes in the areas of forests, FGR conservation and management and national development.
- Adequate protection of intellectual property and reward (e.g. through sales) are required to encourage sharing of improved germplasm.
- A stable investment environment is required.
- The private sector's ability to deliver public goods and benefits may be limited if markets for them are poorly developed or non-existent.
- The private sector tends to address ecological and social objectives only as required by regulation.
- In the interest of maintaining commercial advantage, companies may refrain from sharing improved materials that they deem proprietary. Sharing may occur through sales but may thus be limited where markets do not exist or are limited (e.g. because of lack of capital).
- Information on private-sector germplasm delivery and deployment activities may be difficult to collect because of confidentiality issues and lack of a process for collecting and collating these data.

### Informal sector

In many countries, small-scale production of germplasm and planting materials, and their use in forest and farm plantings, provide rural employment and income which assists in alleviating poverty. For example, traditional home-garden agroforestry practices in Ethiopia provide employment for many people, and propagation and exchange of plant materials are part of the fabric of rural life. Home gardens produce 42 percent of the timber and 27 percent of the fuelwood in Sri Lanka, while forest plantations generate only 11 and 4 percent, respectively; this decentralized, informal system of wood production also produces much of its own planting materials. However, smallholder farmers and other small-scale producers in the informal sector often have little or no access to appropriate germplasm and plant materials, hampered by lack of money, lack of networks or information on the availability of germplasm and its benefits, logistical barriers to delivery or failure of markets.

Informal small-scale collection and propagation of germplasm by farmers and forest-adjacent communities (for use on farms, in home gardens or for sale) is often consistent with centuries-old tradition and practice. Selection, if any, is usually based solely on phenotype, for example harvested from a limited number of parent trees which may be related (half-siblings) and/or relatively isolated with high levels of inbreeding. Such germplasm tends to be of relatively poor genetic quality and to have little variability. The Philippines and Madagascar report that small-scale seed producers or individuals generally collect material from few plants (e.g. less than



ten), which leads to loss of genetic variability. These practices limit opportunities for genetic improvement and maintenance of variability of FGR. Where collection practices do not conform to the requirements of national, regional and international certification schemes (discussed below), producers will have limited ability to sell into germplasm markets that demand this certification.

Despite the difficulties of ensuring adequate variability, ensuring quality and selecting appropriate material, opportunities exist for developing production and use of improved germplasm in the informal sector. These producers require access to affordable and appropriate planting materials, information and market assistance; in this area NTSCs and extension services may have an important role, especially in developing countries. Other strategies include boosting community involvement in germplasm production, for example through participatory models of selection, improvement and plant production. The United Republic of Tanzania recommends "strengthening farmer seed systems" and increasing their access to information to enhance their contribution to conservation and promotion of diversity. Sri Lanka recommends incentives for increased tree planting in home gardens and development of a partnership approach for production of high-quality planting materials.

The germplasm collection and propagation activities of the informal sector may also be supported and improved through establishment of grower cooperatives and associations. In the Philippines, for example, the Agroforestry Tree Seed Association of Lantapan, a farmer association established in 1998, has educated many small seed producers in correct techniques to meet standards and obtain an assured market for their seeds.

Engaging community volunteers is another avenue for production, distribution and deployment of planting materials for conservation purposes in both developed and developing countries alike. In the United States of America, for example, "friends" groups help obtain native plant donations for forest restoration projects. The "Seeds of Success" programme in the United States also mobilizes volunteers. Seychelles reports that the Division of Environment plans to mobilize people to participate in conservation of endemic tree species, first by growing indigenous trees.

## Public–private partnerships

With the complex interplay of complementary, overlapping and competing roles of the public and private sectors in germplasm collection, storage, propagation, delivery and deployment, coordination and collaboration are essential. Countries mention several joint approaches to delivery and deployment.

Some governments offer incentives to private companies for the production of high-quality germplasm and planting materials, particularly for activities consistent with national goals, e.g. for conservation of forests, FGR and biodiversity.

In some countries, associations and organizations with joint public and private sector membership assist in data collecting, standardization, and preparation of guidelines and policy related to FGR, including matters relating to exchange and deployment. Examples include:

- the Canadian Forest Genetics Association, which promotes information exchange and sound practice and policy;
- the National Plant Germplasm System in the United States of America, which has both government and industry involvement and includes accessions of 87 percent of the tree genera in the country;
- in Chile, the Cooperativa de Mejoramiento Genético, a joint enterprise involving public agencies, the private sector and a university, which regulates, certifies and documents seed produced by its members;
- the cooperative tree improvement organization GENFORES in Costa Rica, led by the Technological Institute of Costa Rica and involving 11 reforestation companies and local NGOs.

Sometimes initiatives are devised and implemented jointly. For example, in Germany private seed certification schemes have been developed with input from private organizations and state and federal governments.

In some cases different aspects of the delivery and deployment system may be shared and/or divided between the public and private sectors. In Germany, seed harvest and storage is undertaken by both private and public organizations, but the collection and long-term gene bank storage is undertaken by the state governments. The Islamic Republic of Iran reports that government agencies may directly import and distribute seed or provide oversight of the private sector; "all the seed imports and distribution is done either directly by the Ministry of Agriculture or by private companies after receiving permission from the Ministry".

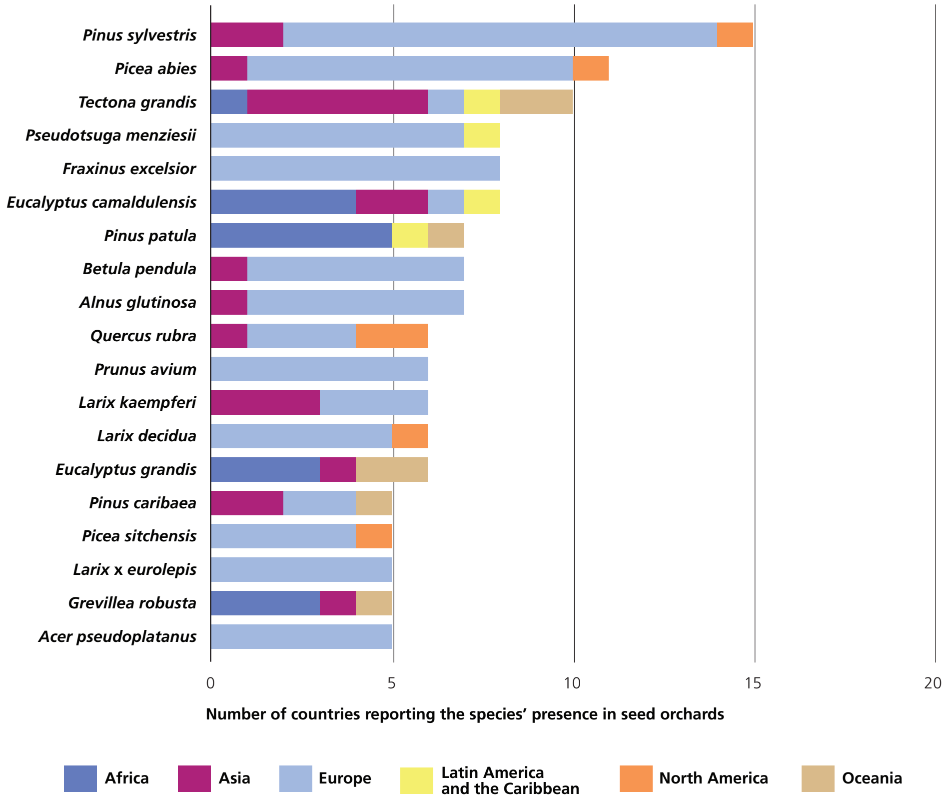
## Production of germplasm and planting materials

Germplasm used by countries as base material for propagation is selected or improved to varying degrees and held in a variety of propagative resources and facilities, including:

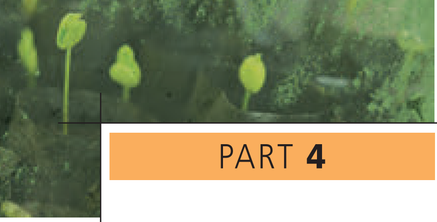
- unimproved but selected forest seed stands;
- seed, cutting and clone orchards of phenotypically selected or genetically improved genetic materials (Figure 15.1);
- seed and vegetative materials from individual trees in *circa situm* situations.

**FIGURE 15.1**

Most widely planted species in seed orchards



Note: Countries of the Near East did not provide data on seed orchards.



In the Philippines, seed stands "are identified and delineated in natural stands or plantations with a high frequency of phenotypically good planting materials", while seed orchards are plantations of selected trees, clones or progenies "which are isolated or managed to avoid or reduce pollination from genetically inferior sources outside the orchard, and intensively managed to produce frequent, abundant, and easily harvested crops of seeds; a seed orchard can also be regarded as a breeding population as a basis for further tree improvement". Vegetative materials for propagation from grafts, stem cuttings and micro cuttings may be sourced from selected clones or seedlings. Cloned materials are favoured for plantations because of their ability to produce true-to-type, genetically uniform plants from improved material; they are especially useful for the heterosis in F1 interspecific hybrids. In many countries, small-scale or individual producers may select seed informally, both for use in their own enterprises or for sale. The implications of small-scale informal selection are discussed below.

Country infrastructure for the production of tree germplasm and planting materials not only includes the above-mentioned propagative resources, but also the organizations, enterprises and facilities dedicated to germplasm collection, storage and propagation (Box 15.1), such as government agencies, national tree seed centres (NTSCs), private corporations, public and private nurseries, community associations, villages and

### Box 15.1

### Germplasm production, storage and progagation and distribution facilities: some challenges

Germplasm production and storage facilities require committed, ongoing management to maintain and operate effectively. They require adequate funding, which can come from government or industry support and/or the sale of germplasm and planting materials.

Dry/cold seed storage facilities are subject to humidity, temperature fluctuations, floods, fires, insect attack and potentially catastrophic power failures (in the absence of backup generators). The need to replace or repair failing equipment is a significant impediment to the success and expansion of *ex situ* programmes and the operation of many national tree seed centres (NTSCs).

Zambia mentions that its seed is stored in deep freezers, "as all the cold rooms need rehabilitation. A standby generator may need to be installed to minimize effects of power disruptions." Zimbabwe notes intermittent power supply to cold storage rooms as a major challenge to its NTSC. Newer freezers with defrosting cycling have fluctuating temperatures which considerably shorten seed lifespan, but some people working with tree seeds may not be aware of this information.

Seed and clone orchards also require ongoing maintenance and management. They may be subject to threats that include neglect, poaching, illegal harvesting and encroachment of agricultural and other activities. Several countries, including Cameroon and Zimbabwe, note decline or disruption in their orchard operations because of such factors.

Political, social and economic stability are required to ensure continuing maintenance and operation of these facilities. Because of the risks, it is not advisable to have a single focal point for the production and distribution of germplasm. Strategies to encourage safety duplication with widespread production by multiple organizations, companies or individuals can reduce the risks.

individuals. Other crucial components include human and organizational resources – expertise, personnel, funding and political support.

Country reports describe great variation in germplasm and plant production capacity, as illustrated in the following examples.

## Country examples

**Africa.** South Africa produces 200 million plants from 37 nurseries, almost all *Pinus, Eucalyptus* and *Acacia* species, for its commercial forest industries. In Ethiopia, the government is the sole supplier of tested seeds in the country, distributing 7.2 tonnes of seed annually, capable of producing 570 to 880 million seedlings; however, the informal sector is also a source of germplasm, which is less reliable (see Box 15.2). In many other African countries seedling production is much lower; for example, Madagascar's NTSC nursery produces 250 000 plants per year. Most small developing tropical countries typically have less than five or ten nurseries producing tree seedlings for production and environmental plantings.

**Asia.** China, with its immense area of plantings, has a vast demand for planting materials of many types and reports a remarkably extensive decentralized network of 336 000 tree seedling nurseries covering 668 000 ha. Tree nurseries in China source their propagation materials from:

- 19 600 ha of improved seed orchards comprising progeny-tested superior families, selected plus trees and introduced superior families, yielding an average of 0.71 million kilograms of seed per year;
- 18 100 ha of improved cutting orchards of bred and introduced superior clones of various species, yielding an average of 1.8 billion seedlings annually;
- 146 000 ha of superior seed stands yielding 1.67 million kilograms of seed per year;
- 630 000 ha of "seed collection bases" of superior provenances of several species and genera, yielding 9.3 million kilograms of seed per year.

### Box 15.2
### Germplasm production and dissemination in Ethiopia

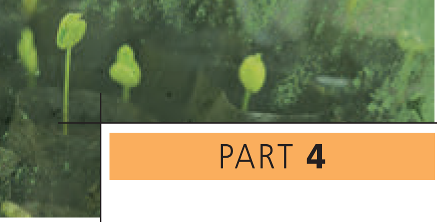
The scenario of germplasm production and use described by Ethiopia demonstrates elements that are common to many developing countries, particularly those with large informal-sector involvement and a multiplicity of actors, including the public sector.

The federal Forest Research Center (FRC, an arm of the Ethiopian Institute of Agricultural Research) is the only supplier of tested forest tree seeds in the country. FRC collects forest germplasm from identified and established stands. It sells the forest germplasm collected from these stands to government organizations, mainly bureaus of agriculture, and to NGOs and private seed growers.

Many smallholder farmers, youth, women and private seed dealers and nursery operators are also engaged in the forest germplasm business. Seeds provided by farmers, private seed dealers and other informal sources are often of low quality and quantity. Movement of forest germplasm within the country is unrestricted and involves a range of stakeholders, including government, NGOs, local people, private seed dealers and nursery operators. Local communities, especially young people, benefit from the production and sale of seedlings of certain forest species.

Smallholder farmers collect and plant seedlings or sow seeds of various trees for their own use in a variety of agroforestry and on-farm plantings, or for sale.

*Source*: Ethiopia country report



China reports that its major forestry programmes increasingly need to use improved genetic materials, but that most of the seed orchards and stands are first generation and low in quality.

Other Asian countries reporting significant productive capacity include Indonesia and India. Indonesia, through the Department of Land Rehabilitation and Social Forestry, produces 29 million kilograms of seed annually from 104 000 ha. India produces 3.8 million kilograms of seed of 27 species and plants 102 million seedlings annually. India has 396 seed orchards covering 7 090 ha (of which 64 percent is teak).

**Europe.** Germany has 425 forest tree nurseries producing 150 million to 185 million plants annually and 800 ha of seed orchards for trees and shrubs, including 215 seed orchards for tree species. In Poland about 90 percent of the currently established planted forests come from planting or sowing; Poland imports large amounts of tree seed (in the order of 10 tonnes per year), but exports tree seedlings. Several European countries, including the Russian Federation, rely heavily on natural regeneration of their forests.

### Meeting increased demand for germplasm and planting materials

As mentioned above (see section on demand), nearly all countries expect increases in demand for planting materials and a shortfall in supply, and many country reports recognize that to fill the gap it will be necessary to boost production. Ethiopia, for example, identifies a need for "…strengthening the tree seed production–supply system for satisfying needs for quality seeds and collection and conservation of germplasm". The Philippines remarks that "the fundamental problem to be addressed at this point is the lack of supply of improved planting materials for production purposes, and of planting materials for conservation of endangered indigenous and other forest genetic resources". Madagascar similarly notes the need for large-scale, low-cost production of planting materials for forestry and mining restoration projects.

Zambia attributes a 38 percent reduction in plantation area since 1982 in part to "reduced national capacity to produce sufficient good quality *Pinus* seed for plantation establishment". Because of this critical shortage of high-quality seed, "seed is at present being imported from Asia and other places, and used for plantation establishment without any screening in provenance or progeny trials…." Zambia notes that the quality of exotic tree seeds of *Pinus* and *Eucalyptus* species collected annually by the Forestry Department has declined and that the quantity has decreased from 250 kg of seed in the 1970s to 25 kg in 2010.

To meet shortfalls in supply of planting materials, a number of countries express an interest in developing their capacity to use advanced propagation techniques. Cloning, for example, offers the prospect of producing large numbers of genetically identical improved planting materials at a low cost. Other techniques such as *in vitro* micropropagation and somatic embryogenesis may assist a range of FGR conservation programmes, particularly where the species involved are difficult to propagate or where mass propagation of superior seedlots is sought.

A cost-effective, low-technology approach to boosting the supply of plant materials, both from seed and through vegetative means, involves encouraging production by small producers, communities, villages or farmers using participatory methodologies.

The time required for seed orchards to produce improved seed is a constraint on the delivery of improved germplasm for deployment, often necessitating the continued use of unimproved seed. A number of advanced techniques in breeding and propagation may shorten the time between improvement and deployment, including for example increasingly powerful selection based on QTLs and marker-aided selection, grafting, micropropagation improvements (e.g. the use of bioreactors), somatic embryogenesis, and application of hormones to promote early flowering in seed orchards.

## Movement and transfer of genetic material

The transfer of forest reproductive material has been a common practice for several centuries. Field trials established with introduced material have provided valuable insight on the performance of different tree species and their provenances, in turn influencing requests for further germplasm transfer and for the opportunity to test new material.

As discussed above in the section on the actors involved, both the public and private sectors carry out activities to promote and deliver improved material (in the latter case for commercial gain). Countries with well developed genetic improvement programmes generally have relatively well developed methods of distributing and deploying their improved materials, whether in the private or public sector.

However, the high collection costs and difficulties of access to FGR have made it increasingly difficult to move forest reproductive material for research purposes. As a result the large international programmes carried out in the past to assess systematically the performance of forest reproductive material would not be possible today.

The transfer of forest genetic materials for use in research and tree improvement contributes to global economic progress by facilitating the production of better adapted trees with superior performance that can produce goods and services more efficiently and cheaply. International transfer and exchange of germplasm allows countries that lack the capacity to undertake their own improvement programmes to partner with or outsource to countries or external organizations with the relevant expertise and resources. Through international trade in germplasm and plant materials, countries are also able to purchase improved planting materials to supply their forest planting and development programmes.

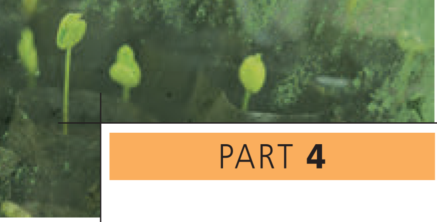
International trade in germplasm and plant materials is an important commercial activity in its own right. China, for example, exports over 300 000 kg of seed and several hundred thousand seedlings annually for over 400 species. Australia also has a major international seed export trade, mainly in *Acacia* and *Eucalyptus* species.

Control mechanisms are required to ensure that the transfer and use of FGR is safe, appropriate and fairly compensated. Brazil, for example, reports: “Any intended utilization of genetic material, native and exotic alike, must comply with specific laws and regulations. The import, export, research and improvement of plant genetic resources are regulated by phytosanitary, environmental, access, benefit-sharing and intellectual property legislation.”

### Prioritizing for delivery and deployment

Priorities for the delivery and deployment of FGR and improved genetic materials are best established at the national level, in national strategies for forests and FGR conservation and management, coordinated with other relevant strategies. Priority objectives include addressing commercial or forest service goals, FGR and biodiversity conservation goals, and development, social and economic goals. Focal areas include development of plantation industries; developing local, small-scale industries and employment; assisting rural communities; contributing to poverty alleviation; reducing harvest pressure on natural forests; promoting environmental and restoration plantings; combating desertification; and conserving genetic variability and threatened species.

Other priorities to be considered for delivery and deployment programmes include desirable genetic traits and production characteristics, genotypes, populations, species, improved varieties and planting locations, as well as the sectors of the economy and society identified



for development or assistance. The private sector mainly prioritizes species, locations and management regimes for deployment on the basis of financial returns, which are in turn determined by market conditions, structure and demand, although government regulations, incentives and support may also have a role.

In developing countries it is important that delivery and deployment of plant materials be matched with the areas of most need, particularly given the importance of trees in alleviating rural poverty. For example, in countries where fuelwood is a major source of energy, the improvement, production, distribution and deployment of multipurpose and fuelwood species may be considered a priority. Several country reports remark on the need to match planting materials more effectively with their intended purpose. China notes that market signals may help in the deployment of appropriate plant materials.

A number of countries, often in collaboration with ICRAF, adopt a participatory approach, engaging rural communities, farmers and villages to facilitate alignment of selection, improvement, production and deployment of FGR with community needs. This type of approach is especially advantageous where markets are lacking, poorly developed or poorly functioning, for example because of poverty, lack of purchasing power, lack of market infrastructure or lack of market signals and information.

## Ensuring the quality of germplasm and planting materials

To give surety to purchasers of germplasm and obtain access to markets that require guarantees of quality, vendors may seek to certify the quality of their seed and plant materials. International, regional and national certification schemes involve adherence to procedural guidelines and protocols. Quality parameters may include the source (e.g. geographic location or biogeographic or genecological zone), whether the material is improved stock, the breeding generation, the level of natural variability represented, improvement in performance of desired characteristics, the collection protocols followed, phytosanitary criteria, and the quality and health of the seed lot or plant material batch, including germination rates.

Other means of assuring, increasing and monitoring quality include regulation, voluntary codes of practice, the use of guidelines and producer education. As mentioned above, in a number of countries private–public collaborations or smallholder, farmer-operated associations (e.g. the previously mentioned Lantapan cooperative in the Philippines) are involved in development of guidelines, quality control, certification and documentation of seed.

Several regional and international mechanisms exist for quality control and certification. The OECD Forest Seed and Plant Scheme (OECD, 2013), for example, governs international exchange of certified material and aims to have "a major role in helping world forests adapt to changing climatic conditions". This scheme emphasizes "preserving species diversity, and ensuring high genetic diversity within species and seed lots thereby enhancing the adaptive potential of forest reproductive material for [the] future". The scheme now specifies six categories of "basic material" from which reproductive material can be selected, i.e. seed source, stand, seed orchards, parents of family/ies, clone and clonal mixture. The components of the basic material will have been selected at the individual level and tested; the superiority of the reproductive material must be demonstrated by comparative testing or an estimate of its superiority calculated from the genetic evaluation of the components of the basic material.

Within the European Union, germplasm is freely exchanged in accordance with EU Directive 1999/105/EC (EU, 1999), which governs particular species and also provides a standard classificatory system for reproductive material. EU regulations allow members to import forest reproductive materials in four categories – source identified, selected, qualified or tested – from EU-approved external third parties.

Various EU member countries have enacted laws to implement EU directives on germplasm production and transfer. EU members may impose regulations if these exceed the quality requirements of EU Directive 1999/105/EC (EU, 1999). Germany's Act on Forest Reproductive Material governs activities relevant to production and exchange of germplasm of tree species, for example by encouraging the improvement of seed quality through certification. It specifies categories to describe forest reproductive material for exchange, and it regulates commercial production and marketing as well as imports and exports of forest reproductive materials. Production and sale of these materials is restricted to registered seed and plant material producers, and all materials must be approved.

International forest certification schemes such as the Forest Stewardship Council and the Programme for the Endorsement of Forest Certification (PEFC), which have been adopted by a number of countries, include requirements related to the quality, nature and genetics of forest germplasm and planting materials.

China has implemented a set of rules requiring and governing the use of improved forest trees in major forestry programmes; however, uptake has not been as high as hoped owing to the lack of incentives for seed producers and users and geographic limitations.

In Denmark the promotion of improved genetic material requires approval by law; approval is granted if the material is deemed above average. Madagascar categorizes the sources used to produce seed in line with OECD guidelines, i.e. assessed sources, selected stands and seed orchards; seed is tested following International Seed Testing Association (ISTA) standards. Other countries encourage the use of improved or preferred germplasm rather than regulating it, particularly where small landholders are the main users; for example, in the Islamic Republic of Iran, "although the use of recommended varieties by the farmers [has] been encouraged by the government, there is not any legal prohibition preventing them from using a farmer's variety".

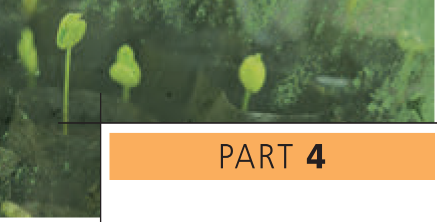
## Identifying regions of provenance and genecological and seed-transfer zones

The identification of regions of provenance and of a country's seed- or germplasm-transfer or genecological zones (i.e. areas possessing consistent biogeographical characteristics to which local populations have adapted) facilitates the selection and deployment of appropriately adapted plant materials best suited to local conditions. The deployment of germplasm from different, non-conforming genecological zones may lead to the loss of adaptive advantage (including through potential genetic impacts on existing populations) as well as poor performance or, at worst, complete failure of the introduced material. Knowledge of the biogeographical origin of germplasm is also essential in international transfer for purposes of research and genetic improvement.

Both the OECD Forest Seed and Plant Scheme (OECD, 2013) and EU Directive 1999/105/EC (EU, 1999) (see above) address matching of tree germplasm to planting sites, in requiring the identification and delineation of provenance regions. The EU directive cites research showing that "it is necessary to use reproductive material that is genetically and phenotypically suited to the site"; that "demarcations of regions of provenance are fundamental to selection"; and that "native species and local provenances that are well adapted to site conditions should be preferred".

Some countries have identified seed-transfer or genecological zones (fully or partly) and have focused their selection and tree improvement programmes on materials adapted to these zones. The zones are also used as the basis for determining the movement and transfer of germplasm.

On the other hand, many developing countries have not yet defined their genecological zones



and have neither identified nor developed appropriately adapted species and improved materials for planting in different zones. Ethiopia identifies the need for "establishing and strengthening a system for the provision of indigenous and exotic tree species and seed inputs that are suitable for the different agro-ecological zones". India identified 147 seed zones in 1978, with the intention of obtaining legislative support to implement a zoning system; although at the time the initiative suffered from lack of support, a bill to enforce the zoning system is now pending before the Indian Parliament.

A number of countries (e.g. Germany) adopt strict controls on the movement of genetic materials across genecological boundaries or seed-transfer zones; other countries focus on identifying, selecting and developing FGR that will perform well in particular zones. The implementation of seed-transfer zones encourages tree breeders to develop appropriately adapted materials by ensuring a market for them. China, however, notes that too narrow a geographic focus for development of improved materials may restrict their application and deployment.

Some countries that apply the seed zone concept have yet to develop national guidelines for transfer within their borders. For example, Canada notes that provinces develop their own propagation materials based on seed zones, often using information from provenance trials, but the country has no national legislation or guidelines regarding transfer within the country. Poland, on the other hand, has strict rules for the movement of forest reproductive materials within its borders, for example through the Forest Reproductive Material Act of 2001. These rules cover movement not only between regions, but also between altitudinal zones.

Several countries (e.g. Germany, Sweden and the United States of America) note that with climate change, species and germplasm identified for adaptation to new and rapidly changing conditions may differ from the materials identified to date as appropriate for existing genecological zones. Germany, for example, is currently increasing its use of climate-change adapted species such as the introduced *Pseudotsuga menziesii*. The United Republic of Tanzania remarks that increased transfer of germplasm may be needed to select and breed trees better adapted to changes in climate, to enrich the variability of local FGR to facilitate their adaptation, and perhaps to assist migration of certain species to ensure their survival. The use of transferred germplasm in this way may run counter to the strict enforcement of genecological zoning approaches; flexibility will be required to accommodate changes, particularly while appropriately adapted species and genetic materials are being identified and developed.

## Managing risks in transfer and exchange of germplasm

Phytosanitary, pest and invasive species risks accompany the transfer and exchange of germplasm and plant materials. To minimize these risks, a number of organizations, including FAO, Bioversity International and the DANIDA Forest Tree Seed Centre, have developed guidelines for the safe movement of tree germplasm (see FAO, 2007b). Various mechanisms and regulations exist at international, regional and national levels to manage the risks, although they are sometimes limited in their application. Where regulations and standards differ between jurisdictions (within a country, regionally or internationally), movement of germplasm and tree planting materials from one jurisdiction to another may be problematic. Indeed, a lack of harmonization in regulations, standards and transfer protocols creates barriers to the efficient exchange of genetic materials; resultant delays in the supply system may cause loss of viability in orthodox seeds and mortality in recalcitrant, dessication-sensitive or short-lived seeds.

## Benefit sharing

Firm, adequate and enforceable benefit sharing arrangements are essential to ensure that the interests of the owners of any materials exchanged are duly recognized and that owners receive an appropriate share of the benefits. Benefit sharing mechanisms are required to ensure that owners of germplasm, or of information contributing to the improvement of that germplasm, are treated equitably. They allow developers of improved varieties and other suppliers of services to capture income generated from their investments and activities, thereby providing incentives for further improvement work. Such arrangements are similarly required when a country contributes genetic material to a collaborative improvement programme.

The dialogue on access and benefit sharing issues for forest genetic resources has thus far been rather limited in most countries; however, these issues are increasingly being considered, following the example of the agricultural sector.

Benefit sharing arrangements require a legislative and regulatory framework and an effective administrative infrastructure for their implementation and enforcement. China emphasizes the need for an improved benefit sharing mechanism to enhance development, delivery and uptake of improved varieties: "The lack of policies and regulations for protection of intellectual properties related to genetic resources, and the lack of effective mechanisms of sharing responsibilities, rights and interests between suppliers and users of the genetic resources, have led to [a situation where] the suppliers cannot benefit from the exploitation and utilization of the genetic resources whereas the users cannot get use right of the genetic resources."

Several international agreements address this subject, such as the CBD, the International Treaty on Plant Genetic Resources for Food and Agriculture (which mainly deals with non-tree agricultural crops) and more recently the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization, adopted by the CBD in 2010. Most countries are signatories to these agreements. Benefit sharing may also be conducted under provisions of patent regulations where applicable. Most countries report that they have patent laws in place; however, they are not commonly applied to FGR.

Benefit sharing may involve profit sharing, access to any improved materials, technology exchange, contribution to *in situ* conservation projects or assistance with other programmes. However, not all agreements adequately protect the rights of both parties in commercial arrangements. To protect the rights of germplasm owners and suppliers (including countries, provinces, companies, communities and traditional owners), strict and legally binding Material Transfer Agreements (MTAs) should govern all exchanges both between and within countries. The Canadian province of British Columbia, for example, has an MTA governing transfer of seed and breeding material; it ensures that ownership or custodianship is recognized and confers limited use rights, for example for seed production. ICRAF uses a standard agreement for the collection of tree germplasm; however, apart from these examples no standard MTA is used.

Papua New Guinea has a history of exchanging and supplying seeds of indigenous and exotic tree species, both for research and commercial purposes. However, while FGR are recognized under the CBD as the property of sovereign nations, in Papua New Guinea they are considered under the Constitution to be the property of customary landowners, who own 97 percent of the land. These landowners are increasingly preventing access to FGR for research purposes, as they seek additional benefits through mechanisms such as an MTA with the Secretariat of the Pacific Community and others.

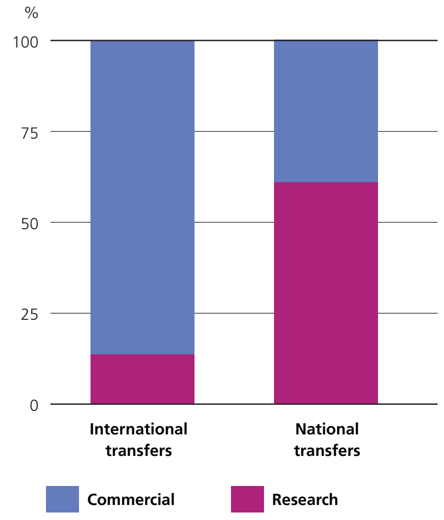
## Magnitude of germplasm transfer

Country reports indicate that germplasm transfer within countries is predominantly for commercial purposes, whereas international transfer is more often for research (Figure 15.2).

By region, Europe reports by far the highest availability of germplasm for within-country transfers for commercial purposes, at 87 percent of the global total. This suggests that European

**FIGURE 15.2**

Purposes of germplasm transfer reported by countries



countries have well developed internal markets for germplasm and/or that they have an effective system for documenting germplasm exchange, incorporating the private sector.

Globally, countries report a total of 412 different species available for national and international transfer, although this is likely to be an underestimate as much exchange of tree germplasm (especially for ornamentals such as palms) occurs through the private sector and is not necessarily recorded in official figures. Latin America and the Caribbean reports an average of 28 species available for transfer per country, Asia 20 species per country, and North America 16 species per country. These data are consistent with the focus on a small number of priority species of high commercial value as noted earlier in this report.

Countries report transferring seed and vegetative material internationally (import and export) for a total of 534 different species. The African region reports the most species transferred (398), followed by Europe (338).

## Information management in delivery and deployment of germplasm

The production and transfer of germplasm for research, breeding and propagation requires excellent documentation for quality control, source identification and the management and monitoring of activities. An efficient, comprehensive and integrated information system is essential. Some countries note that a lack of information on the availability and performance of both non-improved and improved germplasm held by NTSCs and similar institutions is a significant barrier to wider deployment of germplasm held in collections.

Detailed, accurate information is required for certification of forest reproductive material, for example under the OECD Forest Seed and Plant Scheme and EU Directive 1999/105/EC (see above). Information requirements of different schemes vary, and may include, for example, seed source and origin, provenance, region, provenance region/genecological/seed-transfer zone, performance with respect to desirable traits, number of parents, amount of variability represented, germination percentage and adherence to standards.

Adequate documentation allows purchasers and users to verify that the material they acquire is true to type, fit for purpose, and putatively well adapted for the conditions into which it will be planted. Proper documentation also permits genetic material to be tracked, allowing:

- collation of data on performance of improved varieties for evaluation and research;
- use of plants as a source of reproductive material of known origin at a later date – a particularly important feature for conservation plantings;
- assessment of any impacts on native vegetation at the host site.

The adequacy of documentation varies among countries and regions. For example, Germany's Act on Forest Reproductive Material requires the German states (Länder) to register and maintain databases of seed stands, orchards and clones, thereby providing both a degree of oversight and ease of access to site-appropriate, approved sources of germplasm. Poland has an extensive information management system documenting forest reproductive materials around the country. The Islamic Republic of Iran notes that safe storage of data is vital for maintaining and sharing germplasm; the country has a dedicated unit for data management and for dealing with germplasm requests. Some Asian countries gather and disseminate FGR data and information through the websites and portals of relevant government agencies.

On the other hand, a number of other countries identify their documentation as inadequate and recognize the need to improve their information management systems in this area. In developing countries where resources are scarce and much of the germplasm production and exchange is informal, documentation of forest germplasm is largely non-existent.

Some countries report that they have information on public-sector breeding, delivery and deployment but lack information on the activities in the private sector, indicating a need for integrated and harmonized documentation and data gathering activities between the sectors. European countries, under EU Directive 1999/105/EC, have developed a regional system to document the origins and track the movement of FGR – an example of a harmonized, integrated system that facilitates international and regional transfer of germplasm.

## International assistance

Many developing countries have received assistance from international partners, especially ICRAF, in building up their production, delivery and deployment systems. Other examples include the following.

- The Mindanao Tree Seed Centre in the Philippines was established with asssistance from the Australian Overseas Aid Programme.
- Thailand has received assistance in breeding programmes, feeding into delivery and deployment programmes, from DANIDA, Australia's CSIRO and ACIAR, and the International Tropical Timber Organization (ITTO); some programmes date back to the 1960s.
- Guatemala's Forest Guild and Guate Group received technical assistance from Camcore in establishing seed orchards for several *Pinus* species.
- The United Republic of Tanzania has received assistance from the Gatsby Charitable Foundation in improving germplasm for plantations through cloning, with Camcore as a partner.

Unfortunately, in many countries, interventions undertaken internationally to improve the exchange of forest reproductive material are likely to have only a limited impact on the material available for smallholders to plant. In developing countries, formal suppliers are able to provide only a small proportion of the material cultivated by smallholders, and most farmers indicate lack of access to germplasm as a major constraint. There is a need to rethink the operational means by which tree germplasm reaches smallholders.

## Chapter 16

# Institutional framework for conservation and management of forest genetic resources

The institutional framework for FGR refers to the national and international forest programmes, policies and legislation governing FGR development, conservation, management and use; the structures supporting education, research and awareness raising; and the networks, agreements and other mechanisms for promoting and supporting collaboration at the national, regional and global levels.

## National institutions dealing with forest genetic resources

Many different institutions participate in FGR management, both public and private.

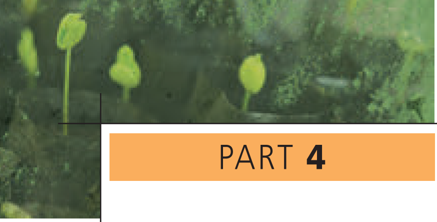
Public responsibility for FGR and related policy falls under different levels of government in different countries. FGR may be integrated in national forest programmes and managed by national government institutions such as the Ministry of Agriculture, Forests or Environment. If the country has a decentralized administration, FGR conservation may be managed under different regions or states.

Most countries have institutions working for the conservation, management and use of forest genetic resources. Their work may include applied research on fast-growing forest tree species, forest seed testing, registration and control of forest reproductive materials, sustainable use of forest resources, *in situ* and *ex situ* conservation, tree improvement, use of improved materials and experimental stations. The national department responsible for forests is often the institution most actively involved in the conservation and use of FGR. Some collaboration usually takes place among different institutions, but a coordination arrangement for FGR-related activities is often lacking.

Especially in developed countries, institutions actively engaged in FGR conservation and management may be numerous, including universities and colleges, federal and provincial departments, research institutes, NGOs and tree improvement councils and programmes.

Regional governments are generally responsible for managing forests within their boundaries. Under this mandate they conduct field and laboratory work. Industry is also often involved in field and laboratory work concerning FGR (for example, research related to biodiversity and ecosystem health). Some jurisdictions have tree improvement councils or cooperatives that are responsible for managing and ensuring the sustainability of FGR, and these groups often support or engage in field and laboratory work.

Over the past decade, many countries have successfully formulated national strategies and programmes for FGR conservation and management and incorporated FGR protection into national action plans – from the banning of harvesting in natural forests to the establishment and protection of nature reserves of key species. These are covered in detail in Chapter 10. However, most countries have no national programme for FGR. National forest programmes have general measures for conserving forest ecosystems, but in most cases there are no specific provisions concerning FGR.



## Legal and policy framework

Many countries have no specific laws on genetic resources or have outdated FGR-related policies and management tools. Some have legislative or policy provisions relevant to, if not specific for, forest genetic resources. The objectives are mainly the conservation and protection of the national forests, and less often the national forest genetic resources. Most countries have no legal framework for FGR strategies, plans or programmes, although there may be provisions in other national legislation.

## Education and training

Many universities around the world offer bachelor's degrees in forestry; some also award advanced degrees (master's degree or PhD). Some colleges have recognized technical forestry programmes that award a diploma upon completion of a two- to four-year programme. Few universities address FGR as an independent discipline or consider it as a thesis subject for graduate students. However, a number of programmes in forestry or natural resource management address forest genetic resources in their courses.

Some universities, colleges, and institutes offer specific courses in forest genetic resources conservation. These may have field and/or laboratory components and may be delivered through extension programmes or as part of certified academic programmes. Some smaller countries note that their courses on FGR are insufficient, but that many students study forest genetics abroad and return after graduation to work in forestry.

In some countries, the provincial or central forestry authorities organize FGR training workshops at different scales. Training on relevant laws, regulations and policies has increased understanding of the importance of FGR and strongly promoted their protection and sustainable use.

Nevertheless, there has been a general worldwide decline in enrolment in forestry programmes over the past several years. Universities and colleges are examining new ways to entice students into their programmes. Some ideas are to rebrand and transform their programmes (e.g. from timber-oriented forestry to sustainable forest management), develop new programmes (e.g. international forestry) and establish new partnerships (e.g. with forest industry and research organizations).

## Research

As touched upon in previous chapters, FGR research and development (including studies on collection, evaluation, conservation and sustainable use of FGR) is generally carried out, often collaboratively, by forest research institutes, universities, and companies or institutions concerned with forest production and management. Some countries, such as Indonesia, have research and development programmes on forest biotechnology and genetic resources under the Ministry of Agriculture.

In some countries, special research projects have been set up to catalogue and document forest genetic resources, establish and network with FGR conservation banks, assess forest genetic diversity, develop information platforms and share FGR information.

Many countries express a need for faster development of scientific infrastructure, advanced methodologies, and modern laboratory equipment; this is related to a need for improved funding, as sustained and stable financial support is often lacking.

China, a country with a vast territory and rich FGR with high genetic diversity, identifies a need for specialized FGR research and for a national-level institution to coordinate FGR collection for research use and provide technical support to government departments for the formulation of relevant policies.

## Raising public awareness and communication

Many countries report a need to raise public awareness on forest genetic resources, as the general population is hardly aware of their function and importance. For example, Germany reports the results of a survey in which many respondents agreed with the statement "Biological diversity should be preserved and passed on to our children and future generations" but could not explain the meaning of the term "biological diversity"; only 12 percent were aware that biological diversity involves genetic diversity within species.

Furthermore, much of the public is sceptical about genetic engineering. In some developed countries, genetic engineering and genetics are often considered one and the same thing. Genetics and all related terms often have negative connotations. This bias greatly hinders promotion of the importance of forest genetic resources.

Some countries report surveys showing that the public and NGOs have the lowest awareness of the roles and values of forest genetic resources, while industry and government rate much higher.

Some large Asian countries note that with an increase in education on forest ecology, public awareness about forest protection has increased continuously over the past ten years. Furthermore, the International Year of Biodiversity, 2010, probably increased public awareness about biological diversity. However, around the world the public generally lacks understanding of forest management and more specifically the planting of productive provenances and forest plant breeding. Most countries do not have specific programmes for creating awareness of forest genetic resources. Institutions that conduct public relations about forests, forestry and nature conservation do not generally make a chief priority of promoting the importance of forest genetic resources.

In some cases, public awareness concerning the value of forests and the species within them is enhanced through programmes and activities of diverse groups including the federal government, botanical gardens, small woodlot partnership programmes, environmental NGOs and forest or tree-specific conservation groups. Federal and jurisdictional *in situ* conservation areas have also raised public awareness of the forest and its genetic resources.

## Support to forest genetic resources

Over the past decade, funding for forest genetic resources has generally decreased slightly. In only a few countries have budgets slightly increased over the past ten years.

Little precise and reliable information is available about budgets for forest genetic resources because the institutions involved may be subordinated to many different ministries. However, the proportion of forestry budget allocated to FGR is often not more than 1 percent.

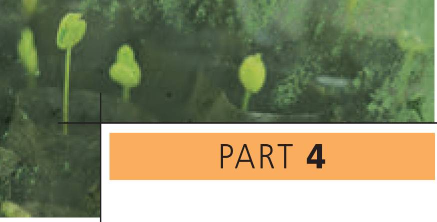
It is also difficult to estimate the funding apportioned to FGR research, since government budget allocations may fall under a number of different ministries and government agencies at both the national and subnational levels; and universities, colleges and various organizations may also allocate part of their budgets to FGR research. In developing countries the national research budget for FGR is usually especially poor, particularly where there is no national research institute, university or school dealing with forestry. These countries may occasionally be involved in small-scale research carried out by forestry schools or institutes abroad or in the frame of small projects.

Since domestic funding is often limited, capacity-building activities are sometimes carried out through bilateral cooperation in the form of project-based technical assistance programmes and research grants from international agencies. The projects normally include funding provisions for training and postgraduate studies overseas.

## International and regional collaboration

The distribution of forest genetic resources does not correspond to political borders, and this is an important basis for cooperation and coordination on issues related to FGR management. Many drivers of change affecting FGR, including climate change, also span political borders.

International forestry cooperation and exchange are developing rapidly. Many countries collaborate with other countries and international



organizations to conserve their forest genetic resources. Collaborative efforts also assist in improving countries' capacity to conserve FGR and manage them sustainably. The main forms of regional and international cooperation are international networks, bilateral and multilateral cooperation, and international conventions. These activites are carried out at both regional and global levels. Many countries, however, do not have any specific budget for international gene conservation purposes.

The paramount objective of international forest policy is to halt further deforestation and forest degradation, thus contributing to the internationally agreed Millennium Development Goals to protect the climate, conserve biological diversity, combat desertification and alleviate poverty, especially in rural regions. To this end, over the past 35 years the number of international, regional and national institutions, mechanisms and discussion fora concerned with forests and forest biological diversity has greatly increased.

Through membership in international institutions such as FAO and IUFRO, countries and institutions participate in global decisions and guidance concerning conservation, management and use of FGR and related research. In addition, in recent years the Ministries of Agriculture and Forestry in many European countries have considerably reinforced their roles in international forestry.

Although many collaborative activities in forestry do not have the direct purpose of conserving forest genetic resources, they safeguard forest habitats and indirectly contribute to the conservation and sustainable use of FGR.

Many international agreements are relevant to the sustainable management, use, development and conservation of forest genetic resources, addressing such issues as access, benefit sharing, biosecurity, intellectual property rights and illegal trade of natural resources.

International cooperation programmes and information exchange efforts such as shared databases, joint research and publications, technical guidelines and germplasm exchange also address forest genetic resources; some do so indirectly by addressing stresses to the forest (e.g. the United Nations Framework Convention on Climate Change [UNFCCC]). International movement of forest reproductive material is discussed in detail in Chapter 15.

## International and regional FGR networks

Many countries and institutions participate in global or regional cooperation and exchange networks related to forest genetic resources. Network activities – including information exchange, database development, sharing of conservation strategies and seed exchange – promote sharing of FGR information, help expand research capacity, and help improve technical standards. Networks that share data on outbreaks of alien invasive forest pests, for example, can help researchers and forest managers to develop proactive responses to future outbreaks in other regions. Some networks focus on particular tree species, and some focus specifically on conservation *in situ* or *ex situ*.

Networks may encourage more intensive communication among the countries in a region. Similarities among countries, for example in forest tree species, ecosystems and sociocultural environments, provide entry points for network development. Some networks reach out to existing regional organizations to gain support from a broader range of stakeholders.

One example of an active network is the European Forest Genetic Resources Programme (EUFORGEN) (Box 16.1). Some developing Asian countries report that they use international networks to share information on the status of research and development of forest genetic resources and to gather relevant inputs for FGR conservation and management.

In the past ten years some African countries that had been members of FGR networks and networking organizations – e.g. Camcore, the Southern African Development Community (SADC) Tree Seed Centres Network, IUFRO and the Global Forest Information Service (GFIS) –

## Box 16.1
## Example of an international FGR network: the European Forest Genetic Resources Programme (EUFORGEN)

The overall goal of EUFORGEN is to promote the conservation and appropriate use of forest genetic resources as an integral part of sustainable forest management in Europe. It was established in October 1994 as a pan-European implementation mechanism of Strasbourg Resolution 2 (Conservation of forest genetic resources) of the first Ministerial Conference on the Protection of Forests in Europe (now known as Forest Europe). EUFORGEN is funded by its member countries and overseen by a steering committee consisting of national coordinators from all member countries. The work is coordinated by Bioversity International in technical collaboration with FAO.

EUFORGEN brings together European experts to exchange information and experiences and to develop tools and methods for better management of forest genetic resources. EUFORGEN has produced numerous outputs such as genetic conservation strategies, technical guidelines, distribution maps of European forest trees, databases, and various publications and reports.

EUFORGEN had a crucial role in the establishment of the European Information System on Forest Genetic Resources (EUFGIS), which provides georeferenced and harmonized data on dynamic conservation units of forest trees in Europe. Since its launch in 2010, the EUFGIS Portal has been maintained by EUFORGEN. EUFORGEN working groups have used the EUFGIS data, provided by national focal points, to develop a pan-European genetic conservation strategy for forest trees and a genetic monitoring scheme for selected conservation units. Recently, other EUFORGEN working groups have focused on the use of forest reproductive material, policies relevant to the conservation and use of FGR, and the implications of climate change on FGR conservation.

have let their membership lapse. As these African economies stabilize they may wish to consider rejoining these networks and organizations for the benefits they can provide to scientists working on forest tree breeding, forest management, and forest and gene conservation.

Not all networks are successful, however. Some developing countries say they have not reaped many benefits from the regional and subregional networks in which they participate, except in some cases where networking has assisted technology development and information sharing. Where networks are ineffective, the cause is often a lack of coordination between the government and the network; a realistic plan of action is required and must be compatible with national priorities. In addition, some governments lack sufficient skilled human resources to participate effectively in networks and benefit fully from them. Inadequate conservation infrastructure can also be an impediment to obtaining benefits from networking.

# Part 5

# NEEDS, CHALLENGES AND REQUIRED RESPONSES FOR THE FUTURE

## Chapter 17

# Practices and technologies for improved management of forest genetic resources

The challenge of achieving food security for all and environmental sustainability in the context of the combined effects of climate change and the increasing human pressure on forests is greater now than it has ever been. More efficient use and management of available forest resources is therefore needed, especially in tropical and less-developed countries, in order to meet the growing demand for forest goods and services.

Managing FGR involves developing overall strategies, applying specific methodologies, developing and applying new technologies, and coordinating local, national, regional and global efforts.

FGR conservation and management considerations need to be better integrated into SFM planning and practices, including undertaking an inventory of FGR, prioritizing FGR for conservation and management, characterizing their variability, defining a management strategy for maintenance of variability, integrating this into utilization protocols and plans, monitoring the impacts on variability, and adjusting the SFM regime as appropriate. FGR value should be mentioned explicitly in assessment of high conservation value forests, and forest certification schemes need to include requirements for effective conservation and management of FGR.

The current growing concern about climate change and its effects on ecosystems and on performance of forest production systems challenges stakeholders in FGR management to better understand forest species' mechanisms for adaptation to current and future climate changes. Genetic diversity is needed in order to ensure that species can adapt, as well as to allow for artificial selection and breeding for improved productivity. Thus genetic diversity, including diversity among species, is the key to the resilience of forest ecosystems and the adaptation of forest species to climate change. Countries should therefore endeavour to support climate change adaptation and mitigation through proper management and use of FGR.

Marginal and/or range-limit populations may be vital for tree species' adaptation to the novel environmental extremes that are expected to occur as a result of rapid climatic change. It is necessary to understand the dynamics of marginal populations through adequate examination of adaptive genetic variation in quantitative traits. Furthermore, conservation efforts in the current context must consider the range of future climatic projections, and appropriate conservation measures must be developed using the principles of risk management. Modelling of species distribution dynamics needs to account for changes in species' distribution areas and in those of their associated environment correlates (e.g. pollinators) and also the possible influences of interactions with other plant or animal species.

## Monitoring

Monitoring of forest genetic resources and biotic stressors (for example, invasive alien species) can support FGR conservation and management at the regional level. It is highly beneficial for developing effective long-term strategies not only for

conserving the resources, but also for minimizing the impacts of the stressors and/or for developing scale-appropriate mitigation strategies. Research priorities identified by countries for improving the monitoring of genetic erosion and for assessing species' vulnerability include:

- assessment and monitoring of particular species' genetic diversity and their adaptive potential in regard to various stressors;
- identification of the resistance of native tree species to high-impact stressors.

Monitoring forest biological diversity and managing FGR require reliable information on the status and trends of these resources. There are no common standard methods for measuring changes in the status of FGR in relation to sustainable forest management as undertaken in most countries. Parameters commonly included in national and global forest resource assessments, such as forest area, species occurrence and richness and forest fragmentation, do not, on their own, provide information on FGR. Adequate and commonly agreed indicators are needed and should be developed and integrated into the national forest assessment policies and monitoring tools.

**TABLE 17.1**
Potential local- to global-scale operational indicators of forest genetic diversity, with verifiers

| Operational indicator | Verifiable indicator | Verifier (direct or proxy) | Primary scale of measure and indicator |
|---|---|---|---|
| **State–Pressure** | | | |
| Trends in species and population distribution pattern of selected species | 1 Number of species with known distribution for which allelic diversity is declining | 1 Number of species with known distribution for which distribution is declining | National<br>Regional<br>Global |
| | 2 Natural distribution range | 2 Geographic and climatic range | |
| | 3 Distribution pattern within the natural distribution range where appropriate | 3 Geographic, climatic and ecogeographic distribution of populations | |
| | 4 Representation within the natural range | 4 Number of populations relative to their potential genecological distribution | |
| | 5 Number of populations, their area and density (abundance) | 5 Area and density of populations | |
| Trends in population condition | 6 Demographic condition of selected populations (diversity in adaptive traits/genes) | 6.1 Age/size class distribution<br>6.2 Number of reproducing trees<br>6.3 Abundance of regeneration<br>6.4 Environmental heterogeneity<br>6.5 Number of filled seeds<br>6.6 Percentage of germination | Local |
| | 7 Genetic condition of selected populations (population genetic structure where appropriate) | 7.1 Effective population size<br>7.2 Allelic richness<br>7.3 Outcrossing/inbreeding rate<br>7.4 Spatial genetic structure<br>7.5 Hybridization/introgression | |
| **Benefit** | | | |
| Trends in plantation performance of selected species | 8 Hectares planted by species/ provenance either locally or as an exotic | 8 Hectares planted by species/ provenance either locally or as an exotic | Local<br>National<br>Regional<br>Global |
| | 9 Profit from breeding vs. loss from ill-adapted plantations | 9.1 Seed source performance (growth and survival)<br>9.2 Realized genetic gain and profit | |

Relevant indicators for monitoring genetic diversity have lagged in development perhaps more than any other type of biodiversity indicator (Laikre *et al*., 2010); recognizing this, the CBD's Strategic Plan for Biodiversity 2011–2020 allows for improved coverage. Nevertheless, identification and implementation of indicators of genetic diversity, including tree genetic diversity, remains a major challenge.

The difficulties in defining sound and realistic indicators arise from the fact that they should be policy relevant, scientifically sound, understandable, feasible to obtain and sensitive to changes over time. The use of a hierarchical approach, introducing the proportion of coverage as a measure of progress on selected indicators at different levels, offers a possibility for general use within the state-pressure-benefit-response (SPBR) framework. FAO has recently developed a set of indicators that span geographic scales from local to global and include state, pressure, benefit and response measures (Table 17.1) (Graudal *et al*., 2014).

*In situ* conservation often comprises maintenance of ecosystem functions and species interactions rather than conservation of

**TABLE 17.1** ***cont.***

| Operational indicator | Verifiable indicator | Verifier (direct or proxy) | Primary scale of measure and indicator |
|---|---|---|---|
| **Response–Benefit** | | | |
| Trends in knowledge of genetic diversity of species | 10 Increase in number of species that are described for which distribution and/or genetic parameters are known | 10 Increase in number of species that are described for which distribution and/or genetic parameters are known | Local<br>National<br>Regional<br>Global |
| | 11 Number of species with mapped genecological variation | 11.1 Increase in number of articles on genetic diversity by species<br>11.2 Number of species with mapped genecological variation | |
| | 12 Among-population genetic diversity (of selected species) | 12 Parameters of genetic differentiation among populations | |
| Trends in education and awareness | 13 Change in number of tree geneticists and tree breeders | 13 Number of university courses or training courses offered in forest genetics related subjects | National<br>Regional<br>Global |
| | 14 Existence of networks | 14 FGR networks (function/operation) | |
| | 15 Use in national forest institutions and programmes | 15 Species presence in national forest institutions and/or programmes | |
| Trends in sustainable use of tree genetic resources | 16 Number of tree species for which regulation of use of forest reproductive material exists | 16 Number of tree species for which regulation of use of forest reproductive material exists | National<br>Regional<br>Global |
| | 17 Number and type of improved seed sources traded/exchanged (status of genetic improvement) | 17.1 Number and type of improved seed sources traded/exchanged<br>17.2 Seed source performance (growth and survival) | |
| | 18 Guidelines/regulations for matching seed source and planting site | 18.1 Certification scheme in place<br>18.2 Use of adapted seed sources | |
| | 19 Guidelines/regulations for composition and harvest of seed sources (number of mother trees) | 19 Use of diverse seed sources | |
| Trends in genetic conservation | 20 Number of tree species directly targeted in conservation programmes | 20 Number of tree species directly targeted in conservation programmes | National<br>Regional<br>Global |

*Source*: Graudal *et al*., 2014.

individual tree species. In addition, forests have a number of native trees and shrubs that may be of minor interest to forest managers, but may be highly valuable in terms of genetic resources and future use. It is therefore important that forest and tree management include indicators related to sustainable FGR management in regular monitoring protocols.

## *In situ* conservation

In the current context of increasing pressure on forest land and forest resources, primary forests and protected areas remain refuges for threatened FGR. An important proportion of wild and/or endemic plants occur only in primary forests and protected forest areas. The genetic structure of species natural populations is best

**TABLE 17.2**

Some constraints, needs, priorities and opportunities identified by countries for *in situ* FGR conservation and management

| Area | Constraints | Needs and priorities | Opportunities |
|---|---|---|---|
| Land use pressures, encroachment and landownership | High exploitation, land clearing and deforestation (from poverty, expansion of agriculture, market demand for timber and fuel, illegal harvesting)<br>Encroachment on *in situ* conservation areas<br>Private or customary ownership of land, with limited control (Cyprus, Solomon Islands), small fragmented parcels (Japan), inability to ensure long-term conservation (Finland) | Reduce pressure on *in situ* conservation areas | Develop renewable energy sources alternative to fuelwood from natural forests (including energy plantations)<br>Improve production forestry (identify areas for forest development, improve germplasm quality)<br>Improve natural resource management and forest restoration<br>Involve private sector in *in situ* and FGR reserve systems, funded through environmental service payments or government assistance; incorporate these lands into public estate through purchase |
| Resourcing and capacity | Lack of expertise and capacity<br>Insufficient funds and resources for training, survey, identification, management and monitoring | Increased, more secure, long-term funding<br>Capacity building – including education, training, resources | Involve and better coordinate efforts of universities, training schools, NGOs and others in conduct of FGR inventories<br>Increase involvement of donors and NGOs in *in situ* conservation<br>Enhance information exchange and participation in regional and international networks and collaborations |
| Public awareness and support | Resistance to expansion of protected areas and conservation reserves (community concern over loss of use and access and increased human–wildlife conflicts)<br>Loss of traditional knowledge and beliefs leading to decrease in valuing of traditional species, forest management and conservation<br>Low or no community participation and lack of benefit sharing arrangements, resulting in conflict over forest resources<br>Lack of public awareness, interest and/or support<br>Lack of political awareness and/or support<br>Lack of alternative livelihood options for local populations | Sustainable livelihood security, access and benefit sharing arrangements<br>Expanded use to increase valuation by community of indigenous FGR<br>Promotion of indigenous and traditional species in research, conservation and local use<br>Payments to compensate traditional forest users where access to forest revenues is denied; incentives for stewardship of FGR<br>Extension, education and awareness raising for forest owners, users, youth and general public<br>Communication strategy, including media campaigns | Greater involvement of local communities in management<br>Sustainable and equitable use of natural resources; benefit sharing for local communities |

conserved in these forests. Natural processes involved in the dynamics of FGR are better assessed and understood in protected natural forests, which remain the best laboratories for studying species ecology and biology.

Almost all country reports identify constraints, needs and priorities, and opportunities for *in situ* conservation of FGR. Those most commonly identified by countries are listed in Table 17.2. The following summarizes the main constraints identified by countries:

- high levels of land clearing and deforestation (resulting from a variety of causes including poverty arising from

**TABLE 17.2** ***cont.***

| Area | Constraints | Needs and priorities | Opportunities |
|---|---|---|---|
| Policy, legislation and enforcement | Lack of coordination among policies, laws, government departments and sectors<br>Insufficient policy support<br>Lack of adequate legal framework and legislative protection for designated areas; inadequate enforcement<br>Lack of knowledge of relevant policies, laws and regulations by stakeholders (including those charged with law enforcement)<br>Lack of policy on how to increase benefits of trees on farms and *circa situm* conservation<br>Concentration on charismatic, priority species at expense of other indigenous species; undue emphasis on a few rare species | Strengthened legal framework for *in situ* FGR conservation<br>More effective enforcement of regulations and laws<br>Poverty alleviation and employment creation strategies | Review, revise or develop supportive policy and legislation for protected areas and for FGR currently on unprotected lands<br>Provide legislative protection for threatened, ecological keystone and culturally important species, including iconic trees and populations<br>Improve land-use planning and policies and tenure systems |
| Technical and operational issues | Lack of FGR strategy, coordinated national plans and integrated approaches linking *in situ* and *ex situ* strategies<br>Underrepresentation of important ecosystems in protected area networks (e.g. lowland primary forests in Indonesia, plains forests in Nepal, lowland dipterocarp forests in the Philippines)<br>Lack of inventory and knowledge on natural distributions and genecological zones, genetic resources and processes<br>Management issues of *in situ* conservation areas, e.g. invasive species, fire management<br>Close-to-nature management approaches in strictly protected areas limiting opportunities to conserve light-demanding or disturbance-dependent species<br>Climate change issues: reduced regeneration of conserved species, range shifts of species and vegetation communities | Better planning<br>Guidelines for designation and management of FGR conservation reserves and for preparation of *in situ* conservation strategies and action plans<br>Rehabilitation and restoration of degraded ecosystems and recovery of threatened species<br>Assessment and monitoring of existing FGR conserved *in situ*<br>Protection of high-priority species (including rare species) and endangered populations<br>Conservation of marginal-range populations<br>Better management of *in situ* sites (including silviculture, regeneration, protected areas)<br>Better knowledge sharing, coordination and networks at national level (government agencies, researchers, park managers, forest and local authorities, farmers)<br>Improved protected area network connectivity and reduced fragmentation | Use gap analysis to identify priority areas for FGR conservation<br>Translate research findings into practical conservation plans and actions<br>Assess existing forest reserves for synergetic use as *in situ* FGR conservation units for main tree species |

population growth, change in land use owing to expansion of agriculture, and increasing market demand for timber and other wood products);
- climate change, leading to reduced regeneration of conserved species and range shifts of species and vegetation communities because of shifts in climatic zones;
- lack of knowledge on genetic diversity, genetic processes and genecological zones;
- lack of or insufficient integration of FGR issues into current wider national policies and laws;
- lack of knowledge of relevant policies, laws and regulations on the part of stakeholders, including those charged with law enforcement.

Adequate *in situ* conservation measures are needed to preserve the natural growing conditions of the tree species in order to study and better understand their evolutionary process and adaptation to changes. Information from *in situ* conservation activities for marginal and/or range-limit populations will be essential in providing options for adaptation to climate change.

### Enhancing the role of protected areas for *in situ* FGR conservation

In many countries protected areas contribute to the conservation of viable forest tree populations of diverse species and of representative ecosystem samples, as well as maintaining vital ecosystem services. Their primary objective is ecosystem and biodiversity conservation; they serve as a refuge for forest species that are unable to survive in intensely managed landscapes. However, the status and role of protected areas differ among countries, as does their impact on conservation.

The extent of protected areas has been increasing over the past decades as a result of national and international efforts to conserve biodiversity. Protection is implemented under many management types and categories including strict nature reserves, national parks, habitat or species management areas, protected landscapes and protected areas with sustainable use of natural resources. National programmes for sustainable use and management of FGR should therefore take the contribution of protected areas into account, even if most of them were initially designed for other purposes such as wildlife protection, recreation and various ecosystem services.

Protected areas also have an important role in enhancing scientific knowledge on FGR. A substantial proportion of wild and/or endemic plants occur only in primary forests and protected forest areas. Only in those forest ecosystems is the natural population's genetic structure conserved. Natural processes involved in the dynamics of FGR are best assessed and understood in protected natural forests; they remain the best laboratories for studying species' ecology and biology. The contribution of primary forests and protected areas to the development of knowledge on plant species therefore needs to be promoted along with their contribution to FGR conservation.

### On-farm management of FGR

On-farm management of trees, including agroforestry systems, contributes to *in situ* conservation of FGR, particularly for domesticated or semi-domesticated tree species (Dawson *et al.*, 2013). The agroforestry parkland, for example, a traditional land-use system in West Africa, has been shown to contribute to on-farm conservation of species diversity (Nikiema, 2005). Many priority species identified in country reports from semi-arid zones are trees growing on farmlands, often in agroforestry systems. Most of them are indigenous species that farmers have managed traditionally for centuries. Tree diversity in farmland varies from a few species in some countries to more than 100 in some others. Some of these species are semi-domesticated species that occur only in agroforestry systems (e.g. *Acacia senegal* and *Vitellaria paradoxa*). Agroforestry systems must therefore be managed sustainably to conserve the genetic resources of the species. *In situ* conservation efforts should also include conservation of natural populations of the species and their wild relatives in order to preserve the variation needed for adaptation to future threats or to improve production.

### Multiple-use forest management and ecosystem approach

Naturally regenerated forests across the tropics provide a wide range of products, ecosystem services and social and economic opportunities and potentially can be managed to meet multiple objectives (Sabogal *et al*., 2013). Multiple-use forest management refers to forest management that combines objectives such as production of wood, habitat for wildlife, soil and water protection, recreation, and the supply of a range of NWFPs (e.g. food, fodder, medicines). This approach enhances sustainable forest management by taking into consideration the concerns of the stakeholders.

The ecosystem approach is a way to manage entire ecosystems in a holistic manner without excluding other management and conservation approaches such as area-based management tools and single-species conservation practices. Ideally all these approaches should be integrated, through regional networks when appropriate.

### Species and thematic networks

Regional collaboration through species or thematic networks should play an important part in implementation of *in situ* FGR conservation strategies and monitoring of progress. While addressing *in situ* FGR conservation, such collaborations should also consider the use of the ecosystem approach, different forest and tree management types and different levels of genetic conservation.

### Opportunities for adding value to *in situ* conservation

Countries identify the following opportunities for adding value to *in situ* conservation and/or improving the functionality of natural forest ecosystems:

- increased use of these areas as seed stands for priority FGR, including development of the forest gene bank concept, whereby genetically diverse material of priority economic and threatened species is planted as a mixture in one (or more) locations;
- use of these areas to raise the living standards of local people;
- ecotourism to generate income from non-consumptive uses of *in situ* conservation areas;
- enrichment planting and regeneration of high-priority and threatened FGR in protected areas, including restoration of degraded areas;
- restoration of the connectivity of protected forest fragments;
- promotion of on-farm or *circa situm* conservation of priority FGR, including fruit-trees and their wild relatives;
- payments for environmental services such as carbon sequestration (e.g. through REDD+), watershed protection and biodiversity (e.g. through bioprospecting licences);
- new employment opportunities from expanded markets for forest products (including NWFPs such as specialized organic forest products).

### Research on *in situ* conservation

Countries identify a number of specific research priorities for *in situ* conservation:

- increased knowledge and monitoring of genetic variation and its distribution in priority FGR, including threatened species, breeding systems and levels of outcrossing, gene flows between conserved populations and introduced/planted materials, and population viability;
- inventory and GIS mapping of FGR in protected areas (including to identify centres of diversity) and in non-protected areas;
- more knowledge of effective *in situ* conservation techniques including selection, establishment, monitoring, restoration and rehabilitation and management;
- prioritization of species;

- research on species importance in maintaining ecosystem function and services, as a focus for *in situ* conservation;
- research on autoecology (the ecology of individual species) and species genetic diversity, including monitoring, to inform and assess effectiveness of FGR conservation strategies and activities;
- development of low-cost technologies for better control of invasive species;
- identification of methods to improve participatory forest and FGR management, including to reduce deforestation;
- research into socio-economic aspects of *in situ* conservation;
- study of the impact of predicted climate change on the effectiveness of *in situ* conservation reserves.

## *Ex situ* conservation

The genetic diversity of forest trees and shrubs, both adaptive and neutral (i.e. in which variants have no direct effect on fitness; see Holderegger, Kamm and Gugerli, 2006), can be maintained through *in situ* conservation methods based on individual tree species distribution ranges. Although it is regarded as the most appropriate, sustainable and cost effective way of conserving FGR, *in situ* conservation can be insufficient, difficult or impossible for some species or species populations under threat because of exotic pests or disease outbreaks, extreme environmental conditions due to climatic changes or loss of habitat. For these species or particular populations of species, *ex situ* conservation is an essential complementary conservation tool.

*Ex situ* conservation may involve management of seed banks, gene banks or field collections. However, countries often lack adequate policies and the necessary means to address the needs of *ex situ* FGR conservation. Because of the high cost involved in *ex situ* conservation programmes and activities, priority should be given to populations of endangered species or taxa that are likely to become extinct. In some cases global or regional initiatives are needed for efficiency.

Needs for ensuring adequate contribution of *ex situ* conservation to overall FGR conservation include:

- good access to *ex situ* conservation data and information on FGR;
- improved capacity for *ex situ* conservation at all levels (national, regional, global);
- appropriate, efficient and economically accessible technologies for the conservation of seed, especially recalcitrant seed;
- expansion of the scientific knowledge base on tree seed physiology and conservation techniques.

With many countries reporting negative trends of overexploitation, land use changes and climate change effects, and consequently increasing loss of inter- and intraspecific diversity, *ex situ* conservation is warranted as a component of conservation strategies at the national, regional and global levels.

## Domestication, breeding and improvement

Tree domestication and improvement can substantially contribute to sustainable development through diversification in food and other commodities that are important to local communities and national economies, such as timber and medicinal plants (used by a large portion of the population in developing countries). Free grazing is still a common practice in many developing countries, and forests are often an essential source of fodder. These various resources are still harvested from wild plants in forest lands which in some cases are threatened by overexploitation. Domestication of such plants will improve the supply of the targeted products while reducing the vulnerability of their genetic resources. Many countries, particularly in the tropics, underline the need to develop domestication programmes to improve the supply of various forest products, including NWFPs.

Tree improvement activities have mostly been limited to a small number of economically important, widely planted tree species, because of financial constraints and because of the specific biological characteristics of trees; most trees are long-lived perennial species with long rotations (usually more than ten years except for pulpwood and biofuels), long regeneration cycles and late sexual maturity. Because of these characteristics, improvement and breeding research in tree species often requires many years (more than for other crops) and considerable resources (trained personnel, finances, land and laboratories). Accordingly there is a need to develop and promote the use of new technologies – e.g. biotechnology, genomics and micropropagation – to accelerate the tree improvement process and help unlock the huge potential of planted forest trees. These new technologies have proved useful for understanding forest ecosystem dynamics and species genetic diversity and processes. They can provide options for practical measures for sustainable conservation, management, restoration and rehabilitation, especially when there is sufficient scientific evidence of the relation between phenotype and genotype.

However, as funding and interest have switched to molecular approaches, many countries have abandoned progeny and provenance trials that had been established for many species. Existing but dispersed data from these trials should be assembled, maintained and evaluated for their potential to inform seed zone delineation, plans for assisting gene flow in response to climate change, and identification of propagation material for restoration and conservation of high-value populations.

### Selection and breeding of trees to respond to climate change

Traditional breeding programmes will need to be modified to consider plasticity and adaptation to increased drought, a substantial change from current practice. Climate change related traits need to be included in selection criteria; this is still rarely done worldwide.

Provenance trials that have been established at multiple locations using germplasm sourced from a variety of ecological conditions demonstrate that variation in adaptive traits is almost always present within tree species. Not only is genetic diversity in important adaptive traits expressed across regions and provenances, but it is also abundant within populations, reinforcing an optimistic view that climate change challenges may be met by standing genetic variation in such species (Hoffmann and Sgro, 2011).

However, many provenance trials were established before the response to large-scale anthropogenic environmental change was considered an important research issue, so trials often have not measured the most important traits from the perspective of adaptation to climate change. Nevertheless, these older multilocational trials provide insight into the performance of provenances from different climatic regions and make it possible to identify sources of locally adapted material. Survival and growth are considered good proxies for fitness (e.g. Ouedraogo *et al*., 2012). New trials specifically established to assess explicit responses to climate change are being established in a number of countries, for example under the Treebreedex project in Europe (http://treebreedex.eu).

Some important traits needed for adaptation to different climatic conditions but not often considered in breeding programmes are pest resistance, drought resistance, fire resistance or tolerance, cyclone resistance, salt tolerance and phenotypic plasticity.

## Germplasm delivery and deployment

Countries report that large plantation areas are being established to serve many purposes, including the production of timber, biofuel and fibre and the provision of environmental services such as soil and water management

and reclamation of degraded land. However, many countries lack adequate forest seed supply systems and therefore face difficulties in getting the quantities and quality of forest reproductive material needed to implement their plantation programmes. Collaboration among tree seed centres should be enhanced to encourage development and use of common seed quality standards, to facilitate forest reproductive material exchange within regions and to support national afforestation programmes. In this regard the International Seed Testing Association (ISTA) standards for seed germination are a widely used reference for the international tree seed market.

Seed is the most available form of germplasm, and distribution and deployment tend to be skewed towards species that produce orthodox seed, since they can be transferred most conveniently and reliably. Since other species may also be useful or require conservation, there is a need for further research and development on storage, propagation and transfer techniques for species with recalcitrant or short-lived orthodox seeds.

In some countries, public agricultural agencies have a longstanding involvement in *ex situ* conservation and in production, storage and distribution of forest germplasm (particularly in relation to food- or crop-bearing trees. Greater cooperation and harmonization of effort between agricultural and forest agencies might prove beneficial in this respect, especially in countries where resources for FGR conservation are limited.

Governments may offer incentives to private companies for the production of high-quality germplasm and planting materials, particularly for activities consistent with national goals, e.g. for conservation of forests, FGR and biodiversity.

The global movement of forest reproductive material should be facilitated. Priority matters reported by countries in the area of germplasm delivery and deployment, including identified strategic priorities, include:

- coordination of public and private sector activities;
- possible centralized organization to coordinate exchange of germplasm and related data collection;
- identification of opportunities for coordinating germplasm collection, storage and deployment with *ex situ* conservation activities, e.g. through tree seed centres;
- clear benefit sharing arrangements and use rights to promote production and deployment of improved trees;
- incentives for adoption and use of improved varieties;
- increased access to improved varieties for farmers, rural communities and others in the informal sector;
- increased capacity for producing adequate quantities of improved planting materials to meet demand;
- closer alignment of delivery and deployment with the needs of communities and market demand through better consultation, coordination, participation of communities setting effective priorities, development of markets (where appropriate) and more effective response to market signals;
- development and expanded use of consistent standards for collection and storage of germplasm for exchange, distribution and deployment at national, regional and international levels, and their harmonization with existing programmes (e.g. the OECD Forest Seed and Plant Scheme [OECD, 2013] and EU Directive 1999/105/EC [EU, 1999]), including promotion of common language and terminology;
- promotion of production and exchange under preferred schemes and guidelines with appropriate rewards, while retaining the vigour of informal germplasm production and exchange systems in developing countries;

- development and promotion of appropriate certification systems;
- use of improved materials in informal germplasm exchange and production systems;
- more effective integration of databases, including accessible information about deployment in the private sector;
- promotion of improved fuelwood plantations to provide carbon-neutral energy and reduce degradation of natural forests and FGR, particularly for countries where wood is currently a major energy source;
- maintenance of genetic variability in the distribution and deployment process.

## Assisted migration to accelerate adaptation to climate change

Trees and tree populations are amenable to "facilitated translocation" or "assisted migration" which involves the movement (by people) of reproductive materials (seeds, seedlings and vegetative parts) from existing ranges to sites expected to experience analogous environmental conditions in the future (Guariguata *et al*., 2008; McLachlan, Hellmann and Schwartz, 2007). The movement could be latitudinal or altitudinal. The objective of such intentional movement is to reduce climate change-related extinction risks (Heller and Zavaleta, 2009; Marris, 2009; Millar, Stephenson and Stephens, 2007). Species or populations that are unable to migrate to new locations or adapt through natural selection can be intentionally moved to a region where stresses are less severe.

Assisted migration can include translocation over long distances (assisted long-distance migration), translocation just beyond the range limit (assisted range expansion) and translocation of genotypes within the existing range (assisted population migration) (Alfaro *et al*., 2014; Winder, Nelson and Beardmore, 2011). Under certain interpretations, assisted migration could include the introduction of new species to maintain ecological services, such as wood production and carbon sequestration. Some guidelines for reforesting harvested sites require the use of seeds from neighbouring sources that are already adapted for expected future climates (e.g. seed from sources south of the area to be planted, in Northern Hemisphere forests). In practice, implementation of such guidelines could be a gradual form of assisted migration.

## Chapter 18

# Political and institutional recommendations

Forest genetic resources offer major opportunities for humankind to cope with important challenges such as climate change and the increasing demand for food, energy, wood products and environmental services from forests. To realize their value fully, countries require political commitment, effective institutions and relevant policies and legislation in order to respond to pressing and increasingly varied needs in conservation and FGR management. Staffing and capacity must be strengthened through FGR education, research, and training. Long-term stable funding support mechanisms should be established, including for FGR research.

Information on the status, trends and characteristics of FGR is needed in order to identify priorities for actions for their sustainable use and conservation as well as for the development of tree domestication and improvement programmes. Awareness building at all levels is a key prerequisite for mobilizing popular support and international collaboration to improve the conservation and management status of FGR. Appropriate advocacy tools need to be developed and used to ensure effective communication and information sharing related to sustainable FGR management and use.

In the context of scarce resources and a great risk of duplication of effort, efforts should be made to promote collaboration, partnership and coordination at the national, regional and international levels and to mobilize the funding required to ensure that the major needs and priorities on FGR identified by countries are adequately addressed by stakeholders.

## National polices and institutions

Commitment at national and local levels to specified objectives and priorities is a prerequisite for the implementation of sustainable FGR conservation programmes.

In many countries, national policies and regulatory frameworks for FGR are currently partial, ineffective or inexistent, partly because FGR are not well understood in these countries. In most countries, forest policies fail to address concerns of sustainable FGR management (e.g. *in situ* conservation of species and species populations), or address them inadequately.

Given the large number of stakeholders involved in using, developing and managing FGR at the national level, countries should develop national strategies and programmes to provide an appropriate framework of action given the national context. For example, demand for forest products including roundwood, fuelwood and NWFPs is increasing in many countries, and in some countries the value of NWFPs is higher than that of roundwood and fuelwood (FAO, 2010a). Sound social and economic policies are needed to ensure the integration of FGR in wider national forest policy frameworks.

For the countries that do not have a national programme for managing and conserving FGR, the main challenge is to develop such a programme with multistakeholder participation. These countries also need to develop national forest genetic resources networks or join regional networks. Networking and institutional twinning, which have long traditions in forestry, should be vigorously promoted.

Countries developing national forestry action plans should be encouraged specifically to include genetic-level responses to climate change in their plans.

Governments ensured broad ownership of the country reporting process for *The State of the World's Forest Genetic Resources* by organizing stakeholder workshops to review and validate their reports. This participatory process needs to continue, to ensure commitment among all stakeholders in the country.

Many countries note that FGR legislation and regulations need to be improved and expanded and the gaps filled. Requirements for reporting and sanctions for non-compliance need to be addressed. Cooperation among national and subnational authorities and other stakeholders concerned with FGR should be enhanced. In some cases, where cooperation among national authorities does not exist, a permanent national commission for conservation and management of forest genetic resources should be established.

Institutional strengthening, training and support to research are needed for countries to be able to respond to pressing and increasingly varied needs in conservation and FGR management. National research systems, including tree seed centres, have a crucial role in this context, as does their support by relevant international programmes and initiatives.

Countries should particularly aim at creating synergy with FGR-related international programmes and conventions (Box 18.1), coordinated by different national authorities, to enable efficient information sharing and resource use and better support of the national FGR priorities identified.

In addition, most countries, in their reports and during the regional consultations, highlighted the need to promote thematic networking to facilitate linkage among stakeholders and enhance institutional development and capacity building.

### Box 18.1
### Integrating forest genetic resources in international forest and natural resource management policy framework

A number of international agreements progressively being implemented under the CBD will serve as useful international frameworks for promoting the sustainable use, management and conservation of FGR at the global and national levels. The Cartagena Protocol on Biosafety is in force, and the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization is now being ratified by member countries.

REDD+, in countries where it is implemented, can be another important mechanism for developing FGR conservation activities – since REDD+ goes beyond rewarding carbon storage and also compensates conservation and sustainable management of forests in order to encourage developing countries to contribute to climate change mitigation.

International harmonization of action is necessary to ensure that wasteful duplication of efforts is avoided, important FGR issues are not inadvertently neglected, the reporting burden on countries is minimized, and provision of data and information is consistent across sectors, thus facilitating cross-sectoral linkages.

## Decentralization

Many developing countries have or are shifting to a decentralized administration for management of natural resources, including FGR; the objective is to improve equitable access to and sustainable management of natural resources by indigenous and local people who rely on them for their livelihood.

In some countries regulatory measures are decided at province or state level. There is therefore a need to provide appropriate technical support to decentralized administrations to ensure that their policy tools provide for sustainable use and management of FGR, for instance by retaining customary use by indigenous and local communities.

To take advantage of the opportunities that decentralization offers, it is important to be aware of the political and environmental limitations of decentralized natural resource management programmes. It is likewise important to be more strategic in building sustainability based on the sociocultural, economic and environmental context of the specific target area, be it a state, a province, a district or a village. Well planned decentralization initiatives are enhanced by people's participation at local level and ownership of management programmes by stakeholders.

It is commonly accepted that *in situ* conservation of FGR has a better chance of success if local or indigenous communities living in or near the forest are responsible for or strongly involved in implementing the conservation programmes. In this regard decentralization represents a useful policy framework for *in situ* FGR conservation in many countries.

## Prioritizing species at the national level

The number of species mentioned by countries as priority species varies from less than 10 to nearly 300. Given the high number of tree species recorded as priority worldwide – about 2 300 recorded from 86 country reports – it is clear that prioritization of the many alternative species should be encouraged for more efficient action at the national, regional or international levels (Box 18.2). Priority setting is complicated greatly by the lack of basic information on the variation, variation patterns and potential of many tree species. A species approach is regarded as an adequate and useful option for understanding and developing FGR. Updated information on the country's forest species, their uses and their conservation status is a good basis for sound identification of country priority species for action. Priority species can be identified at the national or subnational level and shared in existing regional and international fora to enhance focus and efficiency of resource use.

The general aim of priority setting is to compare the consequences and trade-offs of a range of actions. It implies that some areas, species or

### Box 18.2
### Regional collaboration in FGR conservation and management: joint strategies and priorities

Regional strategies for FGR conservation, including regional networks of *in situ* genetic conservation units and corridors of priority species, are needed to ensure the dynamic conservation of key forest genetic resources and their evolutionary ability for the future. Investment in joint regional activities may often be more efficient and cost effective than dealing with common issues at the national level, which can entail duplication of activities. Definition and implementation of regional FGR conservation strategies provide a good justification for coordination and collaboration at the regional level.

Regional priorities for action were identified during the regional consultations held as part of the process for *The State of the World's Forest Genetic Resources*, and some regional priority species were discussed; in many cases, the same species have been identified as priorities by existing regional FGR networks. This process needs to continue in order to define detailed actions for each species and to allocate responsibilities among actors and partners at the national, regional and international levels.

Most of the regional consultation workshops, furthermore, recommended the promotion of regional mechanisms to facilitate access to forest reproductive material for scientific work. It was noted that regulation of transfer and exchange of forest reproductive material under international agreements can sometimes limit access to proper quality genetic material, even restricting transfer among countries sharing the same ecological conditions. This constraint can prevent research programmes from delivering results that will have real impact. The regional consultations encouraged regional networking for exchange of FGR material, in compliance with national legislation and applicable international regulations.

genetic resources will be given lower priority than others. When different stakeholders have similar priorities, concerted action on the part of these stakeholders is possible. When their priorities are dissimilar, independent but harmonized action is more likely to succeed. Governmental, non-governmental and international organizations active in forest biological diversity and genetic conservation will often differ substantially in their priorities as well as in their ability to implement various management techniques. Where such differences exist, it is necessary to form coalitions for action, which must operate under coherent frameworks and at appropriate levels.

## Capacity building

Many countries report weak technical and scientific capacity in FGR-related fields. University training curricula on issues such as FGR conservation, tree breeding and management of NWFPs are rarely available in those countries. In most countries (and particularly in developing countries and countries in economic transition), research and education need to be strengthened in all areas of FGR management and at both technical and professional levels. Establishing, strengthening and maintaining research and education institutions is key to building national capacity to plan and implement priority activities for sustainable use, development and conservation of FGR.

Technical training should be designed to help countries capitalize on recent developments in forest inventory (remote sensing, GIS) and forest genetics (traditional and more recent molecular marker technologies and other biotechnological tools, as applicable).

In particular, many countries report a weakness in policy and institutional capacity related to the conservation, sustainable management and development of FGR. To fill this gap, the following needs should be addressed. Those relating to information and public awareness are discussed further below.

- FGR conservation and management needs must be updated and integrated into wider national policies, programmes and frameworks for action at the national, regional and global levels.
- Coordination and collaboration among national institutions and programmes related to FGR must be promoted.
- National capacity to manage FGR should be assessed, and educational and research capacity strengthened to ensure adequate technical support to FGR-related development programmes.
- The participation of indigenous and local communities in FGR management should be promoted in the context of decentralization.
- Regional mechanisms for exchange of forest reproductive material for research and development, consistent with applicable international conventions, need to be promoted and applied.
- Regional and international cooperation should be reinforced in support of education, knowledge dissemination, research, conservation and sustainable management of FGR.
- Network activities for information sharing on FGR research, management and conservation should be encouraged and developed.
- Public and international awareness of the role and value of FGR should be promoted.
- The necessary resources need to be mobilized.

## Improving information availability and access

With the increasing pressure on forest resources and the high cost of land-use change in terms of forest conservation, the need for reliable data on FGR status and trends has become acute. Reliable data are required at all levels to support decision-making that will enable sustainable management of forest resources, including FGR. This publication on *The State of the World's Forest Genetic Resources* provides the first global overview of the diversity, status and trends of FGR and of national regional and global capacity to manage these resources.

Many country reports indicate that information at the country level is incomplete, scattered and difficult to obtain, although some progress has been made during the past decade. In some countries information is barely available.

Reported gaps in information and data needed to support adequate FGR management relate to:

- availability of updated country-level species lists;
- availability of appropriate indicators that can be easily used to evaluate the status of forest genetic resources or to measure the impact of factors such as changes in land use and overexploitation on diversity within and among species;
- knowledge of reproductive and development characteristics of forest species, required for *ex situ* conservation, production of seedlings, planting and development of species outside their original habitats;
- documentation of traditional knowledge and beliefs related to FGR use and management.

These deficiencies complicate global monitoring of the status and trends of FGR and limit capacity for effective decision- making and action at national and international levels. Global forest information initiatives such as FAO's Global Forest Resources Assessment (FRA) and national forest inventory and monitoring programmes are important sources of information; however, the available information largely relates to forest resources in general rather than to forest diversity and variation within tree species. Information relevant to FGR management needs to be incorporated in such initiatives. In the absence of scientifically assessed intraspecific genetic information, a reasonable short-term alternative would be to maintain a range of populations for the targeted species selected from throughout its natural distribution and covering different climatic zones and soil types.

## National FGR assessment, characterization and monitoring systems

To improve access to information on FGR for all stakeholders, establishment and strengthening of FGR information systems are urgently needed, including databases to store and share knowledge (both scientific and, where available, traditional) on uses, distribution, habitats, biology, and morphological and genetic variation of species and species populations. The use of common protocols for FGR inventories, characterization and monitoring should be promoted to ensure that data collected from different countries are comparable. However, each country may need to adapt the protocols to its specific constraints and frameworks.

As mentioned above, national forest inventories do not usually include the relevant concerns for the planning and sustainable management of FGR. Forest inventory activities should include updating of species lists and development of species distribution maps, as this information is necessary for development of plans for conservation, sustainable management and development of forest genetic resources. However, because of the limited number of plant taxonomists and forest geneticists and the lack of adequate technical infrastructure and financial resources, many developing countries have limited capacity to conduct botanical inventories, to keep updated species lists and to create species distribution maps, as well as to manage national herbaria and gene banks. This problem should be addressed by including activities such as updating of country forest species checklists and monitoring and assessment of populations of important forest species in national programmes where appropriate. Countries with limited resources will need to build synergy among programmes and institutions at the national, regional and international levels to minimize the constraints.

Some countries report that they have information from FGR-related activities in the public sector but lack information from the private sector; this disparity indicates the need for integrated and harmonized documentation and

data gathering activities between the sectors. Industry organizations with comprehensive membership in both the public and private sectors, as exist for example in Canada, might assist in promoting this practice.

### Networks

Regional FGR networks should be strengthened and expanded. Regional networks are particularly important for addressing needs for information, research and strategy development for species that cross multiple national borders.

Collaboration among international networks provides a means to amalgamate FGR knowledge and data hosted by various agencies and institutions, which is beneficial for the design of conservation and management strategies. Shared national forest resource inventories could include forest ecosystem maps and disturbance databases. The opportunity to further strengthen collaborative relationships and cross-border studies will become more apparent as gaps in FGR-related knowledge are studied.

### Preserving and enhancing use of traditional knowledge

Traditional knowledge represents a source of valuable information that must be adequately considered in development of national, regional and global programmes on FGR conservation, sustainable use and development.

Traditional farming systems and practices for using and managing natural resources (including forest genetic resources), based on long-established knowledge, help to ensure food and agricultural diversity, livelihoods, food security and the maintenance of valuable ecosystems. However, traditional livelihoods and indigenous plant varieties and landraces are now increasingly endangered by large-scale commercialization of agriculture and forestry, land-use and land-cover changes and the impacts of climate change.

In many countries, traditional knowledge and FGR use and management are closely linked, for example in agroforestry farming systems. Traditional knowledge on the use of trees and tree products contributes to the welfare of indigenous and local communities in many countries (in terms of food, medicine, shelter), while also representing a tremendous asset for industrial and trade development in such sectors as cosmetics, pharmacy, food technology and biopesticides. Most country reports acknowledge that FGR-related traditional knowledge is an important asset for improving the contribution of forests to national economies as well as people's livelihoods. Furthermore, it contributes to sustainable development through practices such as local conservation and sustainable use of plants; it can also contribute to mitigating serious global problems such as climate change, desertification and land and water degradation.

Traditional knowledge of FGR is increasingly under threat, however, as a consequence of FGR degradation and changes in land use and sociocultural practices; thus the need to preserve this knowledge is becoming acute. Policies on FGR information management should consider traditional knowledge as an important source of information and an essential asset, and this viewpoint needs to be adequately reflected in national assessments, technical programmes and policy documents.

## Priority areas for research

In many ways, understanding of genetic diversity in trees is advancing rapidly, yet the scale of the task ahead remains enormous, especially for tropical species (Box 18.3). With highly diverse forest ecosystems under extreme pressure from human exploitation, changing climate and shifting ecology, the need to improve the state of knowledge is acute. For most species, even basic data are lacking on the standing resources, the mechanisms that maintain them, and their dynamics. It is a vast challenge to gather and interpret available data to discover how contemporary genetic resources were formed and to predict how they may respond to changes in the future.

The following research priorities are recommended as an entry point for addressing this challenge. It is likely that these efforts would be most effective if targeted at the priority species identified by regional forest genetic resources networks, but other species should not be excluded.

- Improve taxonomic knowledge, particularly for tropical tree species.
- Improve understanding of the genetic diversity of important or priority species and the processes that determine the structure of the genetic diversity within and between populations. Identification and understanding of the genetic traits that enhance species' adaptation will be particularly useful in tackling challenges related to climate change, while also providing opportunities to boost the functions of trees and forests.
- Map tropical forest genetic resources. Assess key priority species across their complete range, i.e. map their genetic variation, to provide a context for FGR prioritization. Map layers could include neutral genetic data, genomic data and experimentally assessed phenotypic variation. Existing mapping initiatives such as MAPFORGEN (www.mapforgen.org) provide a lead.
- Promote meta-analysis on key aspects of forest genetic resources for better understanding of the link between characteristics of diversity at species and genetic levels and the processes determining the state of genetic diversity of priority or important forest species.

## Box 18.3
## The state of knowledge on forest genetic resources: a summary

- Knowledge of FGR is reported to be inadequate for well-informed policy or management in most countries.
- Among the 80 000 to 100 000 tree species, studies have described genetic parameters for less than 1 percent, although both the number of studies and the number of species studied have increased significantly in the past decade.
- Most studies conducted during the past two decades have been at the molecular level, either using DNA markers or genomic technologies to characterize genetic resources. Molecular information is accumulating much faster than whole-organism information, with the consequence that little of the accumulating knowledge has direct application in management, improvement or conservation.
- A few species have been well researched – through both molecular and quantitative studies – and genetically characterized; these mainly comprise temperate conifers, eucalypts, several acacias, teak and a few other broadly adapted, widely planted and rapidly growing species.
- Quantitative genetic knowledge has led to significant productivity gains in a small number of high-value planted timber species.
- Genomic knowledge of forest trees lags behind that of model herbaceous species, including the important agricultural crops, but for several tree species the entire genome has been or is in the process of being sequenced, and novel approaches have been developed to link markers to important traits. Genomic or marker-assisted selection is close to being realized, but phenotyping and data management are the biggest bottlenecks.
- Many of the species identified as priorities, especially for local use, have received little or no research attention, indicating a need to associate funding with priority-setting exercises.

## Communication and awareness raising

Most country reports mention inadequate public awareness of FGR, highlighting the need to promote awareness among decision-makers and the general public of the importance of FGR and their role in meeting present and future development needs. Lack of information limits the capacity of countries and the international community to integrate FGR management into cross-cutting policies. Furthermore, lack of general understanding of the importance of FGR is an impediment to generation of new knowledge.

Most countries do not have specific programmes for creating public awareness of forest genetic resources. Throughout the world the public is more aware of threats such as climate change and changes in land use and their implications for forests, particularly boreal and other old-growth forests, as these topics are prevalent in the media. Information about the importance of FGR is not one of the chief priorities of institutions conducting public relations about forests, forestry and nature conservation. In today's information-flooded society, forests in general and forest genetic resources in particular compete for public attention with many other subjects. Even for those people who are interested in and seek information about forests, the many stakeholders each with their respective interests create a rather confusing picture.

Much of the public is sceptical about genetic engineering. In some developed countries, genetic engineering and genetics are often considered one and the same. The word "genetics" and all related terms have often acquired negative connotations. Such preconceptions greatly hinder efforts to convey knowledge of the importance of forest genetic resources.

The increasing urbanization of the population and the lack of knowledge about nature are impediments to public awareness. Forest genetic resources generally have no reference in people's private lives. Only a small fraction of the population works in or derives income from the forest. As a consequence, understanding of forest management is dropping; the forests are perceived most often as natural assets for protection or as the green backdrop of recreational activities. The lack of understanding of forest management is accompanied by a lack of understanding about productive provenances or forest plant breeding.

Some surveys reported by countries showed that the public and NGOs have the lowest awareness of the roles and value of forest genetic resources. Industry and government rated much higher. In general, the value of forest genetic resources has not been widely communicated at the national level.

Awareness raising initiatives or programmes should be created for greater visibility of forest genetic resources. The following are some specific recommendations.

- Countries should develop a genetic resources communication strategy and make forest genetic resources information more accessible.
- Countries should provide training and education on forest genetic resources to improve understanding of their benefits and value.
- Training is required to sensitize policy-makers about the responsibilities and advantages of FGR management action in the short and longer term.
- Awareness can be strengthened by using television, newspapers and other media to inform the public about forest genetic resources and their protection.
- Institutions that can usefully contribute to raising FGR awareness include parks, reserves, territories of regional forestry boards, state forests and game enterprises, educational and practical forest enterprises, and specialized forest schools.

## In conclusion: what needs to be done

**Improve the availability and accessibility of knowledge and information** on species and their genetic diversity, forest ecosystems and related traditional knowledge, to facilitate and enable decision-making on sustainable use and management of FGR and to enhance their contribution to solving serious global problems such as food shortage, land and water degradation, the effects of climate change, and increased demand for various forest products and services:

- Establish and strengthen national FGR assessment, characterization and monitoring systems.
- Develop national and subnational systems for the assessment and management of traditional knowledge on FGR.
- Develop international technical standards and protocols for FGR inventory, characterization and monitoring of trends and risks.
- Promote the establishment and reinforcement of FGR information systems (databases) to cover available scientific and traditional knowledge on uses, distribution, habitats, biology and genetic variation of species and species populations.

**Enhance *in situ* and *ex situ* conservation of FGR,** to maintain genetic diversity and the evolutionary processes of forest tree species:

- Strengthen the contribution of primary forests and protected areas to *in situ* conservation of FGR.
- Promote the establishment and development of efficient and sustainable *ex situ* conservation systems, including *in vivo* collections and gene banks.
- Support and strengthen the role of indigenous and local communities in the sustainable management and conservation of FGR.
- Identify priority species for action.
- Harmonize measures for *in situ* and *ex situ* conservation, including through regional cooperation and networking.

**Enhance the sustainable use, development and management of FGR** to contribute to environmental sustainability, food security and poverty alleviation:

- Develop and reinforce national seed programmes to ensure the availability of genetically appropriate tree seeds in the quantities and of the quality needed for national plantation programmes.
- Promote restoration and rehabilitation of ecosystems using genetically appropriate material.
- Support climate change adaptation and mitigation through proper management and use of FGR.
- Promote good practices and appropriate use of emerging technology to support the conservation, development and sustainable use of FGR.
- Develop and reinforce research programmes on tree breeding, domestication and bioprospecting.
- Develop and promote networking and collaboration among concerned countries to combat invasive species affecting FGR.

**Strengthen policies and institutional capacity** to address major issues related to sustainable FGR management and enable successful medium- and long-term planning for long-term sustainable use, management and conservation of FGR:

- Develop national strategies for *in situ* and *ex situ* conservation and sustainable use of FGR.
- Integrate FGR conservation and management into wider policies, programmes and frameworks of action at the national, regional and global levels.

- Develop collaboration and promote coordination of national institutions and programmes related to FGR.
- Establish and strengthen educational and research capacities on FGR.
- Promote the participation of indigenous and local communities in FGR management in the context of decentralization.
- Promote and apply mechanisms for regional germplasm exchange for research and development, in agreement with international conventions.
- Reinforce regional and international cooperation, including networking, to support education, knowledge dissemination, research, and conservation and sustainable management of FGR.
- Promote public and international awareness of the roles and value of FGR.
- Strengthen efforts to mobilize the necessary resources, including financing, for the conservation, sustainable use and development of FGR.

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# Acronyms and abbreviations

| | |
|---|---|
| **ACIAR** | Australian Centre for International Agricultural Research |
| **AFLP** | amplified fragment length polymorphism |
| **AFTP** | agroforestry tree product |
| **CATIE** | Tropical Agricultural Research and Higher Education Center |
| **CBD** | Convention on Biological Diversity |
| **CIAT** | International Centre for Tropical Agriculture |
| **CITES** | Convention on International Trade in Endangered Species of Wild Fauna and Flora |
| **COFO** | FAO Committee on Forestry |
| **cpDNA** | chloroplast DNA |
| **CSIRO** | Commonwealth Scientific and Industrial Research Organization (Australia) |
| **CTFT** | Centre technique forestier tropical (France) |
| **DANIDA** | Danish International Development Agency |
| **DArT** | diversity arrays technology |
| **DFSC** | DANIDA Forest Seed Centre |
| **DNA** | deoxyribonucleic acid |
| **EEM** | environmental envelope modelling |
| **EST** | expressed sequence tag |
| **ESTP** | expressed sequence tag polymorphism |
| **EU** | European Union |
| **EUFGIS** | European Information System on Forest Genetic Resources |
| **EUFORGEN** | European Forest Genetic Resources Programme |
| **FGR** | forest genetic resource(s) |
| **FRA** | Global Forest Resources Assessment |
| **FSC** | Forest Stewardship Council |
| **GEF** | Global Environment Facility |
| **GFIS** | Global Forest Information Service |
| **GIS** | geographic information system |
| **GM** | genetic modification/genetically modified |
| **ICRAF** | World Agroforestry Centre |
| **INPA** | Instituto Nacional de Pesquisas da Amazônia (Brazil) |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IPGRI** | International Plant Genetic Resources Institute (now Bioversity International) |
| **IPPC** | International Plant Protection Convention |
| **ISSR** | inter-simple sequence repeat |
| **ISTA** | International Seed Testing Association |
| **ITS** | internal transcribed spacer |
| **ITTO** | International Tropical Timber Organization |
| **ITWG-FGR** | Intergovernmental Technical Working Group on Forest Genetic Resources |
| **IUCN** | International Union for Conservation of Nature |
| **IUFRO** | International Union of Forest Research Organizations |
| **MDGs** | Millennium Development Goals |
| **MTA** | Material Transfer Agreement |
| **NGO** | non-governmental organization |
| **NLBI** | Non-Legally Binding Instrument on All Types of Forests |
| **NTSC** | national tree seed centre |

| | |
|---|---|
| **NWFP** | non-wood forest product |
| **OECD** | Organisation for Economic Co-operation and Development |
| **PCR** | polymerase chain reaction |
| **PEFC** | Programme for the Endorsement of Forest Certification |
| **PGRFA** | plant genetic resources for food and agriculture |
| **PNGFRI** | Papua New Guinea Forest Research Institute |
| **QTL** | quantitative trait locus |
| **RAPD** | random amplified polymorphism DNA |
| **REDD+** | reducing emissions from deforestation and forest degradation in developing countries (including the role of conservation, sustainable management of forests and enhancement of forest carbon stocks) |
| **RFLP** | restricted fragment length polymorphism |
| **RNA** | ribonucleic acid |
| **SADC** | Southern African Development Community |
| **SFM** | sustainable forest management |
| **SIDS** | small island developing States |
| **SNP** | single-nucleotide polymorphism |
| **SPRIG** | South Pacific Regional Initiative on Forest Genetic Resources |
| **SSR** | simple sequence repeat |
| **TEK** | traditional ecological knowledge |
| **UNEP** | United Nations Environment Programme |
| **UNESCO** | United Nations Educational, Scientific and Cultural Organization |
| **UNFCCC** | United Nations Framework Convention on Climate Change |
| **USDA** | United States Department of Agriculture |
| **WTO** | World Trade Organization |

Forests and trees enhance and protect landscapes, ecosystems and production systems. They provide goods and services which are essential to the survival and well-being of all humanity. Forest genetic resources – the heritable materials maintained within and among tree and other woody plant species that are of actual or potential economic, environmental, scientific or societal value – are essential for the continued productivity, services, adaptation and evolutionary processes of forests and trees. This first volume of *The State of the World's Forest Genetic Resources* constitutes a major step in building the information and knowledge base required for action towards better conservation and sustainable management of forest genetic resources at the national, regional and international levels.

The publication was prepared based on information provided by 86 countries, outcomes from regional and subregional consultations and commissioned thematic studies. It presents definitions and concepts related to forest genetic resources and a review of their value; the main drivers of changes and the trends affecting these vital resources; and key emerging technologies. The central section analyses the current status of conservation and use of forest genetic resources on the basis of reports provided by the countries. The book concludes with recommendations for ensuring that present and future generations continue to benefit from forests and trees, both through innovations in practices and technologies and through enhanced attention to forest genetic resources at the institutional and policy level.

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