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Are Tree Seed Systems for Forest Landscape Restoration Fit for Purpose? An Analysis of Four Asian Countries

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Abstract: High-quality, suitably adapted tree seed at volume is a key component for the implementation and long-term success of forest landscape restoration (FLR). We analysed the tree seed systems in four Asian countries—the Philippines, Indonesia, Malaysia and India—which have committed to restore in total over 47.5 million hectares of degraded lands by 2030. We assessed the national seed systems using an established indicator framework, literature review and expert surveys and interviews. Additionally, we surveyed 61 FLR practitioners about their challenges in acquiring seed to understand how the strengths and weaknesses identified at the national level were reflected in FLR projects on the ground. Identified key constraints common to the studied countries are (i) a mismatch between the growing demand for priority native species and the limited seed supply in terms of quantity and quality, (ii) lack of effective quality control for seed of native species and (iii) lack of information about the effects of climate change on native species to guide species selection and seed sourcing and to improve the resilience of restored ecosystems. We discuss options to strengthen seed systems for native tree species both in terms of quality and volume to enable them to effectively respond to the national FLR commitments and make recommendations on promising technical solutions.

Keywords: Philippines; Indonesia; Malaysia; India; tree seed supply; ecological restoration; genetic diversity; forest genetic resources

1. Introduction

Reversing ecosystem loss and the related global biodiversity and climate crises has never been more urgent than now. This is being emphasised by the United Nations' Decade on Ecosystem Restoration's aim to halt and reverse ecosystem degradation by 2030 [1]. Through international agreements such as the Bonn Challenge and the New York Declaration on Forests, various governments, private actors and civil society organisations have set ambitious targets to restore hundreds of millions of hectares of degraded and deforested landscapes [2–4]. Forest landscape restoration (FLR) aims to re-establish ecological integrity in deforested or degraded areas and improve forest-based livelihoods [5–7]. Increasing native tree cover is key to reversing biodiversity decline [8,9] and, if done appropriately, contributes to mitigating the impacts of climate change [4,10,11] and enhancing food security [12]. However, to date many of the ambitious FLR initiatives have failed to deliver the intended benefits that are required to tackle the biodiversity and climate crises, such as carbon sequestration, biodiversity recovery and sustainable livelihoods [10,13,14].

Inadequate supply and quality of tree seeds and seedlings is a major bottleneck for the success of tree-based FLR [15,16], particularly in terms of a lack of consideration to which species should be chosen and where and how the seeds are sourced [17–21]. Despite the importance of the genetic quality of planting material for restoration efforts, existing recommendations for seed collection are not consistently integrated in FLR projects and programmes [18,22,23]. Hereafter we use the term 'seed' to refer to any forest reproductive material, including seeds, seedlings, wildlings, vegetative material and any other form of forest reproductive material. Research-based recommendations advise to source seed from within seed transfer zones (biogeographic areas within which species-specific seed can be transferred with minimal risk of maladaptation) [24], large populations and a minimum of 30–60 widely spaced mother trees [22,25,26]. However, in practice, seeds for restoration are often collected from only very few mother trees and have low genetic diversity [18,20,22]. Lack of genetic diversity considerations in current strategies of seed selection and collection can result in negative consequences not only for individual survival, growth and productivity, but also for the resilience of the restored populations as well as the provisioning of ecosystem services [17,18,20,27–30]. Poor growth and survival of seedlings also increase the costs of restoration and result in delays [18]. Improving seed supply in terms of quantity and quality is therefore crucial to ensure that the ambitious FLR targets can deliver the intended benefits and contribute to tackling the global biodiversity and climate crises.

Over 80% of the international FLR commitments accumulated through the Bonn Challenge and the New York Declaration on Forests are in low- and middle-income countries in the tropics [31]. Tropical Asia has the highest proportional plant diversity, and biodiversity overall, for its size [32] and has vast restoration potential [33,34]. In this study, we analyse the strengths and weaknesses in tree seed systems for native tree species in the Philippines, Indonesia, Malaysia and India. All four countries have set national FLR targets but differ considerably in FLR approaches and in how national seed systems are organised. We shed light on the challenges and good practices in tree seed systems in each country through literature review and surveys, both at the policy level and on the ground. We identify priority areas for strengthening the national seed systems and discuss opportunities for improvement to help FLR efforts succeed.

2. Materials and Methods

2.1. Focus Countries

The four study countries have together pledged to restore over 47.5 Mha of degraded forests and landscapes by 2030 (Table 1). While forest cover and number of native tree species vary among the analysed countries, all four are regarded as megadiverse, having extremely rich biological diversity and holding a vast number of endemic species [35]. At the same time, as developing economies, the countries experience continued forest degradation and deforestation. For example, Indonesia ranked as one of the top ten countries worldwide for average annual net losses of forest area between 2010 and 2020 (losing 753,000 ha per year) [36]. To reverse this trend, governments have developed policies and regulations to reduce forest degradation and deforestation, which complement the national restoration targets.

The Philippine government has implemented two important forest policies to reduce forest loss, namely Executive Order 23 in 2011 which declared a logging moratorium in natural and residual forests, and Executive Order 26 in 2014 which initiated the National Greening Program (NGP). This was further expanded to the Enhanced NGP (eNGP) through Executive Order 193, aiming to rehabilitate 7.1 Mha of unproductive, denuded and degraded forest landscapes from 2016 to 2028 [37,38]. Indonesia has initiated a range of rehabilitation programmes since the early 1950s [39], with the goal to restore, maintain and improve forest and land functions so as to maintain the carrying capacity, productivity and supporting ecosystem services for different forest types [40]. Several regulations are in place to protect forests and reduce forest conversion, including strengthened law enforcement to prevent forest fires and land clearing, and a moratorium policy on clearing primary forests and peatlands [41,42]. In 2021, the Indonesian government committed to restoring 2 Mha of peatland and rehabilitating 12 Mha of degraded land by 2030 as part of the Intended Nationally Determined Contribution to the United Nations Framework Convention on Climate Change [43]. The Malaysian government intends to plant 100 million trees on 0.2–0.8 Mha by 2025 through the Malaysian Greening Program launched in early 2021 [44]. Malaysia also launched a new National Forestry Policy in 2021, in which the government commits to maintaining at least 50% of the forest cover and replacing any degazetted Permanent Reserved Forests [45]. The country has also set national commitments to improve forest connectivity through the Central Forest Spine (CFS) initiative, where approximately 0.4 Mha of land have been prioritised for restoration within primary and secondary linkages [46,47]. The restoration targets are modest compared to the other countries, partly due to the relatively high remaining forest cover (58%) [48], smaller total land area and the emphasis on numeric tree planting targets and on improving the connectivity of existing forests, rather than large-scale restoration typically driven by both ecological and socio-economic goals. In India, the two major initiatives that have influenced the forest cover over the last three decades are Joint Forest Management and the Social Forestry Programme [49]. With the largest land cover and a comparably low forest cover (24%) [48], the Indian government has committed to restoring 26 Mha between 2020 and 2030 [50], which contributes to over 50% of the combined restoration commitments in the four analysed countries.

Table 1. Context for forest and landscape restoration commitments in the four analysed countries.

	Philippines	Indonesia	Malaysia	India
Governmental restoration commitments	7.1 Mha by 2028	14 Mha by 2030	100 million trees by 2025 and 0.4 Mha (CFS)	26 Mha by 2030
Total forested area in 2020 [36]	7.2 Mha	92 Mha	19 Mha	72 Mha
% forest area of total land area in 2020 [48]	24%	49%	58%	24%
Number of native tree species in the country [51]	2258	5703	5490	2616

Direct tree planting is only one of many possible restoration techniques and depending on the site context and the availability of natural seed sources, many degraded areas may regenerate naturally if the pressures are removed. However, active tree planting plays an important role in achieving the global FLR targets [11,34]. Based on a conservative estimate of planting 1650 trees per hectare [52] and a 50% seedling mortality rate during the first year [53], achieving the combined restoration targets of 47.5 Mha would require approximately 157 billion seeds. The scale of the volume of required seed emphasises the need to strengthen seed production and supply systems to ensure that these can provide suitable, genetically diverse seed to restore degraded ecosystems and deliver the targeted ecosystem functions and services.

2.2. Analysis of the Tree Seed Systems

To assess the strengths and weaknesses of the national tree seed systems we used an indicator system developed by Atkinson et al. [54] which the authors applied to analyse seed systems for FLR in seven Latin American countries. The indicator system includes five interlinked components determining a well-functioning seed system, namely:

i. Selection and innovation
ii. Seed harvesting and production
iii. Market access, supply and demand
iv. Quality control
v. Enabling environment

Each of these components is represented by two to four indicators, resulting in a set of 15 indicators. We assessed the level of attainment of each indicator in the focus countries through an analysis of scientific literature, official reports and documents, online databases and resources of government agencies and other FLR stakeholders. Expert evaluation was subsequently used to refine and validate the assessment. Experts were identified through contacting the forestry departments and research institutions in each country as well as through the network of experts of the Asia Pacific Forest Genetic Resources Programme (APFORGEN). This resulted in 33 contributing experts (Philippines n = 7; Indonesia n = 8; Malaysia n = 5; India n = 13) whose expertise covered different components of the tree seed system and who represented governmental institutions (50%), research institutions (37%) and civil society organisations (13%). The experts were asked to respond to a questionnaire on the status of indicators in their country and validate the results of the literature review. It should be noted that informal seed systems and unregistered temporary nurseries could not be covered in detail in the national level assessment, due to their localised and often informal nature. Additional methodological details, including the approach for scoring the indicators using a questionnaire, can be found in the Supplementary Materials Tables S1 and S2, and are further described in Atkinson et al. [26,54].

We assessed the underlying structure of each national tree seed system by categorising them into the four overarching frameworks elaborated by Atkinson et al. [26]. The frameworks focus on the role of the government in organising seed supply, consisting of:

i. 'independent': A group of self-sufficient, often project-based systems
ii. 'state-run': A centralised system managed by the government
iii. 'incentives-led': A network of independent actors responding to government incentives
iv. 'market-driven': A network of independent actors responding to demand

The frameworks are not mutually exclusive and the underlying structure in most countries is represented by a hybrid between two or more of the models. The key features of each framework are described in Table 2, and more detailed information can be found in Aktinson et al. [26]. Understanding the underlying frameworks can help put the strengths and weaknesses of the seed systems into context and tailor the required improvement. For example, one approach to improve the tree seed systems could be to establish registration and certification systems for seed collection and production in 'market-driven' or 'incentives-led' systems or capacity strengthening in 'independent' frameworks.

To complement the national-level assessment of the tree seed systems, we employed an online survey assessing the perceptions of FLR practitioners on seed availability and quality for their projects and programmes. The purpose of this second survey was to understand how the strengths and weaknesses identified at the national level were reflected in the planning and implementation of FLR projects on the ground. Furthermore, the practitioners' survey enabled the collection of some information on informal seed systems, though not systematically. The targeted respondents were directly involved in at least one FLR project that involved collecting, buying or selling seed of native tree species. The questionnaire was distributed between April and November 2020 (Supplementary Materials Table S3) through the networks and social media channels of the Alliance of Bioversity International and CIAT; CGIAR Research Program on Forests, Trees and Agroforestry (FTA); Tropical Rainforest Conservation and Research Centre (TRCRC); Asia Pacific Forest Genetic Resources Programme (APFORGEN); Asia Pacific Association of Forestry Research Institutions (APAFRI) and Botanic Gardens Conservation International (BGCI). Potential respondents were also identified through an online search of restoration projects in each country and contacted directly by email. This resulted in 61 complete responses (Philippines $n = 11$; Indonesia $n = 24$; Malaysia $n = 10$; India $n = 19$).

Table 2. Overview of key features of the four frameworks for a tree see system adapted from Atkinson et al. [26].

	Framework 1 'Independent'	**Framework 2 'State-Run'**	**Framework 3 'Incentives-Led'**	**Framework 4 'Market-Driven'**
Leading implementers of FLR	Civil society-led organisations, community groups, private businesses, individual government-led projects	Central and regional government	Wide range of implementers (community groups, private enterprises and academia) who respond to government incentives	Civil society-led organisations, community groups, private businesses, individual government-led projects
Supply system	Directly for own projects	From centralised and regional nurseries	From private nurseries, suppliers and government nurseries	From harvesters, suppliers or nurseries, user-driven choice
(Potential) role of the government	Coordination, information transfer and quality control	Responsible for implementing all aspects of the seed system	Providing incentives, managing sections of the seed supply chain and controlling quality of seed	Limited role, possibly quality and price control

3. Results

3.1. Analysis of the National Tree Seed Systems

The scorings of the national tree seed systems against the indicator framework are presented in Figure 1, indicating the readiness of the systems to support FLR. The identified underlying seed system frameworks in each country are shown in Table 3. The following sections highlight the key findings for each of the four focus countries with regard to the five components determining a well-functioning seed system.

Table 3. Underlying framework for the national tree seed systems, focusing on the role of the government and leading implementers of FLR efforts.

Characteristics	**Philippines**	**Indonesia**	**Malaysia**	**India**
Underlying framework of seed system	Mix of 'state-run' and 'incentives-led'	Mix of 'state-run', 'incentives-led' and 'independent'	Mix of 'independent' and 'market driven'	'state-run'
Leading implementers of FLR efforts	Government (through eNGP) and People's Organisations	Government, to smaller extents also private sectors and communities	Civil society organisations, government agencies, State Forestry Departments, Forest Research Institute Malaysia (FRIM)	Government agencies

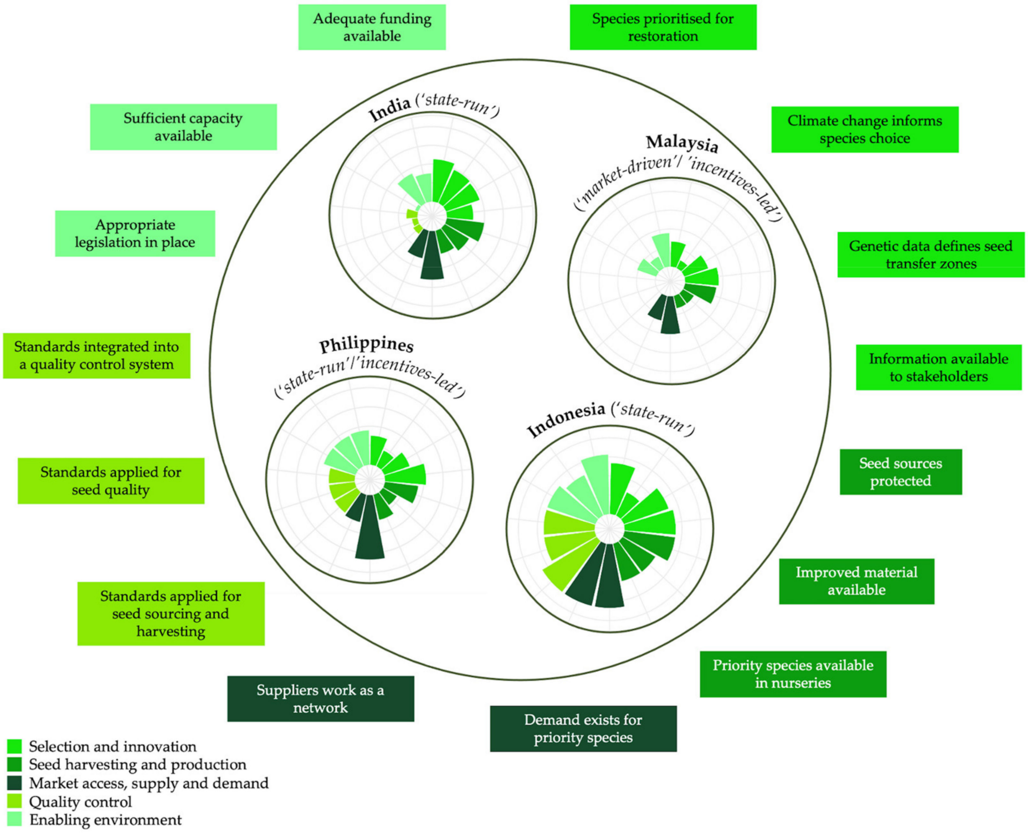

Figure 1. Radar charts illustrating the scores assigned to the 15 seed system indicators for the countries analysed (Philippines, Indonesia, Malaysia and India). The results are colour-coded by the five components (selection and innovation, seed harvesting and production, market access, supply and demand, quality control and enabling environment).

3.1.1. Philippines

The tree seed framework consists of a mix of a 'state-run' and 'incentives-led' model, as the government both produces and distributes seed through its 11 regional mechanised nurseries and incentivises and contracts stakeholders such as People's Organisations (local community organisations), academia and private enterprises to produce seed for implementing the eNGP. Similarly, according to regulations, accredited seed sources can be established on both public and private lands [55,56].

Selection and Innovation

A national list of threatened plant species was established in 2007 and updated in 2017 and includes many threatened tree species such as Dipterocarps of *Hopea* spp. and *Shorea* spp. [57]. Numerous biodiversity documentation and conservation projects have generated information about the availability of native tree species [58]. The importance of native species in restoration is recognised in the NGP [59–61]. Yet, priority native species for the programme have not been identified at the national level and priority species lists are available only from individual studies or projects [62,63]. The Department of Environment and Natural Resources (DENR) has carried out provenance trials on some native species such as the national tree Narra (*Pterocarpus indicus*) and *Vitex parviflora* [58], but the majority of the trials have focused on exotic plantation and agroforestry species such as Eucalypts and Pines. Growth trials, silvicultural and genetic diversity studies have been carried out on selected native species such as *P. indicus* and *Anisoptera* spp. to inform planting strategies and seed source selection [58,64,65]. Propagation protocols have been developed for 19 Dipterocarp and 27 other tree species [66]. However, although the Ecosystems Research and Development Bureau has recently extended genetic diversity studies to other native species [67], few native species remain studied and information on genetic diversity is typically not yet considered sufficiently in restoration projects to help identify suitable seed sources and planting material. For example, inadequate consideration is given to match species with site-specific conditions and the functional roles of species in regenerating forests [68]. Number and phenotype of mother trees is also not commonly considered when collecting planting material [13]. Seed zone maps have not been defined to guide selection and seed transfer. Recent climate modelling studies indicate that many Dipterocarps and other native tree species will be severely affected by climate change [69–71], but such information is not yet applied to inform the selection of species and seed sourcing for restoration.

Seed Harvesting and Production

DENR Administrative Order (DAO) 2010-11 on forest tree seed requires that potential seed sources—including both natural and planted stands—are identified, delineated and monitored [56]. DENR and local government units have designated in total 75 Seed Production Areas for selected species and identified individual plus trees in many regions of the country [66]. For example, the Mindanao Tree Seed Centre, established in 2014, provides seed for 36 native species and several exotic species and maintains 590 plus trees [72]. In Northern Luzon, 22 Seed Production Areas and individual plus trees have been identified in three regions by the Provincial and Community Environment and Natural Resources Offices [73]. Among commonly produced native species are *Alstonia macrophylla*, *Alstonia scholaris*, *Shorea contorta* and *Parashorea malaanonan* [58,62]. However, expert estimates indicate that the number of identified and established seed sources is insufficient for meeting the tree planting targets [13,56,58,62]. Seed sources are unlikely to cover ecogeographic variation within species ranges, as the total number of identified sources remains low compared to the number of native species and distinct eco-geographical regions. Cutting trees in the identified seed sources on public lands is strictly prohibited, except for silvicultural management purposes. Private landowners are responsible for protecting identified seed sources on their lands in coordination with local government units [56]. Due to minimum criteria for seedling height and other characteristics and tight timelines for seedling production, seedlings of native species are mainly produced through collection of wildlings [13,56]. DENR has collaborated with state colleges and universities to establish clonal nurseries for supplying native tree species, partly to help overcome constraints in seed production for species with recalcitrant seed. Past research efforts to identify and develop improved material have focused on commonly used exotic species such as Acacia spp., Eucalyptus, Mahogany, *Gmelina arborea* and *Falcataria moluccana*, rather than native species [55].

Market Access, Supply and Demand

Demand for native tree species has been increasing due to the objectives of the NGP [62]. However, seed demand is mainly driven by income opportunities, and People's Organisations who manage NGP sites prefer exotic species because these generate high income opportunities and grow fast [55,74]. Further, seed from exotic species is often easier available and easier to procure, where the use of many native tree species is constrained by non-existent or inadequate silvicultural information on the plantation development and management. Planting exotic species as part of the NGP was also stimulated by the NGP Commodity Roadmap of 2013, which set targets to plant perennial crops such as coffee, cacao and rubber on approximately 29% of the total NGP target area of 1.5 million hectares. During the first phase of the NGP until 2016, indigenous species were planted on an estimated 14% of the NGP area [74]. DENR has issued several orders to mandate planting of indigenous species, especially in degraded forestlands and protected areas [59,60]. A survey of 29 nurseries across Visayas indicated that supply of native tree species is growing, likely as an indication of growing demand due to the NGP. In total, 73% of the identified 138 tree species at surveyed nurseries were native [62]. DENR supports and incentivises People's Organisations to produce seedlings, but many of these organisations are not able to meet the short timelines for the annual production and planting requirements and they have to procure seedlings from other suppliers such as the regional mechanised nurseries or large commercial nurseries instead. Available species are mostly exotic and fruit tree crops [74]. As the rigorous timelines for production and planting requirements favour large producers, seedlings often have to be transferred over long distances. Consequently, available provenances may not always be well suited to planting sites. According to the DENR newsletter [66] clonal nurseries produce seedlings of mostly Dipterocarps to help overcome constraints in seedling production with recalcitrant seed [66].

Quality Control

DENR Administrative Order (DAO) 2010-11 regulates the production, collection and distribution of forest tree seed and seedlings. Seed collection on public lands is to be carried out by trained and authorised collectors. Seed from both public and private seed sources must be tested at regional Seed Storage and Testing Centres before it can be distributed. Public programs are required to only use quality seedlings from accredited suppliers. Sourcing of material is, however, not effectively monitored and only approximately half of surveyed accredited nurseries reported collecting seed from phenotypically superior trees [13,56]. Funding for quality control is insufficient compared to the high demand for seedlings to achieve national restoration targets. Lack of auditing in accredited nurseries and lack of monitoring of the seed supply chain has resulted in accredited nurseries acquiring and reselling seedlings from unaccredited nurseries [13,55,56,75]. Furthermore, seedling producers are required to meet strict criteria for seedling sizes and survival rates to receive government funding for restoration efforts that are often unrealistic to achieve within the short contract periods. Therefore, fake reporting and use of low-quality wildlings instead of seedlings raised from seed are common [55,74].

Enabling Environment

While standards exist to control seed quality, protect seed sources and encourage the use of native species in planting programmes, there is a lack of legislative power, monitoring and funding to ensure compliance. DENR does not have an established database to monitor the implementation of different components of the NGP, including planted species and numbers of seedlings [74]. Effective enforcement would also require increased investments in capacity strengthening for People's Organisations, which could play a much larger role in seedling production than they currently do, to help improve local availability of quality seedlings as well as livelihood opportunities. The policy that DENR's regional nurseries supply free seedlings for NGP implementation constrains the development of a private nursery sector [55]. A Commissioned Audit of the NGP in 2019 found that local government units lacked human and financial capacities to implement the vast restoration targets imposed on them. Inability to carry out proper surveys and planning for required target areas resulted in problems in site selection, seed sourcing, poor species-site matching and consequently low seedling survival. The audit concluded that under these conditions, species other than the typical commercially important exotic timbers and commodity tree crops such as cacao and coffee were unlikely to survive well [74]. The general focus on quantity rather than quality reported from the DENR [68] has contributed to chronic underfunding for research on native species, their phenology, propagation, silviculture and uses [55].

3.1.2. Indonesia

The tree seed system for FLR in Indonesia resembles a mix of the 'state-run', 'incentives-led' and 'independent' models. The Directorate of Forest Tree Seed (Direktorat Perbenihan Tanaman Hutan, DPTH) in the Directorate General of Management of Watersheds and Protection Forest (Direktorat Jenderal Pengendalian Daerah Aliran Sungai dan Hutan Lindung, DJPDASHL) in the Ministry of Environment and Forestry (MoEF) and local governments in the Regional Technical Unit of Forest Tree Seed Centre (Unit Pelaksana Teknis Daerah Balai Perbenihan Tanaman Hutan, UPTD BPTH) play a central role in incentivising FLR and encouraging local communities and stakeholders to participate in FLR activities, while the Forest Area Lease Use License (Izin Pinjam Pakai Kawasan Hutan) holders operate their own nurseries or buy seed or seedlings from community-based nurseries and private suppliers [76].

Selection and Innovation

Forest and land rehabilitation programs from governmental agencies have been the major FLR efforts in Indonesia since the late 1980s [77]. Two Decrees of the Ministry of Environment and Forestry have stipulated 11 vernacular species—most of them native to Indonesia—as priority species for rehabilitation [40]; the MoEF decree No. SK 707 of 2013 for five species, namely Teak (*Tectona grandis*), Mahogany (*Swietenia* spp.), Sengon (*Paraserianthes mollucana*), Gmelina (*Gmelina arborea*) and Jabon (*Anthocepahlus* spp.) [78], and decree No. 396 of 2017 for six species groups, namely Candlenut (*Aleuritis moluccana*), Cempaka (*Elmerrilia* sp, *E. ovalis, E. tsiampaca*, *Michelia champaca*, *Manglietia glauca*, *Magnolia elegans*), Gaharu (*Aquilaria filaria*, *A. malaccensis, A. macrocarpa*, *Gyrinops resbergii*, *G. verstegii),* Merkus Pinu (*Pinus merkusii*), Sandalwood (*Santalum album*) and Cajuput (*Melaleuca cajuputi*) [79]. Priority native species for each district are also recorded in the atlas of local tree species for forest and land rehabilitation in Indonesia [80]. A further regulation recommends priority species for specific ecosystems such as mangrove and peatland restoration [40]. Endemic, native timber and NTFPs species are recommended for rehabilitation [40]; however, exotic species such as Teak and Mahogany are often preferred for their high economic value. It should be noted that since Indonesia consists of over 17,000 islands, many native species are local endemics and species native in the country may still be exotic at the local level.

Research institutions, universities and companies carry out research on tree species, mostly native ones, covering areas such as population genetics, breeding and silvicultural practices (e.g., [81–85]). In some cases, information from the trials is used for provenance selection in planting programs [86]. Provenance-based selection and use of seed transfer zones however are still limited for native species, even for the priority species for rehabilitation. Some initial research into the effects of climate change on native species has been conducted, for example regarding changes in species distribution and richness [87], altered flowering and fruiting periods of Dipterocarps [88] and Sandalwood [89] in forest stands, identification of drought-resistant species [90] as well as the impact of drought and waterlogging of some native species under controlled conditions [91–93]. However, it is currently not sufficient to inform climate-resilient selection of species and seed sourcing for FLR.

Seed Harvesting and Production

Seed sources have been established on government, private and community-owned lands, following the government standards for seed sources [94]. To date, a total of 11,011 hectares of seed sources of mostly native species throughout Indonesia has been certified and registered in the DPTH [76]. The certificate is valid indefinitely as long as the function and status of the seed source remain unchanged [95] There are no specific mechanisms to protect seed sources after registration, and illegal logging and land conversion therefore still happen within the source populations. Improved material from tree improvement programs is available for many native species such as the Merkus Pine, Jabon and Cajuput (e.g., [96,97]). Priority species are available in the 57 units of Permanent Nurseries, and community nurseries [76,98]. The nurseries produce both native and exotic species, usually a combination of high-demand species for timber and NTFP species. Currently, almost 80% of the seedlings planted for rehabilitation purposes in Watershed Areas are fruit and NTFP species to improve community welfare [98].

Market Access, Supply and Demand

Provision of seeds and seedlings for rehabilitation is managed by the DJPDASHL and implemented in 34 Management of Watersheds and Protected Forest Offices (Balai Pengelolaan Daerah Aliran Sungai dan Hutan Lindung) and two Forest Tree Seed Centres (Balai Perbenihan Tanaman Hutan) under the central government and the UPTD BPTH. In 2020, the implementing management units of DJPDASHL produced a total of 24.3 million seedlings from permanent nurseries and 31.7 million seeds [52,98]. As of 2019, the People's Nurseries (Kebun Bibit Rakyat) have produced about 23.5 million seedlings, and the Village Nurseries (Kebun Bibit Desa) about 50.7 million seedlings [98]. All produced seedlings were distributed for free to support government rehabilitation programs. The MoEF's prioritisation of the 11 species [78,79] mentioned above has driven supply and demand towards these species, leading to widespread use of these species in many rehabilitation areas in Indonesia. The seed suppliers work as a network to support the provision of seed in FLR programs and are registered in the DPTH and the UPTD BPTH. Despite this, the network of suppliers cannot meet the high demand for seed, which can encourage both the use of certified seed of other species and/or uncertified seed of demand species to meet restoration and rehabilitation targets. Civil society-led FLR programs, for example on mangrove rehabilitation or peatland restoration, usually produce their own planting material, using local species present around the restoration area.

Quality Control

The authorised agencies for management of forest tree seed including certification are the Forest Tree Seed Centre Region I and II (under the DPTH in the DJPDASHL) and the UPTD BPTH. Research institutes and universities collaborate with the authorities in inspection and evaluation of seed sources. The standards for seed management such as genetic resource development, breeding, seed procurement, certification, licencing, service fees, reporting and coaching are stipulated in governmental regulations and guidelines to support the implementation of the regulations [94,99]. Currently, only seeds of the 11 priority species mentioned above must be collected from certified seed sources. For other species it remains priority to harvest from seed sources registered in the DPTH and UPTD BPTH or from uncertified sources that meet the requirements accompanied by a letter of statement [40]. Revisions of the existing regulations to improve the effectiveness of the standards of seed sources are necessary [100]. Seed quality standards for a total of 67 forest tree species to support the government regulations [95] are available and explained in more detail in the technical guidelines, for example concerning testing the physical-physiological seed quality [101]. Further, there are several Indonesian National Standards that cover standards for seed quality of forest plant seeds, including seed sources, physical and physiological quality as well as several important native species such as Agarwood (*Aquilaria* spp.) and Sandalwood (*Santalum album*).

Enabling Environment

Regulations from the government and its derivatives exist, such as a regulation to encourage the use of native species [40]. Yet, several constraints remain regarding their implementation. The administration process, for example, is mostly paper-based and lacking a technology-based system to support efficient processes and monitoring within the seed supply chain. The FLR efforts focus on planting activities and less attention is given to monitoring and maintenance of post-planting results. Previously it was estimated that about 85% of the forestry development budget has been spent on ineffective rehabilitation initiatives implemented since the late 1970s [39,77]. This is being addressed with a shift towards community involvement in rehabilitation such as in providing seed and involving 373 villages in the implementation of the Village Nurseries and over 36,000 people in the People's Nurseries program [76]. The government has established the Indonesia Environmental Fund (Badan Pengelola Dana Lingkungan Hidup, BPDLH) to manage funds related to the environment programs [43]. This was followed up with the launching of a public service agency (Badan Layanan Umum) for BPLDH as the "funding hub" for the various funding mechanisms focusing on environmental protection and management in Indonesia [102].

3.1.3. Malaysia

The seed supply system in Malaysia resembles a mix of the 'independent and 'market-driven' frameworks. The leading implementers of FLR are government departments and agencies that work in collaboration with research institutes, academia and civil society organisations. Many implementers of FLR projects source their own seed and select species based on projects goals [103,104]. With the ongoing 100 million tree-planting campaign and the Central Forest Spine (CFS) in Peninsular Malaysia, the underlying framework might shift towards an 'incentives-led' system. For example, while the majority of nurseries providing planting material are currently government-led, the government is beginning to incentivise and fund public-private partnerships in FLR projects, as well as encourage citizens to get involved in restoration projects [105]. Organisation of the seed supply also differs between the different states which all subscribe to common federal policies, but have jurisdictional autonomy over their forest resources [106]. While the Forestry Department of Peninsular Malaysia plays a leading role in the restoration of the connectivity of the CFS which involves eight states [47], the Forestry Department of Sarawak is the lead agency in a forest restoration project aiming to plant 35 million trees in their state [107] and the Sabah state government has committed to planting 36 million trees in Sabah to boost the 100 million tree-planting campaign [108].

Selection and Innovation

The Malaysian Greening Program does not stipulate priority species for restoration or for the use of native versus exotic species. In Sarawak, however, the Forestry Department has issued guidelines for the establishment of nurseries for forest plantation which includes a list of approved native (e.g., Dipterocarps, fruit trees such as *Durio* spp.) and exotic species (e.g., *Acacia* spp., rubber and Mahogany) [109]. Despite the lack of species prioritisation from the Malaysian Greening Program, several individual studies have identified native species for restoration. For example, seven species identified as suitable for the CFS by the Universiti Putra Malaysia [110], a list of 45 native tree species for forest restoration on degraded land developed by the Forest Research Institute Malaysia (FRIM) [111] and a list of tree species important for bird conservation identified by WWF Malaysia [112]. There are existing manuals on the procurement of planting material of native species such Agarwood (*Aquilaria* spp.) or mangrove species [113], but such guidelines mainly focus on the selection of species based on phenotypic aspects, and very rarely on genetic aspects or on adaptation to climate change [114]. The 100 million tree-planting campaign aims to make available information about the forest genetic resources in the region, building on existing research on Dipterocarps [115–117]. Several studies exist on the floristic diversity in Seed Production Areas as well as on the genetics of some native species such as *Shorea leprosula* and other Dipterocarps [118,119]. Genetic structures of important native timber species have been studied to identify seed transfer zones [120]. Provenance trials have been conducted for a number of plantation species, mainly Acacia and Teak [121–123]. The Innoprise-IKEA Tropical Forest Rehabilitation Project (INIKEA) and the Sabah Biodiversity Experiment by the University of Zurich and the University of Oxford [124] have conducted studies on the expected effects of climate change on the distributions of priority native species [125]. However, most institutes host their own databases with information related to planting material, and exchange of this information has been limited.

Seed Harvesting and Production

Seed Production Areas have been identified for economically viable species, mainly Dipterocarps and mangrove species, and established throughout Peninsular Malaysia and Sarawak [126–128]. The Forestry Department in Peninsular Malaysia operates a central nursery (Lentang Seed and Planting Material Procurement Centre, Pahang) which collects seeds from identified Seed Production Areas. FRIM has established species-specific guidelines for seed propagation and testing [129]. In Sarawak, Semenggoh Nature Reserve includes a Botanical Research Centre as well as a seed bank and a nursery, where seeds are collected in the Seed Production Areas established inside the arboretum [127]. Six new nurseries were established across the state between 2018 and 2020 to provide planting material for FLR efforts. There is also a gene bank including fruit and crop trees at the Malaysian Agricultural Research and Development Institute (MARDI) [130]. Existing seed sources receive some protection from the Forestry Department. Depending on the state, much of the seed is still sourced from commercial forest reserves. In 2020, the Forestry Department of Peninsular Malaysia proposed a bill on tree marking process, identification of mother trees and protected trees. While this bill is mainly related to tree felling activities, such regulations could be used in the future to identify new seed sources of native trees [131].

Market Access, Supply and Demand

With the launching of the 100 million tree planting campaign in 2021, demand for priority native species is increasing. The campaign incentivises companies and citizens to volunteer in planting activities by offering tax relief as well as rewards. There is also increasing interest in planting ornamental native tree species in urban and residential areas, like the Putat Laut (*Barringtonia asiatica*) or the Bintangor Laut (*Calophyllum inophyllum*).

As part of the 100 million tree planting campaign, a mobile application was developed to connect customers with listed nurseries and to keep records of the locations, species and number of planted trees [44]. As of early September 2021, there were 11 registered nurseries in the marketplace of the platform, eight of which were from governmental organisations, two from civil society-led organisations and one from Universiti Putra Malaysia. All 11 nurseries were located in Peninsular Malaysia and seven were concentrated in the Selangor state surrounding the capital region, but there have been calls to get more nurseries registered with the platform. The nurseries provide a wide variety of planting material, including native tree species, plantation species such as Mahogany and mangrove species as well as fruit trees. The campaign, however, does not emphasise the use of priority native species, nor of their provenance, indicating an overall lack of awareness and demand for suitable origin and provenance [132].

Quality Control

There is currently no nationwide certification system for seed quality for restoration planting. However, the Seed Technology Laboratory (*Makmal Teknologi Biji Benih* or MTBB) at FRIM conducts seed testing according to the guidelines of the International Seed Testing Association [129,133]. In Sarawak, the Forestry Department has laid out specific guidelines for the establishment of nurseries for forest plantation, for example, to keep a record of all material purchased. Furthermore, all seeds imported to Sarawak must have a phytosanitary certificate [109].

Enabling Environment

Overall, appropriate legislation is lacking to support an operational seed system that would ensure the availability of quality seed of native species for FLR efforts. Regulations that would provide incentives for the use of native species, support the use of material suitable under climate change or define seed transfer zones are currently insufficient at the national level. Awareness about the importance of seed quality and origin for the success of FLR efforts is lacking, which is reflected in limited capacity development for FLR stakeholders. Existing resources for technical capacity development are scarce and trainings are carried out sporadically at best. Generally, there is still a lack of coordination between the different actors in the seed supply system in Malaysia. This is partly due to the country having 13 state governments and three federal territories, which all have jurisdictional autonomy over their forest resources [106]. This results in varying engagement in activities related to organising seed supply in different parts of the country. Financial support for key research and development of seed systems for native species has also been limited. The new restoration programmes are likely to increase attention towards seed supply if planting goals are to be met. However, the programmes have yet to result in increased budget allocations towards the establishment of seed sources, nurseries, research and capacity development.

3.1.4. India

The frameworks underlying the tree seed system in India are a mix between 'state-run' and 'independent'. Government agencies are the leading implementers of FLR efforts, contributing over 90% of restoration efforts [134]. While there are numerous civil society-led FLR initiatives, these are negligible in size when compared to the government initiatives. The regional institutes of the Indian Council of Forestry Research and Education (ICFRE) coordinate the genetic resource activities in their respective jurisdiction states, and most seed for FLR efforts is being supplied by the seed centres run by the State Forestry Departments [135]. There are several smaller, independent projects on private lands initiated by civil society organisations that produce their own seedlings.

Selection and Innovation

The forests of India are classified into 16 major forest types [136,137] and lists of native priority species exist for the priority ecosystems. A large number of native, threatened and exotic forest tree species has been listed for conservation and use [137]. Provenance trials for more than 90 species have been conducted in different ecosystems across India, including many economically important native species, for example Teak *(Tectona grandis)*, *Pinus roxburghii* and *Dalbergia* spp. [135,137,138]. Research on population genetics is being conducted by the ICFRE institutes, the Forestry colleges of different State Agricultural Universities and other institutes of the Indian Council for Agricultural Research. First attempts to identify seed zones to facilitate seed collection and tree improvement were undertaken in 1978 by the Indo-Danish Project on Seed Procurement and Tree Improvement [137,139], but were not successfully implemented due to a lack of legal enforcement of the scheme. Most recently, gene-ecological zones have been identified for Teak that could be targeted for sustainable management, conservation and improvement of Teak genetic resources [140].

Climate change research has been identified as an area that needs urgent attention in the conservation of biodiversity and forest genetic resources [137]. While there has been some research on the effect of climate change on native species across different ecosystems [141,142], the generated knowledge is not yet used for guiding planting decisions.

Seed Harvesting and Production

Tree improvement programs are in place for about 130 species, focusing mainly on fast-growing and economically viable native species such as Teak [135,137]. The project Maruvan 'Forest of the desert' is currently developing the first seed bank of native tree species through collecting seeds from the wild [143].

Market Access, Supply and Demand

Forestry seed is mostly supplied by the Seed Centres run by the State Forestry Departments, following the National Working Plan Code for Sustainable Management of Forests and Biodiversity in India [144]. The Seed Centres are responsible for collecting, processing and supplying seeds for plantation forests and for increasing the seed production based on the needs of the community and the forest condition. Farmers and local communities are mainly interested in planting economically viable tree species, such as Teak and Chinaberry (*Melia azedarach*). The ICFRE Institutes and some state-run organisations, such as the Maharashtra Forest Seed Centre and Kerala Forest Seed Centre, collect, process, store, certify and supply seeds of various forestry species to the stakeholders as per the standards of the International Seed Testing Association.

Quality Control

Currently, there is no quality control system in place for tree seed quality for restoration planting. In 1979, the government launched a certification scheme known as Certification of Forest Reproductive Material in India. The scheme included strict regulations concerning seed collection and production [145]; however, these were not implemented due to lack of legal backing [137]. The scheme was further revised through the Forest Reproductive Material Certification Bill of 2008 to provide a legal framework for ensuring high-quality seed, but it has not been implemented either. To address this, an expert committee report from the Ministry of Environment, Forests and Climate Change suggested to set up a National Forest Seed Corporation and State Forest Seed Corporations for supplying certified seeds [146].

Enabling Environment

Appropriate legislation is still lacking to support the development of tree seed systems, especially for native species, as shown by the pending of key regulations to support use of material suitable for climate change, define seed transfer zones for native species and establish a certification system for native species. The forestry sector in India receives less than 1% of the total governmental budget, and only a fraction of this is allocated for conservation and forest landscape restoration (approximately 0.03% of the government's total annual budget) [137,147].

3.2. Assessment of Challenges for FLR Practitioners in Acquiring Seed

The FLR practitioners' survey received a total of 61 complete responses from the four focus countries, representing a wide range of organisation types, locations, sizes and seed sourcing strategies (Table 4). The most prominent organisation types were governmental (44%) and civil society organisations (34%), followed by academic and research organisations (15%). More than half of the respondents indicated that they work with species listed as threatened on the Red List of the International Union for Conservation of Nature and Natural Resources (IUCN) [148]. Furthermore, 44% of the respondents stated that they work exclusively with native species while another 28% reported that at least 75% of the species they work with are native. Only three respondents (5%) indicated that less than 50% of the species they work with were native. Seed sourcing strategies were rather varied among the different practitioners; 43% of the respondents indicated that they were both collecting and buying seed, 39% that they collected all seed themselves and 18% that they bought all their seed. Of the respondents who collected at least some themselves, 51% indicated that they were doing so to ensure seed quality. Cost and availability were the next most common reasons for practitioners to collect seed themselves (25% and 18% of the respondents, respectively). The following sections shed light on the experiences and challenges met by the surveyed FLR practitioners in terms of seed quality as well as market access, supply and demand.

Figure 2 illustrates the seed characteristics that practitioners perceived as the most important for determining seed quality. Clean seed without pest and without rotting was perceived as the most decisive characteristic for high-quality seed (25%), followed by high germination rate (20%). Seed sourced from many mother trees per species was defined by 18% of the respondents as the most important characteristic and by 26% as the second most important characteristic for high-quality seed. The least important characteristic for high-quality seed was that seed was sourced from large forest areas.

Table 4. Characteristics for surveyed forest landscape restoration projects by country.

		Region	Philippines	Indonesia	Malaysia	India
Responses (% Projects)		61	11	24	10	19
Project leader	Government organisation	44%	25%	75%	30%	20%
	Civil society organisation	34%	33%	13%	50%	60%
	Academic or research org.	15%	33%	4%	20%	13%
	Nursery or other	7%	9%	8%	0%	7%
Main purpose *	Habitat restoration	59%	25%	50%	90%	67%
	Conserve species	36%	25%	50%	50%	13%
Seed sourcing strategy	Collecting all seed	39%	58%	33%	30%	40%
	Buying all seed	18%	9%	21%	30%	13%
	Buying and collecting	43%	33%	46%	40%	47%

* Respondents had the option to choose more than one purpose as their main purpose. Other purposes listed amongst the main purposes of FLR projects were agroforestry, carbon sequestration, timber production, educational purposes and cultural and aesthetic purposes.

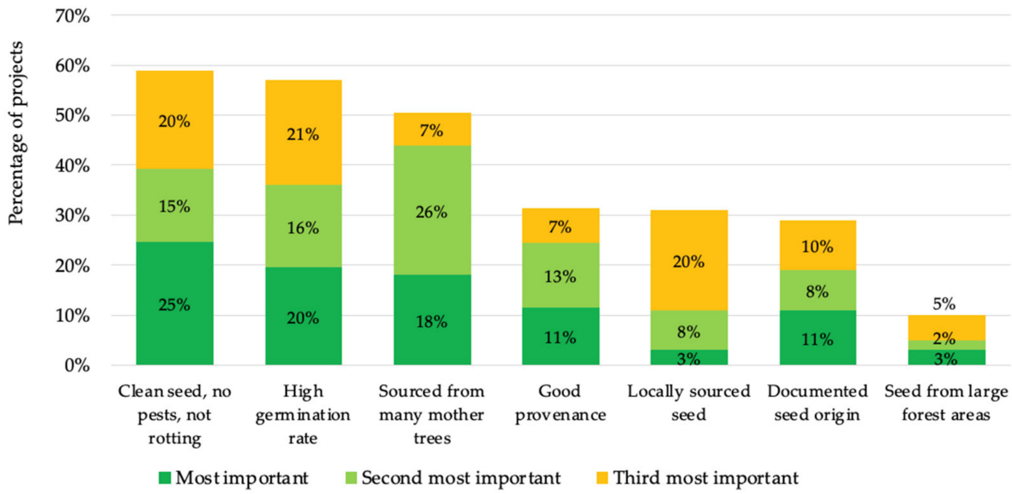

Figure 2. Most decisive characteristics defining high-quality seed from the perspective of the surveyed FLR practitioners (in % of projects, total of 61 responses).

Of the 37 practitioners who reported buying at least some seed, over 50% responded that the most important criteria for selecting seed suppliers was the ability to supply the preferred species. Species name was also the most common information that practitioners received from suppliers, although only 65% of the respondents reported *always* receiving this information (Figure 3). The second most common sort of information provided by seed suppliers was the type of propagation material (propagated from seed, propagated vegetatively, wildling (wild seedling)), and the information least often received was the number of mother trees per species, with 35% of respondents indicating they *never* received this information. The most common challenges which practitioners reported facing with suppliers were an overall lack of suppliers, difficulty of obtaining information about seed quality and difficulty of reaching suppliers. Over 70% of the FLR practitioners reported that they were facing all the mentioned challenges at least sometimes.

Almost half of all surveyed FLR practitioners reported facing one or more challenges regarding seed quality *always* or *often* (Figure 4). In total, 56% of the respondents mentioned that seed was *always* or *often* available only at irregular times, and 51% stated that they *always* or *often* experienced a lack of seed of preferred origin or provenance. Furthermore, 47% of the respondents reported a general lack of the preferred species, and 38% indicated that obtaining seed sourced from many mother trees was *always* or *often* a problem.

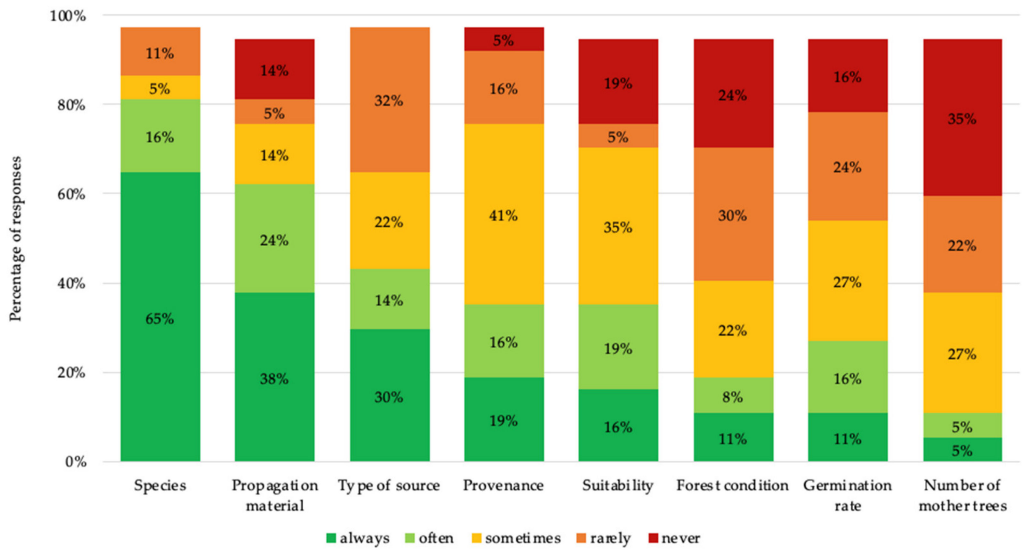

Figure 3. Information about seed that FLR practitioners receive from their seed suppliers (in % of projects per country, total of 37 responses).

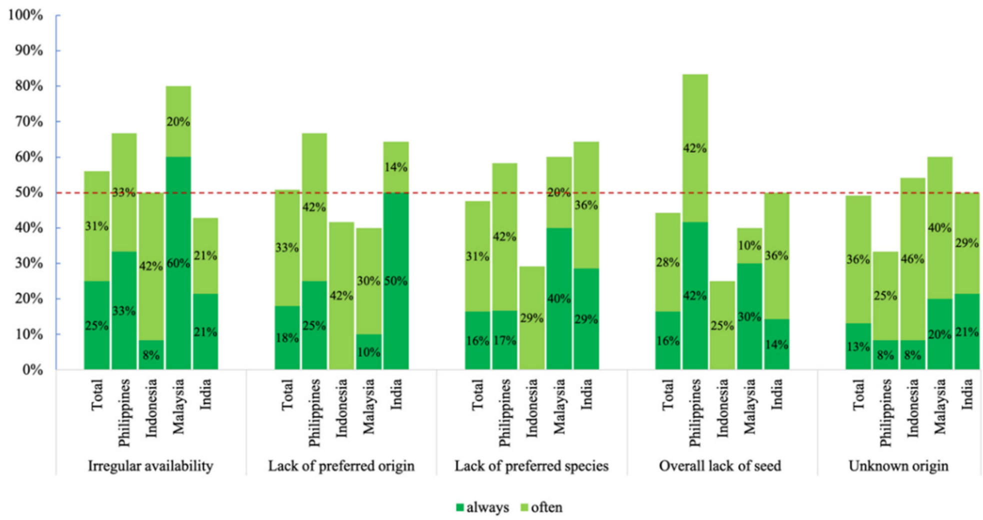

Figure 4. Challenges regarding seed quality reported by FLR practitioners (in % of projects per country, total of 61 responses).

4. Discussion

This study provides the first comparative analysis of the national tree seed systems for FLR in the Philippines, Indonesia, Malaysia and India. Achieving combined restoration targets of over 47.5 million hectares by 2030 would require more than 157 billion seeds. The quality of this seed is crucial to ensure successfully meeting the restoration targets in the long term and to realise the potential of FLR in tackling the global biodiversity and climate crises [13,15,18]. While we note that all analysed countries cover at least some aspects of a fit-for-purpose tree seed system, our results emphasise the need to interconnect the different components of seed production and distribution into a functional seed system. This necessity is further highlighted by the frequency of challenges in obtaining high-quality seed reported by the surveyed FLR practitioners.

Our assessment reveals that the frameworks underlying the national tree seed systems vary between countries, likely as a result of geographical, historical and cultural differences [22,54]. Some of the strengths and weaknesses identified in this study can be directly associated with these underlying frameworks. For example, the overall low scoring of the seed system in Malaysia may be partly explained by the underlying framework ('independent'/'market-driven') where the government's coordinating role is more limited than in the other frameworks. On the other hand, 'state-run' frameworks may lack the flexibility to adapt to the local socio-ecological contexts and needs [22,55,149]. A recent study found that large-scale, government-led tree planting programs in northern India planted only a few tree species valued by local people and failed to increase forest canopy cover [14]. In Indonesia, the dominance of government-driven FLR projects has in the past led to a limited compliance with prescribed rehabilitation techniques by local communities [39]. In the Philippines, the lack of involvement of local communities in the planning and implementation of FLR has contributed to lower seed quality [55]. Insufficient involvement of local communities is likely a limiting component for the success of FLR in other countries as well [150–152]. On the other hand, examples from emerging community-based seed networks in Burkina Faso [55], Brazil [23] and Australia [153] illustrate that informal seed systems can play an important role in contributing seed for a high diversity of native species as well as supporting local livelihoods. Further research is needed to understand how informal tree seed systems operate under different policy and socio-economic contexts and how operators can be supported to participate in formal seed markets. We therefore recommend adding a new indicator to the indicator set proposed by Atkinson et al. [54], addressing the involvement of local communities in seed production and the existence of related incentives and extension to support their role.

Despite the differences in the country contexts and the ways of how seed supply is organised, our results indicate common gaps in the national seed systems: (i) Existing seed supply is inadequate to match the growing demand for priority native species in terms of both quantity and quality, (ii) quality control for tree seed is typically either lacking or ineffectively implemented and (iii) research into the effects of climate change on native species is still limited and the existing knowledge is not effectively applied to guide seed sourcing and seed zoning strategies. We discuss these overarching gaps in more detail in the following sections and provide recommendations on how the diversity of approaches and experiences in organising tree seed systems for restoration can be harnessed through knowledge transfer and collaboration to help improve the seed systems.

4.1. Adequate Seed Supply to Meet Growing Demand for Native Species in Terms of Quality and Quantity

The evaluation of the experience and knowledge of FLR practitioners and experts who represent diverse organisation types and cover different aspects of the seed systems indicates that the demand for native tree species is not met by the existing seed supply networks. We found a limited use of native species diversity despite the (apparent) high demand for such species in all four countries. While research on selection and innovation as well as seed harvesting and production of native seeds has been conducted in all analysed countries, these programs have mainly focused on commercial species such as Teak and often even on exotic species. Traditional focus on safe-bet-economics in the forestry sector [106] has resulted in a research and development focus towards few and often exotic species in many countries [55,154]. Until today, species selection for FLR is largely subject to the same dynamics and as a consequence, use of native species in restoration remains limited [22,54,55,155]. Nevertheless, there are also examples of successful incentives promoting the use of native species in restoration, such as an incentive mechanism based on payments for ecosystem services in Costa Rica or the mandatory use of at least 80 tree species per ha in restoration activities in some regions of Brazil [54]. Atkinson et al. [54] suggested that the overall limited use of native species in FLR in Latin American countries may stem from a lack of knowledge on species propagation or availability of seed. Several studies have found FLR practitioners to lack awareness of the importance of genetic diversity and quality of seed [17,18,20,22], which results in a lack of market demand for native high-quality seed species. Therefore, increasing the diversity of native species in FLR will require increasing that knowledge and creating demand from the end-users [54]. Strengthening practitioners' capacities in seed selection and demonstrating the implications of low diversity or poorly adapted seed for restoration success help develop the demand for quality seed as a key element for mitigating risks and optimising cost-benefit balances in FLR. As our results show, such capacity strengthening efforts are currently lacking in most countries.

The identified mismatch between seed supply and demand emphasises the need to improve the flow of information between the different stakeholders in the supply system. This is further indicated by the lack of priority native species and information on seed quality reported by the surveyed FLR practitioners. As the genetic quality of seeds cannot be identified from merely physical inspection, quality safeguards have to be based on transparency and trust in the supply systems [156]. Digital tools offer significant opportunities to improve the flow of information between stakeholders, as well as to track, manage and diversify seed collections. Further, they have the potential to link suppliers and end-users and create market opportunities. End-user tools such as Diversity for Restoration (D4R; www.diversityforrestoration.org, accessed on 4 November 2021) or SeedIT (https://seedit.io/home, accessed on 4 November 2021) provide exactly the kind of information that appears currently the least available in tree seed systems. D4R takes into consideration the location of the restoration site, restoration objectives, site conditions such as soil characteristics and steepness and climate change scenarios to recommend suitable tree species combinations and seed sourcing areas [157]. The smartphone-based app SeedIT integrates information about provenance, exact location, number of mother trees and site conditions (level of degradation and fragmentation), which is necessary to verify the genetic quality of seed collections [20] and corresponds to the information gaps described by the FLR practitioners in this study. End-user tools that are accessible to anyone in the tree seed system are particularly interesting as research has highlighted the importance of involving different stakeholders and especially local communities in the planning, implementation and monitoring of FLR initiatives to ensure long-term success [15,150,158].

Transboundary research collaboration and exchange of planting material can contribute to matching seed demand and supply and achieving FLR targets across different seed systems. This can be especially useful for species for which seed supply is difficult to organise, for example because of irregular fruiting patterns or recalcitrant seeds that are typical for Dipterocarps, the dominant tree family in Southeast Asian lowland forests [159]. The Philippines, Indonesia and Malaysia share similar key species as they belong to the Malesian floristic region [160,161]. Exchange of germplasm and knowledge between these countries already exist for plantation species and could be expanded for species used in FLR.

4.2. Effective Quality Control for Seed of Native Species

Lack of quality control and failure to integrate genetic diversity and suitability in seed sourcing can have significant consequences for seedling growth, mortality rates and costs of FLR efforts [13,162]. While mechanisms for quality control are lacking in India and Malaysia, the existing regulations in the Philippines are not adequate to provide high-quality seed. The minimum criteria for seedling height and other characteristics in the Philippines have led to a widespread use of wildlings, which have limited potential in upscaling restoration compared to planting material from seed production areas [163]. Notably, the example of the Philippines illustrates the negative consequences of a quality control system that focuses on short-term goals and sets unrealistic quality requirements. As public funds are only allocated after an 85% survival rate is reached, the quality certification system encourages fraudulent reporting [13,55]. Policy on seed quality is poorly monitored and evaluated, and capacities to conduct monitoring and evaluation are lacking. Further, the supply chain is leaky as accredited nurseries can purchase seed from unaccredited nurseries and sell them as accredited ones [13]. Use of low-quality seed was reported as one of the major reasons for the limited success of past restoration efforts in the Philippines [13], and similar concerns about seed quality have also been raised in other countries such as Australia and Chile [19,164].

Quality control systems that are in place for commercially viable species used in the agriculture or forestry sectors could be applied to native species within the context of FLR. Seed systems for commercial timber species were established in tropical Asia starting in the 1970s and developed into efficient systems for seed sourcing, storage and production. While the quality control system in Indonesia is used mostly for exotic plantation species, it offers a comprehensive working model that covers seed sourcing and most aspects of harvesting (e.g., material type, permission to collect) and could be expanded to cover a wider range of species relevant to FLR objectives. While Malaysia currently lacks a nationwide certification system for seed used in restoration, seed quality standards do exist for rice and plantation crops (such as oil palm, rubber and several fruit trees) [130]. Knowledge transfer across different sectors and countries can help countries adjust and improve their control mechanisms. Useful experiences can also be sought from beyond the region: For example, Costa Rica and Mexico have well-established quality control systems encompassing seed sourcing, nursery production and delivery of seed to the planting sites which could be adapted for other countries with similar underlying frameworks [54].

4.3. Research into the Effects of Climate Change on Native Species to Support Seed Sourcing

Species and seed sources for FLR should be chosen so that they can survive and thrive under a changing climate and provide key ecosystem services in the long term [25,165–167]. Climate change is predicted to significantly alter the distributions of some native tree species [71,168] and lead to novel combinations of climate and edaphic conditions, which needs to be considered in seed sourcing and species selection. Research on the effects of climate change on native species to inform selection of species and seed sourcing for restoration is currently insufficient in all countries analysed in this study. This finding is similar to other studies in the tropics, where climate change is typically not considered in species selection for FLR [18,54,55]. Jalonen et al. [18] found that FLR projects with the main objective to mitigate climate change typically focused the least on obtaining genetically diverse seed, compared to projects with other types of objectives. Genetic diversity is crucial for the resilience of the restored populations under changing climate and, therefore, for effective mitigation through carbon sequestration in biomass growth [18,20,27]. Tools such as D4R mentioned above are important to support FLR practitioners in species selection and seed sourcing for climate-resilient forest landscape restoration [157].

5. Conclusions

With the combined national restoration targets of the Philippines, Indonesia, Malaysia and India of over 47.5 million hectares, successful FLR efforts in these four megadiverse countries alone could contribute to approximately 13% of the global goal of the Bonn Challenge to bring 350 million hectares of degraded and deforested landscapes into restoration by 2030. Considering the context of global FLR goals and the UN Decade on Ecosystem Restoration as well as the time needed for trees to grow and reproduce, FLR in these countries has both vast potential and is urgently needed. It is necessary to examine the underlying frameworks and gaps in the national seed systems to guide the development of fit-for-purpose seed systems. Our results highlight the diversity of underlying frameworks and approaches in organising seed systems and identify overarching gaps that need to be addressed in all four countries. Knowledge transfer between countries, other sub-sectors (such as agriculture and forestry) and stakeholders is necessary to interconnect the different components into a functional seed system. Monitoring changes in the underlying frameworks and the organisation of seed systems in individual countries over time may prove helpful to identify ways to adapt the systems to the dynamic contexts. Future deployment of the indicator system for the analysis of tree seed systems is needed. Ideally, the assessment should draw on the existing knowledge of more experts representing different organisation types and consider the involvement of local communities in seed production and include informal seed systems and unregistered temporary nurseries to the extent possible.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/d13110575/s1, Table S1: Indicator System, Table S2: Experts' survey questionnaire, Table S3: FLR practitioners' survey questionnaire.

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