Priorities, challenges and opportunities for supplying tree genetic resources

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Producing the right tree seeds and seedlings is imperative for achieving resilient forest and landscape restoration at scale.

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Seedlings prepared for distribution by the National Tree Seed Center, Burkina Faso

Agricultural practices and population-induced land-use change are increasingly undermining the Earth's capacity to sustain biodiversity and maintain stable climate systems and the equitable provision of goods and ecosystem services (IPBES, 2019). Forests and trees play pivotal roles as important terrestrial carbon sinks (Ellison *et al*., 2017; Doelman *et al*., 2020) and supply many other ecosystem services. The political commitments articulated in the New York Declaration on Forests and the Bonn Challenge include unprecedented targets for the restoration of degraded land and the return of billions of trees to previously forested or tree-dominated landscapes through forest and landscape restoration (FLR) (Brancalion *et al*., 2019).

Tree-based restoration as a strategy for global climate-change mitigation has received much attention (Bastin *et al*., 2019). Although its feasibility and efficacy remain debated (Lewis *et al*., 2019), there is little doubt that tree-based FLR can deliver considerable benefits for societies (Chazdon and Brancalion, 2019).

FLR project success requires suitable high-quality and genetically diverse tree seed delivered through natural regeneration or brought in as planting material for agroforestry, plantations and other restoration interventions (Jalonen *et al*., 2018). Genetic diversity among this reproductive material will provide adaptive potential and help in resisting pest and disease outbreaks and coping with the effects of climate change, including increased drought and extreme weather events. The genetic diversity of trees is a pillar of higher-level biodiversity because genetically diverse tree communities support more diverse and resilient populations of associated organisms (Hughes *et al*., 2008). A failure to take genetic diversity and the quality of reproductive materials into account in FLR, however, will have serious consequences because it will undermine the growth and survival of trees (Tito de Morais *et al*., 2020) as well as the future productivity of tree crops and the ability of restored sites to support overall biodiversity. Governments and some organizations have committed to greatly increasing the area of degraded land subject to restoration, but this requires corresponding investments to ensure sufficient supplies of high-quality seeds and seedlings. Thus, the ability of countries and regions to scale up the delivery of seeds and other reproductive material to meet national and international commitments will be essential for FLR success.

In this article we highlight the challenges involved in delivering seeds at a large scale and the policy initiatives that could be put in place to ensure functional, well-tracked tree-seed delivery. We discuss the need to link the conservation of tree genetic resources (TGR) with their sustainable use and livelihoods in FLR and provide case studies from Burkina Faso, Ethiopia and Tunisia. We give examples of recently developed support tools and innovations to help scale up the delivery of TGR to support FLR goals. Finally, we discuss the opportunities for equitable benefits that can arise from the better integration of TGR into FLR, and we briefly synthesize the current situation as a basis for proposing priority areas for policy and capacity development.

CONSTRAINTS IN TREE-SEED SUPPLY SYSTEMS

Despite growing global commitments on FLR and the accumulation of experiences from the past decade in the implementation of the Bonn Challenge, there is a substantial mismatch between the supply of and demand for tree seeds, especially for native tree species. For example, a lack of attention to tree germplasm sources and delivery systems was evident in a review of larger-scale restoration programmes in tropical regions (considering 38 Clean Development Mechanism afforestation/reforestation project design documents in Africa, Asia and Latin America) (Roshetko *et al*., 2018).

A global survey of 139 FLR projects worldwide indicated that at least part of the seed supply in most FLR projects is collected by the project itself, typically from nearby remnant forest patches (Jalonen *et al*., 2018). The survey found that FLR practitioners preferred to collect seed themselves partly because they felt that seed markets were unable to meet their needs for species and provenances and fulfil their expectations regarding seed quality, but also because they may have had only limited understanding of the importance of seed quality.

Although it is a common practice in FLR and other restoration programmes, sourcing germplasm locally does not necessarily improve the adaptive capacity of the resultant tree populations under current or expected future climate conditions (Hancock, Leishman and Hughes, 2012; Prober *et al*., 2015; Bucharova *et al*., 2017), nor meet desirable quality standards. On the contrary, obtaining germplasm locally may negatively affect seedling survival, growth and resilience if the forests used as seed sources are fragmented or degraded (Kettle *et al*., 2007; Bacles and Jump, 2011; Mimura *et al*., 2017). Insufficient and ineffective seed supply systems also pose problems for smallholder tree-planting farmers, who depend (at least partially) on tree products for their livelihoods and who would benefit from wider access to and availability of planting material (Nyoka *et al*., 2014).

The failure to supply high-quality planting material relates both to the diversity of species used and to their intraspecific genetic diversity, which enhance resistance to stresses. FLR projects often use poorly adapted germplasm from a small number of tree species (Bozzano *et al*., 2014; Thomas *et al*., 2014), with limited information on or understanding of what species to plant or the importance of germplasm sourcing.

Cost may be one of the most important criteria for seed procurement in government-led tree-planting programmes (Dedefo *et al*., 2017; Gregorio *et al*., 2017). In an effort to accelerate tree-planting schemes, governments and non-governmental organizations may (well-intentionally) try to boost planting by donating seedlings that, however, may be of unknown quality and origin (Lillesø *et al*., 2011; Jalonen *et al*., 2018).

POLICY AND REGULATORY INITIATIVES FOR FUNCTIONAL TREE-SEED SYSTEMS

Atkinson *et al*. (2018) identified 15 indicators across five key components of a functional seed system: 1) research to inform and guide species and provenance selection; 2) seed harvesting and production; 3) market access and demand; 4) quality control; and 5) enabling environment. They then conducted a detailed review of tree-seed supply systems in seven Latin American countries. Although the results varied widely, most countries were found to struggle with similar challenges. Most had large networks of nurseries able to produce suitable species for diverse ecosystem contexts, yet the supply of native high-priority tree species was often limited and gave little consideration to the genetic origin or diversity of the seed used. Most countries already had strategies and initiatives in place to support seed supply, but often these were inadequately integrated for effective scaling up (Atkinson *et al*., 2018). Similarly, a recent survey of signatory countries to the African FLR initiative AFR100[1] revealed that national capacity to produce high-quality planting stock of a variety of native species at scale is a serious constraint to meeting restoration targets.[2]

Efforts to scale up the supply and use of appropriate seed for restoration must be supported by clear policies and regulatory frameworks, and adequate investment. There is a need to incentivize the private sector to manage and market improved seeds and seedlings and to empower users to make informed decisions on TGR by providing them with relevant know-how and information (Lillesø *et al*., 2018).

International seed-stand registers (which document the origin of specific seed sources) and provenance zones (which delineate the bioclimatic conditions of provenances) should be identified and established for priority tree species. The establishment of provenance zones should consider the potential for climate change to influence the natural distribution of tree species to ensure that seed zones are adaptive to future conditions. Seed-stand registers would be particularly useful for supporting collaboration among countries that share the natural distribution of a species, thereby enabling access to broader genetic variation in planting material. FLR could be a useful framework for implementing gene-transfer techniques (i.e. the movement of planting material beyond current natural ranges) such as assisted gene flow (the movement of seed sources of specific adaptive capacity) or – in some extreme cases where the risk of extinction or rapid genetic erosion is evident – assisted migration (the planting of novel genotypes) (Ducci, 2015; Fady *et al*., 2016).

International trading regulations for TGR, such as the Organisation for Economic Co-operation and Development Scheme for the Control of Forest Reproductive Material and similar regulations for the European Union (e.g. its directive on the marketing of forest reproductive material and the European Union Council directive on external quality standards for forest reproductive material marketed within the Community), already provide rules on how TGR should be documented for international trade. These mechanisms enable monitoring of the movement of forest reproductive material and the harmonization of certification and identification systems between countries. In practice, however, the movement of forest reproductive material across borders is poorly documented. Improved knowledge and practical advice will become increasingly necessary in view of the limited experience of the many new actors likely to emerge in response to major international commitments on FLR and other restoration approaches. Collaborative and inclusive actions to develop supportive national strategies for conservation and the supply of high-quality TGR featuring native tree species for use in FLR programmes must be encouraged.

LINKING THE CONSERVATION OF TREE GENETIC RESOURCES WITH SUSTAINABLE USE

Globally, there are some 60 000 tree species (Beech *et al*., 2017). The vast majority of these are native to tropical countries and occur in regions with high rates of deforestation and land-use change. These same countries also have high potential for FLR (Brancalion *et al*., 2019). Because seed must be adapted to the (current and future) environmental conditions found at a given restoration site, diverse seed sources are needed covering a range of environmental conditions. The progressive reduction in the availability of genetically suitable seed sources due to forest degradation and loss means there is an urgent need to conserve critical seed sources and to identify how best to deploy these in restoration.

Despite the important ecological and economic value of thousands of tree species, conservation status has been documented for only a fraction – although efforts are under way to assess all known species (e.g. through the Global Tree Assessment – GTA, undated). Given the speed with which species and especially intraspecific variations are being lost (ter Steege *et al*., 2015; Stévart *et al*., 2019), there is a need to identify the conservation status of all species and to conserve and mobilize their remaining intraspecific variation for future use in restoration and other tree-planting programmes (Graudal *et al*., 2014, 2020). For example, a recent study of 65 native tree species across 15 Asian countries indicated that two-thirds of the species are losing natural habitat in parts of their

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[1] See the article on page 82 of this edition for an outline of this initiative.

[2] The survey was presented at the Regional Workshop on the Conservation and Use of Forest Genetic Resources in Sub-Saharan Africa: Strengthening Tree Seed Systems, which was convened by the sub-Saharan African Forest Genetic Resources (SAFORGEN) Programme on 9–11 April 2019 in Kumasi, Ghana.

ranges due to climate change, with some tree populations set to be completely wiped out in certain ecoregions as soon as 2050 (Gaisberger *et al*., in prep). For some species and geographical locations, anthropogenic pressures may pose larger threats to their *in situ* conservation than climate change. A study of 50 tropical dry-zone forest tree species in Ecuador and Peru found that all species face considerable threats across half their distribution ranges and that habitat conversion, overexploitation and overgrazing pose larger and more immediate threats than climate change to most of the studied species (Fremout *et al*., 2020).

Existing protected-area networks can help maintain adaptive variation, but these often provide poor coverage of the broader environmental gradients of tree species and consequently of intraspecies variation, and they are not immune to the impacts of climate change (Gaisberger *et al*., in prep.). National laws often restrict access to TGR; for example, it is often illegal to collect seed in protected areas except for research purposes, thus reducing their role as sources of genetically diverse and site-adapted germplasm. Seed production areas such as seed orchards have been established for a few commercially important tree species but not for the vast majority of tropical and subtropical native tree species. Building up seed supplies to enable planned large-scale restoration requires both the urgent identification and conservation of remaining natural seed sources and a major effort to establish additional seed sources for a larger number of tree species; moves towards this end are under way in some places (Box 1). Such efforts should be supported by the establishment of adequate nursery networks for managing and deploying the available planting material effectively.

APPROACHES AND TOOLS TO GUIDE TREE SPECIES SELECTION AND SEED SOURCING

The selection of the right tree species and planting material is crucial for the success of FLR initiatives. Species selection requires that the environmental requirements of species match the conditions at the restoration site; the uses and products of the species match the needs and desires of local and other stakeholders; and the species are resilient to future change. FLR may occur on degraded soils that differ considerably from original forest soils due to factors such as erosion, compaction and even toxicity (e.g. caused by mining). This can limit the suitability of the original native tree species in restoration efforts because restoring soil fertility will be a major prerequisite (Chazdon, 2003). Therefore, it may be necessary to rehabilitate planting sites through the initial use of carefully selected non-local species with the capacity to improve soil fertility (Chazdon, 2008).

There is a need to identify suitable tree species for FLR programmes in different agroecological zones and to ensure that these are available to a large number of diverse users (Lillesø *et al*., 2018). New decision-support tools covering thousands of tree species are being developed – including suitability maps to ensure that the restored sites are adaptable in the face of future climatic conditions (Gaisberger *et al*., 2017; Kindt, 2018). Such maps can also guide the identification and development of improved seed sources.

Information on tree species biology and key traits is needed to support tree species selection. This is increasingly available in databases such as the Vegetation Map for Africa (van Breugel *et al*., 2015), the Priority Food Tree and Crop Food Composition database (Stadlmayr, McMullin and Jamnadass, 2019; Stadlmayr *et al*., 2019), and the Agroforestry Tree Species Switchboard (Kindt *et al*., 2019), which links information on more than 172 000 plant species and almost 4 000 intraspecific taxa across 35 web-based

Box 1
Provision of Adequate Tree Seed Portfolios: supporting farmer-planting with optimal tree genetic resources

Provision of Adequate Tree Seed Portfolios (PATSPO), an initiative under way in Ethiopia, conducts studies on tree species prioritized for farmer-planting to meet ambitious national forest restoration commitments. PATSPO supports biodiversity conservation in Ethiopia's restoration programmes by providing suitable (site- and purpose-matched) seed of a range of indigenous trees. PATSPO field trials help identify productive planting material matched to restoration sites to effectively support farmer livelihoods and enhance establishment success. After evaluation, the trials are converted into seed sources for use in on-farm planting. PATSPO is also designing a functional system for delivering tree-planting material in Ethiopia with the capacity to provide seeds and seedlings to smallholder growers. This requires ensuring the right mix of public- and private-sector involvement in the system and the assigning of appropriate responsibilities to the various stakeholders involved. Research to design optimal tree-planting-material delivery pathways for smallholder farmers has demonstrated the importance of supporting small entrepreneurial germplasm-suppliers in delivery. Existing seed- and seedling-delivery systems for restoration projects are often ineffective, with insufficient outreach, and projects such as PATSPO offer lessons that can be widely applied.

Source: World Agroforestry (undated).

Box 2
Tree-planting choices and selection of tree-seed sources in Burkina Faso

Research in central Burkina Faso investigated the tree-planting choices and selections of tree-seed sources made by farmers engaged in various planting practices and FLR approaches, including the establishment of small-scale fenced tree plots (Valette *et al*., 2019). It showed that the use of fencing supports a more diverse portfolio of tree species compared with other small-scale efforts by promoting the spontaneous establishment of tree seedlings regenerating from the soil seed bank and by enabling enrichment planting and farmer-assisted natural regeneration. Farmers tend to engage directly in the collection of the planting material they need, mainly from woodlands near their villages, trees growing in their cultivated agricultural lands and pastures, tree plantations, and fenced plots. The majority of farmers, however, do not undergo specific training on best practices in tree-seed collection. Of the 15 most commonly planted tree species, ten supply edible products. Priority food tree species with potential for inclusion in nutrition-sensitive restoration have been identified in Burkina Faso, and threats to them have been documented and mapped (Gaisberger *et al*., 2017). Traditional water-management techniques, such as building stone contour bunds and digging zaï pits and half-moons to capture rainwater run-off (Nyamekye *et al*., 2018), and the use of compost, should be employed to overcome soil degradation.

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Compost is prepared before planting trees at a restoration site in Burkina Faso. Half-moons, excavated in the fields to collect surface runoff, are visible in the background

information sources. The Diversity for Restoration (D4R) tool[3] developed by Bioversity International goes beyond species choice – it enables practitioners to choose appropriate species and seed sources for given project sites that meet desired restoration objectives based on the characterization of tree-species functional traits (Thomas *et al*., 2017). D4R also takes into account climate change in proposing options for plant reproductive material and includes information on the propagation of hundreds of native tree species. Originally developed for the dry forests of Colombia, D4R has been expanded recently to include northwestern Peru and southern Ecuador and is also being deployed to support FLR in Burkina Faso (Box 2) and Cameroon.

Other tools have been developed to support both the tracing and monitoring of TGR from seed collection through to planting. SeedIT, for example, is a user-friendly smartphone application designed to enable the documentation and tracking of tree-seed sources by a wide range of users, from community seed collectors to commercial nurseries. The app is being piloted in community restoration projects in the Lao People's Democratic Republic and Malaysia.

In the future, climate-dependent traits (such as pest and disease resistance, drought resistance, cyclone resistance,

[3] www.diversityforrestoration.org

salt tolerance, and phenotypic plasticity) need to be more strongly selected for in domestication and breeding efforts (Alfaro *et al*., 2014; Stanturf *et al*., 2015).

OPPORTUNITIES FOR OPERATIONALIZING EQUITABLE BENEFIT-SHARING

Although it is probable that spontaneous natural regeneration on abandoned agricultural fields will bring about considerable increases in tree cover (Gilroy *et al*., 2014), meeting the ambitious restoration pledges of countries will require support for tree-planting on smallholder lands. The level and type of engagement of rural people, particularly the poor, will hinge largely on the direct benefits that smallholders can reap from FLR (Galabuzi *et al*., 2014; Baynes *et al*., 2015; Fox and Cundill, 2018).

Tree-based restoration offers several income-generating opportunities for smallholders, including those involving the production, processing and marketing of wood and non-wood forest products and arising from the provision of ecosystem services (e.g. through payments for ecosystem services, including for carbon sequestration) (Aronson *et al*., 2010; Newton *et al*., 2012). Small-scale producers can diversify their incomes and reduce their risks by planting multiple native species to produce timber, woodfuel, foods and medicines, thereby catering to different markets (Vieria *et al*., 2010) and seeking a balance of seasonal and inter-annual production cycles. But producers need early returns because waiting years for trees to mature may be impossible or undesirable in resource-limited communities (Etongo *et al*., 2015). Encouraging both slow-growing hardwood species and fast-growing high-value species will help maintain interest in tree-based restoration. Local women and men, who hold different, overlapping and complementary knowledge of tree species and ethnovarieties (Karambiri *et al*., 2017), can guide the identification of appropriate native tree species (Box 3). It may also be necessary to address community norms that discourage the planting of diverse native tree species because decisions on land use and species are also a function of what is socially acceptable at a given locality (Pannell, 1999).

The availability and quality of tree germplasm and seedlings further shape decisions on species and provenances (Brancalion *et al*., 2017). Hence, it is necessary to strengthen not only the technical capacities of small-scale farmers to grow diverse tree species (and bring their products to market) but also those of seed collectors and nursery owners in collecting and producing high-quality, genetically well-adapted seeds and seedlings. Pricing structures that are sensitive to product quality and enable price premiums for high-quality seed, and access to lucrative markets, are needed to incentivize investments in high-quality germplasm. Building

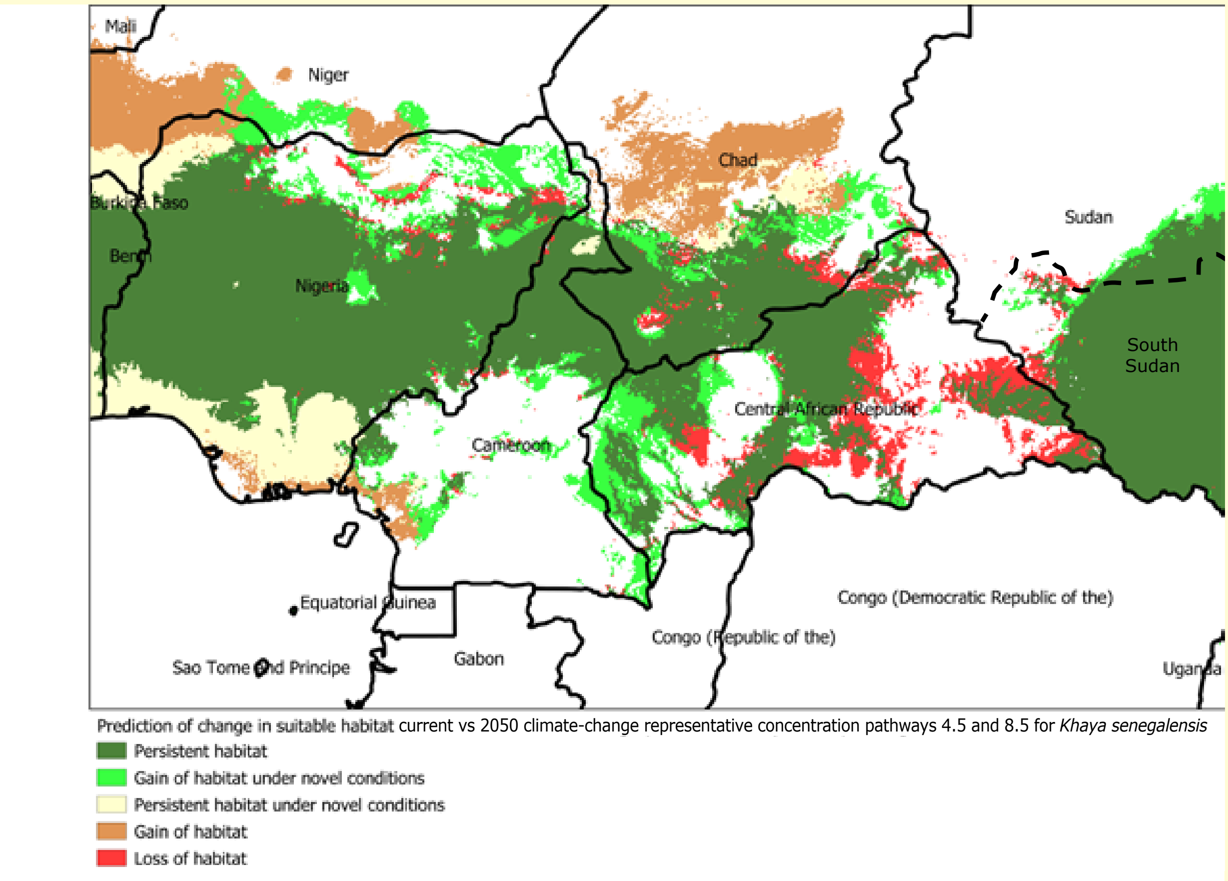
A small-scale fenced restoration plot established with support from the Tiipaalga association in Burkina Faso and managed by a women's group. The perimeter is delimited by metallic fences bordered by a line of* Acacia senegal *trees that will progressively replace the fence and provide an ongoing income from the sale of gum

Box 3
Ensuring the best climate data to model threats to native tree genetic resources across Central Africa

Bioversity is working with partners to support climate-sensitive decisions related to biodiversity and ecosystem services, focusing on priority TGR in the Congo Basin in Central Africa and the Guinean forests in West Africa. These subregions face the multiple threats of unsustainable land use, industrial pollution and climate change (IUCN, 2015). Central African countries have pledged (through the Bonn Challenge and AFR100) to bring more than 38 million ha of deforested and degraded land under restoration by 2030. Achieving this transformation will require overcoming constraints such as those posed by the poor quality and limited diversity of planting materials. This project is helping identify appropriate planting material that is adapted to local restoration sites and resilient to future climatic conditions.

A total of 58 native tree species common to Central and West African countries were selected by a diversity of stakeholders for their inclusion in FLR interventions, based on criteria such as habitat (e.g. savannah or forest), uses (wood and non-wood) and conservation status. Climate-suitability maps were produced for each species using historical climate data and the best available future climate projections (Figure 1). Species distribution models, maps of climate change and other threats, and genetic and ecogeographic diversity assessments will be combined to define appropriate seed-sourcing strategies for successful restoration, at the same time helping conserve the genetic diversity of the tree species used. The results will be made available as part of the D4R platform (see above).

1 Prediction of change in suitable habitat for* Khaya senegalensis *from current to 2050 climatic conditions in Central and West Africa



Source: adapted from Marius R.M. Ekué, Bioversity International, 2017. Conforms to Map No. 4170 Rev. 19 UNITED NATIONS (October 2020) capacity and ensuring the availability of documentation and verification tools such as SeedIT could help enable this change.

Brancalion *et al*. (2017) argued that, to realize its potential to generate jobs and income, reduce poverty and deliver valuable ecosystem services to society, restoration should receive the same attention from state decision-makers and markets as they give to agricultural commodities. This means creating incentives, including financial incentives such as low-cost finance, and supporting producers to gain access to markets for their products.

CONCLUSION

The global ambitions for FLR have never been greater. The Bonn Challenge, the New York Declaration on Forests and the United Nations Decade on Ecosystem Restoration have mobilized extraordinary political commitments to reverse landscape-scale degradation to achieve multiple environmental and societal benefits. The implementation of these commitments will require the effective deployment of TGR via approaches involving assisted natural regeneration, direct seeding and tree-planting in plantations, agroforestry systems and ecosystem restoration. In many developing countries, the capacity to scale up the supply of TGR for FLR remains a major limiting factor on success. Key priorities must be to:

- improve the national and local-level conservation of TGR for priority species by building capacity to identify and map threats to TGR and to safeguard critical seed sources;
- adopt existing decision-making tools to support the choice of the right tree species for given environmental conditions and established purposes;
- gather additional information on the requirements and traits of presently underused native species from a broad set of forest ecosystems;
- raise awareness at all levels of the importance of seed quality for plantation and restoration success while simultaneously developing policies, strategies and regulations that support the establishment of operational seed-supply systems. Any legislation should include requirements to document seed quality and origin and specify quality requirements for the TGR used in publicly funded FLR projects;
- initiate national assessments of the TGR needed to meet FLR targets to inform the development of seed systems and markets capable of meeting seed requirements in terms of both quantity and quality;
- invest at the national level in the development of databases of existing TGR and the infrastructure required to ensure the sustained supply of improved planting material;
- obtain information on the medium- and long-term socio-economic benefits of using appropriate species and high-quality seed sources in FLR programmes;
- put in place incentives and enabling policies to support smallholders in producing, trading and using high-quality genetically diverse reproductive materials; and
- promote educational campaigns, extension, knowledge-sharing and enabling institutional, policy and regulatory frameworks and, crucially, ensure the availability of adequate land and fair and equitable tree-tenure regimes so that diversity-rich FLR (and the products and ecosystem services it provides) is perceived as more attractive than alternative land uses, thereby strengthening economic activities based on native tree diversity.

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