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Delivering tree genetic resources in forest and landscape restoration

A guide to ensuring local and global impact

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Authors

Hannes Gaisberger, Riina Jalonen, Barbara Vinceti, Marlène Elias, Chris J Kettle
Bioversity International, Rome, Italy

Evert Thomas
Bioversity International, Lima, Peru

Benjamin DeRidder, Christophe Besacier, Jarkko Koskela, Giovanbattista DeDato, Giovanni DiMatteo
Food and Agriculture Organization of the United Nations, Rome, Italy

Magda Boudagher
European Forest Institute, Barcelona, Spain and Université Saint-Joseph, Beirut, Lebanon

I Wayan Susi Dharmawan, Vivi Yuskianti
Research Center for Ecology and Ethnobiology, National Research and Innovation, Indonesia

Bruno Fady
INRAE, Ecology of Mediterranean Forests, URFM, Avignon, France

David Odee
UK Centre for Ecology and Hydrology, Penicuik, United Kingdom of Great Britain and Northern Ireland

Huang Ping, Zheng Yongqi
Chinese Academy of Forestry, Beijing, China

Maurizio Rossetto
The Royal Botanic Garden Sydney, Australia

Enrique L. Tolentino, Jr
University of the Philippines Los Baños, Philippines

Rekha Warrier, Ramasamy Yasodha
Institute of Forest Genetics and Tree Breeding, Coimbatore, India

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Manioc planting in Lambert's agroforestry plot in the village of Banghidima, near Yanonge, Democratic Republic of the Congo.
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Abbreviations and acronyms

APFORGEN	Asia Pacific Forest Genetic Resources Programme
BEF	biodiversity–ecosystem functioning
BAFF	Binahon Agroforestry Farm
CAS	Carritt shola
CBD	Convention on Biological Diversity
CIFOR	Center for International Forestry Research
CKPP	Central Kalimantan Peatland Project
COP	Conference of the Parties
DENR	Department of Environment and Natural Resources
DNA	deoxyribonucleic acid
DPTH	Directorate of Forest Tree Seed
EFIMED	European Forest Institute Mediterranean Facility
EUFGIS	European Information System on Forest Genetic Resources
EUFORGEN	European Forest Genetic Resources Programme
FAO	Food and Agriculture Organization of the United Nations
FLR	forest and landscape restoration
GCU	gene conservation unit
GEF	Global Environment Facility
GMS	Glenmorgan shola
HADP	Hill Area Development Programme
ICRAF	World Agroforestry Centre
INREMP	Integrated Natural Resources and Environmental Management Project
IUCN	International Union for Conservation of Nature
IUFRO	International Union of Forest Research Organizations
LA	leaf area
LD	leaf duration
KMS	Kariamund shola
LAFORGEN	Latin American Forest Genetic Resources Network
MoEF	Ministry of Environment and Forestry
NBR	Nilgiri Biosphere Reserve
NCD	nationally determined contribution
NGO	non-governmental organization
NTFP	non-timber forest product
NVS	natural vegetation strip
PDASRH	Directorate General of the Management of Watershed and Forest Rehabilitation

SAFORGEN	Sub-Saharan Africa Forest Genetic Resources Programme
SDGs	Sustainable Development Goals
SLA	specific leaf area
SNI	Indonesian National Standard
SSR	simple sequence repeat
TGR	tree genetic resources
UN	United Nations
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
UPT	Technical Implementation Unit
WD	wood density
WHO	World Health Organization

Definitions

Adaptation to climate change: the process of adjusting to current or expected effects of climate change events.
Common garden or common garden experiment: plantings of species or populations collected from multiple distinct geographic locations.
DNA barcoding: a technique of plant and animal identification that uses DNA-based identification and high-throughput sequencing.
DNA sequencing: a laboratory technique for determining the exact sequence of nucleotides, or bases, in a DNA molecule.
Ex situ: offsite, or away from the natural location, for example in a seed bank or seed orchard.
Forest reproductive material: parts of a tree that can be used for reproduction such as seed, seedlings or vegetatively propagated material (cuttings, scions, shoots and twigs).
Gene flow: introduction of genetic material (by interbreeding) from one population of a species to another population of that species.
Genomics: the study of the complete set of DNA in an individual organism, including all its genes.
Genotype: the complete set of heritable genes that can be passed from parents to their offspring
Guild: a group of species that have similar requirements and play a similar role within a community.
High-throughput sequencing: the comprehensive term used to describe technologies that sequence DNA in a rapid and cost-effective manner.
Hybridization: the process of breeding an animal or a plant with an individual of another species or variety.
In situ: in its natural location.
Late-successional species: those species that establish themselves much later than pioneer species and need more stable and predictable environments.
Multifunctional landscape: terrain characterized by diversified land use and structure, incorporating a wide range of ecosystem services.
Non-forest ecosystem: an ecosystem, such as grassland, shrubland or a desert, where trees are not the dominant life form, although they may be present as scattered individuals or in patches.
Phenophase: an observable stage in the annual life cycle of a plant or animal that can be defined by a starting-point and an end-point.
Phenotype: the observable characteristics in an individual resulting from

the expression of genes.
Phylogenetic: relating to the evolutionary development and diversification of a species or group of organisms.
Pioneer species: first species to colonize a bare substrate in primary succession, or a destroyed habitat in secondary succession.
Population genetic structure: the amount and distribution of genetic variation within and between populations.
Provenance trial: a specific place where trees are grown to compare the performance of germplasm from different geographical locations or, a special type of plantation experiment that helps understand how trees have adapted to different environmental conditions.
Resilience to climate change: the capacity to prepare for, respond to and recover from the impacts of climate change events.
Seed orchard: an intensively managed plantation of trees for mass production of genetically improved seeds or plants for the establishment of new forests.
Seed source: a group of trees growing together from which seed for multiplication can be collected.
Seed-supply system: a set of activities contributing to variety development, including production and delivery of seed to farmers.
Tree genetic resources: heritable materials maintained within and among trees that are of actual or potential economic, environmental, scientific or societal value.
Tree nursery: a place where trees are propagated and grown to a desired size.
Tree-sourced foods: edible products from trees such as fruit, seeds, leaves, roots and other non-timber forest products.

Executive summary

In the last 25 years, almost 50 million hectares of primary forest have been lost due to deforestation. Numerous international initiatives such as the Bonn Challenge and the New York Declaration on Forests have set ambitious goals to restore degraded and deforested lands by 2030. Realizing global commitments on forest and landscape restoration (FLR) will require the establishment of billions of trees on millions of hectares of degraded land to address the triple crisis of biodiversity loss, climate change and failing food systems. A significant amount of FLR will require tree planting or increasing tree cover in production landscapes.

The scaled delivery of tree genetic resources (TGR), in other words, the diversity of species and genotypes from seeds and other forest reproductive material, will be critical to achieving impact. Lack of available forest reproductive material undermines the scaling of FLR and its potential to deliver expected benefits. Achieving impact from FLR requires an abundance of seeds and seedlings from many species and sources of genetic diversity within species.

The aim of this working paper is to highlight key challenges and opportunities for the integration of TGR – from genes and species to landscapes – in current FLR projects.

We first explore why TGR are so important and identify the key role that they play in supporting biodiversity, mitigating and adapting to climate change, and enhancing resilient livelihoods. Second, we evaluate the challenges and barriers to scaling the use of TGR in restoration, and how these undermine the potential of FLR to deliver expected benefits. Third, we review recent opportunities and innovations in the latest literature for mainstreaming TGR in FLR and present 13 case studies from around the world, representing state-of-the-art and best practices for TGR conservation and use. We then summarize the findings from these case studies, covering a range of topics from improved *in situ* and *ex situ* conservation of TGR, strategies for ensuring high-quality, diverse planting material, and evidence to show how increasing the use of TGR in FLR can increase benefits, locally and globally.

We provide practical guidelines for improving integration of TGR in FLR, for consideration by a wide range of stakeholders, in particular: (1) countries and national policymakers; (2) donors and funding bodies; (3) international organizations and regional networks; and (4) restoration practitioners. Finally, we present a list of eight key recommendations to

support the delivery of TGR for maximizing restoration outcomes towards reversing biodiversity loss, mitigating and adapting to climate change, and supporting sustainable food systems and improved livelihoods. We hope that this paper will contribute to achieving the United Nations Sustainable Development Goals (SDGs), specifically SDGs 1 (No Poverty), 2 (Zero Hunger), 13 (Climate Action) and 15 (Life on Land) through greater and more effective use of TGR in FLR implementation.

1. Introduction

Global political commitments for forest and landscape restoration (FLR) are burgeoning, with billions of trees and millions of hectares (ha) of land committed to restoration, to address the global triple crisis of biodiversity loss, climate change and failing food systems (Baldwin-Cantello *et al.*, 2020). While some restoration commitments can be met through cost-effective, natural regeneration of forests, this will only be feasible where soils are not severely degraded, and native vegetation and seed sources are not entirely absent (Chazdon and Guariguata, 2016). A significant amount of FLR will require tree planting or increasing tree cover in agroforestry systems on farm- and pastureland (Brancalion and Holl, 2020; Di Sacco *et al.*, 2021).

Some critical issues pertinent to successful FLR include the need to consider land tenure, social equity and diverse financial interests (CBD, 2016; Elias, Joshi and Meinzen-Dick, 2021). However, the mainstreaming of tree genetic resources (TGR), in other words, the diversity of species and genotypes from seeds, seedlings and other forest reproductive material, and their importance in achieving multiple social and environmental restoration goals, have received much less attention (Kettle *et al.*, 2020). Tree genetic resources, both as a result and as means of ensuring resilient restoration, are not sufficiently mainstreamed and incorporated into agricultural practices, investment, policy, incentive schemes or, more generally, in restoration decision-making. One documented bottleneck is the delivery of tree seed supply (Atkinson *et al.*, 2021; Bosshard *et al.*, 2021; Jalonen *et al.*, 2018).

The lack of available tree seed and forest reproductive material in general, in terms of both quantity and quality (Fady *et al.*, 2021), undermines the scaling of FLR and its success in delivering associated benefits, especially in addressing the triple need to improve biodiversity outcomes, mitigate climate change and make food systems more resilient. Successful FLR requires the provision of abundant, suitable seeds and seedlings from diverse species and sources within species for ecological restoration, agroecological transition, agroforestry and other restoration interventions (Atkinson *et al.*, 2021; Bosshard *et al.*, 2021; Elias *et al.*, 2022; Jalonen *et al.*, 2018; Notenbaert *et al.*, 2021; Di Sacco *et al.*, 2021).

The aim of this working paper is to highlight key challenges and opportunities for the integration of TGR – from genes and species to landscapes – in current FLR projects. Here we review the latest literature and present 13 case studies from around the world, representing state-of-the-art and best practices for TGR conservation and use for sustainable and impactful restoration. The paper aims to provide practical recommendations for a wide range of stakeholders, including governments and national policymakers, donors, international organizations, regional networks and restoration practitioners. Ultimately, our aim is to enable greater consideration of TGR within the restoration community to achieve key restoration objectives. The paper explores how, by increasing the use of diverse TGR, FLR can better deliver solutions to tackle the triple crisis of biodiversity loss, climate change and failing food systems (Baldwin-Cantello *et al.*, 2020) and thus help achieve the United Nations (UN) Sustainable Development Goals (SDGs), specifically SDGs 1 (No Poverty), 2 (Zero Hunger), 13 (Climate Action) and 15 (Life on Land).

Increased conservation and use of tree species and genetic diversity in forest and land restoration increase success in addressing the triple crisis of global biodiversity loss, climate change and failing food systems.

2. The momentum of forest and landscape restoration

Globally, 47 million ha of primary forest have been lost due to deforestation between 2000 and 2020 (FAO, 2020, 2022), and large portions of the remaining forest, including 45 percent of tropical forest, are under severe pressure from anthropogenic threats such as agricultural expansion, logging, livestock farming and fire, leading to fragmentation and degradation (Ceccarelli *et al.*, 2022; Fremout *et al.*, 2020; Gaisberger *et al.*, 2021; Potapov *et al.*, 2017; Venter *et al.*, 2016). Numerous international initiatives such as the Bonn Challenge and the New York Declaration on Forests have set ambitious restoration goals by 2030 (Löf *et al.*, 2019) to establish billions of trees on millions of hectares of degraded and deforested land.

With the recent launch of the three UN decades on, respectively, family farming, action on the SDGs, and ecosystem restoration (FAO, IUCN CEM and SER 2021), and several regional initiatives such as the African Forest Landscape Restoration Initiative (AFR100), the Latin American and Caribbean Initiative 20x20 and the Agadir Commitment for the Mediterranean region, the opportunity for and political commitment to FLR continue to grow. Forest and landscape restoration seeks to restore ecological integrity and improve human well-being in deforested or degraded forest landscapes (Baldwin-Cantello *et al.*, 2020; Chazdon and Brancalion, 2019; Mansourian *et al.*, 2021).

In 2022, investments of 26 billion USD across 18 countries brought 14 million ha of degraded land across a variety of ecosystems under restoration, according to the Barometer Report (IUCN, 2022). This reflects the major commitments reported on by countries but still accounts for only about 30 percent of the collectively pledged area. Despite the political and financial engagement, there has been growing concern that past large-scale restoration has failed to deliver local benefits (Fleischman *et al.*, 2022), and in some regions of the world, up to 40 percent of planted trees are failing even to survive after 5 years (Banin *et al.*, 2023).

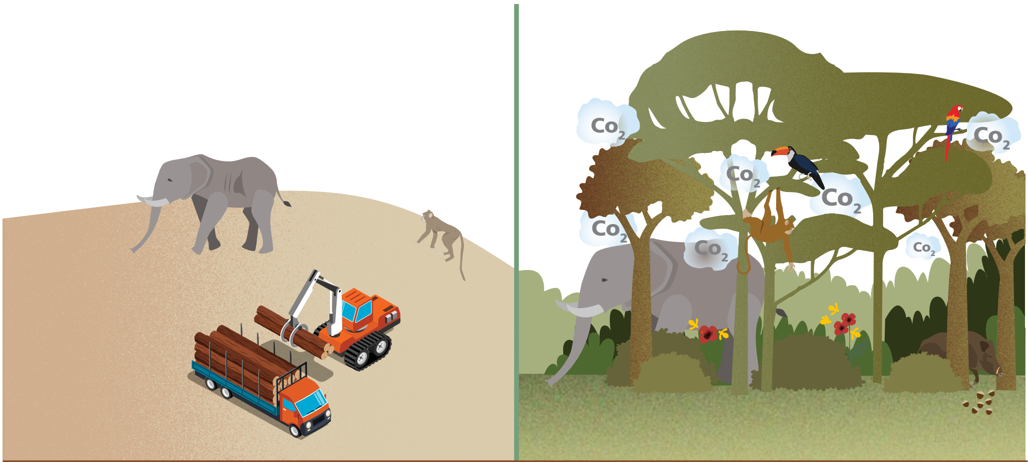
There is a growing awareness of the need to avoid extensive monoculture plantations (Lewis *et al.*, 2019) or afforestation of valuable, non-forest ecosystems (Veldman *et al.*, 2015) and to ensure that restored landscapes meet expected ecological, social and economic benefits both locally and globally (Elias, Joshi and Meinzen-Dick, 2021; Mansourian *et al.*, 2021). Restoration commitments will also need to be embedded in efforts to transform food production systems, through agroecological transition for example (Jones *et al.*, 2022), to prevent deforestation and agricultural expansion occurring hand in hand with restoration (Fagan *et al.*, 2020) and to ensure that restoration interventions lead to net positive outcomes (Di Sacco *et al.*, 2021).

3. Why are tree genetic resources so important?

To meet global restoration targets, the delivery of more diverse native trees for FLR is critical, and greater consideration should be given to genetic resources in FLR using natural regeneration and tree planting, both in degraded natural forests and in agroforestry and silvopastoral systems (Harrison *et al.*, 2022; Nef *et al.*, 2021).

Using a diversity of TGR is critical for three main reasons. First, more diverse tree species both phylogenetically and spanning a range of species, genera and families will not only enhance ecosystem functioning and service provision (Isbell *et al.*, 2011; Le Provost *et al.*, 2022), including carbon stocks (Yan *et al.*, 2022), but also support a greater level of overall biodiversity (Ampoorter *et al.*, 2020; Messier *et al.*, 2022). Second, ensuring highly diverse TGR can enhance resilience to climate change through redundancy (Monge-González *et al.*, 2021; Schwaab *et al.*, 2020) or adaptive capacity to environmental change (Varas-Myrik *et al.*, 2022). Third, integration of highly diverse TGR, especially for fruit, nuts and other non-timber forest products, can contribute substantially to more resilient livelihood options (Dawson *et al.*, 2020) for a wider range of people from different backgrounds, genders and ages (Gachuiri *et al.*, 2022; Karambiri *et al.*, 2016), more sustainable and nutritious food systems (Jansen *et al.*, 2020), and importantly, more profitable farming (Lagneaux *et al.*, 2021).

Genetically diverse FLR supports the restoration of forests and tree cover. But it also promotes conservation of forest genetic resources and wider forest-dependent biodiversity while enhancing the resilience of farming systems, reducing negative agricultural impacts and supporting multifunctional landscapes to deliver more ecosystem services. To this end, regional forest genetic resources networks, like those established in Asia and the Pacific (APFORGEN), Latin America (LAFORGEN), sub-Saharan Africa (SAFORGEN) and Europe (EUFORGEN), can play an important role in TGR conservation and use (Jalonen *et al.*, 2016). These networks seek to enhance technical and scientific cooperation among member countries and to mobilize political and financial support for better inclusion of TGR in sectoral and cross-sectoral programmes on climate, biodiversity and food systems.



A high diversity of native tree species as well as high genetic diversity within and among tree species better support the diversity of other organisms such as plants, microbes and animals and help stabilize ecosystem functions. The evolutionary resilience of these trees helps withstand the effects of changing climatic conditions and effectively mitigate climate change and carbon emissions.

3.1. RELEVANCE OF TREE GENETIC RESOURCES TO HALT BIODIVERSITY LOSS

Incorporating species and genetic diversity into FLR interventions not only contributes to conserving the genetic variation and evolutionary resilience of native tree species (Sgrò, Lowe and Hoffmann, 2011; Thomas *et al.*, 2014) but also plays a fundamental role in supporting the diversity of other plant, microbial and animal communities (Li *et al.*, 2022; Whitham *et al.*, 2006; Wymore *et al.*, 2014). High tree genetic diversity has also been shown to increase tree stand productivity (Nadrowski, Wirth and Scherer-Lorenzen, 2010), stabilize ecosystem functions, for example through nutrient cycling and plant–herbivore interactions, and sustain more resilient pollinator communities (Krishnan *et al.*, 2020) due to complementary and independent species dynamics (Lázaro *et al.*, 2022; Schindler *et al.*, 2010).

3.2. RELEVANCE OF TREE BIODIVERSITY TO MITIGATE CLIMATE CHANGE

In the face of accelerating climate change (Tollefson, 2022), it is crucial to ensure that the planting material used in FLR is well adapted to the environmental conditions existing at the restoration site. But it is also important to ensure that there is sufficient genetic diversity for evolutionary processes to happen so that the planting material will withstand the direct and indirect effects of changing climatic conditions and associated biotic responses (Breed *et al.*, 2013; Kettle *et al.*, 2008; Sgrò, Lowe and Hoffmann, 2011; Thomas *et al.*, 2014). Only genetically diverse tree populations with the adaptive potential to respond to climate change will be able to effectively mitigate climate change and carbon emissions through long-term persistence and long-term carbon sequestration (Alfaro *et al.*, 2014; Beugnon *et al.*, 2022; Fady *et al.*, 2016b; Lewis *et al.*, 2019; Roshetko *et al.*, 2018). Furthermore, natural forests restored to be biodiverse have high evolutionary potential to adapt, support greater ecological functionality and are able to capture more carbon in their biomass and soil than monocultural tree plantations (Yan *et al.*, 2022).

3.3. RELEVANCE OF TREE GENETIC RESOURCES TO REDESIGN SUSTAINABLE FOOD SYSTEMS AND EQUITABLE LIVELIHOODS

Despite there being an extraordinary diversity of tree-sourced foods, including fruit, leafy vegetables, nuts, berries, seeds and edible oils, the vast majority of our food comes from a few staple crops (Michler and Josephson, 2017). This leaves food systems, and the people who depend on them for their sustenance and income, vulnerable to shocks. Underutilized, edible and highly nutritious tree-based foods have a huge and largely untapped potential to simultaneously deliver environmental, cultural, nutritional and livelihood benefits at the local and global scale (Jamnadass *et al.*, 2015; Jansen *et al.*, 2020; Vinceti *et al.*, 2022). Fruit tree plantations, typically used to produce foods, such as avocados, macadamia nuts or oranges, for global markets are often monocultural intensive systems (Brofeldt *et al.*, 2018; Higonnet, Bellantonio and Hurowitz, 2018; Nesper *et al.*, 2017). Income from these plantations is commonly concentrated in the hands of better resourced male farmers (Elias *et al.*, 2021), and these systems neglect the wider needs of local communities (Höhl *et al.*, 2020), lead to poor soil and pest and disease management, and do not deliver the multiple benefits that better integration of neglected and underutilized TGR can offer through biodiverse agroforestry systems (Jamnadass *et al.*, 2015; Jansen *et al.*, 2020; Reed *et al.*, 2017).

The extraordinary diversity of tree-sourced foods, such as fruits and nuts, and other non-timber forest products, have a huge potential to deliver equitable environmental, cultural, nutritional and livelihood benefits.

4. Key challenges and barriers to scaling the use of tree genetic resources in restoration

Currently the most commonly used planting material in restoration projects are seedlings from private and public nurseries (Haase and Davis, 2017; Jalonen *et al.*, 2018; Thomas *et al.*, 2014). Nurseries typically produce commercially available species that they expect to sell, only growing a small number of native species from limited provenances and with insufficient documentation of origin (Bosshard *et al.*, 2021; Jalonen *et al.*, 2018; Lillesø *et al.*, 2018; Nyoka *et al.*, 2014). Due to lack of awareness and capacity, nurseries often do not pay enough attention to seed selection and seed sourcing, which results in the use of planting material that is not well suited to the restoration site and with low genetic diversity (Broadhurst, 2013; Jalonen *et al.*, 2018; Thomas *et al.*, 2014). Maladaptation and low seed genetic diversity have negative impacts on germination, growth, productivity and survival, and lead to decreased fitness and resilience of restored tree populations (Jalonen *et al.*, 2018; Roshetko *et al.*, 2018; Thomas *et al.*, 2014), resulting in delays, increased costs or a complete failure of FLR projects (Banin *et al.*, 2023; Jalonen *et al.*, 2018; Nef *et al.*, 2021).

Other major bottlenecks to scaling TGR are the decline in areas covered by natural tree populations and the associated loss of seed sources, the high demand for fuelwood and the complexity of storing recalcitrant tropical tree seeds. Also, the loss of traditional ecological knowledge and expertise in forest botany is an important aspect, which leads to reduced awareness of the numerous benefits of native tree species in terms of nutrition, health and biodiversity. These factors are particularly limiting for ecological restoration as it aims to restore the integrity of forest ecosystems that have been heavily disturbed, but they also apply to a considerable extent in restoration that has other goals, including land restoration for production purposes. In addition, the full potential of native tree species to deliver specific goods and services is not sufficiently explored (Ulian *et al.*, 2020), which means that the demand concentrates on a few well-documented, but often less suited, exotic species (Godefroid *et al.*, 2011).

4.1. CONSTRAINTS ON HALTING BIODIVERSITY LOSS

Recent studies across many plant and animal species show that shrinking geographic ranges are causing dramatic losses of genetically distinct populations (Ceballos, Ehrlich and Dirzo, 2017), and that the remaining genetic diversity is not sufficiently protected *in situ* or *ex situ* (Fady *et al.*, 2016a; Khoury *et al.*, 2019). Therefore, ecological restoration is a crucial component for enhancing biodiversity conservation across landscapes as well as the provision of ecosystem services (Rey Benayas *et al.*, 2009).

In severely degraded and fragmented forests, where many tree species remain with low genetic diversity and non-viable populations, ecological restoration is the only approach that can mitigate extinction rates (Newmark *et al.*, 2017; Zucchi *et al.*, 2018), as habitat protection is no longer sufficient to reverse biodiversity loss (Possingham, Bode and Klein, 2015). When landscape-wide biodiversity is low, and habitat cover and connectivity are inadequate, there is a high risk of local extinctions, as important ecological processes such as pollination and seed dispersal are impaired (Arroyo-Rodríguez *et al.*, 2009; Newmark *et al.*, 2017; Rappaport, Tambosi and Metzger, 2015).

Tree nurseries and restoration practitioners only have a fraction of species and the genetic diversity of tree species within their portfolios of options that are required to reconstruct diverse and resilient restoration outcomes (Shaw, 2019; Volis, 2016). Furthermore, large-scale projects aimed at restoring species-rich forests often use planting material with low genetic diversity collected from very few parental trees in nearby forests (Bosshard *et al.*, 2021; Jalonen *et al.*, 2018; Nyoka *et al.*, 2014). If these few parent trees are located in restored or planted forests (Jalonen *et al.*, 2018), there is an even higher likelihood of inbreeding in subsequent tree generations, leading to reduced survival and productivity (Lengkeek, Jaenicke and Dawson, 2005).

4.2. CONSTRAINTS ON MITIGATING CLIMATE CHANGE

Although climate change is predicted and observed to have a major impact on many restoration sites (Hobbs, Higgs and Harris, 2009), it is typically not considered in species selection and seed sourcing practices for FLR (Atkinson *et al.*, 2021; Bosshard *et al.*, 2021), even in restoration projects aimed at mitigating climate change through long-term carbon sequestration in biomass and soil (Jalonen *et al.*, 2018). A general lack of awareness and demand for a suitable origin and provenance for planting material (Bosshard *et al.*, 2021; Nyoka *et al.*, 2014; Thomas *et al.*, 2014; Vinceti *et al.*, 2020) severely limits the use of adapted, climate-resilient and genetically diverse planting material (Jalonen *et al.*, 2018).

Nearby seed sources are usually associated with local adaptation, but this is not always the case (Boshier *et al.*, 2015; Breed *et al.*, 2019; McKay *et al.*,

2005) if, for example, local adaptation was driven by particular environmental conditions that are expected to change rapidly (Sgrò, Lowe and Hoffmann, 2011), or if local populations are small and inbred. Moreover, local adaptation is often perceived in a very narrow sense, and seed is collected from as close to the restoration site as possible.

4.3. CONSTRAINTS ON REDESIGNING SUSTAINABLE FOOD SYSTEMS AND EQUITABLE LIVELIHOODS

Global food production and consumption are major contributors to anthropogenic climate change, land degradation and biodiversity loss (Foley *et al.*, 2011; Poore and Nemecek, 2018). In recent decades, large-scale agricultural expansion has taken place, particularly in tropical regions, at the expense of intact forests (Gibbs *et al.*, 2010). One-third of the global crop production (on a mass basis) is consumed by livestock, which produces human food indirectly and much less efficiently (Foley *et al.*, 2011). Half of the human calorie intake today is provided by only three crops – wheat, rice and maize – which makes our food supply extremely vulnerable (Reeves, Thomas and Ramsay, 2015) and is negatively affecting dietary quality (Jansen *et al.*, 2020). The negative social and environmental consequences of industrial food production make it increasingly clear that the current model cannot be sustained in the long term (Foley *et al.*, 2011; Godfray *et al.*, 2010) and that alternative strategies need to be considered to reconcile biodiversity conservation, food production, nutrient adequacy, health and equity (Lachat *et al.*, 2018; Sayer *et al.*, 2013; WHO, 2020).

Tree-sourced foods including forage species for livestock offer an opportunity to generate income and improve diets while bringing ecological benefits. Food tree species tend to remain largely neglected or underutilized in local, national and international markets due to constraints at the production stage, value-chain related obstacles, and challenges related to consumer demand and marketability (Van Loon *et al.*, 2021). Indigenous tree species, which often offer better income prospects for women than male-controlled, commercial tree crops (Elias *et al.*, 2021) tend to be particularly overlooked by research, governments and the international community (Omotayo and Aremu, 2020).

5. Opportunities and innovations for mainstreaming tree genetic resources in forest and landscape restoration

Accumulated evidence over the last 40 years shows that tree populations should exhibit large, effective population sizes – ideally more than 1 000 reproductive trees – to maintain their evolutionary potential to adapt to environmental change over time (Frankham, Bradshaw and Brook, 2014; Hoban *et al.*, 2020). In practice, using at least 50 reproductive trees as seed sources for FLR would already be an improvement on current practices and would help avoid inbreeding and the consequent decrease in biological fitness. Accounting for species and genetic diversity and appropriate population sizes in FLR can significantly contribute to the conservation of native tree species and ensure the long-term viability of restored tree populations and other associated plant, microbial and animal communities. Furthermore, targeted restoration of habitat and landscape connectivity is needed to improve the survival and resilience of tree species, the overall forest biodiversity and the associated ecological processes and ecosystem functions.

Seed production and supply systems need to be improved from the local to the national and transnational level to ensure that sufficiently diverse planting material is available, able to adapt to specific site conditions and demands in the short term, and to a changing climate in the longer term (Atkinson *et al.*, 2021; Bosshard *et al.*, 2021; Jalonen *et al.*, 2018). The generation and exchange of knowledge among diverse stakeholders about the most appropriate choices of species, seed sources and provenances play a key role. They require the integration of gendered traditional and local knowledge with insights from scientific research, including species ecology and functional traits, provenance and progeny testing, seed zoning, genetic and genomic analysis, and habitat suitability modelling under current and projected future climate conditions (Atkinson *et al.*, 2021; Douterlungne *et al.*, 2010; Fremout *et al.*, 2021, 2022; Gaisberger *et al.*, 2020, 2022; Thomas *et al.*, 2017). Besides improving species and genetic diversity, additional measures have been proposed to increase climate change resilience in FLR, such as increasing restored tree population sizes, restoring landscape connectivity through linking restored patches and trees on farms with surrounding forest remnants, and identifying and protecting evolutionary refugia (Frankham, 2022; Thomas *et al.*, 2014; Zucchi *et al.*, 2018).

Forests are critical for supporting the livelihoods of 1.6 billion people globally who live near them (Newton *et al.*, 2020). It is estimated that natural and planted forests together provide about 22 percent of total household income across rural areas in developing countries through the provision of food, fuel, fodder, construction materials, medicine and other non-timber forest products (Angelsen *et al.*, 2014; Wunder, Angelsen and Belcher, 2014). Tree-sourced foods as well as forage species for livestock have an enormous potential to deliver environmental, nutritional as well as livelihood benefits in a sustainable way. Increasing the number of trees on farms can provide additional food and income sources, diversify farming systems and therefore enhance the resilience of local communities and their ability to adapt to market or climatic shocks. A promising way to increase supply of and demand for tree-sourced foods is to develop nutrition-sensitive value chains focusing on their dietary and nutritional quality to address malnutrition and to contribute to income generation and poverty reduction (Powell *et al.*, 2015; Vinceti *et al.*, 2013, 2022). The development of value chains for products from a diversity of fruit trees, including indigenous species, can provide more gender-equitable and inclusive income-generating opportunities than if focusing only on typically male-dominated mainstream commodities, such as various monoculture fruit, nut or timber species (Kristjanson *et al.*, 2019). In addition, due recognition of the services that tree species provide to agricultural production, such as soil fertility and shading, can further contribute to an increased popularity of native tree species in agricultural landscape restoration initiatives.

6. Case studies

Despite the constraints outlined in Section 4, a number of scientific advances and technological innovations offer great promise to support and accelerate the mainstreaming of TGR. Below we present 13 case studies that illustrate these opportunities and solutions.

6.1. CASE STUDIES ON HALTING BIODIVERSITY LOSS

Five case studies presented in the annex show how TGR can contribute to halting biodiversity loss. **Case Study 1** addresses the implementation of *in situ* genetic conservation units to ensure that the adaptive and evolutionary potential of a tree species, namely European silver fir *Abies alba,* across its entire range is preserved for future restoration programmes. **Case Study 2** illustrates a combination of measures to preserve and restore an ancient and fragile tree-based ecosystem: shola pockets in the Nilgiri Biosphere Reserve, India. **Case Study 3** compares two active restoration methods and assesses the survival rates in sites exhibiting different degradation states across the dry forest of Antioquia, Colombia. **Case Study 4** examines the fire vulnerability of peatland forest and carbon stocks in Central Kalimantan, Indonesia, the circumstances under which natural recovery is possible and when protection from recurring fires is needed. **Case Study 5** illustrates the use of the DNA metabarcoding method to identify the relationships between tree species and mammals as seed dispersers in Lebanon, which are essential for the long-term viability of tree populations.

Case Study 1

***Conservation of forest genetic resources and strategies for* in situ *preservation: example of the European silver fir* Abies alba**

A European network of protected areas has been established for the *in situ* conservation of the genetic diversity of most tree species, including *Abies alba* Mill., the European silver fir. Natural selection is the key demographic factor in choosing these protected areas, called gene conservation units (GCUs), to ensure the evolution of genetic diversity as the environment changes over time. Gene conservation units are both a natural experiment of climate change adaptation and natural selection and an ideal source of genetic resources for ecological restoration projects. New GCUs for *Abies alba* have recently been added to the French network, as genetic analysis has suggested a previously unrepresented ancestral lineage in the western part of the Pyrenees.

The European silver fir is currently experiencing climate- and insect-related dieback, mostly at its low elevation margins in Central Europe. For this reason, and because of their faster growth in common gardens, related Mediterranean *Abies* species are seen as potential alternatives in restoration projects outside of the species' current range. However, there are significant risks associated with this strategy as their potential for adaptation to new sites and climates is unknown. For example, research results have shown clear trade-offs between growth and drought resistance. As post-dieback regeneration is likely to occur with more adapted and resilient genotypes, we urge managers not to transform *Abies alba* forests by introducing other putatively climate-adapted species, but rather to allow natural selection and eventually collect seeds for *ex situ* storage and conservation. We also recommend that the GCU network should be better embedded in the European biodiversity strategy, that its protection status should be better recognized at national level and that it should be the focus of sustained monitoring efforts. Protection and sustainable management of genetic diversity in the wild should be a priority for biodiversity conservation of all forest tree species.

Case Study 2

Temporal analysis of shola pockets in the Nilgiri Biosphere Reserve to inform species reintroduction in India

Tropical montane forests, called sholas, are ancient evergreen forests occurring as isolated patches in a forest–grassland mosaic. The sholas of the Nilgiri Biosphere Reserve in the Western Ghats in South India play an important role in the hydrology of lowland ecosystems, and their integrity has broader conservation importance. These montane ecosystems have distinct biological communities and high levels of endemism and are severely threatened by human impact, such as conversion of grasslands to exotic monoculture plantations and heavy extraction, likely to be further aggravated by climate change. Restoration of shola–grassland mosaics can help recover lost habitat and ensure the viability of native tree populations, but the present invasive species can prevent the establishment of native vegetation.

In 2014, the Indian Forest Department conducted a campaign to remove many exotic species in the reserve, such as *Acacia mearnsii*, and the sholas have started to reoccupy the canopy gaps. In addition, the findings of this case study in three selected shola forests suggest that these open patches should be fenced, and that native species should be reintroduced. Species able to establish in open landscapes, such as *Syzygium cumini*, can be beneficial in restoration initiatives as many other shola species require shade during their initial stages. Projected changes in rainfall patterns and temperature could endanger intolerant endemic species, due to their narrow genetic base. Restoration of species with small population sizes is a challenge, and introduction from adjacent forest patches could be necessary to increase the genetic diversity of these populations. Being unique, the sholas require a long-term perspective and coordination between different stakeholders. A socioecological landscape management process should be implemented in a participatory manner with Indigenous Peoples' communities interested in protecting their traditional values.

Case Study 3

A comparison of two active restoration interventions in the tropical dry forest of Antioquia in Colombia

It has been shown that small-scale studies can be used to monitor growth and survival rates of different tree species and can help select the most promising species for large-scale planting. In this case study, two active restoration methods in the tropical dry forest of Antioquia, Colombia were compared, one involving plantation-style establishment of more than 20 tree species per plot ("diversity plantation") and a second one using forest islands according to the nucleation methodology, in which as much plant diversity as possible was concentrated, including tree and non-tree species, through active planting, transplanting and seed broadcasting ("diversity nodes"). Survival rates of planted seedlings in the "diversity plantation" plots were dramatically low, largely due to water shortage after planting. Twice as many seedlings survived in areas with intermediary canopy cover compared to bare land, probably due to the nurse function of the resident vegetation. Although the survival rates were low, the number of trees surviving per hectare could still be sufficient to initiate the regeneration process of the tropical dry forest, but the high cost of applying this strategy over large areas is likely to be a limiting factor. Although the net cost per hectare was higher for "diversity nodes", the higher survival rates may make it a more viable restoration strategy. This intervention could be applied on small scales where the expansion of the trees from islands into surrounding land is likely and possible according to the nucleation theory. However, the species to plant should also be chosen well since each species had variable survival rates depending on the degradation of the restoration sites. Our results suggest that there are specialists for the different successional phases, and the right species should be selected according to the conditions of the planting site.

Case Study 4

Species diversity and carbon stock dynamics in restored burnt peatland forest in Central Kalimantan, Indonesia

Since the 1980s, peatlands in Indonesia have continued to experience degradation and decline in forest cover due to various human activities such as land conversion to agriculture and plantation forests. In Central Kalimantan, degradation has further increased with the occurrence of peatland fires, releasing greenhouse gas emissions and reducing biodiversity. This threat also inhibits natural regeneration, which is why rehabilitation and restoration efforts are required to speed up recovery.

This study was conducted in different peatland forest plots in Central Kalimantan with different annual fire regimes to investigate the fire vulnerability of these forests. Burnt areas of peat forest with a single fire event were found to be able to recover naturally if the burnt area was limited and protected from recurring fires. The number of species and their corresponding carbon stocks were found to increase in areas that had burnt only once after 3 years and 8 years, compared to peat forest that burnt every year. The potential for carbon sequestration in peat forests with a single fire event is still very high or exceeds the CO_2 emission factor due to peat drainage. The number of species and amount of carbon stock in burnt peat forest with a single fire event after 3 years and 8 years can be a used as a benchmark for judging the success of burnt peat forest restoration initiatives.

Case Study 5

Seed dispersal as a key element for the sustainability of restored ecosystems in Lebanon

This case study present the results of the study that applied a scat DNA metabarcoding technique to describe the seasonal plant diet composition of mammal species from a highly biodiverse Lebanese forest in the eastern Mediterranean. We recovered all plant seeds found in the scats for identification. In this way, a total of 18 vertebrate species and 133 plant species from 54 different families were analysed. This study supports the dogma of restoration ecology, which is that a variety of native species should be planted in order to promote and preserve rich wildlife. Native plant species identified as commonly consumed by mammals should be considered for reforestation and ecological restoration projects, especially *Rosaceae* and *Fagaceae* trees. Planting these species will help attract wildlife to Lebanese forests and preserve Mediterranean biodiversity. Seed dispersal mediated by frugivores is a crucial process in the regeneration of habitats. A seed disperser guild component should be included in every ecological restoration plan. This case study emphasizes the importance of a holistic approach to biodiversity, in which ecological interactions should be of equal importance when planning forest landscape restoration.

6.2. CASE STUDIES ON TOOLS TO INTEGRATE TREE GENETIC RESOURCES INTO CLIMATE CHANGE-RESILIENT FOREST AND LANDSCAPE RESTORATION

These four case studies showcase critical insights and opportunities for improving the way TGR are integrated into FLR to ensure that the trees and interventions are resilient to climate change. **Case Study 6** demonstrates how long-term provenance trials using Mediterranean pines can provide important insights into the adaptive capacity of various native tree species to climate change, and also to biotic stresses. Such trials provide vital information on which species or provenances are the most promising for restoration and can act as both *ex situ* conservation and seed sources for targeted species. **Case Study 7** illustrates how establishing a seed source certification scheme in Indonesia has been critical to helping ensure high-quality and diverse seed and seedlings for climate-resilient FLR programmes at the national scale. **Case Study 8** and **Case Study 9** illustrate the use of molecular techniques in combination with climate change models to identify genetically diverse tree populations, for example native teak species in India (Case Study 8) and national level genomic inventories of genetic diversity across large numbers of tree species with high potential for climate resilience in Australia (Case Study 9) for application in large-scale conservation and restoration programmes.

Case Study 6

Long-term provenance trials using Mediterranean pines: latest research outcomes and their usefulness in future forest restoration activities in Europe

This case study aims to demonstrate how a long-term provenance trial network across ten countries, established between 1974 and 1985 as part of *Silva Mediterranea* (FAO 4bis project, http://www.fao.org/docrep/006/k1203e/K1203E08.htm) and Interconnecting Forests, Science and People (IUFRO) activities, can provide important insights into the adaptive capacity of native tree species to climate change and biotic stresses. Many of these trials are still in good condition, despite many years of neglect and can provide relevant information on the intraspecific performance of these species. Various studies on Mediterranean pine species have taken advantage of these long-term experiments and created decision-making models for the proper use of genetic diversity in reforestation, ecological restoration and assisted migration activities, thus strengthening these species' chances of survival in the face of climate change. Other studies have focused on extrapolating the adaptive capacity of pine provenances to future climate conditions by measuring existing genetic differentiation between populations and height growth in common garden trials to forecast future performance. The results revealed that Aleppo pine forests that are currently experiencing the most favourable climate conditions in coastal areas of France, Greece and Spain, and northern Africa, may experience growth decline by the end of this century, in contrast to Aleppo pine forests in more arid and continental areas, which are likely to better withstand the effects of future high temperatures.

Case Study 7

Certification of seed sources to support forest and landscape restoration programmes in Indonesia

Indonesia has set ambitious targets to restore 2 million ha of peatland and rehabilitate 12 million ha of degraded land by 2030. Billions of forest tree seeds and seedlings are required to meet the target. A recent study has found a scarcity of quality seed to support FLR programmes in Indonesia.

This case study illustrates how the establishment of a national seed source certification scheme in Indonesia is critical to help ensure high-quality and diverse seed and seedlings for climate-resilient FLR programmes. Currently, the obligation to use seeds from certified seed sources is regulated for 11 groups of forest tree species while for other species, this is not required but highly recommended. Government agencies, state-owned and private companies, farmer groups and individuals are among the owners of certified seed sources. Despite many implementation challenges, the Directorate of Forest Tree Seeds, which is the central authority for managing forest tree seeds, aims to apply the same standards to all available seed sources. In addition, a database was created to monitor the availability of certified tree seed sources throughout the country. Unfortunately, the database is currently paper based, but an online forest tree seed database system is expected to be developed soon to store and share up-to-date information and allow easy monitoring.

Case Study 8

Teak genomic resources and their applications in seed zone delineation in India

In recent years, the timber plantation sector has gained momentum as a means of mitigating climate change effects. Tropical plantations are predicted to be the dominant supplier of wood by 2050. The increased area of plantations is backed by tree improvement programmes adopting advanced technologies to enhance the productivity per unit area in operational plantations. A study was undertaken by the Institute of Forest Genetics and Tree Breeding, Coimbatore and the Kerala Forest Research Institute to develop gene-ecological zonation for natural teak distributed in India. Genome sequencing across 18 Indian populations combined with bioclimatic and topographic information were used to identify three gene-ecological zones with distinct bioclimatic profiles and genetic diversity. Gene-ecological zones are delineated to aid the transfer of seeds for raising plantations. In general, planting should be done in the same zone where the seeds are collected. An understanding of the distribution of adaptive alleles can guide assisted migration to similar climate zones and restoration under future climate change scenarios. Furthermore, the data collected may be used to preserve genetic diversity in breeding populations and protect genetic resources using *in situ* and *ex situ* approaches. This study can serve as the foundation for creating genetic strategies and best practices for timber trees with longer rotation cycles.

Case Study 9

Upscaling genomic studies in support of resilient forest and landscape restoration in Australia

Targeted landscape-genomic studies across multiple species can quickly and cost-effectively guide FLR projects in relation to provenance, maximizing diversity and establishing adaptive resilience. Ambitious multispecies objectives across replicable, standardized workflows that rely on the partitioning of tasks are key to the economy of scale that makes such projects effective. In addition, they can provide well defined "bundles" with clear scientific and practical outcomes that are attractive to funding bodies. A bundle should preferably target co-distributed species, and sampling should be representative of each species' distribution while being reasonably constrained to manage the time and resources involved. Six individuals sampled from up to 30–40 distribution-wide sites usually provide sufficient interpretative data to acquire the necessary knowledge. As an example, Restore & Renew (https://www.restore-and-renew.org.au/) is a large-scale project using distribution-wide landscape genomics and climate modelling to provide restoration practitioners with relevant provenance information. So far, relevant data have been obtained for over 150 species representing all vegetation types in New South Wales and beyond. The new knowledge supports the translocation of threatened species, the establishment of seed production areas, the development of "climate-ready" community restorations and more. Training practitioners in sampling techniques and scientific staff in the streamlining of sequencing and analytical interpretations is very effective once the right workflows are established. Costs involved will vary from country to country, as will the right ratio of staff numbers to project size for achieving economy of scale. Once the right balance is identified, however, costing becomes unambiguous in relation to the finalization of practical outcomes and consequently more attractive to funding agencies, interested investors and benefactors.

6.3. CASE STUDIES ON REDESIGNING SUSTAINABLE FOOD SYSTEMS AND EQUITABLE LIVELIHOODS

The final four case studies highlight critical ways in which TGR can be central to transitioning to more sustainable food systems. **Case Study 10** provides scientific evidence of how species richness and genetic diversity improve the productivity as well as the resilience of restored forests in China. **Case Study 11** focuses on selecting locally adapted food trees to improve the year-round availability of edible products and diet diversity for rural populations in Burkina Faso. **Case Study 12** highlights the combined impact of tree planting, natural resource management and entrepreneurship on forest degradation and poverty in the Philippines. **Case Study 13** illustrates how highly productive and drought-tolerant varieties of tree species in Ethiopia and Kenya can be identified through provenance and progeny trials to ensure the selection of suitable and high-quality seeds for FLR at the national level.

Case Study 10

The role of species richness and genetic diversity in improving the productivity and resilience of restored forests in subtropical China

In China, monoculture plantations of species with high productivity and fast growth are on the rise, playing a significant role in forest and landscape restoration in the short term. This case study focuses on recent studies conducted as part of the "biodiversity–ecosystem functioning experiment in China" (BEF-China). This was carried out in a highly diverse subtropical forest in southeast China and was characterized by a high species-richness gradient among plots, multiple simulated extinction scenarios, high replication and extended duration (2009 to the present). Its aim was to better understand the effects of changing tree species richness on forest ecosystems. The studies provide strong evidence for the importance of tree species richness on stand-level forest productivity and its relevance for restoring subtropical forest ecosystems. The findings suggest that similar or potentially even higher productivity and carbon storage capacities can be achieved with mixed plantations of native tree species, bringing co-benefits in terms of biodiversity conservation and management in future FLR programmes. Intraspecific genetic diversity may also contribute to stand productivity as it may influence functional trait variation and stand-level forest characteristics. The productivity and stability of forest ecosystems depend on species richness, genetic diversity and tree functional diversity, which could enhance the adaptation potential and resilience of forest ecosystems. Species richness and genetic diversity are therefore both important considerations in FLR practice.

Case Study 11
Promoting food tree species in forest and landscape restoration in Burkina Faso

This case study focused on the contribution that different food tree products can make to improving the diversity of otherwise mostly monotonous staple-based diets prevalent in Burkina Faso. A scoring system was developed, based on seasonal availability of edible products and the food groups covered, and was integrated into a freely available decision-making tool, which helps make optimal, context-specific choices of tree species to be considered in forest and landscape restoration. The inventory included 56 food tree species, belonging largely to the Fabaceae family (18 species), providing 81 edible products, mainly fruits (supplied by 79 percent of tree species), followed by seeds (52 percent) and leaves (41 percent). The main food groups represented were "other fruits" (other than vitamin A-rich fruits), covering 52 percent of the edible products, and dark-green leafy vegetables (29 percent). About two-thirds of the species listed produce more than one single edible product, with a few producing up to four. A total of 11 species supplied edible products throughout the year. The results clearly show that seasonal scarcity of food and nutrients in Burkina Faso can be partly mitigated by consuming edible tree products. The methodology can be easily scaled to other geographies.

Case Study 12
Ecotourism and agroforestry as strategies for forest and landscape restoration coupled with conservation of forest genetic resources in the Philippines

This case study describes the transformation of the Binahon Agroforestry Farm (BAFF) from simple farm to complex agroforestry resource centre. The BAFF is located in the Manupali watershed in the south of the Philippines, which provides water for 21 000 ha of farmland. The farm has developed different models of sustainable upland agriculture and water management, produces a variety of seedlings of tree and crop species, and organizes integrated capacity-building activities with local non-governmental organizations (NGOs) and governmental institutions. The BAFF is a successful example of how integrating natural resource management and entrepreneurship can help address the dual problem of forest degradation and poverty in this part of the Manupali watershed. Through a programme of agroforestry farming coupled with ecotourism, its owners have built a knowledge resource centre on diverse, climate-resilient and sustainable upland farming systems, which is also a tourist attraction.

Case Study 13

Provenance and progeny trials of indigenous and naturalized tree species in Kenya

Research on tree genetic resources and improvement in Kenya has mainly focused on commercial timber species such as exotic eucalypts, pines and cypresses. Recently, there has been an upshift of research attention to indigenous and naturalized tree species with potential for diverse and multipurpose local use, but the number of studies is still limited.

Two sets of provenance and progeny trials of indigenous and naturalized multipurpose tree species were used to assess and select specific traits of interest such as high productivity and drought tolerance. One study focuses on the establishment of seed orchards and progeny trials of *Melia volkensii* in Kenya and the other one on *Moringa oleifera* and *Moringa stenopetala* provenance and progeny trials, also in Kenya. The trials in both examples can be converted into seed production orchards after selective thinning, and they are therefore crucial not only for identifying the genetic component of observed phenotypic differences but also for providing suitable germplasms for FLR. The selection of the species to restore is key to balancing biodiversity conservation and the socioeconomic and cultural needs of the local communities.

7. Summary of case study findings

The findings of the 13 case studies on contributing and accelerating the mainstreaming of TGR in FLR fall within three thematic key areas and can be summarized as follows:

7.1. CONSERVING TREE GENETIC RESOURCES

- Developing and implementing genetic *in situ* conservation units across tree species ranges is an efficient strategy for ensuring that adaptive and evolutionary potential is preserved and available over generations.
- Long-term common garden trials such as provenance tests can provide valuable information on the adaptive capacity of tree species to respond to climate change and to specific pests and diseases, as well as on their threatened status.
- A combination of conservation measures such as removing invasive species, providing fencing and planting tree seedlings may be needed to allow native tree species to reoccupy their former habitats.
- Peat forests need to be actively protected from recurring fires to avoid a drastic decline in tree species numbers and carbon stocks.

7.2. ENSURING DIVERSE, HIGH-QUALITY PLANTING MATERIAL

- Establishing a national tree seed certification system that covers seed sources, and seed and seedling quality, is an important measure for ensuring the supply of high-quality planting material in FLR.
- Indigenous and scientific knowledge is essential in sourcing and selecting quality germplasm with desirable traits for restoration.
- Selecting tree species for restoration should be done in close consultation with local communities, taking into account local cultural preferences and availability of planting material.
- Gene-ecological zonation or seed transfer zones based on genetic variation or on environmental distances, as surrogate data in the absence of genetic data, are valuable methods for optimizing the quality of seeds collected for reforestation, tree improvement and conservation purposes.
- Digital tools may facilitate the aggregation of useful data about characteristics and uses of locally suitable native tree species, based on

different sources of information, including local knowledge, enabling better informed selection of tree species in FLR projects.

- Targeted landscape-genomic studies across multiple species can contribute to meeting specific goals such as improving the selection of site-adapted planting material and maximizing genetic diversity to establish climate resilience in restored tree populations in a cost-effective way.
- Provenance and progeny trials are essential tools for the selection of varieties of multipurpose tree species that are highly productive or drought-tolerant or both.

7.3. BENEFITS OF INCREASING THE USE OF TREE GENETIC RESOURCES IN FOREST AND LANDSCAPE RESTORATION

- Having a high number of native, genetically diverse tree species in mixed plantations may have strong positive effects on wildlife, forest stability, productivity and carbon storage capacity.
- An analysis of the guild component of tree seed dispersers should be included in ecological restoration since frugivore-mediated seed dispersal is a critical process in the life cycle dynamics and regeneration of various vegetation types.
- Forest restoration should tackle the need for multiple plants, animals and microorganisms and the ecological roles that they perform with equal importance, if long-term stability is to be guaranteed.
- High-diversity planting of tree and non-tree species in forest islands results in much higher survival rates compared to other active restoration methods, regardless of the site's initial state of degradation.
- Concentrating FLR efforts on multipurpose trees would harness the provision of different critical goods such as food, medicine, fodder, shade and income for a substantial proportion of rural households. The inclusion of native tree species with multiple uses should therefore be increased significantly above current levels.
- Among the many objectives of FLR, addressing nutritional needs of rural communities could be facilitated by increasing the representation of tree species that provide edible products in FLR initiatives, and designing optimal portfolios of species that supply year-round availability of edible products with different nutritional profiles, which could contribute to diversifying the local diets of rural populations.
- By combining tree planting, natural resource management and public–private partnerships, it may be possible to address the problems of forest degradation and poverty through the creation of coherent and diverse agroforestry systems coupled with ecotourism as sources of income.

8. Guidelines for improved integration of tree genetic resources in forest and landscape restoration

We divided the FLR stakeholders into different groups, based on the key roles that we think each of them should play in increasing the integration of TGR in FLR: (i) countries and national policymakers, and NGOs should develop the necessary enabling environment through conservation strategies, seed zone maps and seed quality control, for example; (ii) donors should recognize, support and reward best practices; (iii) international organizations and regional networks should contribute to reducing knowledge gaps, creating evidence-based policies and fostering the exchange of information and sharing of experiences, including through capacity development; and (iv) restoration practitioners should source quality seed and work with suppliers who follow good collection practices, meaning those that increase seed genetic diversity.

The following selection of key recommendations draws on the findings of our literature review and the case studies presented. They aim to help identified stakeholders promote successful and resilient implementation of FLR activities and thus contribute to the achievement of forest-related SDGs. These recommendations are also directly related to the 23 targets of the recent Kunming-Montreal Global Diversity Framework of the Convention on Biological Diversity (CBD) Conference of the Parties (COP) 15 (CBD, 2022).

8.1. GUIDELINES FOR COUNTRIES AND NATIONAL POLICYMAKERS

1. Implement range-wide conservation strategies to ensure persistence of large native tree populations and vulnerable populations as seed sources for restoration.
2. Support gender-responsive and inclusive restoration interventions that consider a high number of native, genetically diverse tree species in mixed plantations meeting the priorities of diverse users.
3. Restore habitat and landscape connectivity and identify and protect evolutionary refugia.
4. Establish and enhance national systems of tree seed certification to ensure the supply of high-quality, genetically diverse planting material.

5. Support the development of local businesses and local women's and men's capacities in the production of quality seed and the marketing of planting material.
6. Develop policies that specifically protect and encourage sustainable use of multipurpose trees as important sources of food, medicine, fodder, shade and income for rural households, especially for women and socioeconomically marginalized groups, including in production landscapes.
7. Empower rule of law as well as gender equity and social inclusion principles in all steps of FLR decision-making, policymaking and project funding.
8. Support the implementation of long-term provenance trials and other relevant common gardens as a key source of information on the adaptive capacity of tree species.

8.2. GUIDELINES FOR DONORS

1. Provide funding to support range-wide conservation strategies to protect large native tree populations and vulnerable populations as seed sources for restoration within and outside protected areas.
2. Consider and reward best practices in seed sourcing that promote the use of high-quality, genetically diverse seed and consider climate change and site matching.
3. Provide funds that support the development of local businesses and local women's and men's capacities in production of high-quality, genetically diverse seed, propagation (nurseries), and marketing and sale of planting stock.
4. Provide funds to support countries to establish national systems of tree seed certification to ensure the supply of high-quality, genetically diverse planting material.
5. Set rules on seed quality and sourcing, and on the number of tree species used in all project calls.
6. Provide funds to promote food and multipurpose trees as important sources of food, medicine, fodder, shade and income for rural households, and particularly for women and socioeconomically marginalized groups.
7. Consider and reward restoration projects that select tree species in close consultation with local women and men, taking into account local cultural preferences and availability of planting material.

8.3. GUIDELINES FOR INTERNATIONAL ORGANIZATIONS AND REGIONAL NETWORKS

1. Promote the implementation of range-wide strategies to protect large native tree populations and vulnerable tree populations as seed sources for restoration.
2. Recommend that forest restoration should address the need for a variety of plants, animals and microorganisms and the ecological roles that they perform.
3. Support the generation and exchange of knowledge among stakeholders, including rural associations and civil society organizations, about the most appropriate choice of species, seed sources and provenances for trees intended to be used in FLR.
4. Translate complex scientific data into tangible evidence-based policies and recommendations for member countries and related stakeholders.
5. Promote restoration interventions that consider a high number of native, genetically diverse tree species in mixed plantations.
6. Promote the use of multipurpose trees as important sources of food, medicine, fodder, shade and income for rural households, and particularly for women and socioeconomically marginalized groups.
7. Recommend tree species for selection in FLR in close consultation with local women and men, taking into account local cultural preferences and availability of planting material.
8. Encourage the implementation of long-term provenance trials that will provide valuable information on the adaptive capacity of tree species to climate change and abiotic stresses.

8.4. GUIDELINES FOR RESTORATION PRACTITIONERS

1. Ensure that planting material derives from many widely spaced trees – more than 50 reproductive trees per species – from at least one and, preferably several, large and viable populations.
2. Ensure planting material derives from environmental conditions that reflect current as well as projected future climatic conditions at the restoration site.
3. Ensure to collaborate with suppliers who follow best seed collection practices that are transparent and include proper management of metadata associated with those collections.
4. Consider a high number of native tree species from different seed sources in the selection of the reproductive material.
5. Consider increasing the use of food tree species in nutrition-related restoration interventions.
6. Ensure that project funding is used to strengthen existing supply

chains.

7. Promote gender equity and social inclusion principles in all steps of FLR decision-making, implementation and monitoring.
8. Set aside enough time and resources for sourcing quality seed in project workplans.

9. Conclusion

To address the global triple crisis of biodiversity loss, climate change and failing food systems, the systematic integration of TGR in FLR projects is crucial. Particular attention should be paid to massively scaling up the supply of genetically diverse and high-quality tree seed and forest reproductive material in all types of tree planting activities, from enrichment planting of degraded forests to increasing tree cover in cropping systems, and agroforestry or silvopastoral systems. An integrated approach to environmental and socioeconomic aspects is needed because these aspects are deeply interdependent and sometimes conflicting (e.g. biodiversity conservation versus production, and carbon sequestration versus production). The SDGs provide a compass and an example of an integrated framework, but delivery is falling short of the targets set in 2015, and the triple crisis requires us to look beyond the 2030 deadline (Baldwin-Cantello *et al.*, 2020).

The objectives of this paper were threefold: (i) emphasize how TGR can be mainstreamed into FLR to achieve the SDGs; (ii) highlight new trends and issues in TGR delivery to FLR based on the 13 case studies; and (iii) identify current bottlenecks impeding the deployment of TGR in FLR and emerging opportunities. Fundamental to mainstreaming of TGR is ensuring their adequate conservation and availability for provisioning scalable seed systems and forest reproductive material to restoration practitioners. This involves a diverse and broad group of stakeholders, including smallholder farmers as well as NGOs and private sector companies.

In adopting the Kunming-Montreal Global Biodiversity Framework in 2022 at the COP 15, countries have clearly committed to setting targets to conserve genetic resources. Under long-term Goal A, the framework sets the global ambition for 2050 that "the genetic diversity within populations of wild and domesticated species, is maintained, safeguarding their adaptive potential." Achieving this goal will require effective documentation and monitoring of the adaptive potential of thousands of tree species. The case studies outlined here offer critical tools. Tree genetic resources are not only critical for maintaining resilience of ecosystems to climate change through their adaptive potential but can also provide key options for social adaptation, which many rural and poor communities require. For example, nature positive solutions that deliver multiple ecosystem services, such as agroforestry, can mitigate drought and extreme rainfall events while diversifying livelihood options for communities who will be better prepared to manage climate extremes. Finally, it is clear that global food systems require a major transition to mitigate their impact on land degradation, biodiversity loss and greenhouse gas emissions. Trees and TGR play a crucial role in achieving low-carbon production systems that prioritize nutritious food and are therefore central to addressing the triple crisis.

We highlight the following **eight key recommendations** that can ensure effective mainstreaming of TGR in FLR to produce the global and local restoration outcomes that are needed to achieve biodiversity, climate, food and livelihood objectives.

9.1. BIODIVERSITY LOSS

1. There is an urgent need for regional range-wide conservation strategies to ensure persistence of large native tree populations and vulnerable tree populations as seed sources for restoration, with a focus on high-value, nutritious and underutilized tree species for multiple uses.
2. Restoration planning should incorporate spatially explicit priority setting to account for landscape connectivity, climate change and species ecology in order to identify and protect evolutionary refugia of native trees.
3. Ensure that local FLR interventions adequately meet the needs of both men and women locally to avoid continued degradation of remaining forests and recently restored areas.

9.2. CLIMATE CHANGE MITIGATION

1. Establish and enhance national and regional tree seed systems including certification, monitoring and verification of seed quality and diversity (with advanced genomic tools) to ensure that adequate volumes of the appropriate TGR are available, adaptive to climate change and resilient to other shocks.
2. Support the development of local businesses and local women's and men's capacities to engage in the provision of diverse native trees and developing green economies, value chains and incentive schemes that ensure long-term persistence of trees and carbon stocks within farming landscapes.
3. Provide alternatives to fuelwood that bring about systemic change in preferences for tree use, leading to reduced reliance on short-cycle growth and increased production of non-timber forest products.

9.3. SUSTAINABLE LIVELIHOODS AND FOOD SYSTEMS

1. Provide incentives and build capacity of smallholder farmers to specifically protect and encourage sustainable use of multipurpose

trees as important sources of food, medicine, fodder, shade and income for rural households, especially for women and socioeconomically marginalized groups, including in production landscapes.

2. Raise awareness among farmers and increase their capacity to select tree species for FLR based on full knowledge of their nutritional value and also taking into account cultural preferences of women and men locally, and the availability and ecological suitability of planting material.

10. References

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CASE STUDIES

CASE STUDY 1

Conservation of forest genetic resources and strategies for *in situ* preservation: example of the European silver fir *Abies alba*

Bruno Fady,[1] François Lefèvre[1] and Caroline Scotti-Saintagne[1]
[1] INRAE, Ecology of Mediterranean Forests, URFM, Avignon, France
Bruno Fady (bruno.fady@inrae.fr), http://orcid.org/0000-0003-2379-7617
François Lefèvre (francois.lefevre.2@inrae.fr), https://orcid.org/0000-0003-2242-7251
Caroline Scotti-Saintagne (caroline.scotti-saintagne@inrae.fr), https://orcid.org/0000-0001-6891-7315

Colonization of formerly grazed landscapes from an *Abies alba* genetic conservation unit, at the species southern margins in the southern French Alps

BACKGROUND

In traditional biodiversity conservation and ecological restoration programmes, the focus is placed on landscapes and species, rarely on populations within species and their genetic diversity (Thomas *et al.*, 2014). Yet, locally, the ability of species and communities to evolve and adapt when environmental changes occur in different habitats, depends greatly on the size and genetic diversity of their populations. Thus, within-species diversity matters for the success of conservation and ecological restoration. Only when genetic diversity is sufficiently high, will populations and ultimately species resist environmental changes that are bound to happen, by adapting to new constraints through natural selection (Reusch *et al.*, 2005). Protecting the processes that shape genetic diversity and create adaptation, such as gene flow and natural selection, is thus a valid biodiversity conservation endeavour (Jump, Marchant and Peñuelas, 2009). For populations facing high demographic or genetic risk, specific actions may be considered such as population reinforcement, translocation (Seddon *et al.*, 2014) or assisted gene flow (Grummer *et al.*, 2022).

Abies alba Mill., the European silver fir, is widely but patchily distributed in the mountains of southern Europe and at lower elevations in central Europe. It is rarely found in northern Europe, the British Isles or Scandinavia (Wolf, 2003). As it is somewhat tolerant to warm conditions, but not to drought, *Abies alba* is increasingly seen as a candidate species for diversification in several countries in central and northern Europe where the search for new or seldom used genetic material has become desirable in the face of the worsening impacts of climate change on local forest tree species and communities. In countries where *Abies alba* is present and shows climate- and insect-related dieback, mostly at its low-elevation and southern margins in the mountains of Europe, phylogenetically related Mediterranean *Abies* species are increasingly seen as suitable replacement species.

Several risks are associated with such assisted gene flow or replacement strategies for *Abies alba*. Evidence from common gardens has shown that some southern provenances show higher growth rates, making them potentially predominant targets of seed and seedling commerce for restoration and plantations outside of their current distribution areas even though their overall adaptive potential to new climates is not known. For example, research results show a trade-off between growth and drought resistance (Csilléry, Buchmann and Fady, 2020). In its home range, the benefits of hybridization of European silver fir with Mediterranean firs are largely unknown and could thus equally turn out to be a curse or a blessing. And although sensitivity to recurring summer droughts regularly leads to dieback, regeneration is often impressive after dieback events.

APPROACH PRESENTED

While composite provenancing or other no-regret strategies can protect climate-smart restoration projects that would be interested in using *Abies alba* as a resource outside of its range, against the risk of using reduced diversity material, together with high-density planting to encourage natural selection and increase adaptation efficiency (Bucharova *et al.*, 2019), the strategy for conservation and restoration of the species at its home range margins should be quite different.

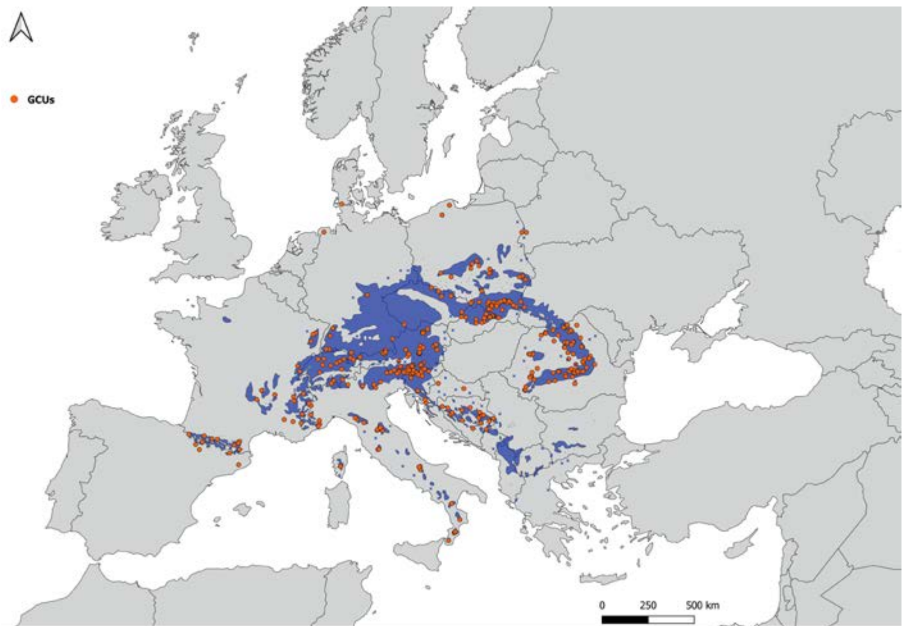
In Europe, as part of the EUFORGEN strategy, networks of protected areas aim to promote *in situ* conservation of the genetic diversity of most European forest tree species, including *Abies alba* (Figure 1). These protected areas, called gene conservation units (GCUs), are representative of the genetic lineages that exist within each species. They contain the original genetic diversity for a given region following historical diversifying selection and are managed under guidelines that (1) mostly prevent the introduction of exotic material that might hybridize with the local resources and (2) aim to facilitate ample and diverse natural regeneration from many seed trees. The aim of these guidelines is thus to promote forest management for genetic diversity, where natural selection is the major demographic player, thereby ensuring evolution of genetic diversity of each GCU with environmental changes over time (Koskela *et al.*, 2013; Lefèvre *et al.*, 2013).

The European GCU network is described in the information system EUFGIS (http://portal.eufgis.org/). The activities of EUFORGEN, which manages EUFGIS, are financed by countries of the FOREST EUROPE process. In countries such as France, GCUs are recognized as protected areas by decree of the Ministry of Forests and are listed and described in a national register, which is updated as needed. For example, recent genetic analyses have suggested that the Pyrenees are home to two major ancestral genetic lineages (Scotti-Saintagne *et al.*, 2021), and GCUs were added to the French network to include the previously unrepresented western part of the Pyrenees. There is a large body of scientific knowledge on *Abies alba*. However, when knowledge is lacking, ecological and bioclimatic proxies can be used to delineate areas where GCUs would be needed, under the assumption that local adaptation is rather marked in forest tree species (de Vries *et al.*, 2015, xii, 3).

CONCLUSIONS AND RECOMMENDATIONS

The European GCU network evolves by becoming simpler or more complex depending on scientific progress. These protected areas conserve adaptive processes that are usually not the focus of conservation, restoration or traditional forestry plantations. Their management does not prohibit silviculture but still makes hybridization with exotic material virtually impossible. Gene conservation units are thus both a natural experiment of the potential of climate change adaptation that relies on local genetic diversity and natural selection, and a source of diversified genetic resources for ecological restoration projects. Genetic conservation units at low elevations or at the southern margins of distribution areas currently experience spectacular dieback in some cases. As regeneration often occurs after these events, theoretically with new, better adapted and more resilient genotypes, we urge managers to avoid transforming these forests by introducing supposedly climate-adapted species, but instead to let natural selection take its course and eventually collect seeds for *ex situ* storage and conservation. We also recommend that the network of GCUs be better integrated within the biodiversity strategy of European countries, that their protection status be better recognized nationally and that they should be the focus of sustained monitoring efforts. Protecting and sustainably managing genetic diversity in the wild should be a biodiversity conservation priority for all forest tree species and constitute a sound adaptive solution in the era of uncertain future climates (Hoban *et al.*, 2021).

Figure 1. Map of the geographic distribution range (blue) and the 268 *Abies alba* gene conservation units (red dots) listed in the EUFGIS database



Note: Geographic range coverage is excellent while some marginal environments may still be lacking. *Source*: EUFORGEN, https://www.euforgen.org/species/abies-alba/ (last accessed 6 December 2023) graciously provided by E. Esposito (EFIMED).

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CASE STUDY 2

Temporal analysis of shola pockets in the Nilgiri Biosphere Reserve to inform species reintroduction in India

Rekha R. Warrier,[1*] S. Jeevith,[2] C. Kunhikannan[1] and N. Krishnakumar[3]
[1] ICFRE-Institute of Forest Genetics and Tree Breeding, Coimbatore, India
[2] Research biologist
[3] Former Principal Chief Conservator of Forests and Head of the Department, Tamil Nadu Forest Department, now Chairperson, State Environment Impact Assessment Authority, Tamil Nadu
* Corresponding author

BACKGROUND

Tropical montane forests called sholas are compact, closed-canopy, evergreen forests occurring as isolated patches at more than 1 800 metres. These montane ecosystems of the Nilgiri Biosphere Reserve (NBR) play an important role in the hydrology of lowland ecosystems, and their integrity has broader conservation implications (Sasmitha, Iqshanullah and Arunachalam, 2021). Due to their complex topography and a biogeographic history featuring regular altitudinal migrations of vegetation zones in response to climate change, the montane ecosystems in NBR have distinct biological communities and high levels of endemism. Human impact on the natural vegetation, such as conversion of grasslands to monoculture plantations, heavy extraction from sholas and encroachments interfere with natural succession, which is likely to be further aggravated by climate change (Arasumani *et al.*, 2019).

Our study area included three selected shola forests in the NBR (Table 1): chainlinked fenced enclosures at Kariamund shola (KMS), non-chained enclosures at Glenmorgan shola (GMS) and a reference site – a well stocked natural ecosystem – at Carritt shola (CAS) (see map on page 57).

Table 1. Coordinates and altitude of shola study sites

Study site	Category	Location		Altitude (m)
Kariamund shola (KMS)	Chainlinked	11°26.651′ N	76°37.248′ E	2 195
Glenmorgan shola (GMS)	Degraded	11°29.520′ N	76°32.726′ E	2 105
Carritt shola (CAS)	Reference	11°25.563′ N	76°32.248′ E	2 286

In the process of preserving the fragile shola–grassland mosaic, the Forest Department implemented chainlink fencing and gap filling within the sholas under the Hill Area Development Programme (HADP). About 300 hectares were fenced between 1985 and 1990. The vegetation was analysed for two decades using field observations. Climate data for the study area were also collected over a 25-year period (1992–2018).

OBJECTIVE

Here we attempt to understand the changes in tree diversity, species richness and landscape composition that have occurred in the last 25 years. We specifically examine the following questions:

1. Has chainlink fencing differentially impacted the sholas?
2. What is the extent of diversity enhancement observed? Have any endemic species re-established?

Any change in this period must have resulted from natural events alone since no major planting activities took place during this time (1992–2018).

KEY RESULTS

Fifty-six common tree species were observed across the three sholas. In KMS, 39 percent of species were endemic, compared to 29 percent in GMS and 32 percent in CAS. Of the 337 tree species identified in the three study sites, 108 species were endemic; of these, 21 were endemic to the Western Ghats, 68 were endemic to the southern Western Ghats and 15 to Peninsular India.

Figure 1. Relative density of three commonly occurring species in the three study sites in 2018

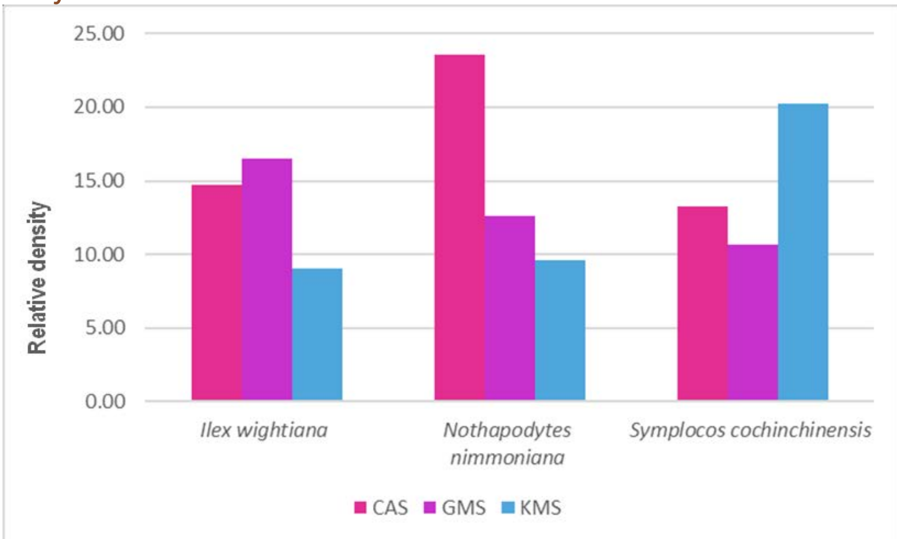
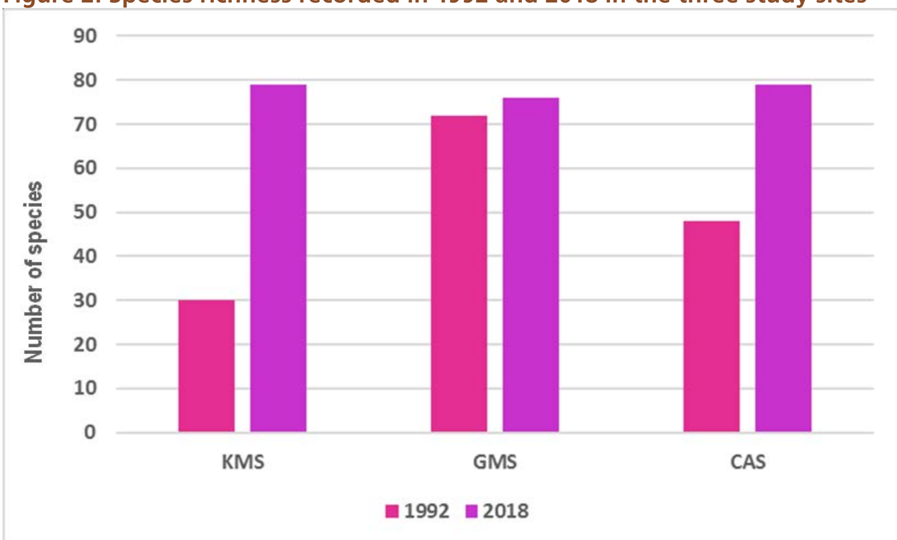


Figure 2. Species richness recorded in 1992 and 2018 in the three study sites



A total of 1 154 individuals were recorded as regenerants (producing seedlings) in all three sites. The highest contributions were by *Symplocos cochinchinensis* (110), *Nothapodytes nimmoniana* (109) and *Ilex wightiana* (106) (Figure 1). Endemic species *Vaccinium leschenaultii*, *Syzygium calophyllifolium* and *Mahonia leschenaultii* also showed good stocking. Exotic species such as eucalyptus, *Acacia mearnsii*, cinchona and pine, and shrubs such as *Lantana* *camara*, *Parthenium* and *Cestrum aurantiacum* are fast growing: they easily compete with native plant species by invading the forest–grassland ecosystem. Further, gaps caused by the removal of trees pave way for easy invasion. Chainlink fencing has prevented easy entry of exotic species into the sholas, protecting the trees against subsequent invasion of exotics. A comparison of the invasion by exotics reveals 36 percent of *A. mearnsii* in GMS compared to low percentages in KMS (20 percent) and CAS (4 percent). The diversity of tree species increased by 163.3 percent in KMS, 5.6 percent in GMS and 64.5 percent in CAS, indicating the possibility of recovery of shola vegetation when protected through chainlink fencing (Figure 2).

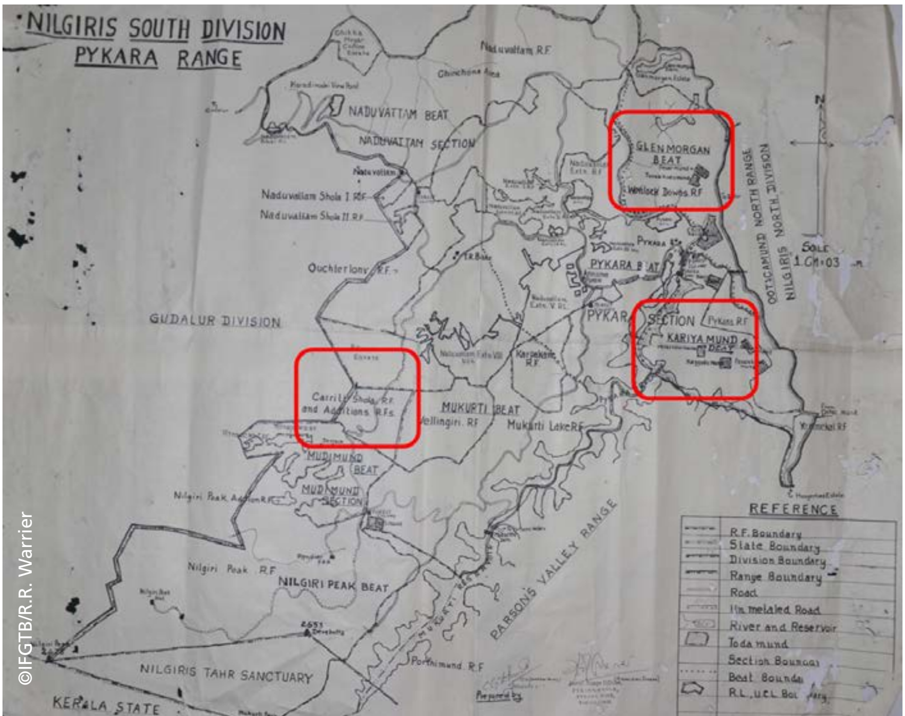
The phenophases of flowering, fruiting and leaf fall and the vegetative phase recorded in relation to seasonal rainfall and temperature at the community level revealed two peaks; the first coinciding with the southwest monsoon (July to September) and the second coinciding with the northeast monsoon (October to November). Climatic factors were observed to affect the flowering and fruiting phenology of the species studied. *Ilex denticulata*, *Myrsine wightiana*, *Phoebe lanceolata* and *Schefflera racemosa* did not show any reproductive phase throughout the period of study. These species may have to be monitored and if need be, introduced from other shola patches so that the different stages of succession prevail in the sholas. For species that showed alternating flowering and fruiting phases, reintroductions can be carried out to increase the number of individuals.

CONCLUSIONS AND RECOMMENDATIONS

The shola–grasslands are ancient ecosystems, naturally biphasic and maintained by climate (Joshi *et al.*, 2018). Expansion of exotic plantations and invasion of weeds were the main reasons given for the landscape change. Efforts to restore the shola–grassland mosaic will help in recovering the lost habitat and ensuring the viability of populations of indigenous and endemic species (Arasumani, Bunyan and Robin, 2020). With the intervention of the judiciary, in 2014, the Forest Department removed large patches of many of the invaders such as *A. mearnsii*, and the sholas have started to occupy the canopy gaps, leading to restocking of past vegetation. Once established, exotics prevent the establishment of native species (Najar, Puyravaud and Davidar, 2019). Hence the suggestion that the open patches could be fenced, and shola species could be reintroduced. Species such as *Syzygium cumini* could be beneficial for the restoration of shola patches due to their ability to establish in open landscapes, where most shola species are shade demanding during their initial stages. Early successional species – *Berberis tinctoria*, *Daphniphylum neilgherrense*, *Syzygium densiflorum*, *Rhododendron arboreum*, *Syzygium calophyllifolium* and *Viburnum erubescens* (Mohandass *et al.*, 2016) – could be introduced from adjacent patches to increase genetic diversity of a particular population within the locality.

Statistical data on climate variability for the study area revealed that rainfall patterns show a tendency towards rainfall reduction during the southwest monsoon and rainfall increase towards the northeast monsoon. Such changes could result in changes in the phenophases (Tabassum, Somashekar and Ahmed, 2019). These changes could also cause a shift and altering of fruiting and flowering patterns of the shola species. A corresponding change in overall temperatures could endanger intolerant endemics, due to their narrow genotype range. Restoration of species with smaller population sizes could be a major challenge in the restoration of this ecosystem.

Being unique, the sholas require plans with a long-term perspective and coordination between different stakeholders. A socioecological landscape management process could be established in a participatory manner with Indigenous communities interested in protecting their traditional values, like the Todas (Cordero *et al.*, 2018).



Map of the selected shola forests in the Nilgiri Biosphere Reserve

A tropical montane ecosystem with sholas, grassland and adjoining stream

Chainlink fencing along the shola boundary with adjoining grassland and eucalyptus plantation

Chainlink fencing along the shola boundary with adjoining grassland at Kariamund shola

Degraded shola at Glenmorgan with invasion of exotics

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CASE STUDY 3

A comparison of two active restoration interventions in the tropical dry forest of Antioquia in Colombia

Jakob Aping,[1] Luis Gonzalo Moscoso Higuita[2] and Evert Thomas[3]
[1] Hamburg University, Faculty of Mathematics, Informatics and Natural Sciences, Germany
[2] Forestpa SAS, Medellin, Colombia
[3] Bioversity International, Lima, Peru

BACKGROUND

Tree plantations can be a successful way of kick-starting forest restoration, but due to their cost, it is important to establish small-scale experimental designs before implementing large-scale restoration (Zahawi and Holl, 2009; Brancalion *et al.*, 2012; Holl, 2017). Small-scale studies can be used to monitor growth and survival rates of different trees and help select the most promising species for large-scale planting (Park *et al.*, 2010). An alternative and potentially more cost-effective approach for recovering large areas of degraded land is applied nucleation (Corbin and Holl, 2012), which is based on the nucleation theory (Yarranton and Morrison, 1974), where patches of pioneer species naturally enhance seed dispersal and successional processes by improving the establishment conditions for late-successional species (Zahawi *et al.*, 2013). Based on this naturally occurring phenomenon, it has been proposed to plant trees concentrated in patches or islands as an alternative to large-scale plantations to increase diversity and reduce costs because fewer trees are planted (Zahawi and Augspurger, 2006; Benayas, Bullock and Newton, 2008). These hotspots of floristic diversity are effective for restoring large areas at low cost (Zahawi *et al.*, 2013). In a tropical dry forest area in Antioquia, Colombia, a long-term, small-scale field experiment was established to determine and compare the effectiveness of different restoration interventions. The long-term objective was to devise strategies to compensate for forest loss associated with the operationalization of a hydroelectric power plant in Ituango.

APPROACHES TESTED

As part of this experiment, we applied two active restoration methods: one involving plantation-style establishment of more than 20 tree species per plot ("diversity plantation") and a second one involving forest islands, according to the nucleation methodology, in which as much plant diversity as possible was concentrated, including tree and non-tree growth farms through active planting, transplanting and seed broadcasting ("diversity nodes"). To assess the performance of both methods under different degrees of land degradation, we installed experimental plots both in high and intermediate degradation areas where the existing canopy cover was less than 5 percent or in the 5–20 percent range, respectively. Depending on the existing canopy cover, we planted different quantities of seedlings per hectare. The higher the degradation, the more seedlings were planted to anticipate higher mortality (2 000 and 4 000 seedlings per hectare for canopy cover in the range of 5–20 percent and less than 5 percent, respectively).

A temporary nursery was set up in 2017 in which more than 50 000 seedlings of more than 30 species were produced. For the plant material produced in the nursery, seeds were harvested in the zone to be flooded by the hydroelectric plant and partly from other tropical dry forests of the country with similar environmental conditions. For the establishment of the seedlings in the field, it was necessary to transport the plant material from the nursery to the plot sites, partly by truck and partly on the backs of mules. Planting holes were dug out to a depth of 40 centimetres (cm) with an approximate diameter of 30 cm. In each planting hole, a mix of 5 grams (g) of Terracotem® (a water-retaining soil conditioner containing macro- and micronutrients) and 1 kilogram (kg) of organic fertilizer was applied. In the diversity plantation, species were selected randomly by the workers and then planted in the prepared holes. For the establishment of the diversity nodes, stem and leaf cuttings, stakes, wildlings, seeds and soil seed bank from the nearby area were collected. Among the species propagated by cuttings were *Opuntia* cacti, which have an arborescent life form reaching 5 metres (m) in size, and fique (*Furcrae andina*), a species traditionally used for fibre extraction, which also has an important nurse function for other species to establish. *Opuntia* cacti and fiques were arranged in 0.20 m wide and 0.20 m deep furrows and fertilized with the Terracotem® soil conditioner and composted organic fertilizer.

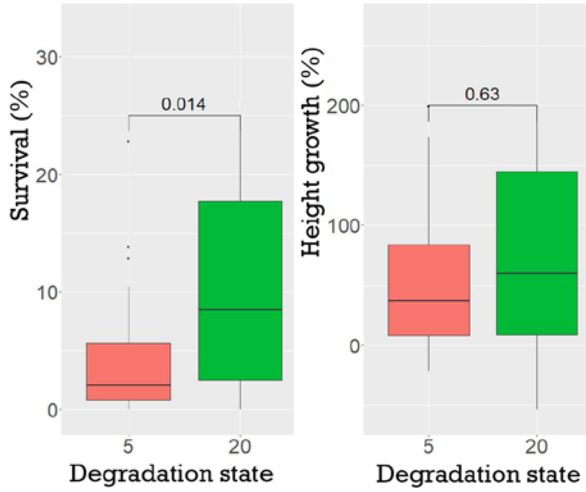
Figure 1 shows the survival rates within the diversity plantation plots according to degradation states. Mortality rates were very high, with only 3.9 percent and 8.9 percent of planted seedlings surviving on average 1.5 years after planting in the plots with high and intermediate degradation, respectively ($p=0.014$). The relative height growth showed no significant differences between the degradation states. Negative growth occurred in both degradation states when the main shoots dried out or were broken. Survival rates were much higher in the diversity nodes but did not differ between degradation states, with 43 percent and 41 percent of seedlings surviving 1.5 years after planting in the plots with high and intermediate degradation, respectively ($p=0.3$; Figure 2). A comparison of the relative height growth rates revealed no significant difference ($p=0.63$) between the two degradation states. Negative growth occurred in both degradation states when the main shoots dried out or were broken.

CONCLUSIONS AND RECOMMENDATIONS

Survival rates of planted seedlings in diversity plantings were dramatically low, largely due to water shortage after planting. As no irrigation was applied, seedlings relied on available rain until their roots were able to reach groundwater. Absence of rain after planting is therefore likely the main reason for the high mortality rates. The reason that twice as many seedlings survived in areas with intermediary canopy cover compared to bare land, was probably due to the nurse function of resident vegetation. Although the survival rates were low, survival rates of 3.9 percent (high degradation plots) and 8.9 percent (intermediate degradation plots) at densities of 4 000 and 2 000 trees per hectare mean that 156 and 178 trees, respectively, survived per hectare. These numbers could still be sufficient to initiate the regeneration process of the tropical dry forest, but the high cost of applying this strategy over hundreds of hectares of land is likely to be a limiting factor. Although the net cost per hectare was higher for diversity nodes, the much higher survival rates may make it a much more viable restoration strategy. This intervention could be applied on smaller scales where the expansion of the tree islands into surrounding land is likely and possible (nucleation theory).

However, the species to plant should also be chosen well since each species had variable survival rates in the two degradation states (Figure 3). Although some trees showed superior survival in both degradation states, our results suggest that there are specialists for the different successional phases, and the right species should be selected in accordance with the conditions of the planting site.

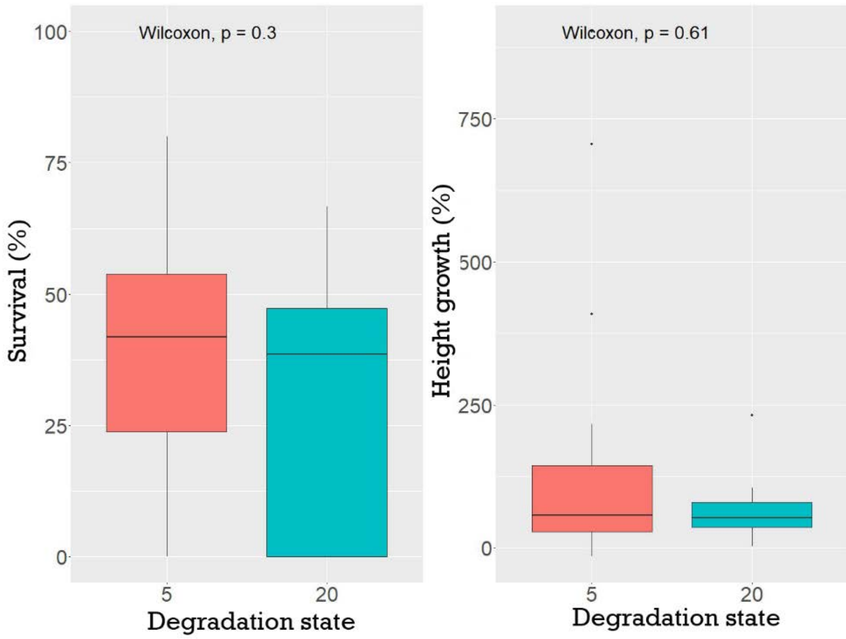
Figure 1. Survival and relative height growth rates in the diversity plantation plots in areas with different states of degradation



Note: 5 = high degradation; 20 = intermediate degradation.

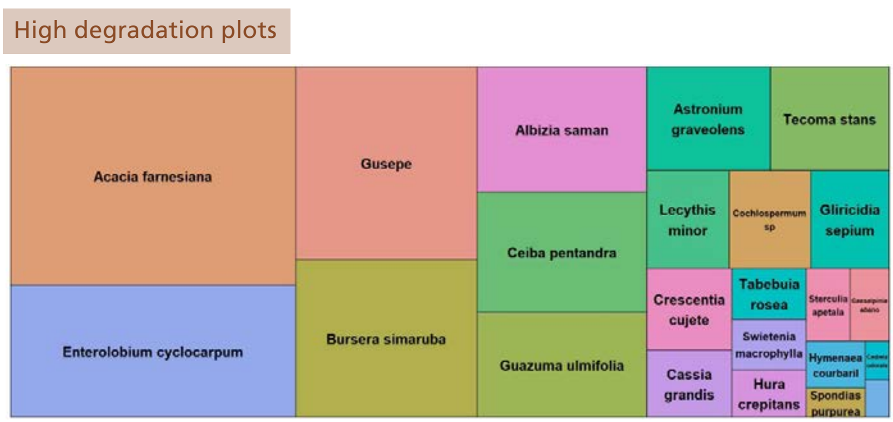
General appearance of the area where the experimental plots were installed, Angelina, Buritica, Antioquia, Colombia

Figure 2. Survival and relative height growth rates in diversity node plots in areas with different states of degradation

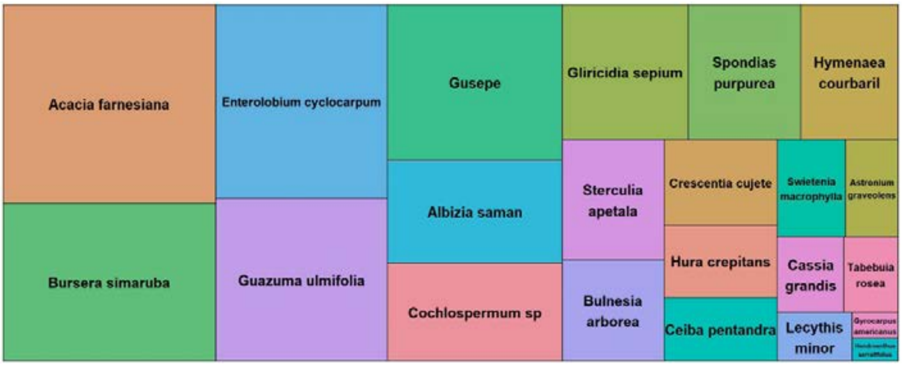


Note: 5 = high degradation; 20 = intermediate degradation.

Figure 3. Survival rates of planted tree seedlings in high and intermediate degradation plots



Intermediate degradation plots



Note: The sizes of the species boxes are proportional to the number of seedlings of each species surviving out of all seedlings planted.

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CASE STUDY 4

Species diversity and carbon stock dynamics in restored burnt peatland forest in Central Kalimantan, Indonesia

I Wayan Susi Dharmawan,[1*] Bambang Hero Saharjo,[2] Supriyanto,[2] Hadi Susilo Arifin[2] and Chairil Anwar Siregar[1]
[1] Research Center for Ecology and Ethnobiology, National Research and Innovation Agency, Indonesia
[2] IPB University
* Corresponding author

BACKGROUND

Indonesia is the country with the largest area of tropical peatlands in the world, covering 13.43 million hectares (ha) spread across Sumatra, Kalimantan and Papua (Anda *et al.*, 2021). However, these peatlands have continued to experience degradation and decline in forest cover, especially since the 1980s, due to fires and other activities for making land canals for timber exploitation, and due to land conversion to agriculture and the establishment of plantation forests (Bonn *et al.*, 2016). Degradation increased with the occurrence of peatland fires in 1997 in Central Kalimantan, with estimated carbon emissions reaching 0.23 gigatonnes over a burnt area of around 700 000 ha (Page *et al.*, 2002). Peatland fires, especially if they occur repeatedly in the same location, not only cause greenhouse gas emissions but also reduce biodiversity (Wijedasa, 2016). This threat also inhibits natural regeneration, meaning that rehabilitation and restoration efforts are required to speed up recovery.

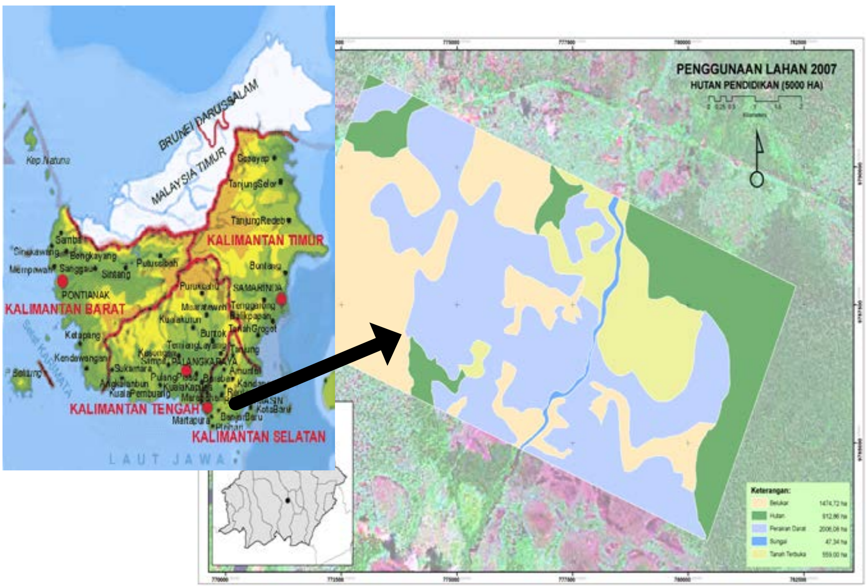
The impact of forest fires on the dynamics of species diversity and carbon stocks in peat forests needs to be studied carefully, taking into account the different ages of the tree species, in order to estimate the potential for recovery. The research was carried out in the experimental forest of the University of Palangkaraya, Hampangen and the Central Kalimantan Peatland Project (CKPP) research forest, Kalampangan, Central Kalimantan (see the study location in Figure 1). The research plots were located in a primary peat forest (as the control plot or HGP), a peat forest repeatedly burnt every year (HG1) with an area of ± 51.5 ha, a burnt peat forest after 3 years with no fire (HG3), with an area of ± 150.9 ha, and a burnt peat forest after 8 years with no fire (HG8), with an area of ± 37.4 ha. Burnt peat forest is defined as peat forest that has experienced a fire due to natural disturbance and a trigger. Research locations, coordinates and altitude are presented in Table 1, and the horizontal and vertical profiles of the research plots are presented in Figure 2.

Table 1. Coordinates and altitude of the research locations

Forest type	Coordinates		Altitude (m)*
	South	East	
HGP	01°52,077′	113°31,632′	54
HG1	02°19,219′	114° 03,484′	14
HG3	01°52,775′	113°28,456′	45
HG8	01°53,279′	113°30,961′	47

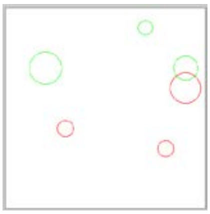
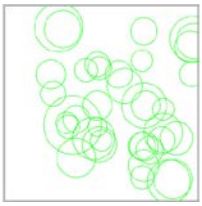
Note: * above mean see level.

Figure 1. Map of the study area



Source: **Ciptadi, U.A., Uda, S.K, Corlett, R., Rosa, M.P. & Afentina.** 2010. Baseline study for preparation of REDD implementation at the educational forest of Palangkaraya University. Bahan presentasi pada Second International Workshop on “Wild Fire and Carbon Management in Peat Forest in Indonesia”, 28–29 September, 2010. Palangkaraya, Indonesia.

Figure 2. Profiles of burnt peat forest stands

Forest type	Horizontal profile	Field condition	Vertical profile
HG1			
HG3			
HG8			

OBJECTIVE

The research conducted aimed to examine:

a. The dynamics of species diversity.
b. The dynamics of carbon stocks.
c. Changes in species diversity and carbon stocks as a reference for assessing rehabilitation and restoration.

Study activities were carried out in areas that were burnt every year due to repeated fires and in areas with only one fire incident.

KEY RESULTS WITH DATA

Species diversity in burnt peat forest after 3 years and 8 years shows an increase in the number of species at seedling, sapling and pole level as shown in Table 2.

Table 2. Number of species at seedling, sapling and pole level per forest type

Forest type	Stand level and number of species		
	Seedling	Sapling	Pole
HG1	4	1	1
HG3	12	14	3
HG8	28	39	14
HGP	32	40	18

The average annual change in carbon stocks in peat forests with fire as a removal factor is 4.4 tonnes of carbon (C) per hectare per year or 16.1 tonnes of carbon dioxide equivalent (CO_2eq) per hectare per year (Table 3). This indicates that the potential for carbon sequestration in burnt peat forests is still very high or exceeds the CO_2 emission factor due to peat drainage. The emission factor due to peat drainage is 9 tonnes CO_2eq/ha per year for every 10 centimetres (cm) of peat depth reduction (VCS, 2010).

Table 3. Dynamics of carbon stocks in burnt peat forest and primary peat forest

Forest type	Carbon stock (tonne C/ha)*	Change of carbon stock (tonne C/ha/year)
HGP	72.8	NA
HG1 (T1)	2.4	NA
HG3 (T2)	13.1	5.4**
HG8 (T3)	25.7	3.3**
		Average = 4.4

Notes: *Carbon stock is the total number of seedlings, saplings, poles and trees; ** calculated based on carbon stock at T3 or T2 minus T1 and divided by the difference in years.

Based on carbon stock data, the seedling level is dominated by *Sarcotheca rubrinervis* Hall F., *Ilex cymosa* Blume and *Cratoxylon arborescens* Bl. (at HG1); *Combretocarpus rotundatus* (Miq.) Danser, *Cratoxylon arborescens* Bl. and *Chionanthus* sp. (at HG3); *Endiandra* sp., *Ilex cymosa* Blume and *Mezzetti parviflora* Becc. (at HG8); *Chionanthus* sp., *Dialium kunstleri* Prain and *Calophyllum pulcherrimum* Wall. (at HGP). The sapling level is dominated by *Cratoxylon arborescens* Bl. (at HG1); *Combretocarpus rotundatus* (Miq.) Danser, *Cratoxylon arborescens* Bl. and *Stemonurus scorpioides* O.Ktze. (at HG3); *Syzigium* sp., *Cratoxylon arborescens* Bl. and *Combretocarpus rotundatus* (Miq.) Danser (at HG8); *Memecylon* sp., *Baccaurea bracteata* Muell.Arg. and *Ilex cymosa* Blume (at HGP). The pole level is dominated by *Combretocarpus rotundatus* (Miq.) Danser (at HG1); *Combretocarpus* *rotundatus* (Miq.) Danser, *Cratoxylon arborescens* Bl. and *Tetramerista glabra* Miq. (at HG3); *Combretocarpus rotundatus* (Miq.) Danser, *Cratoxylon arborescens* Bl. and *Tetramerista glabra* Miq. (at HG8), also in and *Ilex cymosa* Blume, *Diospyros dajakensis* Bakh. and *Syzigium* sp. (at HGP).

CONCLUSIONS AND RECOMMENDATIONS

Burnt areas of peat forest in Central Kalimantan with a single fire event can recover naturally if the burnt area is limited and protected from recurring fires. This is indicated by the increase in the number of species and associated carbon stocks in peat forests that have burnt only once after 3 years and 8 years with no fire, compared to peat forest burnt every year. The potential for carbon sequestration in the peat forests with a single fire event is still very high or exceeds the CO_2 emission factor due to peat drainage.

The number of species and the amount of carbon stock in burnt peat forest with a single fire event in 3 years and 8 years can serve as a reference value for assessing the success of efforts to restore burnt peat forest.

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CASE STUDY 5

Seed dispersal as a key element for the sustainability of restored ecosystems in Lebanon

Magda Bou Dagher Kharrat[1,2] and Rhea Kahale[1]
[1] Laboratoire Biodiversité et Génomique Fonctionnelle, Faculté des Sciences, Université Saint-Joseph, Campus Sciences et Technologies, Beirut, Lebanon.
[2] European Forest Institute, Mediterranean Facility, Sant Pau Art Nouveau Site, Sant Leopold Pavilion C/ Sant Antoni M. Claret, 167, 08025 Barcelona, Spain.
Magda.boudagher@efi.int

BACKGROUND

Seed dispersal is an essential process for maintaining the viability of plant populations since it enables the mobilization of seeds from the parental plants to the sites where they can germinate and establish (Howe and Smallwood, 1982). Understanding the dispersion of seeds allows management strategies to be developed for the conservation of ecosystems.

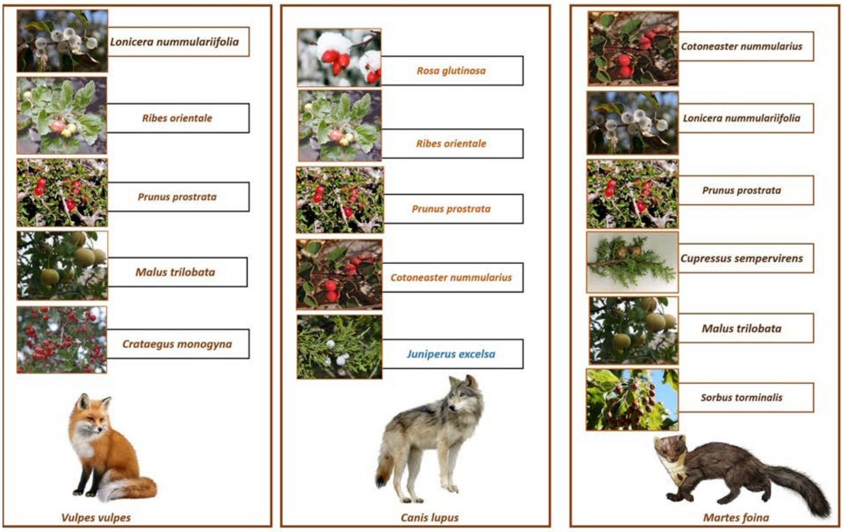
Furthermore, deciphering predator–prey relations within an ecosystem, as well as investigating seasonal food web variation throughout the year, provide powerful insights into an ecosystem's structure and dynamics at the population and community levels (Elton, 1927; Cohen *et al.*, 1993; Soulé *et al.*, 2003; Yu *et al.*, 2012; De Barba *et al.*, 2014). Thus, managers involved in reforestation, forest ecosystem restoration and wildlife conservation activities in forests must know which plant species each animal consumes and for which species it disperses seeds.

Despite the importance of a diverse set of interspecific interactions for forest regeneration, many reforestation projects have been conducted using plantations with one or only a limited number of species (Lamb, Erskine and Parrotta, 2005) and without considering the animal wildlife component.

In Lebanon, reforestation programmes in the 1960s mainly involved monoculture plantations of *Cedrus libani* and *Pinus pinea* (MoE, UNDP and GEF, 2014). Recently, an ecosystem restoration approach requiring the planting of multiple species was adopted to restore stabler forest functions. Besides conifers whose seeds are dispersed by the wind, many broadleaved trees bearing fleshy fruits were also planted to build a community closer to that of the reference ecosystem (Pollock, Beechie and Imaki, 2012).

For such plantations to be sustainable, it is necessary to ensure that the frugivorous guilds responsible for dispersing the seeds of those trees are still present in the area. But which animal disperses which seeds? And what do those animals eat outside of the fruiting season?

Figure 1. Plants seeds dispersed by *Vulpes vulpes*, *Canis lupus* and *Martes foina*



Source: **Boukhdoud, L, Saliba, C., Parker, L.D., McInerney, N.R., Kahale, R., Saliba, I., Maldonado, J.E. & Bou Dagher Kharrat, M.** 2021b. Using DNA metabarcoding to decipher the diet plant component of mammals from the Eastern Mediterranean region. *Metabarcoding and Metagenomics*, 5: e70107. https://doi.org/10.3897/mbmg.5.70107

APPROACH AND KEY RESULTS

In this case study, we present the results of our study by Boukhdoud *et al.* (2021b), in which we applied a scat DNA metabarcoding technique to describe the seasonal plant diet composition of mammal species from a highly biodiverse Lebanese forest in the eastern Mediterranean. We also recovered plant seeds, when present, from the scats for identification.

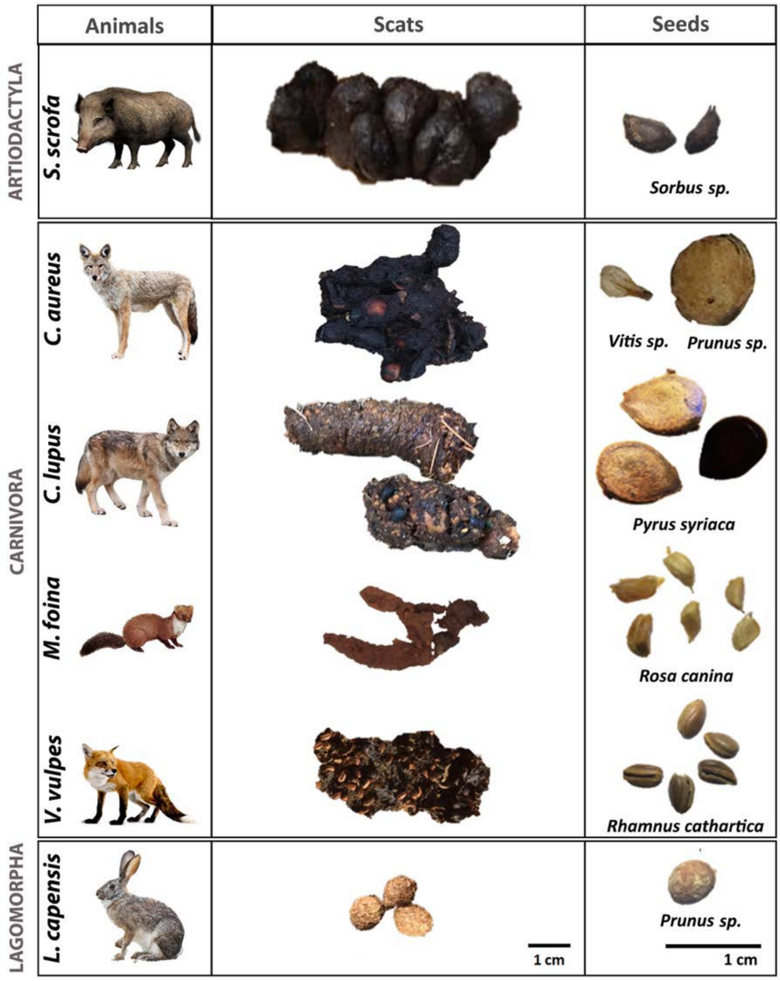
This non-invasive DNA-based approach involves the amplification and sequencing of short DNA barcode fragments using universal primers to simultaneously determine the identity of multiple prey species present in individual scat samples collected in the field (Valentini, Pompanon and Taberlet, 2009; Taberlet *et al.*, 2012). The information needed to study the diets of animals can be found hidden in their scats, which contain not only the animals' DNA but also that of the species that they have consumed. The DNA sequences obtained from such material were identified by comparing them to a reference library of animals and plants of eastern Mediterranean countries, which we built previously (Boukhdoud *et al.*, 2020, 2021a). This approach was applied in a complex and highly biodiverse protected area – Horsh Ehden Nature Reserve in North Lebanon – to decipher plant–mammal interactions in a pristine ecosystem.

A total of 18 vertebrate species (15 mammals, 2 birds and 1 lizard) and 133 plant species from 54 different families (out of 72 recorded in the nature reserve) were identified through the DNA metabarcoding technique.

For several animal species, our results showed seasonal shifts in dietary plant components. The diet of the red fox was dominated by Rosaceae species in autumn and winter but shifted to a predominance of Poaceae species (mainly *Hordeum leporinum*) in spring and Fabaceae species in summer, especially *Onobrychis* sp. The diet of the wild boar included mainly *Quercus* species (Fagaceae) in winter and summer but shifted to include more Rosaceae species in autumn. Species from the Fabaceae family had higher representation in Cape hare samples during winter and summer compared to spring, when the diet of this animal included mostly members of the Poaceae family, and autumn, when *Sedum* sp. (Crassulaceae) was mainly detected. Concerning the golden jackal, its diverse diet included primarily *Ficus carica* (Moraceae) in autumn, Rosaceae species in winter, *Quercus* species in spring and *Medicago* sp. (Fabaceae) in summer.

Prior to DNA extraction, plant seeds, when present, were recovered from the scats and cleaned using diluted ethanol to remove scat residues and identify the seeds. The reference seed collection of the Jouzour Loubnanseed bank was used to do this (www.lebanon-flora.org; www.jouzourloubnan.org). Plant seeds were found in 33 percent of the collected scat samples. These belonged to six mammal species from three different orders: the golden jackal, grey wolf, Cape hare, beech marten, wild boar and red fox. The seeds detected in the scat samples are shown in Figure 2.

Figure 2. Plant seeds detected in scat samples



Source: **Boukhdoud, L, Saliba, C., Parker, L.D., McInerney, N.R., Kahale, R., Saliba, I., Maldonado, J.E. & Bou Dagher Kharrat, M.** 2021b. Using DNA metabarcoding to decipher the diet plant component of mammals from the Eastern Mediterranean region. *Metabarcoding and Metagenomics*, 5: e70107. https://doi.org/10.3897/mbmg.5.70107

Seeds were most present in the scat samples collected in summer and autumn. The identified seeds belonged to species from several families, including *Rhamnus cathartica* (Rhamnaceae), *Ficus carica* (Moraceae), *Vitis vinifera* (Vitaceae) and Rosaceae species (e.g *Crataegus* spp., *Malus trilobata*, *Rosa canina*, *Prunus* spp., *Sorbus* spp. and *Pyrus syriaca*). Many samples contained seeds from more than one plant species. Syrian pear seeds (*Pyrus syriaca*) were only identified in the grey wolf samples. Grape seeds (*Vitis vinifera*) were only found in the red fox and golden jackal samples. Only red fox scat samples contained buckthorn seeds (*Rhamnus cathartica*). All plant species for which we identified seeds in scat samples were also detected by DNA barcoding.

Native plant species that we identified as commonly consumed by mammals in this study should be considered for reforestation and ecological restoration projects, especially Rosaceae and Fagaceae trees. Planting these species will help attract wildlife to Lebanese forests and thus preserve Mediterranean biodiversity.

CONCLUSIONS AND RECOMMENDATIONS

This work supports the dogma of restoration ecology, which is that a variety of native species should be planted to promote and preserve a rich wildlife. Since seed dispersal mediated by frugivores is a crucial process in the life cycle dynamics and regeneration of several vegetation types, a seed disperser guild component should be included in every ecological restoration plan.

Finally, the forest refers to all life forms found within forested areas and the ecological roles that they perform. It encompasses not just trees but the multitude of plants, animals and microorganisms that inhabit forest areas – and their associated genetic diversity. They should all be tackled with equal importance when forest restoration is applied.

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Horsh Ehden Nature Reserve in North Lebanon

CASE STUDY 6

Long-term provenance trials in Mediterranean pines: latest research outcomes and their usefulness in future forest restoration activities in Europe

Giovanni Di Matteo,[1] Giovanbattista de Dato[1] and Jordi Voltas[2, 3]
[1] Committee on Mediterranean Forestry Questions – *Silva Mediterranea*, Forestry Division, FAO, Rome, Italy
[2] Department of Crop and Forest Sciences, University of Lleida, Av. Alcalde Rovira Roure 191, Lleida E-25198, Spain
[3] Joint Research Unit CTFC-AGROTECNIO-CERCA, Av. Alcalde Rovira Roure 191, Lleida E-25198, Spain

BACKGROUND

The Mediterranean region represents a harsh environment for pinewoods (Scarascia Mugnozza *et al.*, 2000; Tapias *et al.*, 2004; Matesanz and Valladares, 2014) where they are threatened by multiple abiotic stressors, such as erratic droughts of varying intensity, low nutrient availability and mild winters, as well as biotic stressors, such as pest outbreaks and diseases, and by disturbances, including fires and strong winds. In addition, these forest ecosystems have been shaped by people over thousands of years, and they are now also negatively impacted by climate change. These anthropic factors are causing genetic impoverishment and increasing the risk of extinction, especially of endemic species and marginal populations. To cope with this array of natural and human-induced conditions, pine species can adjust to the environment through local adaptation or phenotypic plasticity. In this context, the growth of pine species and their morphophysiological performance are involved in adaptation to different climates (i.e. functional variability) and should be considered simultaneously when evaluating genetic materials for conservation, selection and breeding programmes.

The present natural range of pines of the *Pinaster* subsection comprises nearly every Mediterranean country from Spain to the Syrian Arab Republic (Fady, Semerci and Vendramin, 2003). The Aleppo pine *Pinus halepensis* Mill. covers an amplitude of about 15° in latitude and 35° in longitude. The range of Brutia pine *Pinus brutia* Ten. is smaller, extending across Crimea and Anatolia, Palestine and Crete. Latitude and longitude are not the only important determinants of adaptive trait differentiation; altitude, climate and soil characteristics jointly contribute to developing these species' different characteristics as well as their intraspecific variability. Another species of this subsection from the western Mediterranean basin, maritime pine *Pinus pinaster* Ait., exhibits wide phenotypic variation for different life history traits across its distribution range (Santos del Blanco *et al.*, 2013; Di Matteo and Voltas, 2016; Zas *et al.*, 2020), as well as marked neutral variation characterized by a strong spatial population structure (Bucci *et al.*, 2007; Jaramillo-Correa *et al.*, 2015).

Altogether, these pine species cover more than 5 million hectares (ha) of the Mediterranean region and play a significant role in maintaining landscape quality, soil protection, and water stocking and quality while also providing fuelwood and several other purposes. They thus contribute to improving the livelihoods and quality of life of local populations. In this context, an extensive international network of trials was established across ten countries between 1974 and 1985 as part of *Silva Mediterranea* (FAO 4bis project, http://www.fao.org/docrep/006/k1203e/K1203E08.htm) and IUFRO 2.02.13 activities. The rationale was to understand the adaptive characteristics of the different pine species at the intraspecific level to provide useful information to stakeholders. Most of these trials are currently still in good condition despite many years of neglect and several forest fires. They can therefore provide relevant, updated information on the intraspecific performance of Mediterranean pines at adult stages under the effects of climate change. This article aims to summarize the latest research results published by a Mediterranean collaborative research network on Aleppo and maritime pine provenances grown in such common gardens.

KEY RESULTS

Initial investigations at the turn of this century focused on the variation of these species in terms of growth and productivity and its relation to the interactions between genetic and environmental factors – known as genotype-by-environment interactions – and on the prospective evaluation of tree breeding programmes, especially for Aleppo pine provenances (Ducci and Guidi, 2000; Fusaro, Di Matteo and Righi, 2007). In parallel, the extent of intraspecific variation in resistance or tolerance to stress factors like frost and drought was characterized under controlled conditions (Calamassi, Paoletti and Strati, 2001). Results were confirmed in experimental field networks, mostly in Europe, after the severe frost of 1985, when temperatures fell to -20 °C for two weeks (Eccher, Fusaro and Pelleri, 1987; Ducci and Guidi, 2000). In this way, the climatic envelope under which these species could be deployed was delineated, together with their main uses, namely soil protection and landscape improvement along coastal areas for Aleppo pine, and both protection and production for Brutia pine and Eldar pine – a subspecies of Brutia pine – thanks to their favourable tree form and relatively fast initial growth.

Overall, these studies have demonstrated that Aleppo pine populations dwelling in dry environments exhibit different characteristics from their counterparts originating from mesic areas, hence revealing complex anatomical, morphological and physiological adjustments and adaptations at the intraspecific level. A more recent study (Voltas *et al.*, 2018) reviewing trials from across the Mediterranean has shown ecotypic differences in survival of Aleppo pine provenances, but of relatively minor relevance. These differences were approximately constant across trials, suggesting lack of genotype-by-environment effects. With regard to growth, subhumid cool climate populations from the eastern Mediterranean, such as Greek populations showed general adaptation and high reactivity to favourable climate conditions, as opposed to populations from the driest ecological extreme of the species, such as southern Spain and Maghreb populations, which exhibited specific adaptation to harsh environments.

Several recent studies are focusing on extrapolating the adaptive capacity of Aleppo pine provenances to future climate conditions by obtaining climate response functions, which describe the relationship between the performance of a population across test sites and the climates of those sites (Rehfeldt *et al.*, 2002). These can be useful in forecasting the effects of climate change on tree species (Peterson, Doak and Morris, 2019). Thus, the response of populations to the new environments at the test sites can be interpreted as a simulation of their response to climate change. In particular, the study of Patsiou *et al.* (2020) exemplified that, for improving the accuracy of such future projections, the height growth of Aleppo pine provenances evaluated in common garden trials can be useful for predicting their performance under future climatic conditions. Based on climate response models (precipitation and temperature), and integrating the existing genetic differentiation between populations, the future growth of the species in 2071–2100 has been projected under two scenarios of greenhouse gas concentrations: moderate (RCP 4.5) and pessimistic (RCP 8.5). The results revealed that the forests of the species that are currently experiencing the most favourable conditions, that is, wetter conditions, which correspond to coastal areas of France, Greece, Spain and the Maghreb, may experience a decline in their current growth rate by the end of the twenty-first century, unlike forests in more arid and continental areas, which are likely to better withstand the effects of future high temperatures.

As part of research on maritime pine provenances conducted by the *Silva Mediterranea* trial network, some studies have focused on the assessment of intraspecific resistance to biotic stress, particularly to the scale insect *Matsucoccus feytaudi* Duc., which feeds exclusively on this species. This insect devastated about 120 000 ha of forest in Provence pinewoods in the late 1960s (Carle and Pontivy, 1968; Schvester, 1971), and previous studies conducted in French common garden trials have shown that some maritime provenances could be resistant or partially resistant to *M. feytaudi* (Schvester and Ughetto, 1986). The basis of this resistance can mainly be attributed to the existence of mechanical factors related to stembark structure, such as bark thickness, which constitutes a first obstacle to the settlement of crawlers. This has a genetic basis and can also be influenced by site conditions (Yanchuk, Murphy & Wallin, 2008). In Italian trials, Di Matteo and Voltas (2016) revealed that provenances exhibiting specific adaptation to near-optimal growing conditions showed high susceptibility to the insect; conversely, those provenances better adapted to poorer conditions could be less affected by the outbreak. This result is in line with the "Resource Availability" hypothesis according to which trees investing more in plant defences, for example through resin ducts or thick bark, may be more exposed to trade-offs with other functions, including growth, which demonstrates the cost of resource allocation.

CONCLUSIONS AND RECOMMENDATIONS

By taking advantage of a long-term experimental effort, these studies can help establish timely strategies if implemented in decision-making models for the proper use of genetic material of Mediterranean pines in reforestation, ecological restoration and assisted migration activities, thus strengthening the species' chances of survival in the face of climate change and in accordance with the Forest Genetic Resources Strategy for Europe (EUFORGEN, 2021).

The most recent activities conducted aim to revive some genetic trials that have been neglected in the last few decades due to a lack of attention to such research activities. Under the project RESILPINE (Understanding the Evolution of Integrated Phenotypes for the Resilience of Mediterranean Pines in a Changing Environment; RTI2018-094691-B MCIU/AEI/EU) led by the University of Lleida in Spain, dedicated sampling campaigns using dendrochronological assessments have been carried out that may be useful for reintegrating several abandoned trials of Aleppo pine from Sardinia (Pixinamanna, Cagliari) and Rome (Castel di Guido), and maritime pine from Sardinia (Vallermosa, Cagliari) into the operative network of *Silva Mediterranea*. Thanks to these campaigns, for example, the experimental plots have been reidentified, and surviving trees have been surveyed.

Maritime pine common garden trial in Vallermosa, Sardinia, Italy

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CASE STUDY 7

Certification of seed sources to support forest and landscape restoration programmes in Indonesia

Vivi Yuskianti,[1] Dede J. Sudrajat[1] and Ambar Dwi Suseno[2]
[1] National Research and Innovation Agency (BRIN), Indonesia
[2] Directorate of Forest Tree Seed, Ministry of Environment and Forestry, Indonesia

BACKGROUND

In its updated national determined contribution (NDC) submitted to the United Nations Framework Convention on Climate Change (UNFCCC), Indonesia has set ambitious targets to restore 2 million hectares (ha) of peatland and rehabilitate 12 million ha of degraded land by 2030 (Government of Indonesia, 2021). Billions of forest tree seeds and seedlings are required to meet these goals. However, a study has found that there is a scarcity of quality seeds to support the forest and landscape restoration (FLR) programmes of some Asian countries (Bosshard *et al*., 2021). The use of quality seeds is critical in FLR programmes because of their importance for restoring land functions and improving ecosystems, which have a huge impact on people's livelihoods and resilience to climate change.

SOLUTION IMPLEMENTED

The supply of forest tree seeds is essential for any tree planting programme, including FLR programmes, industrial plantation forests and community forests. In Indonesia, FLR includes land and forest rehabilitation, restoration and reforestation. There is a seed quality certification system regulated by Law No. 12 of 1992 on plant cultivation systems (Indonesia, 1992). This law is implemented through Government Regulation No. 44 of 1995 on plant seeds (Indonesia, 1995). The certification of forest tree seeds is established by a Ministry of Environment and Forestry (MoEF) regulation on the implementation of forest tree seeds (Indonesia, 2020). The system aims to protect seed suppliers, distributors and users and to guarantee that the seeds that they trade are of good quality. This system also establishes a link to the international seed distribution system. The regulation sets out the rules for three types of certification, covering seed source, seed quality and seedling quality.

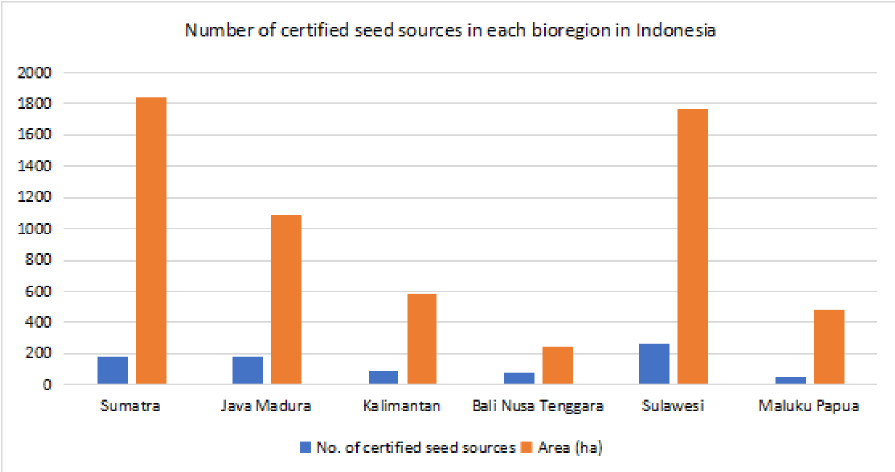
Seed source certification is the first step in ensuring that seed is collected only from seed sources that meet certain standards. These seed source standards are set according to guidelines provided in a decree of the Director General of Land Rehabilitation and Social Forestry (Indonesia, 2010). Based on these guidelines, the general standards for certified seed sources cover accessibility, flowering and fruiting, safety, stand health, boundaries and appropriate management while the specific standards are divided into seven classes depending on the genetic material used:

1. Identified seed stand
2. Selected seed stand
3. Seed production area
4. Provenance seed stand
5. Seedling seed orchard
6. Clonal seed orchard
7. Hedge orchard

The criteria for seed source classes have also been defined in Indonesian National Standard (SNI) 8806:2019 on forest tree seed sources.

National monitoring and evaluation for updating information on certified seed sources involves all technical implementation units (UPTs) of the Directorate General of the Management of Watershed and Forest Rehabilitation (PDASRH) at the MoEF as the central authority for the management of forest tree seeds in Indonesia, and regionally, the provincial technical implementation units (UPTDs) under the Governor. The information is routinely updated every year. All data on species, seed source locations, areas, owners, flowering and fruiting times, and seed production potential, are recorded every year and stored in the database of the Directorate of Forest Tree Seed (DPTH) under the PDASRH. According to the 2022 database, certified seed sources are found in ± 850 locations with a total area of more than 6 000 ha. Seed source locations are distributed across six bioregions spanning an island or several adjacent islands. The Sumatra bioregion has the highest area of certified seed sources, followed by Sulawesi and Java Madura (Figure 1).

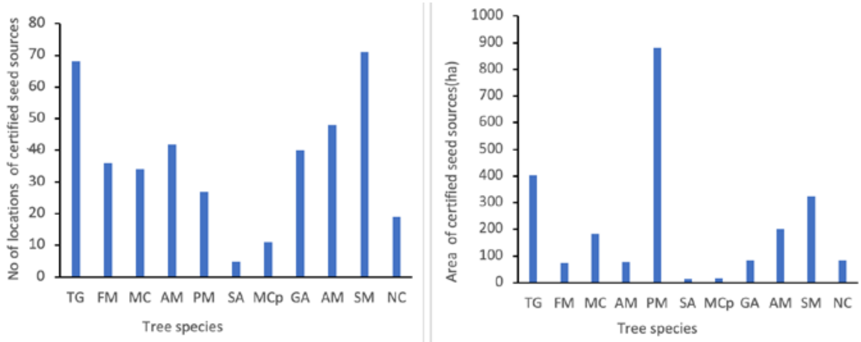
Figure 1. Number and total area of the certified seed sources in each bioregion in Indonesia



Certified seed sources consist predominantly of native tree species such as *Diosypyros celebica*, *Shorea leprosula*, *Eusideroxylon zwageri* and *Intsia bijuga*, with only a few exotic species such as *Swietenia macrophylla*. They are owned by government agencies, such as research institutes, forest management units and provincial forestry and plantation services, as well as state-owned and private companies, farmer groups and individuals.

The number of certified seed sources for each species is typically limited to one to three. Eleven tree species groups have a significant number of certified seed sources as they fall under an obligation to collect seed from certified seed sources (Figure 2). This requirement is contained in an MoEF decree of 2013 (Indonesia, 2013) covering five tree species, namely, teak (*Tectona grandis*), mahogany (*Swietenia* spp.), sengon (*Falcataria moluccana*), gmelina (*Gmelina arbore*) and jabon (*Antocephalus* spp.), and another MoEF decree of 2017 (Indonesia, 2017) covering six other species, namely candlenut (*Aleurites moluccana*), cempaka (*Elmerrilia* sp., *Elmerrilia ovalis*, *Elmerrilia tsiampaca*, *Michelia champaca*, *Manglietia glauca*, *Magnolia elegans*), agarwood (*Aquilaria filaria*, *Aquilaria malaccensis*, *Aquilaria microcarpa*, *Gyrinops resbergii*, *Gyrinops verstegii*), pine (*Pinus merkusii*), sandalwood (*Santalum album*) and cajuputi (*Melaleuca cajuputi*).

Figure 2. Number and area of certified seed sources for several tree species whose seeds must be collected from certified seed sources



Notes: TG = *Tectona grandis* (teak); FM = *Falcataria moluccana* (sengon); MC = *Magnolia champaca* (cempaka); AM = *Aquilaria malaccensis* (agarwood); PM = *Pinus merkusii* (pine); SA = *Santalum album* (sandalwood); MCp = *Melaleuca cajuputi* (cajuputi); GA = *Gmelina arborea* (gmelina); AM = *Aleurites moluccana* (candlenut); SM = *Swietenia macrophylla* (mahogany); NC = *Neolamarckia cadamba* (white jabon)

CONCLUSIONS AND RECOMMENDATIONS

Currently, the obligation to use seeds from certified seed sources extends only to 11 groups of forest tree species. We recommend that certified seed sources are also used for other species. Despite many challenges encountered in implementation, the system provides assurance that the same standards are applied to all seed sources. Certification of seed sources also demonstrates the government's strong commitment to ensuring the availability of quality tree seeds to support FLR programmes in Indonesia.

The database maintained by the DPTH at the MoEF as the central authority for managing forest tree seeds is very helpful for monitoring the availability of certified tree seed sources throughout Indonesia. Unfortunately, it is still paper based, which means that there is some data overlap. Therefore, the directorate could be supported in the development of an online database system for forest tree seeds. This would provide more up-to-date information and would also be easier to maintain than paper-based databases.

Seedling seed orchard of red jabon *Anthocephalus macrophyllus* in Maluku

Identified seed stand of mahogany (*Swietenia* spp.) in East Java and traditional climbing equipment for seed harvesting

Seedling seed orchard of pine *Pinus merkusii* owned by a state-owned company in West Java

Candlenut *Aleurites moluccana* seeds collected from an identified seed stand in Central Sulawesi

Identified seed stand of teak *Tectona grandis* owned by a private company in Central Java

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CASE STUDY 8

Teak genomic resources and their applications in seed zone delineation in India

Ramasamy Yasodha,[1] Maheswari Patturaj,[1] Swathi Balakrishnan[2] and Suma Arun Dev[2]

[1] Institute of Forest Genetics and Tree Breeding, Coimbatore, Tamil Nadu, India

[2] Kerala Forest Research Institute, Thirssur, Kerala, India

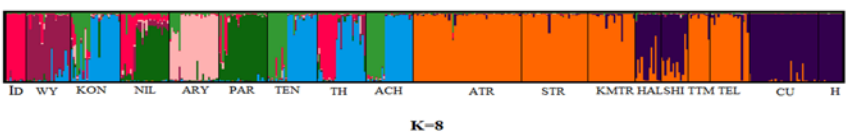
The ever-growing global population requires more wood resources, and accordingly, global timber consumption is estimated to increase by 170 percent to 4.3 billion cubic metres by 2050 (Gresham House, 2020). Commercial timber plantations are expanding continuously to meet the demand for wood and wood products and provide food security for dependent communities. In recent years, the timber plantation sector has gained momentum because of its potential to mitigate climate change effects. The increased area of plantations has gone hand in hand with tree improvement programmes that adopt advanced technologies to enhance the productivity per unit area in operational plantations.

Teak *Tectona grandis* L.f is prioritized in over 20 tropical countries to fulfil the requirements of the timber industry and is ranked first for *in situ* conservation and large-scale cultivation. Tropical plantations are predicted to be the dominant supplier of wood by 2050 (McEwan *et al.*, 2020). Smallholders and agroforestry systems will become increasingly important for production since further expansion of the land area for pure forestry plantations will no longer be possible. These systems demand planting of genetically improved planting stock that favours short rotation with better productivity and timber quality. Teak is one of the valuable hardwood species experiencing technological growth in tree improvement aspects. Yield improvement of teak requires application of principles of genetics, tree biology and breeding, silviculture and economics, to develop improved clones that will enhance the quantity and quality of harvested products.

Studies have been carried out to understand the genetic structure within and among populations and provenances, and to determine the capacity of the species to adapt to biotic and abiotic stresses (Alfaro, Fady and Vendramin, 2014). The amount of genetic diversity present within a species determines its potential for breeding and trait improvement. Patterns of genetic variation across the landscape reflect the responses of species to the evolutionary forces operating within current and past environments and can tell us how species have evolved and adapted in the changing climate. Gene-ecological zonation or transfer zones are determined based on the magnitude of genetic variation, spatial distribution of genotypes and patterns of mating within populations, which influence the genetic composition and quality of seeds collected for reforestation, tree improvement and conservation purposes.

The Institute of Forest Genetics and Tree Breeding, Coimbatore, Tamil Nadu, undertook a study in collaboration with Kerala Forest Research Institute, Peechi, Kerala (Balakrishnan *et al.*, 2021), to develop gene-ecological zonation for natural teak distributed in India. Genome-wide simple sequence repeat (SSR) loci of teak were identified through whole genome sequencing (Yasodha *et al.*, 2018) and used to genotype a selection of 18 Indian populations covering the states of Kerala, Karnataka, Tamil Nadu, Gujarat and Madhya Pradesh. Simple sequence repeat genotyping in an automated capillary electrophoresis system was performed using 23 fluorescently labelled, highly polymorphic, genome-wide SSR markers on the selected populations to estimate allele sizes and numbers. The maximum genetic admixture was observed within nine Kerala populations. The climatically wet populations of Kerala had the most genetic diversity followed by moist/dry Tamil Nadu and Karnataka. Climatically dry populations in Gujarat and Madhya Pradesh exhibited very similar genetic diversity estimates. The overall mean genetic differentiation coefficient revealed that 80 percent of genetic variation was dispersed within groups and 20 percent between populations. Identical population structure (Figure 1) was shared among a few populations, namely, Thenmala (TEN), Achenkovil (ACH) and Konni (KON), and Parambikulam (PAR) and Nilambur (NIL) populations of Kerala; among Tamil Nadu (Anamalai Tiger Reserve [ATR], Satyamangalam Tiger Reserve [STR], Kalakkad-Mundandurai Tiger Reserve [KMTR]) and Karnataka (Thithimathi [TTM] and Sakrebyle [TEL]) populations; between two Karnataka populations (Haliyal [HAL] and Shivamoga [SHI]); and between Gujarat (Chota Udaipur [CU]) and Madhya Pradesh (Hosangabad [H]) populations.

Figure 1. Population genetic structure of teak populations



Integrated analysis of bioclimatic variables, geography and genetic information divided the 18 natural teak populations into three gene-ecological zones: moist Kerala populations (NIL, WY, PAR, TH, ID, KON, ACH, ARK and TEN) with high annual precipitation and genetic diversity, moist/semi-dry teak populations of Tamil Nadu (ATR, STR and KMTR) and Karnataka (TTM and TEL) with moderate genetic diversity, and outlier populations (Gujarat [CU], Madhya Pradesh [H]), and Karnataka populations (SHL, HAL) with less annual rainfall and higher temperatures and lower genetic diversity. Gene-ecological zones are delineated to aid the transfer of seeds for raising plantations. In general, plantings should be done in the zone where the seeds are collected. The delineation of zones also offers the opportunity to transport seeds to adjacent areas with similar physiographic conditions and to prescribe the silvicultural practices to be adopted.

An understanding of the distribution of adaptive alleles would guide in assisted migration to similar climate zones and restoration under future climate change scenarios. Furthermore, the data collected may be used to preserve genetic diversity in breeding populations and protect genetic resources using both *in situ* and *ex situ* approaches. This study serves as a foundation for creating genetic strategies and best practices for timber trees with longer rotation cycles.

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CASE STUDY 9

Upscaling genomic studies in support of resilient forest and landscape restoration in Australia

Maurizio Rossetto
Research Centre for Ecosystem Resilience, Australian Institute of Botanical Science, The Royal Botanic Garden Sydney, Australia

Practitioners can now readily access genomic tools that can help guide the restoration of resilient forest landscapes. Genetic diversity is vital for ensuring evolutionary resilience and an important consideration in restoration efforts if they are to achieve the goals of the United Nations Decade on Ecosystem Restoration, especially in view of continuing anthropogenic impacts and the climate crisis (Forzieri *et al.*, 2022). Although climatic and distributional proxies can be used to develop putatively resilient restoration scenarios (Prober *et al.*, 2015), ideally decision-making should be supported by species-specific genetic data (Fremout *et al.*, 2021) as generalization can be misleading, even among closely related and co-distributed species (Rossetto *et al.*, 2020).

Until recently, associated costs and technical complexities were preventing the wide adoption of genetics in general, but the advent of the genomic era has made relevant genetic knowledge increasingly available to the restoration community (Breed *et al.*, 2019). The decreasing costs of high-throughput sequencing and the availability of broadly applicable molecular workflows make the necessary analytical tools widely accessible to researchers and practitioners. Indeed, interested parties no longer need to establish dedicated genetic laboratories as DNA extraction, sequencing and even interpretational analyses can be commercially outsourced (Hogg *et al.*, 2022). As a result, obtaining genetic knowledge supporting the establishment of diverse and resilient tree populations is now more accessible than on-ground practitioners realize.

Targeted landscape-genomic studies across multiple species, can quickly and cost-effectively guide forest and landscape restoration (FLR) projects in relation to provenancing, maximizing diversity and establishing adaptive resilience. Ambitious multispecies objectives across replicable, standardized workflows that rely on partitioning of tasks are key to the economy of scale that makes such projects effective (Rossetto *et al.*, 2019; 2021). Such objectives provide well-defined "bundles" with clear scientific and practical outcomes that are attractive to funding bodies. A bundle should preferably target co-distributed species, and sampling should be representative of each species' distribution while being reasonably constrained to manage the time and resources involved. Six individuals sampled from up to 30–40 distribution-wide sites usually provide sufficient interpretative data to acquire the necessary knowledge (Lotterhos and Whitlock, 2015; Rossetto *et al.*, 2019).

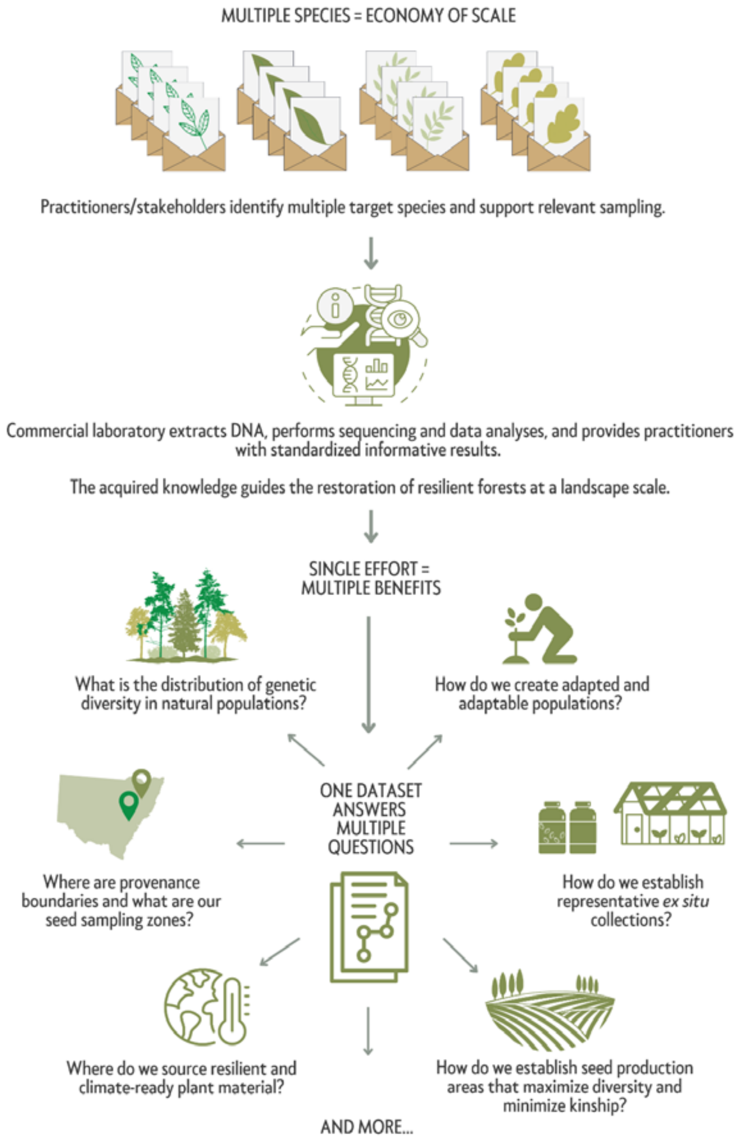
Figure 1 briefly summarizes the process involved. Practitioners identify a set of target species that are commonly used in local restoration projects and ideally become directly involved in uniform, replicated and representative sampling strategies. The number of species targeted will depend on local factors but will need to represent a realistic bundle that delivers economy of scale, while providing sufficient information to attract funding (e.g. 10–12 species is a good starting point). The involvement of trained community groups or external contractors, or both, can simplify infrastructural and staffing requirements as well as increase the cost-effectiveness of the sampling strategy. Once the necessary plant material (usually as little as one silica-dried leaf per individual) and standardized metadata are collected, they can either be directly sent to a low-cost commercial sequencing facility (prices will vary, but a few thousand United State dollars should enable DNA extraction and sequencing of around 100 samples) or to a collaborating scientific institution where a centralized approach can help maintain rigour and uniformity.

The one, low-cost dataset can provide information on the distribution of genetic diversity, provenance boundaries, the potential relationship between genetic and climatic patterns, and more (Rossetto *et al.*, 2019). This knowledge can directly guide a broad range of applied restoration-focused questions, such as how to maximize genetic diversity in mixed planting strategies, how to establish a representative *ex situ* collection or seed production area, or how to maximize diversity while also introducing climate resilience (Bragg *et al.*, 2021, 2022). Relevant solutions and scenarios will be directly available to the practitioners initiating the project but can also be made publicly available through webtools and dedicated portals.

As an example, Restore & Renew (www.restore-and-renew.org.au), is a large-scale project using distribution-wide landscape genomics (based on DArTseq technology; www.diversityarrays.com) and climate modelling to provide restoration practitioners with relevant provenancing information. Support is derived from project-specific funding (e.g. resourcing and infrastructure corporations, biodiversity management agencies, benefactors and donors), and so far, relevant data have been obtained for over 150 species representing all vegetation types in New South Wales, Australia, and beyond. The new knowledge supports the translocation of threatened species, the establishment of seed production areas, the development of "climate-ready" community restorations and more.

In our experience, training practitioners in sampling techniques (e.g. use of collection apps, and handling and storage of leaf material) and scientific staff in the streamlining of sequencing and analytical interpretations is very effective once the right workflows are established. Costs involved will vary from country to country, as will the right ratio of staff numbers to project size for achieving economy of scale. Once the right balance is identified, however, costing becomes unambiguous in relation to the finalization of practical outcomes and consequently more attractive to funding agencies, interested investors and benefactors.

Figure 1. Example of a workflow for upscaling restoration genomic studies across multiple species and providing multiple benefits towards the establishment of resilient forest and landscape restoration, as well as well-defined and meaningful targets for potential investors



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CASE STUDY 10

The role of species richness and genetic diversity in improving the productivity and resilience of restored forests in subtropical China

Huang Ping[1] and Zheng Yongqi[1]
[1] Research Institute of Forestry, Chinese Academy of Forestry, China

BACKGROUND

Forests cover 31 percent of the Earth's land area and not only contribute to human survival but also play a critical role in mitigating climate change as a carbon sink. However, forest and land degradation and desertification are serious challenges because of population growth and economic development. Forest and landscape restoration (FLR) and sustainable land use provide possible solutions to stop the continuing deforestation and degradation. However, the rehabilitation of a forest ecosystem is a long-term and complicated process. Previous reports have suggested that plant diversity promotes productivity in grasslands (Reich *et al.*, 2012), but forest ecosystems are complex and other causalities may be important. As part of the biodiversity–ecosystem functioning experiment in China (hereafter, "BEF-China"), previous studies have discussed the relationships between species richness, intraspecific genetic diversity and forest productivity, the effect of species and genetic diversity, and their contribution to tree functional diversity and trophic feedbacks, and provided new insights into FLR (Huang *et al.*, 2018; Bongers et al., 2020; Tang *et al.*, 2022).

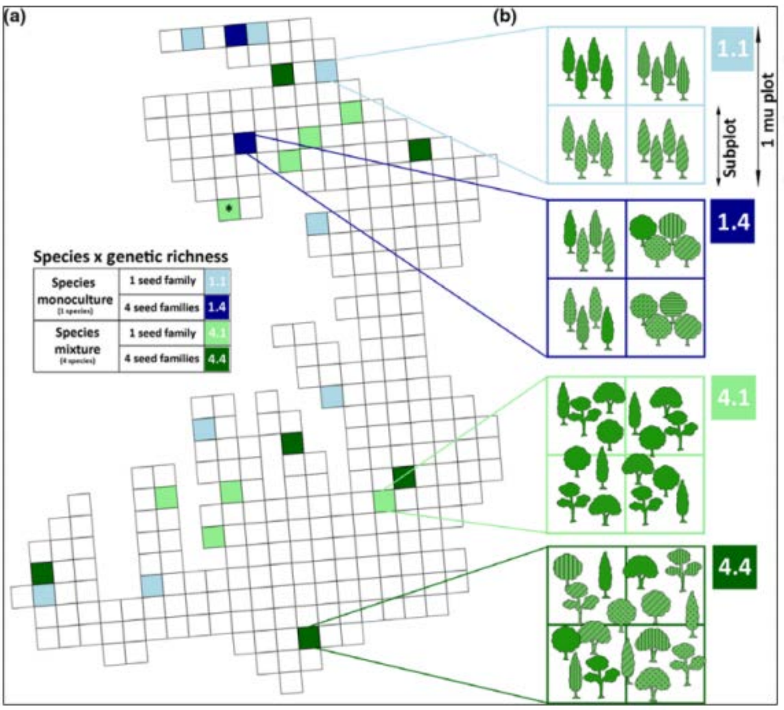
KEY RESULTS WITH DATA

To understand the effect of tree species richness in forest ecosystems, an experiment was performed as part of BEF-China in a highly diverse subtropical forest in southeast China, characterized by a high species richness gradient (in plots with 1 to 16 species, over 1 500 00 trees), multiple simulated extinction scenarios, high replication and extended duration (2009 to the present). This experiment was conducted at two sites of 20 hectares (ha) each, with communities assembled from six partially overlapping species pools (three per site). A complete pool represented a 16-species community, which was repeatedly divided into yield-reduced richness levels. A special feature of the design was that within each pool, communities formed nested series that simulated different trajectories of trait-based species extinction. Trajectories related to the means and diversities of three functional traits – leaf duration (LD), specific leaf area (SLA) and wood density (WD) – were analysed. The results showed significant positive effects of the logarithm of tree species richness on stand basal area and stand volume as well as on the annual increments of these two variables, and these effects grew steadily over time. The average 16-species mixture stand stored 31.5 megagrams of carbon per hectare (Mg C/ha) above ground with a 95 percent Bayesian credible interval (CI) of 25.5 to 37.6 during 8 years of growth, which is more than double the amount found in monocultures (11.9 Mg C/ha; CI: 10.6–13.5) and close to the carbon storage of commercial monoculture plantations of *Cunninghamia lanceolata* (26.3 Mg C/ha; CI: 19.0–33.2) and *Pinus massoniana* (28.5 Mg C/ha; CI: 20.8–36.1). Moreover, the effect of species richness was strongly related to functional and phylogenetic diversity. In addition, an experiment to understand the effects of genetic diversity within species was performed in parallel, on 24 plots with 400 individuals pertaining to one to four species, over an total area of 1.608 ha. The results showed the extent to which species differing in their traits varied among traits, such as larger leaf area (LA) in *Idesia polycarpa* and higher chlorophyll in *Daphniphyllum oldhamii*, and that seed families also significantly contributed to trait variation, such as LA, LN (leaf nitrogen content), SA (stomatal aperture) and chlorophyll. These results indicate that traits can change plastically in response to species richness (Bongers *et al.*, 2020). In a recent tree species richness × genetic diversity experiment, functional diversity and trophic feedbacks were used to explain the effects of tree species richness and genetic diversity on productivity. The results showed that species diversity increased productivity via increased tree functional diversity, reduced soil fungal diversity and marginally reduced herbivory. On the other hand, tree genetic diversity produced positive effects on productivity via functional diversity and soil fungal diversity in the mixture stand (Tang *et al.*, 2022).

CONCLUSIONS AND RECOMMENDATIONS

In China, monoculture plantations of species with high productivity and fast growth are on the rise, which makes critical contributions to FLR in the short term. This case study provides powerful evidence and advocates for the importance of tree species richness on forest productivity at stand level in establishing subtropical forest ecosystems. These findings suggest that a similar or potentially even higher productivity and carbon storage capacity can be achieved with mixed plantations of native species, bringing cobenefits in terms of biodiversity conservation and management in future FLR programmes. Intraspecific genetic diversity may also contribute to stand productivity as it may influence functional trait variation and stand-level forest characteristics. The productivity and stability of forest ecosystems depend on species richness, genetic diversity and tree functional diversity, which enhance the adaptation potential and resilience of forest ecosystems. This shows that species richness and genetic diversity are both important considerations in FLR practice.

Figure 1. Overview of the designed genetic tree experiment within BEF-China



Note: (a) There were 24 plots in total; (b) Each 1 mu (0.067 ha) plot was subdivided into four subplots, which were used to create different seed-family monocultures in the 1.1 richness and different seed-family compositions of four seed families in the 1.4 richness level.

One plot of biodiversity–ecosystem functioning experiment in China 10 years after the restoration intervention

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CASE STUDY 11

Promoting food tree species in forest and landscape restoration in Burkina Faso

Barbara Vinceti,[1] Tobias Fremout[2,3] and Celine Termote[4]
[1] Bioversity International, Rome, Italy
[2] Bioversity International, Lima, Peru
[3] Forest, Nature and Landscape Division, Department of Earth and Environmental Sciences, KU Leuven, Leuven, Belgium
[4] Bioversity International, Nairobi, Kenya

BACKGROUND

Modern food systems are increasingly based on a narrow range of commercial crops, such as rice, maize and wheat, which provide a large share of the calories consumed at global level. However, a vast array of currently untapped edible plants could be considered to address food security and at the same time supply the diverse set of nutrients needed to avoid the burden of malnutrition, and related morbidity and mortality. Sahelian countries are particularly affected by micronutrient deficiencies, with a high prevalence of critical wasting.

A recent worldwide assessment of existing edible plants pointed to more than 7 000 edible species (Ulian *et al.*, 2020), and therefore, exploring the potential offered by neglected and underutilized, domesticated, semidomesticated or wild species can dramatically enhance the prospect of succeeding in diversifying poor diets.

Plants are recognized as valuable sources of micronutrients and supply a diversity of nutritious fruits and vegetables and other edible products such as nuts, oils, leaves, flowers, roots and berries. Among them, trees also play an important indirect role in food systems through the supply of woodfuel and the provision of ecosystem services that sustain agricultural production, and by generating employment and income opportunities (Gitz *et al.*, 2021).

Despite this, trees tend to be largely neglected in nutrition-related interventions, but the considerable global interest and support for forest and landscape restoration provide an opportunity to increase the contribution of food tree species in restoration efforts and to improve access to nutrients for rural populations in countries characterized by monotonous staple-

Baobab tree providing nutritious fruits and leaves, shade to the animals and fuelwood from dead branches

based diets, like Burkina Faso. The flora of Burkina Faso includes many food plants, both in the wild and cultivated, which can be further promoted. Ways of processing edible products from trees vary from eating them raw to cooking them or processing them further (e.g. through fermentation), and recipes vary based on the environmental context and cultural background, among other factors.

KEY RESULTS WITH DATA

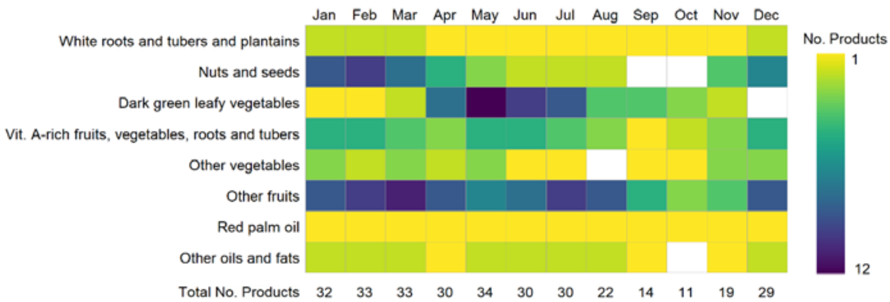
A well-designed selection of locally adapted food trees can contribute to maximizing the availability of edible products throughout the year as well as diet diversity. We thus focused on characterizing the contributions that different food products from trees could make to improving diet diversity in Burkina Faso.

We integrated information on the seasonal availability of edible items from food tree species found in Burkina Faso and the food groups that they belong to, which correspond to distinct nutritional profiles, into the decision-making Diversity for Restoration tool (D4R). This helps select appropriate tree species and seed sources for restoration and other planting purposes (Fremout *et al.*, 2022).

The seasonal availability of different edible tree products was determined based on phenological data supplied by local experts. Edible tree products were categorized in the food groups used in the methodology developed by FAO to assess the adequacy of the diets of women of reproductive age at population level, using the Minimum Dietary Diversity for Women indicator (MDD-W) (FAO, 2021).

The indicator developed by FAO helps determine the percentage of women consuming a minimum number of food groups per day, corresponding to a minimum dietary diversity. The number of food groups in MDD-W is ten, and a subset was found to be relevant to cover edible items from food tree species, namely white roots and tubers and plantains; nuts and seeds; dark green leafy vegetables; vitamin A-rich fruits and vegetables; other vegetables; and other fruits. Furthermore, two food groups considered as optional in the MDD-W indicator were also included, namely, “red palm oil” and “other oils and fats”.

Figure 1. Availability of edible products from 43 food tree species in Burkina Faso

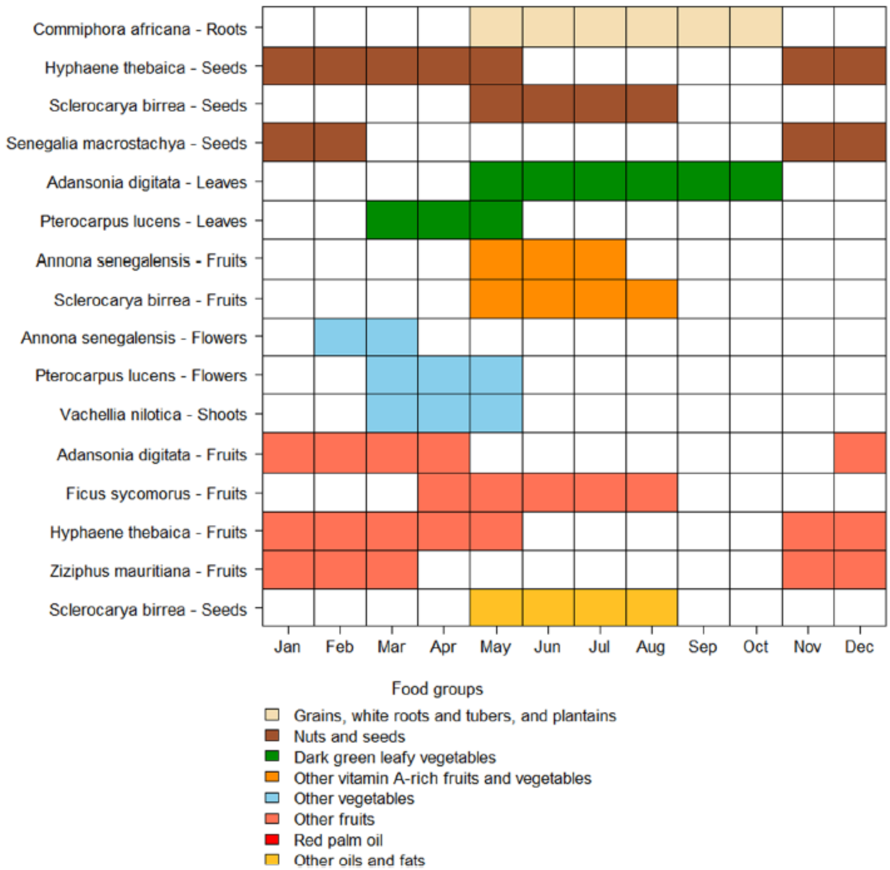


Note: Edible foods are counted only if consumed in quantities greater than 15 grams.

Over a total of 56 food tree species documented in Burkina Faso, 81 edible items from these trees can be consumed as food, mostly in the form of fruits (79 percent of tree species), followed by seeds (52 percent) and leaves (41 percent). Out of these species, 43 can be counted as providing edible foods under the different MDD-W food groups as they supply foods that are consumed in quantities above 15 grams. Considering all 43 food tree species jointly, availability of edible products was found to be highest between December and July, with the total number of products ranging between 30 and 34 (Figure 1). This period of the year overlaps with the first part of the lean season associated with a scarcity of cereals.

The tool can be used effectively for generating recommendations for planting food tree species combinations that maximize nutritional diversity as shown in Figure 2, which shows the range of food groups available throughout the year for a particular species combination.

Figure 2. One of the recommended combinations of food tree species to be planted in a specific location with a view to maximizing year-round nutritional diversity as identified by the different colour-coded food groups



CONCLUSIONS AND RECOMMENDATIONS

The D4R tool aggregates useful data from expert sources, which are usually scattered and not easily accessible. In addition, it turns nutritionally relevant information into concrete applications. The recommendations obtained using the tool are meant to be a knowledge base for planning nutrition-sensitive forest and landscape restoration projects. The final combinations of tree species to plant should be selected in close consultation with local communities, considering local cultural preferences and availability of planting material for the selected tree species.

Link to the paper: https://nph.onlinelibrary.wiley.com/doi/full/10.1002/ppp3.10304

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Stocking pods of Parkia biglobosa after harvest

CASE STUDY 12

Ecotourism and agroforestry as strategies for forest and landscape restoration coupled with conservation of forest genetic resources in the Philippines

Enrique L. Tolentino Jr
Professor at the College of Forestry & Natural Resources, University of the Philippines Los Baños, Laguna, Philippines

BACKGROUND

The Manupali watershed spans two protected areas, the Mount Kalatungan Range Natural Park and The Mount Kitanglad Range Natural Park, which is home to the endangered Philippine eagle (Figure 1 and Figure 2). This watershed is vital in supporting 21 000 hectares (ha) of farms, the National Power Corporation's 255 megawatt Pulangi IV hydropower plant and Bukidnon Province's seven Indigenous Peoples. In recent decades, a significant area of forest has been lost due to complex interacting factors, leading to biodiversity loss, soil erosion, carbon emissions, poor farm productivity, low incomes and other challenges.

The recently concluded Integrated Natural Resources and Environmental Management Project (INREMP) of the Department of Environment and Natural Resources (DENR) listed three main issues and challenges relevant to forest and landscape restoration (FLR) (DENR-INREMP, 2021): (a) protecting the remaining forest resources; (b) rehabilitating the remaining forests; and (c) sustaining the interest and engagement of the Indigenous Peoples communities in the protection and rehabilitation work. INREMP has reported that in 2010–2015, the forest area declined to around 600 ha and remains threatened by increasing migrant populations, lack of livelihood opportunities, poor choices of plants and programmes to protect the forest, lack of law enforcement and poor governance.

The Binahon Agroforestry Farm: a prosperous and innovative model upland farm

Originally only 2.75 ha when Henry and Perla Binahon bought it in 1992, the Binahon Agroforestry Farm (BAFF) now covers a total of 8 ha. The couple from the local DENR office engaged in years of self-study and participatory learning through available training and seminars to gain knowledge on the various aspects of agroforestry, soil and water conservation, forest rehabilitation and watershed management. This knowledge and years of practical experience have been instrumental in making the BAFF what it is today. Their enterprising spirit, courage and dedication paid huge dividends throughout the creation, nurturing and achievements of the agroforestry farm.

Espaldon (2008) described the metamorphosis of the BAFF from a simple agroforestry farm into a complex agroforestry resource centre. The BAFF began by showcasing various models of sustainable upland farming, expanded to include the seedling business for tree species and agricultural crops, and has also added capacity-building activities with local non-governmental organizations (NGOs) and government institutions.

The BAFF was founded on the principles of unity, diversity, balance and sustainability, which are incorporated into its various features, as described in Espaldon's case study (2008). The BAFF showcases contour hedgerow farming, natural vegetation strips, a multistory system, waste management, ecotourism and associated activities, such as camping, guided farm tours, swimming, sales of seedlings, vegetables, and food and drink, research and development, and the hosting of capacity-building programmes.

The BAFF owners practise an approach that balances conservation and income-generating activities and which, they firmly believe, will encourage upland farmers to pursue forest restoration initiatives (H. Binahon, personal communication, 2022). They demonstrated this by introducing innovations in contour farming and the natural vegetation strips on the BAFF. To enhance soil and water conservation, the Binahons have established high-value crops in the natural vegetation strips instead of ordinary grasses or other naturally growing vegetation, as with the original strip concept. Espaldon (2008) described some examples: (1) combination of crops in contour lines or hedgerows, with *ampalaya* at the upper level, calla lily at the back of the natural vegetation strip, which consists of coffee, banana, durian, lansones and timber trees; and (2) banana, durian and eggplant cultivated above the hedgerow where lemon grass or a combination of banana, coconut, pomelo and coffee are grown. Recently, the Binahons have used *madre de agua* and *camote* as hedgerows, with high-value vegetable crops in between. Madre de agua is an excellent fodder crop for a variety of livestock, including goats, cattle, horses and water buffalo (*carabaos*).

The BAFF owners have focused on increasing diversity in their cropping system, both in terms of the major crops and the other plant and tree species grown, some to provide non-forest timber products. Visitors to the farm also appreciate these various plants and trees. Having continuous production protects the farm from market price instability and enables it to meet varying customer demands. It is also part of the BAFF's integrated management scheme to control pests and diseases.

The BAFF also demonstrates and practises organic farming. Farm and household or restaurant waste is collected and mixed with other biodegradable waste including from livestock. This is composted in a separate area of the farm and when ready, is used to fertilize the crops.

Multistory systems in the BAFF include a first level of tall, native trees, then shade-tolerant trees and plants, and the nursery. The system mimics a tropical rainforest in the way that it optimizes the use of space, resources and energy. The nursery produces a variety of plant and tree seedlings for various customers and the visiting tourists. Seeds are mainly sourced from healthy and dominant mother trees or plants from the natural forests in the Manupali watershed. This helps conserve and promote diverse forest genetic resources that meet the various planting needs of the farm's customers and visitors.

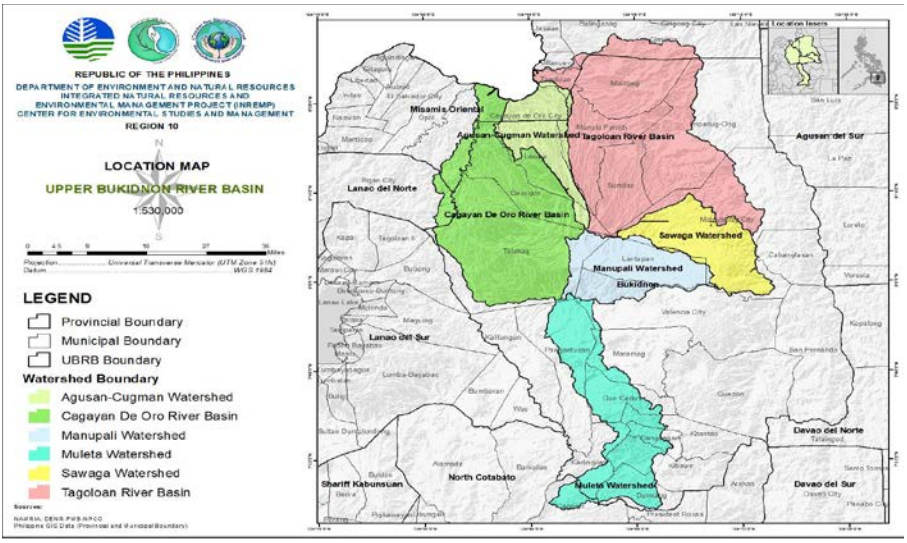
The BAFF serves as a natural resource centre as well as a knowledge and information hub. Various capacity-building activities are hosted at the farm for local government officers, government agency representatives and NGOs in the region. Participants can learn all about actual farming systems that work and share the rich knowledge and experience of the Binahons. The BAFF also partners with researchers to develop knowledge-generating and scientific projects. This increases the Binahons' knowledge and capability in managing their farm.

The various cropping patterns and systems, use of technology and varied practices have made the BAFF an attraction for tourists in the region and the adjoining islands, who wish to experience a different kind of tourism that nurtures not only the body but also the mind.

CONCLUSIONS AND RECOMMENDATIONS

The Binahons have been successful in integrating natural resource management with entrepreneurship to address the twin problems of forest degradation and poverty in this portion of the Manupali watershed. They have applied a coherent diversification strategy using agroforestry farming coupled with ecotourism. The farm has become a tourist attraction and knowledge resource centre thanks to the efforts of its owners to showcase upland cropping systems that are diverse, climate-resilient and sustainable.

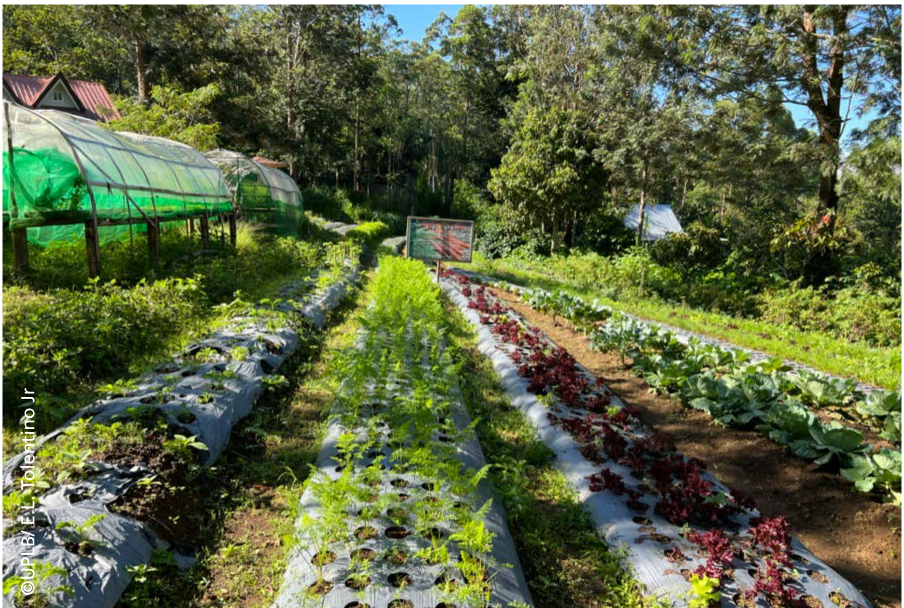
Figure 1. Map showing the Manupali watershed in Mindanao, Philippines



Source: **DENR-INREMP.** 2021. *Rehabilitation Management Plan for the Manupali Watershed in the Upper Bukidnon River Basin*. Produced in partnership with DENR Region 10 and the Bukidnon Watershed Protection and Development Council, with technical assistance from the Center for Environmental Studies and Management, Quezon City, Philippines.

Figure 2. The Binahon Agroforestry Farm in the Manupali watershed showing degraded land and remaining forests in the protected areas

Contour hedgerow and multistory planting at the Binahon Agroforestry Farm



An example of contour hedgerow planting at the Binahon Agroforestry Farm

Biodiverse forest is an attraction for visitors on the trails on the Binahon Agroforestry Farm

Organic fertilizer production at the Binahon Agroforestry Farm

Example of livestock raising practised at the Binahon Agroforestry Farm

Partnership between the Binahon Agroforestry Farm and researchers

Production of seedlings for sale at the Binahon Agroforestry Farm, maximizing diversity in the space available

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CASE STUDY 13

Provenance and progeny trials of indigenous and naturalized species in Kenya

David Odee,[1] Emmanuel Makatiani,[2] Annika Perry,[1] John Otieno[2] and Stephen Cavers[1]

[1] UK Centre for Ecology and Hydrology, Penicuik, Midlothian, United Kingdom of Great Britain and Northern Ireland

[2] Kenya Forestry Research Institute, Nairobi, Kenya

BACKGROUND

The significance of forest and landscape restoration (FLR) cannot be gainsaid. Forests are vital natural resources, covering about 31 percent of the Earth's land surface or 4.06 billion hectares (ha), but just in the last decade, the forest area has decreased by 10 percent (420 million ha) because of deforestation (FAO, 2022). Africa's dryland forests and woodlands have been severely impacted by excessive harvesting of wood for timber, charcoal and firewood production. Forest and landscape restoration is one of the key pathways for improving environmental management and human livelihoods and meeting cultural needs. Several global restoration commitments recently made by nations will require the availability of native tree genetic planting material that best matches the site conditions and objectives of restoration in a changing climate (Fremout *et al.*, 2021). In Africa, the AFR100 is a country-led effort aiming to restore 100 million ha of deforested and degraded landscapes across Africa by 2030, and which seeks to accelerate restoration in order to enhance food security, increase climate change resilience and mitigation, and combat rural poverty (Djenontin, Zulu and Etongo, 2021). The Great Green Wall for Sahara and the Sahel is another restoration initiative in Africa, which focuses mainly on drylands (see https://climateinitiativesplatform.org/index.php/Great_Green_Wall_for_Sahara_and_the_Sahel_Initiative). Its objective is to grow a line of trees and plants across the entire Sahel over 8 000 kilometres (km), from the Atlantic coast of Senegal to the east coast of Djibouti – halting desertification and creating a huge swathe of green across the entire African continent. More than 20 African countries are involved: Algeria, Benin, Burkina Faso, Cabo Verde, Cameroon, Chad, Djibouti, Egypt, Eritrea, Ethiopia, Gambia, Ghana, Libya, Mali, Mauritania, Niger, Nigeria, Senegal, Somalia, Sudan and Tunisia. The Great Green Wall provides another opportunity for restoration actions in sub-Saharan Africa under the United Nations Convention to Combat Desertification (UNCCD) seeking to build resilient landscapes in the face of climate change.

In Kenya, forest restoration is of high priority and enshrined in the government's legislation and policies. For instance, the Constitution of Kenya (Kenya, 2010) calls for reforesting and maintaining a tree cover over at least 10 percent of the country (Ministry of Environment and Natural Resources, 2016). The Kenyan Government has committed to restore 5.1 million ha under the AFR100 initiative, focusing on seven key priority intervention areas, namely afforestation and reforestation of natural forests, rehabilitation of degraded natural forests, agroforestry, commercial tree plantations, tree buffers along water bodies, tree buffers along roadways and railways, and rangeland restoration and management. To achieve these goals, it is important to consider the genetic quality and suitability of planting material for the varied priority intervention areas. Much research on tree genetic resources and improvement has been devoted to species having commercial value for timber – mainly the exotic eucalypts, pines and cypresses. However, there is now an upward trend in research attention to indigenous or naturalized species identified as priorities with potential for diverse and multipurpose local use, but the number of studies is still limited. Provenance trials are used to compare the performance of germplasm from different geographical origins within a single location (hence the often-used name of common garden). Progeny trials are used to compare the performance of specific mother trees or families within a provenance, also in a common garden. The two can be converted into seed production orchards after selective thinning. Thus, common gardens are crucial not only for identifying the genetic component of observed phenotypic differences but also in the development of appropriate tree germplasms for the restoration of landscapes. Here, we report on two case studies on seldom researched indigenous or naturalized species with potential for landscape restoration that considers the balance between biodiversity conservation and local communities' socioeconomic and cultural needs.

These two examples of provenance and progeny trials analyse and select for traits of interest such as productivity and drought tolerance.

EXAMPLE 1

Establishment of seed orchards and progeny trials: the genetic performance and plus tree traits for *Melia volkensii* in the drylands of Kenya (based on Kariuki *et al*., 2021)

Melia volkensii, locally known as mukau is a broadleaved tree species belonging to the Meliaceae family, native to arid and semi-arid areas (ASALs) of eastern Africa with geographical distribution in Ethiopia, Kenya, Somalia and the United Republic of Tanzania (Kariuki *et al.*, 2021). Mukau is a fast-growing, termite-resistant tree producing wood of excellent quality and non-timber forest products, which is suitable for commercial forestry and agroforestry. The wood is good for making furniture, acoustic drums, containers, mortars, door and window frames, and doors, shutters and rafters. The tree is also used to produce beehives, for wood carving and as mulch. The mukau seed orchard progeny trials were established through collaboration between the Kenya Forestry Research Institute (KEFRI) and the Japan International Cooperation Agency (JICA) on a project on the development of drought-tolerant trees.

Seed orchards

One hundred candidate plus trees (CPTs) of *M. volkensii* were identified and selected for progeny (scions) collection from its native range in the ASALS of Kenya. Candidate plus tree selection was based on stem straightness, growth vigour, branch size and number and health. Scions from the 100 CPTs were used for grafting. The grafted seedlings were raised in the nursery for 4 months and made to establish at two sites, Kitui and Kibwezi. Each orchard had 100 clones of plus trees each, where five ramets were planted at 6 metre (m) x 6 m spacings in six blocks, resulting in 3 000 seedlings per site.

Progeny trials

Progeny trials were established from the seed orchards, and from the original CPTs in the field for orchard families that had not started seeding. The trials were established in four ecoregions based on climate and the distribution range of *M. volkensii*. The progeny tests were of two types – main and subprogeny – and were located in Marimanti (main), Gaciongo (sub) and Makima (sub) in the north; Tiva (main), Kibwezi (main) and Ikithuki (sub) in the middle areas; and Kasigau (main) and Voi (sub) in the south. Tree height and diameter at breast height (DBH) were assessed twice a year, starting at 6 months, until the trees were 5 years old.

General growth trends

There was wide variation in growth parameters. The average height at 5 years ranged from 3.4 m to 9.8 m, while DBH ranged from 3.1 centimetres (cm) to 21.6 cm. The best performing clones were different among the sites, indicating a site effect. Evaluation of fecundity showed that there were 477 progeny trees with fruit, representing 13.5 percent of the total trees. Similarly, evaluation of disease tolerance showed that 240 progeny trees were infected by fungal disease, representing 6.8 percent of all trees in the progeny trials at 5 years. Overall, tree height showed highest heritability. On the other hand, stem growth had low heritability but showed that tree form is a heritable trait in *M. volkensii*. Heritability varied among sites, which was demonstrated by small environmental effects on the ranking of tree height across the sites.

EXAMPLE 2

Moringa oleifera and _Moringa stenopetala_ provenance and progeny trials (based on Odee _et al._, forthcoming; Kumssa _et al._, 2017a, 2017b)

The drumstick tree *Moringa oleifera* (Moringaceae) is a multipurpose tree that is probably native to the foothills of northwest India but is now cultivated in all tropical countries. The lesser-known cabbage tree *Moringa stenopetala* is native to southern Ethiopia and northern Kenya. Both are fast-growing, drought-resistant trees cultivated for their nutritious leaves, but their various tissues are also used as food, herbal medicine, fodder, fuelwood and gum. The trees are also used for hedges and water purification.

The moringa provenance and progeny trials were implemented through the NERC-UKCEH subproject Using Genetic Resources for Better Trees of the wider project on Sustainable Use of Natural Resources to Improve Human Health and Support Economic Development (SUNRISE), in collaboration with several national and international research agencies in East Africa, namely, South Eastern Kenya University, KEFRI and World Agroforestry (ICRAF). The main objectives of the provenance and progeny trials were to characterize genetic variation in important productive trees, select moringa varieties optimized for key locally preferred traits (e.g. production, nutritional quality, drought and disease resistance), establish resources to supply the market, such as gene and seed banks, and build capacity among local stakeholders through training in finding, conserving and using genetic resources sustainably.

These trials were established in three ecoclimatically contrasting dryland sites to study genetic variation at provenance and within-provenance levels. The trials will be used to determine whether local populations provide sufficient, genetically diverse seed suitable for restoration; assess the extent to which genetic variation in phenotype reflects adaptation to source site conditions; evaluate the extent to which desirable traits are under genetic control and therefore accessible to selection for improvement; understand how trade-offs among traits deliver preferred trait qualities and how this might be optimized to plan source matching for new planting; assess the extent of plastic response in mean family or provenance phenotype using spatial environmental variation to assess likely variation in preferred traits with planting site or temporal climatic variation.

Indigenous knowledge, engagement and capacity building are essential in sourcing and selecting quality germplasm with desirable traits for restoration. Prior to seed collection, an extensive survey was conducted in moringa-growing areas with local communities to assess the uses of moringa. Nearly 80 percent of moringa-growing households used moringa leaves as a source of food. Other uses of moringa include as medicine and fodder, for shade and agroforestry, and as a source of income, thus indicating the value of moringa as a multipurpose species.

Seed collection

One hundred and twenty moringa trees (up to 20 trees per population) were sampled from ten natural populations in Kenya, equivalent to eight provenances of the naturalized *Moringa oleifera* (Kitui, Kilifi, Mtongwe, Ramogi, Mbololo, Kibwezi, Gede and Msambweni), and two provenances of the native *M. stenopetala* (Baringo and Isiolo). At least ten mature fruits (pods) were collected per mother for trait analysis of pods and seeds. Progeny seedlings were raised in the nursery for 4 months and transplanted to three trial sites (Kitui, Kibwezi and Ramogi) at 3 m × 3 m spacings laid out in a randomized complete block design. There were eight populations of *Moringa oleifera* (provenances Kitui, Kilifi, Mtongwe, Ramogi, Mbololo, Kibwezi, Gede and Msambweni) and two populations of *M. stenopetala* (provenances Baringo and Isiolo); seven families of each population and ten individuals per family.

Genetic status

Previous genetic analysis reported high levels of population differentiation and suggested at least two sources for the *Moringa oleifera* germplasm introductions to Kenya from India (Muluvi *et al.*, 1999). Genetic analysis of present collection (provenances and progenies) using single nucleotide polymorphism (SNP) markers has shown similar trends but with higher resolution suggesting a third source of introduction. However, the native *Moringa stenopetala* populations revealed lower diversity and a higher degree of inbreeding than *Moringa oleifera* (unpublished data). The mother trees showed high variation in fruit and seed traits between the Kenyan species and among the Kenyan populations. The observed variations can be explained in part by the interactions between genetics and the environment (local conditions, including management).

Early assessments of the trials showed significant differences in tree survival and growth between the species and among provenances, indicating genetic differences. The differences varied depending on the trial sites.

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For more information, please contact:

Forestry Division - Natural Resources and Sustainable Production
E-mail: NFO-Publications@fao.org
Web address: www.fao.org/forestry/en

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