Conserving and using tree diversity for global climate change adaptation and food system resilience

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A report to the Global Crop Diversity Trust, Centre for International Forestry Research-World Agroforestry (CIFOR-ICRAF) and Botanic Gardens Conservation International (BGCI)

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Executive summary and recommendations

This report, focussed on tropical developing countries, explores:

1. How tree diversity can most effectively be conserved and used for smallholder livelihoods and food security in resilient landscapes, in particular in the face of a changing climate, and

2. The role of collections-based R&D organisations in supporting such conservation and use.

It is noted that tree diversity, both species diversity and intra-specific genetic diversity, is crucial for the resilience of food production systems in the face of global change which includes increasing human populations, declining agricultural productivity, climate change and extremes, and invasive species. A remarkable 7,770 tropical tree species have been recorded as being used for human food, but the majority are scarcely utilised. Furthermore, about 30% of the approximately 60,000 known tree species are considered threatened and with their genetic diversity steadily being eroded. Loss of intraspecific diversity is not only a precursor to extinction, but reduces the opportunities for adaptation and genetic improvement, including of many lesser-known and underutilized food trees vital to human nutrition and food security.

Both large scale reforestation projects, for climate change mitigation and to address desertification, as well as major plantation projects and smallholder plantings are too often using inappropriate or sub-optimal tree germplasm. This is due to lack of awareness, lack of technical know-how and lack of seed of the most appropriate species and sources in the quantities needed, typically at short notice.

The key recommendations and observations of this report are that:

1. Greater emphasis is placed on incorporating local tree species in all reforestation and tree planting: these species are often well-known and appreciated by local people[1], generally well-adapted and needed for biodiversity conservation.

2. In choosing seed sources, a balance needs to be struck between using strictly local sources and a broader mixture of seed sources, as the latter will have greater diversity, reduced inbreeding in subsequent generations and allow for adaptation to the site, especially as climate change is altering local environmental conditions, including pest and disease vulnerabilities. More research is needed on the relative benefits of using local seed sources, compared with nearby seed sources and mixed provenance seed sources, including those which may be better climatically adapted (as a result of experienced and modelled climate change).

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[1] Within a generation there can be an almost complete loss of traditional tree and agrobiodiversity knowledge and this is a global problem.

[2] These could be local 'offshoots' of field gene banks and used for local multiplication (L. Graudal, pers. comm.)

3. Breeding tree seedling and seed orchards, preferably as mixed plantings of unrelated species, need to be established in many key locations throughout the tropics to provide high quality, diverse seed of many useful local tree species (including both for socio-economic value and food, and also for ecological restoration). These orchards need to be managed so as to provide a level of genetic improvement which will enhance tree performance. For seed orchards of food tree species then these ideally would be located near to a market, and managed by a local community, cooperative or an extended family, such that surplus produce-as well as seed-can be sold to defray the costs of managing the orchards[2]. A complementary activity is to identify, register and protect seed stands, both natural and planted, for the main tree species in demand for tree planting (as is being done in the Norwegian-funded ICRAF/Ethiopian PATSPO project).

4. The role of collections-based research organisations in supporting conservation and use of tree has been expanding, with excellent examples being Kew's Millennium Seed Bank Partnership, ICRAF's field gene banks and its PATSPO project, CSIRO Australian Tree Seed Centre's seed orchards in Australia and SE Asia, BGCI's Ecological Restoration Alliance of Botanic Gardens and planned Global Biodiversity Standard, a certification system focussed on biodiversity conservation, and safety duplication of tree seed samples from the MSB and ICRAF GRU in the Svalbard Global Seed Vault. It is vital and recommended that donors continue to provide long-term support and substantially upscale these and similar efforts.

5. It is recommended that the returns on investment in diverse tree seed production for new tree plantings, in terms of carbon sequestered, socio-economic benefits including enhanced food security and nutrition, and biodiversity conservation, be properly investigated and quantified. Such investments are expected to deliver massive benefit:cost ratios greater than 50, as found in tree improvement and seed development projects in Asia, and being demonstrated in Ethiopia, and will spur much needed investment in this fundamental activity underpinning human advancement and survival in the developing tropics.

6. It has long been known in agriculture that "*Good Seed Does Not Cost – It Pays*!" (de Jong, 1960), and the same applies to cultivating trees. The costs of failing to support diverse tree seed development and not having available seed of "the right tree, to plant in the right place for the right purpose" in sufficient quantities will be dire. Negative consequences include a greatly reduced amount of carbon sequestered (considerably less than half of that from well-designed plantings), the loss, often irreplaceable, of unique tree species and intra-specific diversity, and risk of alien species transforming and obliterating native forest ecosystems.

7. Agroforestry systems require the use of diverse tree species and hence the longterm vision for ICRAF and partners must be to support the conservation and use of all tree species that local communities value and use. It is recommended that ICRAF continue to take the lead in enhancing tree diversity in agroforestry systems and more broadly in forest landscape restoration, building on its pioneering work in domestication of African tree species, including the African Orphan Crop Consortium initiative, and development of markets for agroforestry products.

8. It is essential that longer-term funding be secured for ICRAF GRU to manage and expand its seed bank and live *ex situ* collections—the most extensive agroforestry collections globally and vital for human food security and nutritional balance, smallholder

agroforestry systems and livelihoods. As an initial step, and to be completed within the next three years, it is recommended to expand the ICRAF GRU genebank through coordinating with national partners to fill gaps in seed collections of the 13 priority agroforestry tree species identified in 2017. The need is much bigger, however, and the ambition ought to be to cover many hundreds of tree species based on a network of bilateral partnerships with many countries.

9. For BCGI members and partners, it is recommended, when allocating the limited available resources to conservation of rare trees in reforested areas, that species priorities be on:

    - genetically distinctive species, e.g. monotypic genera and those with few other related species,
    - species that play a unique role in ecosystem functioning,
    - commercially valuable species which have been threatened due to overharvesting,
    - wild food trees and their close relatives given increasing recognition of the roles of food trees for human nutrition and health, and
    - species with poor dispersal mechanisms, including those whose animal seed pollinators and dispersers may be reduced or absent.
      R&D is also needed into new methods and technologies that support these initiatives, including direct payments to conservers, digital technologies including GPS, citizen science, and individual tree microchipping.

10. The first State of the World's Forest Genetic Resources was published in 2014, based on reports from 86 countries (FAO, 2014). However, much of the report was developed from information that was ten or more years old and much has changed especially the impacts of climate change and invasive species on forest and woodland ecosystems, and reduced institutional capacity in developing countries to conserve, manage, improve and use their tree genetic resources. A second State of the World report is currently under preparation and will provide a vital resource for forest scientists, decision makers and donors.

1.0 Introduction

This report focusses on tropical developing countries and will explore:

1. How tree diversity can most effectively be conserved and used for smallholder livelihoods and food security in resilient landscapes, in particular in the face of a changing climate, and

2. The role of collections-based R&D organisations in supporting such conservation and use.

After a discussion on the scope of tree diversity (1.1), chapter 1 looks at an increasing role for tree diversity in underpinning resilience of food production systems and climate change adaptation and mitigation (1.2), followed by an introduction to the key organisations holding tree diversity germplasm (1.3). Chapter 2 examines the roles of tree genetic resources in sustainable livelihoods and food systems within resilient landscapes in the context of climate change (2.2), in promoting sustainable livelihoods (2.3) and in promoting sustainable, safe and nutritious food systems (2.4). Chapter 3 discusses the role of collections-based research organisations in supporting resilient landscape approaches to tree diversity conservation and management. Strategies to strengthen the integration of different approaches to tree diversity conservation, including *ex situ*, circa situm and in situ, are examined in chapter 4. Approaches to enhancing the use of diverse tree genetic resources are discussed in chapter 5, including through reference to important examples of current tree planting and reforestation programs and their sources of germplasm (5.1), germplasm now being used in tree plantings and reforestation in the developing tropics (5.2), and in agroforestry, restoration and reforestation (5.3). Chapter 6 discusses approaches to prioritising tree species for conservation and use being developed by ICRAF (6.1), BCGI (6.2) and used in large-scale reforestation projects (6.3).

1.1 The scope of tree diversity

Forest and tree genetic resources—the genetic diversity present in thousands of useful forest and woodland trees, other woody species and tree-like plants—have long been recognised as an intergenerational resource of vast social, economic and environmental importance (Amaral et al., 2004). Tree diversity abounds at different taxonomic levels: Firstly, the diversity at higher levels in conifers (gymnosperms), flowering trees (angiosperms), tree-like monocotyledons (bamboos and palms), their constituent plant families and genera with 58,497 known tree species[3] (Beech et al., 2021). Secondly, the intraspecific or within-species diversity is very high in trees—typically outbreeding, long-lived organisms—compared with other organisms. Genetic diversity within tree species—vital to their conservation, management and use—is also essential to the functioning of the man-made production and more natural ecosystems in which they grow. Devastatingly, intraspecific diversity is continuously and increasingly rapidly being lost due to extirpation of genetically distinct populations of tree species from land use change, climate change, overharvesting and invasive alien species (BCGI, 2021).

[3] More thorough botanical exploration and research, especially in the humid tropics, will likely reveal many more tree species that are currently unrecognised or unknown.

Trees, woody shrubs and arborescent monocots (bamboos, bananas, palms) are vital to smallholder agroforestry food production systems in the developing tropics. Their roles include as food producing species – several thousand species producing edible nuts and seed, oils, fruits, shoots and leaf, staples, nutraceuticals, spices and flavouring agents, with many species providing multiple food types. Indeed 7,770 tropical trees have been documented as providing human food (Food Plants International database and Bruce French, pers. comm.). However, the majority of these wild plants are scarcely used for food (e.g., Termote et al., 2012), but may be vital in times of food scarcity and famine. Some examples, to illustrate the importance of food trees in tropical, developing countries as well as the vast diversity across plant families and genera are given in Annex 1. There are also several thousand wild relatives of food trees in genera such as Acacia (wattles), Adansonia (baobabs), Artocarpus, Barringtonia, Burkella, Canarium, Citrus, Diospyros (ebony), Garcinia (mangosteens), Mangifera (wild mangoes), Musa (wild bananas), Myristica (wild nutmegs), Olea europaea subsp. cuspidata (African olive), Syzygium and Terminalia. Trees are also the source of nutrients for many edible fungi: these include numerous edible ectomycorrhizal fungi, such as truffles (mainly Tuber spp.), which have symbiotic relations, many quite specific, with tree root systems. Other edible mushrooms such as cloud ear fungus (Auricularia polytricha) and shitake mushrooms (Lentinula edodes) are cultivated on the dead wood of Quercus and many other tree species.

Tree diversity is also important for providing food for both domesticated and wild animals, including foods derived from natural and farmed systems in the tropics. There are thousands of tree species providing essential food resources for honey bees (e.g., Workman & Struthman, 2015), as well as native bees and other pollinators. These pollinators are often necessary for fruit and seed production in many horticulture, agroforests and native forests. A few examples of tree species acting as honey bee nectar sources include Calliandra (powder puffs), Citrus, Corymbia (bloodwoods), Cordia africana (Sudan teak), Englerophytum, Eucalyptus (gums), Geiossois (vure), Grevillea (silky oak), Julbernardia, Maerua, Melaleuca (paperbarks), Mimusops, Arecaceae (palms), Pterocarpus (rosewoods) and Vitex. Examples of trees that are excellent pollen sources for honey bees include Acacia (wattles), Archidendron, Artocarpus, Calophyllum, Citrus, Dichrostachys, Dodonaea, Eucalyptus, Helicia, Horsfieldia, Peltophorum, Pimenta, Syzygium and Zizyphus. A smaller number of tropical tree species are sources of the resinous compounds used by bees to make propolis: these include Dalbergia cochinchinensis (Thai rosewood) in SE Asia, Clusia major and C. minor in Cuba and Venezuela, Populus euphratica (desert poplar) in the Middle East and China, and P. ilicifolia (Tana River poplar) in Kenya (Bankova et al., and author observations). New research has revealed that honey bees are seeking out diverse floral tree resources in tropical landscapes, including where trees are scarce (Cannizzaro et al., 2022).

Diverse fruit-bearing tree species such as Cananga (ylang-ylang), Canarium, Dysoxylum (rosewoods), Elaeocarpus (quandongs), Endospermum (whitewoods), Ficus (figs), Fragraea, Litsea, Musa sect. Australimusa (fehi banana – species and cultivar groups, Thomson et al., 2021), Macaranga, Myristica (nutmegs), Phyllanthus, Planchonella, Pleiogynium timorense (Timor plum), Rhus and Syzygium provide food sources for pigeons and fruit doves which in turn are important dispersers of fruit and seeds and important local human food sources. Wild fruit trees are used by local peoples to hunt and catch frugivorous birds for a protein-rich meal. Large, flightless Cassowaries are recorded eating over 238 species of rainforest fruits, mostly tree and shrub species (Westcott et al., 2005) and in turn they play an important role in seed dispersal and maintaining the diversity of the rainforest. Correspondingly, the diversity in their rainforest food tree species is essential to the diets of cassowaries, with the northern species of cassowary being the most highly regarded and expensive human food in Papua New Guinea. These examples represent a tiny fraction of the nexus that exists between tree species diversity, animals and human food in the developing tropics.

In the wet/dry tropics, semi-arid and arid zones there are many hundreds of tree and woody shrub species browsed by ruminants (cattle, camels, goats and sheep). These tree forages are vital to the productivity and sustainability of rangeland agro-ecosystems, especially during the dry season and times of drought when other feed is not available. In West Africa some local tree forages include Acacia/Sengalia spp., Boscia albitrunca (motlopi), Colophospermum mopane (mophane), Combretum spp. (bushwillows), Euclea spp., Grewia damine (mogwana), Gymnosporia senegalensis (mothono), Lonchocarpus capassa (mhata), Peltophorum africanum (mosetlha) and Terminalia prunioides (motsiara) (Aruwayo & Adeleke, 2019). In East Africa, important forages for dairy cattle include mainly exotic N-fixing trees, viz. Calliandra calothyrsus (calliandra), Chamaecytisus palmensis (tree lucerne), Gliricidia sepium (gliricidia), Leucaena diversifolia, L. pallida and L. trichandra (leucaena), Morus alba (white mulberry) and Sesbania sesban (sesban) (Wambugu et al., 2006).

There are also myriad other minor uses of trees that feed into food systems including, for example, eating utensils such as chopsticks from bamboo species, toothbrushes from Salvadora persica (toothbrush tree) and Dalbergia sissoo (shisham), and as natural insecticides, e.g., the dried leaves of Azadirachta indica (neem) are placed at the top of containers of seeds and flour to deter weevils in West Africa.

Throughout the developing tropics there are myriad different tree species that are essential and useful components of traditional and modern agroforestry systems: this tree diversity, including within-species diversity, is integral to the productivity and sustainability of such agro-ecosystems including through providing both services (increased soil fertility, windbreak function, shade) and products (food, animal fodder, traditional medicines, fuelwood, timber). Trees are essential for maintaining the fertility of soils in agroforestry systems (e.g., Pinho et al., 2012) through nutrient addition (fixation of atmospheric nitrogen by N-fixing trees) and organic matter, both labile and longer lasting forms of carbon, mobilisation of fixed plant nutrients through their mycorrhizal associations, especially phosphorus), release of chelating organic compounds which enable uptake of some plant nutrients, cycling of mineral nutrients which are located or which have leached below the crop root zone and sand stabilization (Figure 1).

Nitrogen-fixing trees and woody shrubs for agroforestry include Acacia, Faidherbia, Senegalia & Vachellia (acacias/wattles), Albizzia (silk trees), Alnus (alders), Calliandra (powder puffs), Casuarina & Allocasuarina (sheoaks), Cynometra, Cytisus proliferus (tree lucerne), Dalbergia (rosewoods), Erythrina (coral trees), Falcataria moluccana (Moluccan albizia), Flemingia, Gliricidia sepium, Gymnostoma (velau), Hippophae (sea buckthorn), Inocarpus (Polynesian chestnut), Leucaena (ipil-ipil), Maniltoa, Parkia, Pithecellobium (blackbeads), Pongamia, Prosopis, Pterocarpus (rosewoods), *Serianthes* (vaivai), *Schleinitzia*, *Sesbania* (rattle pods) and *Stryphnodendron* (barbatimão). Some tree species which are noted to have outstanding potential to increase soil fertility in agroforestry systems include *Acacia mangium* (mangium), *Acioa barteri* (monkey fruit), *Bischofia javanica* (koka), *Faidherbia albida*, *Grevillea robusta* and *Guettarda speciosa*. The N-fixing Faidherbia albida has been referred to as the keystone of sustainable agriculture in seasonally dry tropics in Africa with its unique reverse deciduous habit which makes it ideal for inclusion in agroforestry cropping systems. In the humid tropics Acacia mangium and Acioa barteri in Asia-Pacific and Africa, respectively, have a remarkable ability to transform acidic tropical soils in a few years, with degraded soils quickly becoming enriched with organic matter and mineral nutrients, turning dark brown, and with a layer of decomposing litter and worm castings.

Figure 1. *Acacia crassicarpa* and *Casuarina equisetifolia* planted for sand stabilization, Hainan, China: these two tree species fix atmospheric nitrogen using different microbes, viz. *Rhizobium* and *Frankia*, respectively, and increase soil nitrogen and carbon (Photo: Khongsak Pinyopusarerk).

Fuelwood and charcoal remain the cooking and heating fuels of choice for most people in the developing tropics; with an estimated 880 million people worldwide spend part of their time collecting fuelwood or producing charcoal, many of them women (FAO & UNEP, 2020). In Africa, Latin America and Asia, 58%, 15% and 11%, respectively of the energy supply comes from fuelwood and charcoal (Salim & Ullsten, 1999). Several thousand different tree species are used as fuelwood on a daily basis, which constitutes a major and carbon-neutral fuel when trees are replanted and regrown. While much fuelwood comes from fairly common secondary species and planted trees, the removal of substantial amounts of wood, including harvest of rarer tree species for charcoal manufacture, threatens local forest biodiversity. Utilization of the genetic diversity present in fast-growing, coppicing, fuelwood species, such as *Eucalyptus camaldulensis* (river red gum) and *Leucaena leucocephala*, will be required for their most effective deployment in new planted forests and agroforestry settings (e.g., Burley, 1980). A focus of development agencies and NGOs has been to develop cleaner burning stoves in order to reduce the health hazards posed by wood smoke. On the other hand, sometimes the smoke generated helps to protect traditional buildings from insect attack, or is useful for food preservation, e.g., *Canarium harveyi* (nangai) nuts are preserved from wood stove smoke in Torba province in northern Vanuatu.

Tropical tree diversity is also vital for timber and fibre production, providing environmentally friendly materials for buildings (i.e., carbon-sequestering wood cf. energy intensive cement, bricks and steel), clothing (e.g., rayon cf. petrochemically-derived synthetic fabrics which are major of microplastics), and packaging (i.e., paper cf. plastics). Many thousands of tropical tree and arborescent monocot species are utilised for timber and fibre:

- *Agathis* (kauri), *Chlorocardium rodiei* (greenheart), *Gmelina arborea* (white teak), *Intsia bijuga* (*merbau*) and *Tectona grandis* (teak) for boat building;
- *Parchira quinata* (*pochote*), *Cordia alliodora* (Ecuador laurel), *Dicorynia paraensis* (*angelique*), *Syncarpia glomulifera* (turpentine) for teredo-resistant marine piles;
- *Callitris intratropica* (blue cypress-pine), *Flueggea flexuosa* (*poumuli*), *Fagraea gracileps* (*buabua*), *Milicia excelsa* (African teak) and *Syzygium inophylloides* (*asi toa*) for naturally durable timber, poles and posts in high decay environments;
- *Khaya*, *Entandrophragma* & *Swietenia* (mahogany), *Dalbergia*, *Diospyros* & *Pterocarpus* (rosewood and ebony), and *Cedrella*, *Dysoxylum* & *Toona* (cedar) for furniture;
- *Bambusa*, *Dendrocalamus*, *Chusquea*, *Guadua*, *Phyllostachys*, *Oxytenanthera abyssinica* bamboo timbers, including to provide flexible, strong, safe buildings in earthquake zones;
- *Borassus*, *Cocos* and *Hydriastele* for dense palm wood flooring;
- *Aquillaria* & *Gyrinops* (eaglewood), *Boswellia* (frankincense) *Commiphora* (*myrrh*) and *Santalum, Osyris* & *Vavaea* (sandalwood/false sandalwood) for fragrant woods (Figure 2);
- *Pinus* for long-fibred pulp (tissues and bags with high burst strength) and
- *Eucalyptus* and tropical *Acacia* spp. for veneers and short-fibred pulp (paper for liquid packaging, containerboard and high-quality printing).

There are hundreds of genera and species—including numerous species of *Acacia*, *Eucalyptus* and *Pinus*—providing building timbers. A high proportion, possibly the majority, of tropical tree species are multipurpose and will have various wood, cultural and traditional medicinal uses. Furthermore, it needs to be borne in mind that smallholder income derived from the sale of wood and other tree products is often vital for their food security.

This brief introduction to tropical tree diversity serves to underline the importance of diversity, both within and among tree species, for providing a vast range of forest services and products, especially to smallholder farmers and tree growers. It also indicates the importance of prioritisation of tree species for conservation and their effective deployment in planted and managed natural forest and agroforestry systems, a challenging subject which will be addressed later.

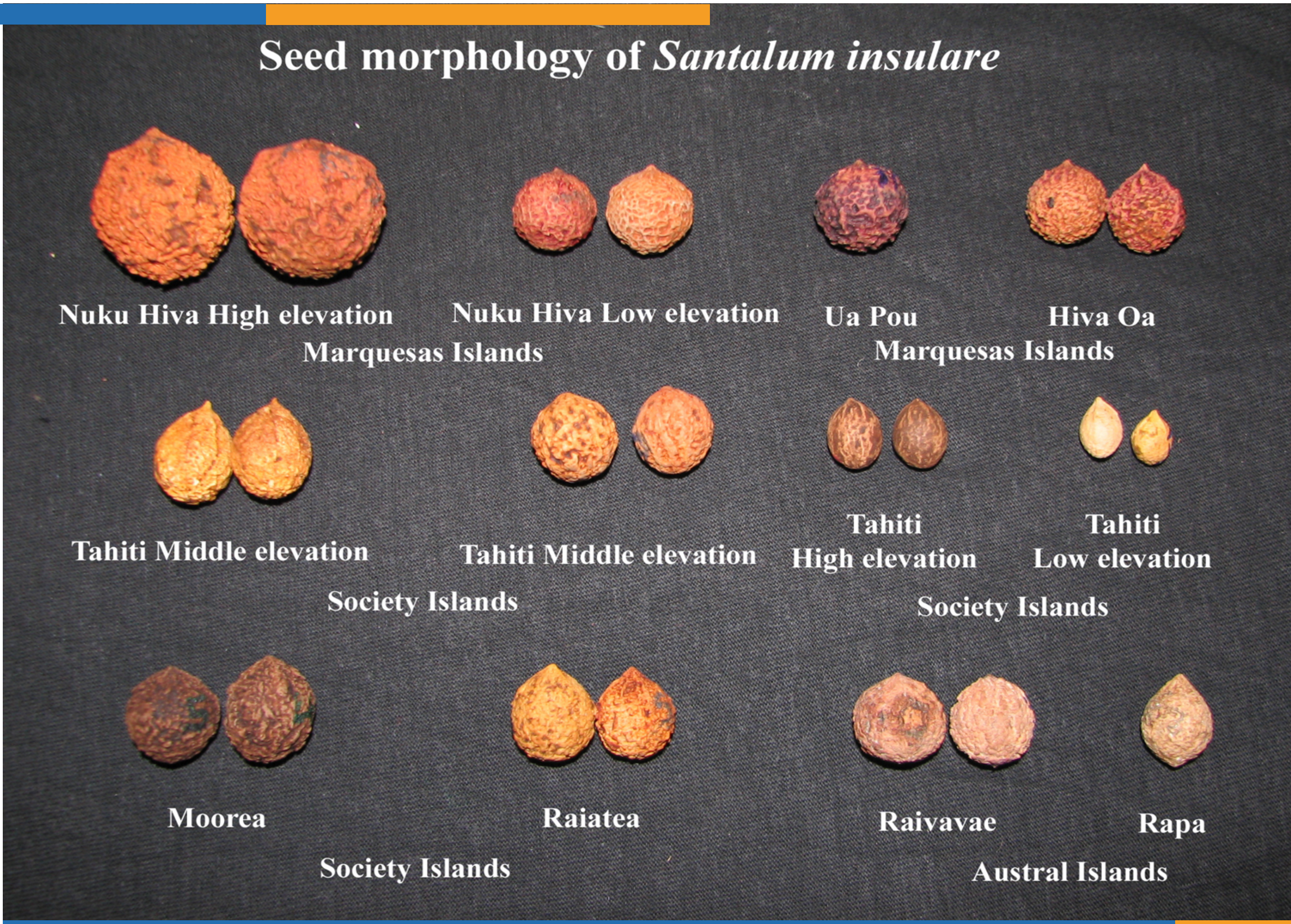

Figure 2. Variations in nut characteristics in Polynesian sandalwood (Santalum insulare), the nut being previously consumed on the Marquesas Islands (Photo: J-F Butaud). Genetic variation is also high in traits such as the chemistry of the precious heartwood.

1.2 The biological key to sustainability in the face of climate change

The growing global human population, and its need to be fed, is putting increased pressures on food production systems. The global food system is, at present, founded on extraordinarily low diversity, which is negatively affecting dietary quality (Jansen et al., 2020). Large scale monocropping systems of corn, wheat and rice, which produce more than half of the human food calories globally, are now running into sustainability issues due to declining soil fertility, loss of soil structure, increased salinization, erratic and less predictable weather patterns and other factors which have yet to be properly understood. Increased demand for meat protein has been leading to the clearance of lowland tropical forest for cattle ranching, as evidenced in the Amazon basin in Brazil. Such land use changes are having massive detrimental effects for greenhouse gases, firstly the release of carbon from the cut trees and secondly the methane produced by the ruminant cattle. One of the first casualties of broad-acre, mechanised farming is the loss of trees in the landscape. Similarly, there has been a breakdown of smallholder traditional tree-rich agroforestry systems due to *agrodeforestation*—a process that has destroyed traditional agroforestry systems, in which a wide range of culturally and ecologically valuable trees, plants and wild and domesticated animal life were deliberately planted and protected within a matrix of staple food and other ground crops (Thaman 1989, 1992, 2014). It will be essential for trees to be reintegrated back into both large-scale commercial and smallholder farming systems as part of a suite of measures to restore and sustain their productivity. In the Amazon and elsewhere, it will be necessary to convert some pastoral lands and other deforested sites back to forest, to sequester carbon in the effort to avert dangerous climate change. The availability of germplasm of diverse pioneer/early successional or framework tree species[4] will be critical to the success of such reforestation programs. It is imperative that carbon sequestration and other reforestation projects pay greater attention to the choice, sourcing and delivery of planting material, to better ensure the quality and performance of the planted trees (Jalonen et al., 2018; Roshetko et al., 2018).

While deforestation continues in some tropical regions, forest cover has increased in others (Aide et al., 2013; Asner et al., 2009; Redo et al., 2012; Rudel et al., 2005; Sloan 2008). Globally, tree cover has increased by over 2.24 million km^2 since 1984 (Song et al., 2018), with this net increase due to an expansion of temperate forests (both planted and from natural regeneration) while biodiverse tropical forests are being lost. Nevertheless, the proportion of total forest area designated primarily for biodiversity conservation increased in all global regions between 1990 and 2020 (FAO, 2020).

Tropical and temperate forests are already being forever altered due to climate change, both in their structure and species composition. The most radical changes follow extreme weather events, such as severe tropical cyclones in rapid succession or droughts coupled with heat waves and wildfire. In New Caledonia (2006) and SE Queensland, Australia (2019) intense fires burned into lowland tropical rainforest, which have never experienced fire in human history, and has devastated these plant communities and threatened many tree and other species (UNESCO, 2020). Over the past 20 years there have also been massive fires in sclerophyllous-chaparral forest in southern Europe, southern Australia and California, the latter extending into the iconic Sequoia National Park in 2021. These forest communities are adapted to fire, but the intensity and scale of the fires mean they will take a long time, if ever, to recover. In 2021, boreal forests in Canada, Siberia and the Far East region of Russia were hit by unprecedented wildfires, following record-breaking heat waves and drought. The burning and destruction of peat forests in Indonesia and many parts of the world (Page & Hooijer, 2016), while often associated with their drainage, is closely connected with new warmer and drier climate regimes. Similarly, overwintering fires in deep organic soils in boreal forests are associated with climate change (Scholten et al., 2021).

Some tree species with narrow climatic envelopes and/or limited options for movement, such as mountain top forest species, will likely disappear altogether from their native habitats. Globally many tree species are committed to extinction from climate change as their former climates will disappear, e.g., climatic modelling predicts that the habitats for 16 eucalypt species in Australia will disappear altogether (González-Orozco et al., 2016). However, depending on the time frame involved, some tree species will be able to adapt and survive in their new climates as a result of their inherent high levels of genetic diversity. Human intervention will be needed to assist selected and priority tree species and populations to survive climate change. One example of many would be the Barrington Tops and Ebor (Northern New South Wales, Australia) populations of *Eucalyptus nitens* (shining gum).

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[4] Framework species are indigenous forest trees which, when planted on deforested land, help to re-establish the natural mechanisms of forest regeneration and accelerate biodiversity recovery. Characteristics of framework species include ease of propagation, hardiness and high survival on degraded sites, rapid growth and dense spreading crowns which shade out weeds and quickly ‘capture’ the site, flowering and fruiting from a young age to attract seed-dispersing wildlife (Elliott et al., 2006)

These species/provenances are important for plantation forestry in the Republic of South Africa (e.g., Purnell and Lundquist 1986) but will disappear from the wild due to warming temperatures, unless translocated to appropriate wild habitats further south. However, in this case and indeed the overwhelming majority of cases it will not be feasible—or rather advisable—for humans to intervene to save individual tree species threatened with extinction from changing climate regimes through their translocation into other climatically more suitable natural settings (as may be determined through modelling). Conservation of tree species threatened by climate change will be more effective in more formal and carefully managed *ex situ* settings, including e.g., mixed species field gene banks.

In the face of new climates, perhaps the best that can be hoped for is that native forest ecosystem functions can be preserved, and especially that forest carbon stocks are maintained; with many of their extant species/ populations able to persist through inherently high adaptability and/or high levels of genetic diversity. In situations where the local trees are unable to adapt, and the forest is in clear decline, then it may be necessary as a last resort, to introduce hardy, ecological framework species with wide climatic tolerances to restore forest function. An analogous situation will apply for planted trees. Smallholder tree growers and farmers will need to be supplied with diverse germplasm of their preferred tree species—as well as promising new species/ provenances that can supply the desired products and services—in order that they can make local selections that are well adapted to the new climates. In summary, tree species diversity, both within and among species, will be key to native and planted forests, including agroforests, being able to adapt to climate change and maintain their ecosystem services and products.

As noted in FAO's SOFO 2020: "*Agricultural expansion continues to be the main driver of deforestation and forest fragmentation and the associated loss of forest biodiversity. Large-scale commercial agriculture (primarily cattle ranching and cultivation of soya bean and oil palm) accounted for 40 percent of tropical deforestation between 2000 and 2010, and local subsistence agriculture for another 33 percent. Ironically, the resilience of human food systems and their capacity to adapt to future change depends on that very biodiversity – including dryland-adapted shrub and tree species that help combat desertification, forest-dwelling insects, bats and bird species that pollinate crops, trees with extensive root systems in mountain ecosystems that prevent soil erosion, and mangrove species that provide resilience against flooding in coastal areas.*"

1.3 Key organisations holding tree diversity germplasm

Over the past fifty years, there have been major changes in the operations of organisations involved in the *ex situ* conservation of forest and tree genetic resources, including as seed collections, field gene banks and other living collections, notably botanic gardens and within tree improvement programs. During the period from 1960s to 1980s there were a relatively small number of national organisations, often operating in an international mode, maintaining their own national tree seed centres and supporting the development of tree seed centres in developing countries in Africa, Asia and the Pacific Islands and the Americas. Support included provision of designs/buildings, training and equipment, including software for management of tree seed operations. Some of the key players were the DANIDA Forest Seed Centre (Denmark), Centre Technique Forestière Tropical (France), Oxford Forestry Research

Institute (UK), CSIRO Australian Tree Seed Centre (Australia) and CATIE's Latin American Tree Seed Bank (Costa Rica). Most of these agencies collaborated closely with the FAO Forestry Department, including through its Panel of Forest Gene Experts, with major tree seed collections being reported in its Forest Genetic Resource Information bulletins. In the early 1990s the Nitrogen-fixing Tree Association, based in Hawai'i and with support from Winrock International, was important for the collection and distribution of seed of nitrogen-fixing trees.

The Consultative Group on International Agricultural Research (as it was initially known, later simply CGIAR) first became involved in R&D on forests and trees during the early 1990s through its World Agroforestry Centre (ICRAF), Centre for International Forestry Research (CIFOR) and International Plant Genetic Resources Institute (IPGRI, now Bioversity International). While each of these centres is involved in conservation and management of forest genetic resources, a major contributor has been ICRAF's Multi-Purpose Tree-Germplasm Resource Centre, conceived in 1992, and established the following year. Now referred to as the ICRAF's Genetic Resources Unit (GRU), its genebank has been crucial in both conserving and making use of priority agroforestry germplasm through its distribution of germplasm in Africa, Latin America and elsewhere.

Botanic gardens have long been important for conserving trees through their living collections and exchange of tree germplasm. This work has taken on an urgent imperative, that being to mount a fundamental defence of plant diversity (Blackmore & Oldfield, 2017; Smith, 2019), in the face of the planet's sixth mass extinction of biodiversity including plant species, their animal and microbial associates and genetic diversity. The efforts of individual gardens became better coordinated with the establishment of the Botanic Gardens Conservation International in 1987. BGCI links the botanic gardens of the world in a global network for plant conservation in more than 100 countries. The Global Trees Campaign, a joint initiative between BGCI and Fauna & Flora International, in association with other partners around the world, is the only global conservation programme dedicated to saving the world's threatened tree species. It recently released its State of the World's Trees report, which found that 30% of all tree species—more than 17,500 species—are threatened with extinction.

2.0 The role of tree genetic resources in sustainable livelihoods and food systems within resilient landscapes

2.1 Introduction

In nature, resilience is the capacity of an ecosystem to respond to a perturbation or disturbance, including natural and human disturbances, climate and other environmental changes, by resisting damage and through recovery and regeneration processes. Most landscapes in the developing tropics are highly disturbed, comprising a mosaic of settlements/infrastructure, agriculture, agroforests, secondary forests/remnants, often with little or no relatively undisturbed forest. As these highly modified landscapes involve both humans and natural systems the concept of social-ecological resilience needs to be considered (Folke et al., 2016).

Climate change threatens production of a wide range of goods—both wood and non-wood—and provision of environmental services from forestry and agroforestry production systems. Building resilience in these systems involves enhancing the prospects for maintaining smallholder livelihoods when their normal income streams are disrupted. Forest and tree management practices need to be adjusted to improve the capacity of forests, agroforests and trees to cope with the negative impacts of climate change. Braatz (2012) has identified that, for many communities, forests and trees play important roles in livelihood resilience in the face of climate change, including as:

- safety nets in times of emergency;
- sources of products important for production and income diversification for farm households and rural families; and
- sources of employment, which is particularly important once farming and other rural livelihoods become non-viable.

The components of vulnerability of forests and trees to climate change in the Pacific Island countries, and small island developing states (SIDS) generally, have been discussed by Thomson and Thaman (2016). They include direct weather-related impacts—such as from increasing temperatures and changed rainfall regimes, both amount and seasonality; prolonged drought connected with El Niño / La Niña, extreme weather and tidal events (such as tropical cyclones), and king tides (which can briefly submerge entire atolls), as well as a range of indirect impacts associated with flooding, drought, erosion and fire events, from pests and diseases, including environmentally invasive weeds, and associated impacts on beneficial forest ecosystem associates (microbial symbionts, seed dispersers and pollinators). The main economic impacts from these vulnerabilities may be indirect, related to fire, pests and diseases, and damage to ecosystem services—especially water supply—provided by forested catchments (from fire, cyclones and flooding). However, there will also be direct economic impacts on the less easily quantified informal/subsistence sectors related to forest food banks, traditional medicines, rough building timbers and fuelwood. Tree diversity, including intraspecific diversity, will be vital to the survival of atoll-dwelling peoples who suffer an existential threat from climate change and associated sea-level rise: a case point is the salt- and drought-tolerant *Pandanus tectorius*, e.g., with 170 named varieities in Kiribati, most being selected edible fruit female cultivars with low oxalate levels (Thomson et al., 2018a, Figure 3).

Figure 3. *Pandanus tectorius* (beach pandanus): an extremely diverse multipurpose species—food, timber, woven handicrafts, sails, mats, medicines—on the Pacific Islands frontline against climate change. [A] Pagaimotu sinking island, Tonga. [B] Ha'apai atoll relict, Tonga.[C] Volcanic lunar landscape, Tanna, Vanuatu.[D]Pandanus Jam, Taveuni, Fiji. [E] Pandanus fruit paste (*te tuae*), Kiribati. [F] Pandanus juice, Marshall Islands. (Photos: Lex Thomson [A,B,C,E], Father Petero Matairatu [D], Robert Reimers Enterprises [F])

There will be differential impacts of climate change on productivity and resilience of tree-based production ecosystems compared with crop and/or livestock based systems. As a generalization, longer-rotation tree crops are more susceptible to extreme wind events but less susceptible to drought, due to access to deeper sources of groundwater, when compared to annual crops and livestock. Accordingly, future tree planting and reforestation will need to consider using tree species which are resistant to climate extremes, especially strong winds, and which have broad climatic envelopes. The latter include tree species with wide natural distributions and especially those which have evolved near drainage lines or seasonal watercourses in the wet/dry tropics or semi–arid environments. Such tree species include, for example *Acacia ampliceps*, *A. auriculiformis*, *A. citrinoviridis*, *A. maconochieana*, *A. salicina*, *A. stenophylla, Adansonia digitata, Casuarina cunninghamina* subsp. *miodon, C. junghuhniana*, *Conocarpus lancifolius, Eucalyptus camaldulensis*, *E. microtheca-E. rhodoclada* complex, *Faidherbia albida, Khaya senegalensis*, *Melaleuca cajuputi, Melia volkensii, Populus euphratica, P. ilicifolia* and *Vachellia nilotica*: these species, and others from such habitats, combine high productivity and resilience as they need to be able to grow rapidly when conditions are favourable, but then survive drought periods.

The next sections outline a few, of many, examples of agroforestry and planted forestry systems which aim to highlight the roles of forest and tree genetic resources in bolstering sustainable livelihoods and food systems within resilient landscapes: these have been selected to provide examples for different agro-ecological zones across the developing world.

2.1.1 Africa

Agroforestry parklands (Sudan zone, West Africa)

The indigenous trees in the West African agroforestry parklands include *Adansonia digitata* (baobab), *Parkia biglobosa* (African locust bean), *Tamarindus indica* (tamarind), *Vitellaria paradoxa* (shea butter), *Faidherbia albida* (*gao*) and planted mangoes (*Mangifera indica*) in different varieties. The main crops grown are pearl millet, sorghum, maize, peanut, cotton and cowpea. The trees in this system are needed for food/nutrition, wood, medicine, income, animal browse, and for the services they provide including protecting fragile soils and recycling nutrients from below crop root zones. *Faidherbia* fixes atmospheric nitrogen and its unique reverse deciduous habit, leafless in wet season, combine to make it an ideal tree to combine with crops and sustainably increase crop yields (Roupsard et al., 1999; Orwa et al., 2009). The diversity present in local and exotic trees is essential for sustainable food production and livelihoods in the Sudan zone of West Africa. Indeed, the resilience of these agroforestry parklands—now being tested by increasing human populations and a long-term decline in rainfall associated with climate change—will in large part depend on the genetic diversity of the local tree species, supplemented by introduction of useful tree species from the neighbouring Sahel zone.

Farmer managed natural regeneration with traditional crops (Sahel zone, Niger, West Africa)

The near total destruction of Sahelian trees and shrubs in the agricultural zone of Niger between the 1950s and 1980s had devastating consequences. By 1981, the whole country was in a state of severe environmental degradation; an already harsh land was turning to desert. Without protection from trees, pearl millet and sorghum crops were being blasted by 60-70 km per hour sand-laden winds and stressed by higher temperatures and lower humidities. The NGO SIM began promoting farmer managed natural regeneration (FMNR), which at its essence involved protecting coppice regrowth during crop establishment. The protected coppice quickly grew into trees which in turn protected the crops and provided a wide range of products including building timbers, fuelwood, food and traditional medicines. Slowly over a 20-year period, FMNR spread from farmer-to-farmer, with six million hectares of farmland now re-vegetated with a diverse array of local trees. In many cases, cereal yields have doubled or more per hectare. Farmers are producing an additional 500,000 tons of cereal per year than in the 1970s and 1980s, with 2.5 million people now being more food secure (Pye-Smith, 2013; Reij et al., 2009; Rinaudo et al., 2021). Two of the regenerated local species, *Guiera senegalensis* (moshi medicine) and *Piliostigma reticulatum* (camel's foot), have recently been demonstrated to bio-irrigate the adjacent crops and produce major increases in crop yields (Bogie et al., 2018, Figure 4).

Figure 4. *Piliostigma reticulatum* (camel's foot) showing bio-irrigation, improved survival and growth of adjacent sorghum crop, Senegal (Photo: Tony Rinaudo).

FMNR in Niger is one of the most successful dry zone reforestation projects in the world and its success is attributed to the utilisation of the existing native tree species and their diversity by:

- regenerating trees from living stumps and existing seeds in the ground, thereby avoiding the expense and high failure rate of tree nurseries and field plantings.
- farmer control over selection, management and utilization aspects of FMNR.
- indigenous trees regenerated through FMNR met multiple needs simultaneously and relatively quickly. Benefits included increased soil fertility, reduced wind speeds, fuel wood and building poles, fodder, wild foods and traditional medicines.

Australian sub-tropical dry zone acacias were successfully trialled as windbreaks at the ICRISAT Sahelian Centre and elsewhere and several species, such as *Acacia colei* (Cole's wattle) and *A. torulosa* (torulosa wattle), showed promise for production of fuelwood, charcoal, straight building poles and importantly seed for human food (Thomson, 1992; Thomson et al., 1994; Rinaudo et al., 2002, Figure 5). *Acacia* seed flour and dried powdered *Moringa oleifera* (drumstick tree) leaves mixed with millet flour to produce a highly nutritious baby food porridge was strongly promoted from 2010. Lack of institutional support has seen the demise of this initiative; however, individual farmers continue to incorporate acacia flour into various traditional mixes. Ground Australian acacia seeds are being used for coffee, *tuwo* (porridge), *fura, kose* (beancake), *panka* (pancake) (Tony Rinaudo pers. comms.).

A landscape on the brink of desertification has been converted into a resilient and productive agroforestry parkland, but threats remain from population increase, lawlessness and climate change.

Nevertheless, it is difficult to determine where and for whom FMNR is the most appropriate restoration technique and where it might be necessary to combine it with enrichment planting. Further research, followed by development of guidelines, are needed (Chomba et al., 2020).

Figure 5. The hexaploid *Acacia colei* has proven useful windbreak, firewood/charcoal [A, B], and source of protein-rich seeds in famine-prone tropical dry zones in sub-Saharan Africa and India [C,D]. (Photos: Tony Rinaudo [A,C,D] and Lex Thomson [B])

Tea plantations with shade trees, especially Grevillea robusta (east African Highlands)

Camellia sinensis (tea) has long been grown in the east African highlands, in sustainable systems together with high shade trees, including frequently *Grevillea robusta* (silky oak). Shade trees are necessary for reducing transpiration in the tea crop and recycling soil nutrients from depth and reducing fertiliser requirements. Research has shown the original introduction of *Grevillea* into east Africa was likely from a single tree, and resulted in inbreeding depression[5] and declining vigour. The introduction of diverse germplasm of *Grevillea* from Australia is crucial for revitalising its diversity in east Africa and ensuring its future as a vigorously growing shade tree for tea; also providing timber for building and copious nectar for honey bees. Climate change in the east African Highlands, manifest as warmer temperatures and declining rainfall, is impacting the choice of shade trees with heavy water users, such as *Eucalyptus*, falling out of favour and being replaced by grevillea, avocadoes, mangoes and macadamia which provide food and income (Harwood & Owino, 1992; Kalinganire, 1999; Orwa et al., 2009).

Cocoa agroforest (Cameroon)

Cocoa agroforests are developed through the modification of lowland tropical forest. These agroforests conserve considerable local tree diversity, e.g., 206 tree species with an average of 21 tree species per agroforest in southern Cameroon. Cocoa agroforests are in turn dependent on the canopy trees to provide shade and cycle soil nutrients within a sustainable, healthy, biodiverse production system. The local trees also provide high-value non-timber forest products, food, traditional medicine, charcoal and other products for household consumption and sale. However, with increasing market access, population pressure and land use intensity, specific interventions are now needed to promote local forest tree species in cocoa agroforests, or else these will progressively lose importance and be gradually replaced by common exotic species or simpler, and/or less biodiverse and ultimately unsustainable production systems. Options might include development of markets for local forest species and provision of rewards to farmers for their conservation efforts (Sonwa et al., 2007).

2.1.2 Asia

Regeneration of broad-leaved trees and shrubs through Chir pine reforestation (Nepal)

In the mid-hill forests of the Himalayan foothills in Nepal, smallholder farmers harvest the foliage of a select range of broad-leaved trees and shrubs as supplemental fodder for their livestock during the dry winter months. These include more than thirty fodder tree species in 24 genera: *Albizia julibrissin*, *Boehmeria rugulosa*, *Brassaiopsis glomerulata*, *B. hainla*, *Bridelia retusa*, *Brucea javanica*, *Buddleja asiatica*, *Castanopsis indica*, *Celtis australis*, *Choerospondias axillaris*, *Diploknema butyracea*, *Erythrina arborescens*, *Eurya acuminata*, *E. cerasifolia*, *Ficus auriculata*, *F. hispida*, *F. subincisa*, *F. neriifolia*, *F. semicordata*, *Fraxinus floribunda*, *Grewia optiva*, *Litsea monopetala*, *Persea odoratissima*, *Premna serratifolia*, *Prunus cerasoides*, *Rapanea capitellata*, *Saurauia*

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[5] Inbreeding is caused by mating between close relatives. Generally, inbreeding in forest trees leads to inbreeding depression. Inbreeding depression is characterised by reduced growth rates, increased susceptibility to disease, high abortion rates of seed, and high and ongoing mortality of seedlings and young trees. Managing seed orchards and breeding populations to avoid inbreeding is therefore among the highest priorities for tree breeders.

nepaulensis, *Schima wallichii*, *Symplocos paniculata* and *Xylosma controversa*. The composted manure is then put onto their fields to fertilise crops of canola, dhal and upland rice, ensuring the sustainability of this production system. Farmers were concerned about the decline in broad-leaved trees and shrubs and interested to re-establish them. Through the Nepal-Australia Community Forestry project it was found that the local broad-leaved species, were able to colonise the plantings of indigenous chir pine (*Pinus roxburghii*): this was due to the changed microclimate, improved microsite conditions for germination and establishment, and the physical protection afforded by the pines against wandering cattle, including to regeneration from roots and stumps of favoured broad-leafed species. This example illustrates the importance of local tree diversity, including the seral chir pine, in maintaining a sustainable food production system in Nepal.

Multistrata agroforestry system using damar, rubber, durian and cinnamon (Indonesia)

Multistrata or complex agroforests are able to provide sustainable livelihoods to smallholders as well as ecosystem services including biodiversity conservation, carbon sequestration and water catchment. In Indonesia these agroforests provide 80% of the rubber latex consumed and exported by; 95% of various tropical fruits and spices marketed in the country and 75-80% of the dipterocarp resins traded in and outside the country. They also provide a significant portion of rattans, bamboo and firewood, and the bulk of medicinal plants and handicraft material produced in Indonesia. One example of these sustainable and resilient agroforestry systems is that based on *Shorea javanica* (damar) for production of resin, as well as *Hevea brasiliensis* (rubber) and other fruit and spice tree species including *Durio zibethinus* (durian) and *Cinnamomum burmanii* (cinnamon). This system was developed more than a century ago by villagers in south Sumatra, and now covers 50,000 hectares. These agroforests provide a sustainable alternative to cropping on infertile soils. Their productivity and resilience derives from the diversity present in their constituent tree and other plant species, mainly local but also some introductions (de Foresta et al., 2000; Roshetko & Purnomosidhi, 2013).

Restoration of mixed deciduous and coniferous forest on degraded hills (NE China)

In north-east China, and elsewhere in China, there have been major tree-planting efforts over the past forty years. In Jilin Province reforestation was undertaken on degraded hills with limited agricultural potential. While there may have been limited consideration to tree species and provenance choice, the use of a range of broad-leaved and coniferous tree species and sources and then letting nature and natural selection to take its course appears to have worked splendidly. The restored forests are critical for ecosystem services, protection of soils and water catchment, and sustainability of rice and corn fields on the flat lands below. The new forests are also becoming increasingly important for harvest of edible ectomycorrhizal fungi, Siberian ginseng and other traditional medicinal plants: wood prunings can also be ground up and bagged for cultivation of clouds ear or black fungus (*Auricularia polytricha*) (Figure 6). Production of diverse and nutritious forest foods and medicines in China, in sustainable and resilient production systems, is highly dependent on diverse forest genetic resources.[6]

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[6] http://www.xinhuanet.com/english/2020-03/31/c_138935800.htm; https://www.cifor.org/publications/pdf_files/Books/Bchokkalingam0603.pdf; https://global.chinadaily.com.cn/a/202011/16/WS5fb1d62da31024ad0ba94412.html

Figure 6. Cultivation of clouds ear or black fungus (*Auricularia polytricha*) on wood substrate derived from thinnings and prunings from new forests, Jilin Province, China. (Photo: Lex Thomson)

Eucalyptus agroforests and plantations in combination with upland & lowland rice and cassava (Laos and Thailand)

The private forestry sector including SilviCarbon (and their antecedents Stora Enso) and Burapha Agroforestry have been working with smallholders in Laos to develop sustainable plantations and agroforests for production of timber and carbon sequestration. The *Eucalyptus* plantations are established in degraded land where the primary forest has been cut down long ago for swidden agriculture. These companies work closely with local farmers to develop their agroforestry models: these systems contribute to food security, though intercropped, rotational plantings of upland rice, cassava and fallow for rough grazing for cattle, and reduce swidden cultivation. A whole-of-landscape planning approach is adopted with remnant pockets of biodiverse, secondary forest protected. Seasonal and perennial streams are now buffered by native vegetation to provide important wildlife corridors, protect water quality and aquatic biodiversity, and retain the natural resources that provide for rural Lao communities. These resilient and efficient production systems are built on almost sixty years of domestication and breeding of *Eucalyptus*—made possible through range-wide individual tree seed collections of promising *Eucalyptus* species by the CSIRO Australian Tree Seed Centre—and which has produced fast-growing, adaptable trees of excellent bole form which enables wide spacing and intercropping, including in upland rice and cassava, lowland rice, wheat and corn crops from China to Pakistan (Figure 7).[7]

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[7] https://www.buraphawood.com/;
https://varoenergy.com/en/news/silvicarbon-acquires-stora-enso-plantation-operations-in-laos;
https://finnfund.fi/en/news-andpublications/reports_publications/other_reports_and_publications/case-study-in-sustainability-work-burapha-agroforestry-laos/;
https://www.storaenso.com/en/newsroom/news/2015/1/trees-food-and-bombs-in-laos

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Figure 7. Improved selections of *Eucalypus camaldulensis* growing on irrigation bunds in rice fields in Thailand. (Photo provided by Stephen Midgley from Khun Prachak)

2.1.3 Latin America and Caribbean

Forest succession management and use of traditional knowledge (Brazil)

In parts of the Brazilian Amazon such as in the Xingu Indigenous Territory in Mato Grosso—and many other lowland tropical humid regions—traditional shifting agriculture is coming under stress due to population pressures leading to reduced fallow periods. Indigenous traditional knowledge can be utilised to develop improved fallow systems. Local experts—among the Kawaiwete and Ikpeng peoples—know that certain tree species indicate fallows are following their successional recovery, such that the forest could be reused for productive agriculture. These tree species include *Dipteryx odorata* (*cumaru*), *Enterolobium schomburgkii* (*dormidero*), *Hymenaea courbaril* (*courbaril*), *Ocotea leucoxylon* (loblolly sweetwood), *Qualea* (*quaruba*), *Trattinickia* (*amesclão*) and *Xylopia amazonica* (*rim*). Food and other useful trees are planted and actively encouraged in cassava swiddens: these include *Caryocar* spp. (*pequi), Hancornia* sp. (*mangaba*), *Anacardium occidentale* (cashew) and *Talisia* spp. (*tomkorowo*) as well as for construction, medicines and other purposes. The diversity in local tree species, including those that can rapidly restore soil fertility and other productive useful trees is essential to the sustainability and resilience of these fallow systems in the face of climate change, notably more frequent and severe droughts (Schmidt et al., 2021).

Hedgerows/alley cropping to control soil erosion (Jamaica)

Hedgerow/alley cropping entails the growing of crops, usually food crops, in an alley formed by trees or woody shrubs cut back at crop planting and maintained as hedgerows by frequent trimming during cropping. The small leguminous tree *Calliandra calothyrsus* is the species of choice for Jamaican smallholder farmers due to its adaptability to wide variety of soil types, strong coppicing ability and vertical rooting habit which minimises competition with planted crops: calliandra enhances soil fertility through nitrogen fixation and it leaves can be used as animal fodder, copious nectar flows for honey bees, and its cut branches for fuelwood. However, there are several other tree species which might be used for alley cropping in Jamaica and globally there many tropical N-fixing tree species including *Alnus nepalensis* (Nepalese alder), *Acacia tumida* (pindan wattle), *Casuarina equisetifolia* (beach she-oak), *Flemingia macrophylla* (large-leaf flemingia), *Gliricidia sepium* (gliricidia), *Leucaena leucocephala* (*ipil-ipil*), *Sesbania sesban* (sesban) and *Tephrosia candida* (white tephrosia). These species and their within-species diversity is vital for developing ally cropping agroforestry systems in different environments and with different objectives.

Hybrid in mosaic of retained and restored native forest (Brazil)

In Brazil, several major forestry corporations are playing critical roles in restoring and maintaining native forest biodiversity. This is being done through a landscape planning approach with remnant biodiverse vegetation, including riparian forest strips, protected and reforestation of degraded pasture lands. One such company is Suzano Papel e Celulose, a major producer of eucalyptus pulp. Suzano has an innovative forest restoration program, which seeks to restore degraded habitat and promote environmental conservation of ecosystems in four out of the six Brazilian biomes (Amazon Rainforest, Atlantic Forest, Cerrado and Caatinga). Over the past decade 31,200 ha have been restored and 925,600 hectares (38% of Suzano's total area) has been conserved. The success of these sustainable pulpwood production operations derives from both the genetic resources in selected tropical eucalyptus species, and diversity in the vast number of indigenous tree species which enables biodiverse, resilient forests to be restored on degraded soils and in the face of climate change.

2.1.4 Pacific Islands

Improved Temotu traditional agriculture (Solomon Islands)

In Temotu Province (Solomon Islands) population growth has resulted in shortening of the fallow period and extension of the cropping period, with consequent declines in soil fertility and crop yield. This is particularly a problem in the Reef Islands group and outlying islands. In order to address the low crop yields and loss of soil fertility, the Department of Agriculture and some farmers developed a farming system known as the Improved Temotu Traditional Agriculture (ITTA). The system is tree-based, integrated with legumes, root crops and vegetables and has been adopted by more than 400 farmers, mainly in the Reef Islands. It uses food-producing trees and legumes including fruit trees, mainly *Artocarpus altilis* (breadfruit) and indigenous nuts including *Barringtonia* spp. (cutnut), *Terminalia catappa* (sea almond), *Inocarpus fagifer* (*nabo*/Tahitian chestnut) and *Canarium harveyi* (ngaili nut). ITTA is a farmer-led response to declining crop yields and made possible by thousands of years of selection and improvement of indigenous fruit and nut tree species, many of which have high potential in other similar environments such as large-kernelled morphotypes of sea almond and an anthocyanin-rich, purple-fleshed breadfruit known as *bia ningabo* (Allen et al., 2006; Thomson et al., 2021a).

Agroforestry (New Guinea highlands)

Ancient agroforestry systems based on the two subspecies of *Casuarina oligodon* (NG Highlands sheoak) developed independently in Papua New Guinea and Indonesia: in these systems the casuarinas are valued as windbreaks and for soil improvement—cycling nutrients and fixing atmospheric N through a symbiotic root association with the actinomycete *Frankia*—as well as providing roundwood and fuelwood (Ataia, 1983; Askin et al., 1990; Bourke, 1985). *Casuarina* species and the related *Gymnostoma* species are valuable for productive, resilient and sustainable agroforestry and forestry systems on degraded and infertile soils throughout the tropics and sub-tropics from Egypt and Kenya, through to China, India, Thailand, Timor Leste, Vietnam and New Caledonia (Haruthaithanasan et al., 2020; Thomson & Gâteblé, 2020, Figures 8 & 9).

Figure 8. *Casuarina equisetifolia* agroforestry with free range hens, Guandong, China. The trees improve microclimate, provide leaf litter, organic matter and invertebrates for hen's diet. (Photo: Khongsak Pinyopusarerk)

Figure 9. *Casuarina equisetifolia*/pineapple agroforestry, Thailand. The vast intraspecific diversity in this casuarina species has enabled selection of fast-growing, well-formed trees ideal for agroforestry, timber and pulpwood utilization. (Photo: Khongsak Pinyopusarerk)

Shifting cultivation/crops with acacias (Western Province, PNG)

Agriculture in the south of the Fly River (Western Province, PNG) is not easy due to often infertile podzolic soils and a pronounced dry season and associated wildfire. Food from planted crops in shifting cultivation systems is supplemented with wild bush foods (including sago, fish, prawns, wallabies, deer, pigs, cassowaries, pigeons and other birds). Gardens of root crops are cleared from lowland forest, and after several years of cultivation are left to revert to fallow. The whole region is rich in tropical acacias, including *Acacia auriculiformis* (earpod wattle), *A. crassicarpa* (PNG red wattle), *A. leptocarpa* (slender-fruited wattle), *A. mangium* (mangium), *A. peregrina* (PNG salwood) and *A. simsii* (Sim's wattle) and fallow areas are quickly colonised by these species, especially *A. mangium*. The restoration of soil fertility from the *Acacia* succession, along with changed microclimate, can occur within a few years. Following the cropping cycle these old garden places can develop into highly biodiverse lowland forest within 40–50 years and give the appearance of primary, untouched forest. The genetic diversity within and among these tropical acacias is essential for cropping to be able to occur on a sustainable basis in such impoverished soils. Indeed, these tropical acacias have vast, largely untapped, potential to act as pioneer catalyst species for rainforest regeneration in other tropical regions. They are generally short lived, and will scarcely regenerate in the absence of fire, and accordingly are ideal framework species for rainforest restoration.

2.2 Role of tree genetic resources in resilient landscapes, in the context of climate change

Throughout the tropics, once sustainable agricultural practices and systems are becoming less productive; some are at risk of collapsing altogether as a result of population pressures, accelerating climate change and associated land degradation and desertification. At risk agricultural systems are to be found in the Sahel, Ethiopia and other parts of sub-Saharan Africa through to the Amazon basin impacted by warming and drought, while near coastal zones of South & SE Asia, the Pacific and Caribbean Islands impacted by intense tropical storms. Tropical and sub-tropical littoral forests and mangroves are threatened to varying degrees by steadily rising sea levels, record-breaking king tides and intense storms, with consequent impacts on coastal forests their ecological and productive functions as well as on inshore and pelagic fisheries. Accordingly, rapid stabilisation and/or reduction of greenhouse gas emissions are crucial for the continued functioning of agricultural and forest production in the tropics and subtropics.

In the meantime, climate change adaptation and other emergency measures will be needed in order to prevent more frequent famine, displacement and migration of the most severely impacted and desperate human populations. Effective climate change adaptation measures might include modifications to existing agroforestry systems, to improve their resilience; the inclusion of trees into climate-stressed agricultural systems, including through farmer managed natural regeneration and/or their replacement with more climate robust arboricultural systems. Initiatives that aim to sequester carbon in forest plantations can minimize their potentially negative impacts on food production, biodiversity and water supplies by instead establishing diverse, multispecies plantations of local species and siting plantations on degraded, non-arable, lands. Recent research has found that stands of mixed tree species will generally provide more stable total productivity and sequester more carbon, being on average about 25% more productive than monocultures (Fitchner et al., 2018; Forrester & Bauhus, 2016; Jucker et al., 2014; Pacquet & Messier 2011; Liu et al., 2018; Zhang et al., 2012).

The above approaches and measures will require access to and utilisation of diverse germplasm of a large number of adaptable and useful tree species. In other words, tree genetic resources are becoming increasingly central, if not imperative, to measures for effective climate change adaptation and mitigation. Perversely some of the most threatened tree and woody shrub species are those that have the highest economic and cultural values and which have been overharvested; a few examples in sub-Saharan Africa are certain species of *Boswellia* (frankincense), *Commiphora* (myrrh), *Osyris* (sandalwood), *Prunus africana* (pygeum) and *Securidaca longipedunculata* (mother-of-medicine).

2.3 Role of tree genetic resources in promoting sustainable livelihoods

As the basis of productive forestry and agroforestry systems, tree genetic resources are fundamental to sustainable rural livelihoods throughout the developing tropics. The correct tree species and provenance/seed source matching will be vital for tree performance and in delivering the desired products to smallholder tree growers in the shortest possible time frame. Until recently, it was expected that the local tree species and seed sources were well/best adapted to the local environment; indeed, this was the basis of seed zone systems which restricted or in some cases prohibited movement of tree germplasm across gene-ecological and climatic zones. However, it is no longer or not always the case that local seed sources are the best adapted due to changed climates, sometimes changed substrates (such as increase in salinity and soil acidity) and introduced pests and diseases. Accordingly, while local tree species and seed sources often have many advantages over non-local tree species, increasingly smallholder tree growers will need access to diverse genetic materials from which new local selections can be made. For example, in some situations it will likely be necessary to introduce tree species or provenances which are better adapted to warmer, droughtier and/or more variable climates.

Increasingly it will be advantageous for agroforestry systems to incorporate a greater mixture of tree species and genotypes: more species can provide a greater number of desired products while complementing and better using the above and below ground environments. For example, recently in the Solomon Islands it has been found that root architecture and function of two naturally durable timber tree species, *Tectona grandis* (teak) and *Flueggea flexuosa* (*mamafua*) are highly complementary (Vigulu, 2020). Furthermore, different tree species cycle mineral nutrients differently, while at least one N-fixing tree will help ensure adequate N is available. Having a mixture of species and genotypes with slightly different climatic preferences can make better use of a site during periods of variable weather and rainfall. Inclusion of some multipurpose species with broad ecological tolerances such as *Acacia auriculiformis* (earpod wattle), *Eucalyptus camaldulensis* (river red gum), *Melia azedarach* (white cedar), *Moringa oleifera* (drumstick tree) and *Populus euphratica* (desert poplar) is a good insurance policy for smallholders, as is the inclusion of highly cyclone resistant trees in cyclone prone areas such *Agathis robusta* (smooth-barked kauri), *Calophyllum brasiliense* (jacareúba) and *C. inophyllum* (beach tamanu), *Cocos nucifera* (*niu leka*- Fiji dwarf coconut), *Endospermum medullosum* (whitewood), *Pinus caribaea* (Caribbean pine) and *P. palustris* (longleaf pine), *Pterocarpus indicus* (PNG rosewood) and *P. officinalis* (*sangre de drago*), *Terminalia catappa* (beach almond) and *T. richii* (*malili*).

A greater diversity of genotypes is desirable to buffer planted populations for climate fluctuations and pests and diseases, and to allow for both natural selection and for farmers to make their own selections that best suit their needs and conditions. Many, if not most, tropical tree species have inherently high levels of genetic diversity which is manifest at both between and within population/provenances. This genetic diversity is of critical importance for tree growers, including small holders, and is necessary for breeders to be able to conduct efficient selection and breeding programs. Simple selection of the best adapted seed source for a given species will often lead to major gains in survival, tree health, vigour and productivity, e.g., ≥30% gains in production of wood, fruit and other products above the average yield. These greater yields are incredibly useful to the income derived by smallholder tree growers as the costs of establishing and maintaining trees derived from average or inferior germplasm are the same or greater—due to the need for increased watering and weeding—than when using better adapted and more vigorous germplasm sources. There is also a need to research traits that impact ecosystem service provision such as water use efficiency[8], i.e., quantum of water used to fix a given amount of carbon during photosynthesis. Simple selection among tree seedlings for high water use efficiency ($\Delta^{13}C$ isotope ratio), followed by their mass vegetative propagation (e.g., > 20—30 clones of several tree species) and deployment in catchments where water yield is high priority, would help balance the needs for carbon sequestration, wood and water production.

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[8] Carbon isotope composition ($\delta^{13}C$) of plant material and that of atmospheric CO_2, whose difference reflects discrimination against ^{13}C ($\Delta^{13}C$) occurring during diffusion of CO_2 through stomata and assimilation by photosynthesis.

[7] Rabi Islanders are some of the world's first environmental refugees. In 1941, the Banabans of Ocean Island in the Gilbert Islands (Kiribati), whose home island had been ravaged by phosphate mining, were relocated in Rabi in north-eastern Fiji.

Greater diversity increases value-adding and other options for tree growers. For example, in production of gluten free flour from breadfruit. Normally in Fiji two small to medium fruited cultivars '*balekana*' and '*uto dina*' are preferred for cooking and export, but for processing into gluten-free flour large fruited varieties such as '*vula*' are preferred as the processing time and yield is considerably higher. Furthermore, breadfruit varieties brought to Fiji by Rabi Islanders[9] —hybrids between *Artocarpus altilis* and *A. mariannensis* —fruit in the off-season for breadfruit and are suited to providing year-round breadfruit supply for processing into flour and chips.

2.4 Role of tree genetic resources in promoting sustainable, safe and nutritious food systems

The examples in section 2.1 serve to provide a flavour for the vital importance of trees, and their genetic diversity, to sustainable and resilient food and forestry production systems. Viewed through a longer term and broader lens, it is evident that almost all tropical smallholder agriculture and food production systems are dependent upon and include trees.

2.4.1 Trees and forests are critical for healthy terrestrial and inshore marine ecosystems, their food production and potable water

Healthy diverse forests and trees reduce soil erosion which in turn helps protect coral reefs, seagrass meadows and inshore fisheries, and reduces reef damage and disturbance which contributes to ciguatera (fish poisoning). Agroforests, native forests and woodlands, including mangroves are essential sources of food in many parts of the tropics. The health and productivity of agri-food production systems may be reliant on honey bees for pollination services, while the bees are in turn supported by trees for their nectar, pollen and resin (see Table 1).

Increasingly—due to land pressures and inconsistent rainfall—farmers are cultivating, often illegally, to the edge of waterways and drainage lines. Frequently these crops are damaged or destroyed by flash floods, with the alluvial soils eroded and deposited downstream damaging freshwater aquatic and marine ecosystems and their food production potentials. Ofcourse there are alternatives, and forested/treed riverine strips can not only protect waterways but also provide major food resources, including from the food staples sago, breadfruit and *Inocarpus fagifer* (Tahitian chestnut): are all well adapted to temporary, shallow freshwater inundation. Tahitian chestnut is ideal for riverside protection plantings due to extensive buttressed root system and for production of healthy nuts (https://www.healthbenefitstimes.com/tahitian-chestnuts/), nectar for honey bees and other products. The extremely long-lived, N-fixing, cyclone- and waterlogging/brackish-tolerant and diverse Tahitian chestnut should be considered for much wider planting throughout the tropics, including for climate change mitigation and adaptation (waterway and coastal protection, green firebreaks) and for food and nutritional security (Thomson, 2018, Figure 10).

Well-forested catchments are required for production of clean water, with water yields modulated throughout the year, such that flash flooding events downstream are reduced with more water flowing through the dry season (e.g., Bruijnzeel et al., 2004; Qazi, 2020). Notwithstanding, it is frequently observed that reforestation of degraded catchments can lead to a decrease in total water yields (Filoso et al., 2017). Additionally, individual trees, palms and forest vines can provide safe sources of drinking fluids, the most well-known being *Cocos nucifera* (coconut) which can be the only source of clean drinking fluid in some situations, on atolls and in tropical coastal regions after tsunami. The liquid from coconuts may also be used in medical emergencies when sterile intravenous fluids are not available. The processed seeds of *Moringa oleifera* (drumstick tree) can be used to purify and clarify water (Delelegn et al., 2018) inexpensively and sustainably in the developing world.

Figure 10. Tahitian Chestnut (*Inocarpus fagifer*), Ha'apai, Tonga, a long-lived nitrogen-fixing tree with major intraspecific diversity in edible seed and other characters. Flanged trunks protect waterways, large nuts/seeds offer potential as a noval super food, and nectar-rich flowers feed honey bees. (Image: David Bush/CSIRO)

2.4.2 Food tree diversity for food gardens

With increasing urbanisation, home, school and peri-urban gardens will become increasingly important in providing food (fresh with low food miles). The diversity in food tree species is vital with dwarf fruit and nuts varieties and dwarfing rootstocks for grafting useful for maximising diversity of food production in a small area. Multiway grafting using varieties with different fruiting seasons can be used to extend the period of fruit availability. In Niger, grafting of improved fruiting cultivars of 'Sahel apple' onto hardy local rootstock of *Zizyphus mauritiana* (jujube) has produced much larger and sweeter fruits. Selecting and using elite fruiting tree varieties is important, but care needs to be taken to narrow the genetic base and inherent risks from climate change and extremes and exotic pests and diseases. In Thailand, *Nephelium* *lappaceum* (rambutan) had been reduced to two main production cultivars, viz. *ngoh rong-rien* and *ngoh si* (some spintern colour variants), but recently a third cultivar *ngoh si-thong* has been added (large sweet flesh, freestone) and it will be important to increase cultivar diversity further. In the case of rambutan, there are other little-known varieties which might be promoted or used in breeding to broaden diversity in cultivated germplasm, e.g., a rare, delicious yellow-skinned, large-fruited freestone cultivar with tiny seed in south Sulawesi (Indonesia). It is essential that both older and less domesticated varieties of fruit and other food trees are conserved and available for deployment in future and breeding programs.

2.4.3 Food tree diversity for human nutrition and health

Foods derived directly from trees typically provide only a minor contribution to total calories in the human diet. However, tree-derived foods have a major role in human nutrition through providing a more balanced and wholesome diet (Gitz et al., 2021; Jamnadass et al., 2011, 2015; Vinceti et al., 2008, 2013; Vira et al., 2015). A more diverse diet is increasingly recognised as a healthier one: diverse food products and diets from agroforestry systems and native forests (wild foods) are inherently healthier than diets which are cereal and carbohydrate based, especially when the grains are highly processed. ICRAF has promoted food tree diversification to support diets year-round through a food tree portfolio approach (McMullin et al., 2019). This has involved working with local communities to determine a recommended list of tree foods whose increased production can help fill nutrient gaps in food consumption calendars. These recommended foods are generally derived from a mixture of exotic and indigenous food trees, the seedlings of which are then made available through local tree nurseries established by farmer groups, nursery businesses and schools. In the last decade, portfolios have been developed for 17 locations in East Africa and the methods involved are now being expanded to other regions.

The foods derived from tree species are often intrinsically healthy:

- healthy fats and oils, such as polyunsaturated and monounsaturated fats in *Canarium* (*galip* & *pili* nut), *Caryocar brasiliense* (*pequi*) and *Persea americana* (avocado) and medium-chain triglycerides in *Cocos nucifera* (coconut) and *Elaeis* spp. (palm kernel) oils;
- edible tree legumes produce seeds and leaves which are valuable sources of vegetable protein;
- tree fruits are rich in carotenoids, vitamins and other antioxidants; and
- foods derived from trees often contain high levels of essential mineral elements, dietary fibre and other complex carbohydrates, such as oligosaccharides, which may be indigestible but essential for gut health and production of the strong antioxidant, 3-indolepropionic acid.

In particular, tree nuts have long been underutilised in human diets: they are typically nutrient dense including high amounts of unsaturated fats, fibre, protein, and essential micronutrients. However, the nutrient potential for tree nuts is becoming increasingly recognised, including roles in the prevention and management of obesity, type 2 diabetes and heart disease, as well as protection against age-related health conditions (Tan et al., 2021). While several tree nuts, such as brazil nuts and cashews, are well known, there are many more tree nuts that are important locally, but virtually unknown outside of their native distributions (see Table 1).

The traditional domestication and improvement of *Canarium indicum* (nagai nut) has been going on for thousands of years in Melanesia, and culminated in superior nut morphotypes with larger and more easily cracked kernels (Walter & Sam, 1996; Thomson & Evans, 2006; Randall et al., 2018, Figure 11). Even though *nagai* nut has been a prehistoric traditional food in Melanesia, its export from Vanuatu to Europe was prohibited on the grounds it was classified as a 'novel food' and showing the challenges for international marketing of lesser-known tropical tree foods. The genus *Canarium,* comprising about 87 tropical trees, is illustrative of the largely untapped potential of tree species, and their intra-specific diversity, to contribute to sustainable human food systems and nutritional security. The marketable products from *Canarium* include edible nuts (e.g., *C. indicum*, *C. decumanum*, *C. harveyi*, *C. kaniense, C. lamii*, *C. ovatum*, *C. patentinervium*, *C. pilosum*, *C. solomonense*), timber (e.g., *C. indicum*, *C. oleosum* and indeed most *Canarium* species), edible oils for the food and cosmetics industry (e.g., *C. indicum*, *C. solomonense*, *C. kaniense*, *C. decumanum* and *C. lamii)* and resins for the incense, paint and varnish, lithographic and perfumery industries (e.g., *C. album* and *C. vrieseanum* in SE Asia; *C. vitiense* in Pacific Islands; *C. schweinfurthii* in W. Africa) (Verheij & Coronel, 1992). As well as the direct *Canarium* food products, income derived from the sale of *Canarium* products also contributes to food security. In many developing countries smallholders regard trees in their farming systems as 'living bank accounts' and they often sell timber products when they experience greater or unexpected needs for cash (such as after natural disasters), including to procure food.

Figure 11. Variation in kernel size in *Canarium indicum* associated with traditional domestication in Papua New Guinea. (Photo: University of the Sunshine Coast)

2.4.4 Food trees as human food staples

There are few tropical tree and arborescent monocotyledon species that have potential to contribute substantially to human energy intake as carbohydrate staples: these include *Artocarpus altilis* (breadfruit), *Ensete ventricosum* (Ethiopian banana), *Metroxylon* (sago palm) and *Musa* (banana, plantains and fehi). Feral and planted breadfruit trees constitute a large reservoir of diversity that exhibits recombined characters of parental trees of *A. altilis*. When a breadfruit tree shows outstanding or uncommon characters, it is given a cultivar name and may be propagated by root suckers and planted in other places (Labouisse, 2016). Desirable varieties have been selected and widely distributed in Pacific Islands both in ancient and modern times including in Fiji (55 varieties; Koroveibau, 1967), Pohnpei, Federated States of Micronesia (131 varieties; Raynor, 1989), Society Islands, French Polynesia (66 varieties; Ragone, 1991), Solomon Islands (147 varieties; Ragone, 1991), Vanuatu (132 varieties; Walter, 1989) and many other Pacific countries and territories. The genetic and varietal diversity in the breadfruit complex underpins its roles in sustainable and productive agroforestry systems in often extremely different environments in the Pacific Islands (Figure 12).

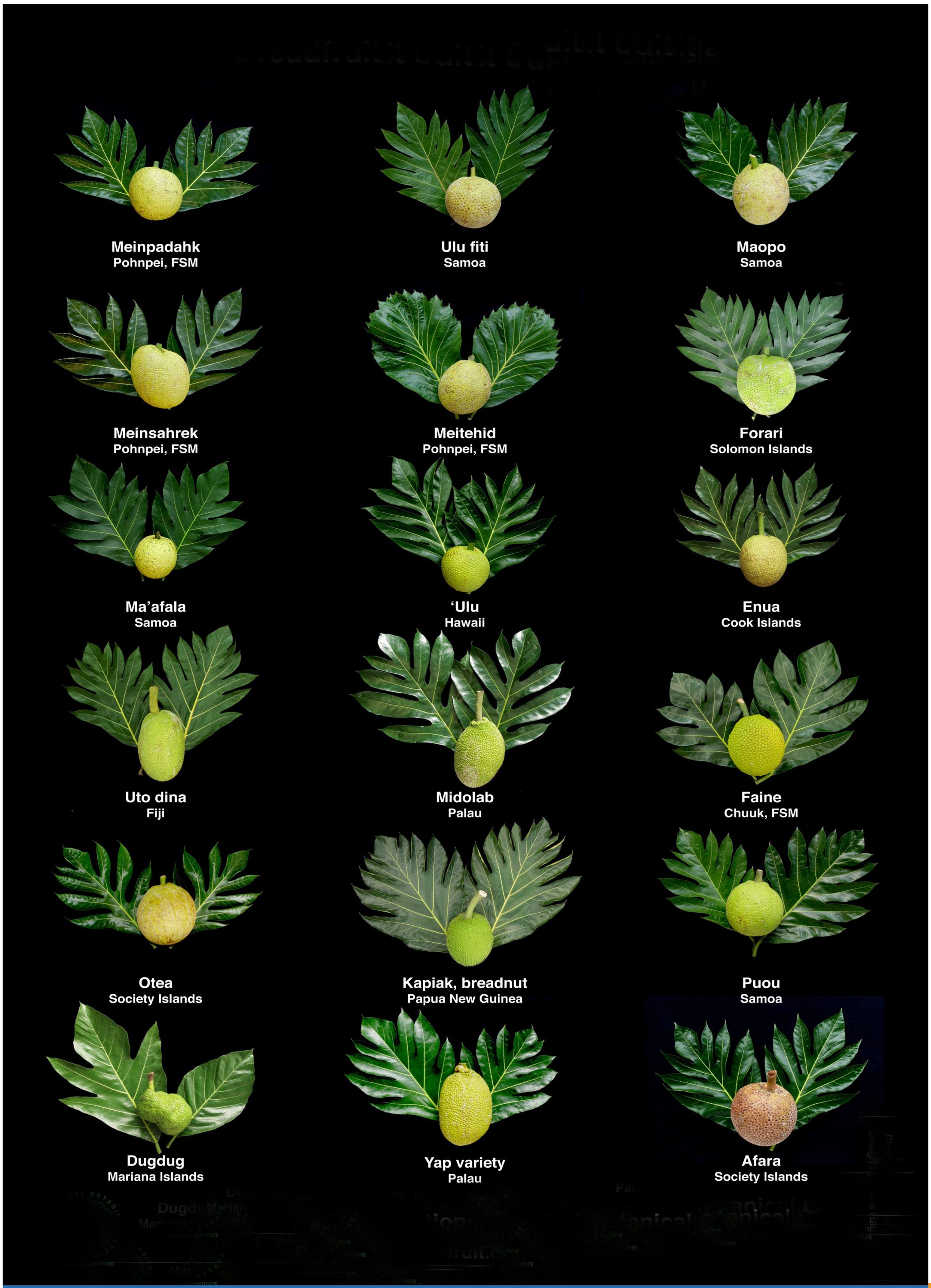

Figure 12. Cultivar variation in fruit and leaf morphology in breadfruit (*Artocarpus altilis* and its hybrids with *A.mariannensis*, and Annex 1 tree crop. (Photo: Jim Wiseman)

Traditional breadfruit agroforests on Pohnpei are incredibly diverse with more than 120 useful plant species and many breadfruit cultivars, almost exclusively *A. mariannensis* × *A. altilis* hybrids. These systems yield an average of 6.7 tonnes of fresh breadfruit per ha per annum in low input systems, as well as numerous other food, fibre, medicines and cultural products. Cultivation of phenotypically diverse cultivars of breadfruit with variable fruiting patterns has resulted in an extended, near year-round fruiting season (Atchley & Cox, 1985; Fownes & Raynor, 1993; Redfern, 2007). Breadfruit is an Annex 1 crop under the ITPGRFA—perfectly suited to address climate change mitigation and adaptation, and food security—but its genetic resources have yet to be widely utilised for sustainable, resilient smallholder agroforestry systems in the lowland humid/sub-humid tropics (Figure 12).

3.0 The role of collections-based research organisations in supporting resilient landscape approaches

3.1 Introduction

Many tree germplasm collections in developing tropical countries, i.e., national tree seed banks or centres, have been in decline since their glory days of the 1970s–early 2000s[10] (FAO, 2014; Graudal et al., 2014, 2020). During that period, national tree seed banks were either established or revamped, staff trained and tree seed field collections funded through national and international development agencies and projects. A considerable literature was developed on the technical aspects of tree seed collection and storage in the tropics (e.g., Thomson, 1995; Schmidt, 2000; Sacandé et al., 2004; DANIDA Forest Tree Seed leaflets; Schmidt et al., 2021a). The DANIDA Forest Tree Seed Centre was active in Africa (Burkina Faso, Eritrea, Ethiopia, Sudan, Tanzania, Uganda, ICRAF), Asia (Cambodia, India, Indonesia, Laos, Nepal, Thailand, Vietnam) and the Americas (Nicaragua, CATIE) (Graudal & Lillesø, 2007). The Centre Technique Forestier Tropical (and CIRAD -French Agricultural Research Centre for International Development) were active in tree seed centre development in francophone Africa (including Burkina Faso, Burundi, Cameroun, Ivory Coast, Niger, Rwanda and Senegal); while German, Swedish, Finnish and Swiss and other European Development Agencies also supported tree seed R&D in the tropics including Madagascar. Oxford Forestry Research Institute was active in collections and field trials of important tropical tree genera and species, especially in Africa and the Americas. The CSIRO Australian Tree Seed Centre supported tree seed centres in PNG and in other South Pacific countries through the SPRIG (South Pacific Regional Initiative on Forest Genetic Resources).

Between 1992 and 1998 the Canadian International Development Agency (CIDA) funded the Southern Africa Development Community (SADC) Tree Seed Centres Network project. USAID, including through the USDA Forest Service and Winrock International, supported seed collection and R&D on nitrogen fixing trees, including through the Nitrogen-fixing Tree Association. Camcore (Central America and Mexico Coniferous Resources Cooperative) was established in 1980 as a non-profit, international tree breeding organization, headquartered at North Carolina State University. Camcore works on behalf of its private industry members to maintain broad genetic bases of the best-adapted and productive species for use in plantation forestry. Then UNDP and FAO, along with development Banks, such as the Asian Development Bank and the World Bank, supported forest genetic resources R&D in

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[10] The decline in funding of national tree seed centres arises from ODA agencies looking to fund other priorities, perhaps not fully comprehending the long term nature and associated major benefits of tree species R&D (conservation, management and improvement) while national governments in developing countries often have more immediate priorities in health, education, infrastructure rather than activities that underpin sustainable rural development.

the developing tropics including in, for example, Indonesia, the Philippines, Sri Lanka and Vietnam.

FAO provided technical backstopping and a coordinating role for international collaboration in forest genetic resources, including both through their Forest Management Division, Panel of Forest Gene Experts and publication of their FGR journal. The 1970s–early 2000s was an era of major R&D in FGR management and improvement. During this period the crucial importance of seed source (geographic or provenance) variation was recognised for almost all tree species investigated. Range-wide or extensive seed collections were undertaken of major commercial timber trees, nitrogen-fixing trees and multipurpose trees for arid-zone forestry for international provenance/progeny field trials. These included (non-exhaustive list) *Acacia anuera* (Midgley & Gunn, 1985; Ræbild et al., 2003), *A. auriculiformis/A. crassicarpa & A. mangium* (Awang et al., 1994; Chittachumnonk & Sirilak, 1991; Gunn et al., 1988; Gunn & Midgley, 1991; Minquan & Yutian, 1991), *Acacia colei/A. holosericea & A. tumida* (Thomson & Cole, 1987; Cossalter, 1988; Chege & Stewart, 1991; Rinaudo et al., 2002), *Agathis* spp[11]. (Bowen & Whitmore, 1980), *Azadirachta indica* (FAO, 2000), *Calliandra calothyrsus* (Macqueen, 1993; Pottinger & Dunsdon, 2001), *Casuarina equisetifolia* (Pinyopusarerk et al., 2004), *Cordia alliodora* (Boshier, 1984), *Eucalyptus camaldulensis* (Midgley et al., 1989, Figure 13), *E. microtheca* (Johansson & Tuomela, 1996), *E. urophylla* (Vercoe & Clarke, 1994;, Hodge & Dvorak, 2015)*, Gliricidia sepium* (Hughes, 1988; Dunsdon & Simmons, 1996), *Gmelina arborea* (Lauridsen & Kjær, 2002; Hodge & Dvorak, 2004), *Leucaena leucocephala* (Stewart et al., 1991; Brewbaker & Sorensson, 1994), *Pinus kesiya* (Costa e Silva & Graudal, 2008), *Pinus greggii P. maximinoi*, *P. patula* and *P. tecunumanii* (Birks & Barnes, 1985; Hodge & Dvorak, 2012), *Tectona grandis* (Kjær et al., 1995), *Terminalia superba* (Corbasson & Souvannavong, 1988) and dry zone species, including African acacias and *Prosopis* (Graudal, 1995).

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[11] Comprehensive *Agathis* species/provenance seed collections were done, an expensive undertaking, but then lost viability due to London postal strike and could not be recollected or field tested

Figure 13. Variation in *Eucalyptus camaldulensis*. [A] Variation in salt tolerance on salt pan at Whiteheads Creek, Vicotoria, Australia. The better performing provenance in foreground is from Silverton, New South Wales. [B] Half-sibling family variation in trials in Terai, Nepal – while matching of correct geographic/climatic source will lead to gains in productivity of more than 100%, the selection of superior families (middle row), can lead to additional productivity gains of more than 30%. [C] Poor performance of local landrace (R) compared with northern Australian source (L), northern Vietnam. **Lessons:** 1. Selection and breeding of diverse tree species, such as *E. camaldulensis*, go hand-in-hand with their optimal utilisation in agroforestry systems, 2. There may be trade offs in terms of productivity and stress adaptation, and optimal tree germplasm and site matching needs to take into account within-species genetic variation. 3. It can be challenging to supplant poor and inbred tree germplasm even when the economic benefits of doing so are evident. (Photos: Lex Thomson [A,B], Khongsak Pinyopusarerk [C])

For many tropical tree species, a gain in productivity of 10–40% over the average was evidenced simply through identifying and selecting the best seed source (e.g., Brown, 1987; Foster et al., 1995). When combined with simple selection and one breeding cycle then productivity gains are of the order of 30-100% over average unselected seed source performance (e.g., Kanowksi & Borralho, 2004; Lillesø et al., 2021). The importance of site-species-seed source matching and appropriate well-adapted, superior and/or diverse germplasm became widely recognised in private and public sectors, importantly donors, and among NGOs and others involved in tree planting and landscape restoration. Reviews of donor-funded tree seed projects, such as the AUSAID-funded ‘Seeds of Australian Trees’ project, revealed often massive economic and livelihood gains from these investments. This was especially the case for tree germplasm development for species desired by forest industry and smallholders alike such as *Eucalyptus* spp. in southern China (Turnbull, 2007). *Ex ante* economic impact assessments of ACIAR R&D projects in Asia on tree species/ provenance trials, species-site matching, seed production, seed orchards, improved seed have invariably shown massive benefit-cost ratios, i.e. 145:1 (hybrid acacia in Vietnam, van Bueren, 2004), 79:1 (improved tree species in Vietnam, Fisher & Gordon, 2007) and 57:1 (eucalypt tree improvement, van Bueren, 2004a). Nevertheless, this common knowledge—at least among tropical tree breeders—appears to have been lost as demonstrated by the lack of attention to seed source in most current tree-based restoration efforts (Jalonen et al., 2018; Roshetko et al., 2018).

CGIAR

In the early 1990s the Consultative Group on International Agricultural Research (CGIAR) included forests and trees in its research program. This was done through the inclusion of ICRAF (then International Council for Research in Agroforestry, now World Agroforestry) and the newly created Centre for International Forestry Research (CIFOR). IPGRI (now The Alliance of Bioversity International and the International Centre for Tropical Agriculture) was the third CGIAR centre to initiate work on forest genetic resources. At the outset CIFOR developed a research program on forest genetic resources (Boyle, 1996), but this was subsequently marginalised with conservation of forest genetic resources more treated as an outcome of improved forest policies and sustainable forest management, and later taken completely out of the programme of CIFOR. IPGRI and several of its R&D partners developed a substantial portfolio of research on tropical forest genetic resources, but without a strong focus on germplasm development and supply, and more applied institutional capacity development. The Musa Germplasm Transit Centre (ITC), part of the Alliance of Bioversity International–CIAT, houses the world's largest and most diverse collection of banana germplasm. The collection of more than 1,500 accessions of edible and wild species of banana, is hosted at the Katholieke Universiteit Leuven in Belgium.

ICRAF

ICRAF leads the flagship on tree genetic resources in the CGIAR Research Program on Forests, Trees and Agroforestry (FTA): the research under this CRP aims to bridge production gaps and promote resilience to provide solutions for the more effective safeguarding, domestication and delivery of these resources by and to farmers, foresters and other stakeholders. Indeed, ICRAF has had a major continuing program on forest genetic resources since joining the CGIAR in 1991, especially R&D on priority African indigenous multipurpose tree species, including their domestication (e.g., Dawson et al., 2012; Leakey et al., 2012), integration into smallholder agroforestry and development of markets for their products. ICRAF collaborates with national partners in 16 countries spread across all the five ICRAF regions to establish and manage field genebanks of agroforestry species. In addition to conservation, ICRAF's field genebanks also act as research sites for species evaluation, characterization and for seed multiplication. ICRAF maintains field genebanks in East and Southern Africa (Kenya, Malawi, Tanzania, Uganda, Zambia and Zimbabwe), West and Central Africa (Burkina Faso, Cameroon, Mali, Niger and Senegal); South Asia (India, Bangladesh and Sri Lanka); East Asia (China and Vietnam), and in Latin America (Peru). Currently, the ICRAF's living collection comprises a total of 60 genetically diverse fruit, medicinal, and multipurpose tree and shrub species. ICRAF holds more than 14,000 accessions of fruit and multipurpose trees (including 5,800 seed accessions) representing about 190 species, in its laboratory and field sites, and managed by its Genetic Resources Unit. Most of the tree seed distributed by ICRAF goes to recipients in countries within Africa, especially Kenya, with 90 percent of samples distributed directly to farmer organizations, individual farmers and NGOs.

The FTA program *"has sought to address twin concerns: first, how to make available quality tree planting material; and, second, how to ensure that tree seeds and seedlings are planted in the right places for the right purposes. It has addressed availability through building stakeholder partnerships and model tree seed systems; delivering improved orphan tree crops through supporting breeding pathways; mainstreaming food trees through nurseries; conserving and making available diverse tree germplasm to support delivery and use; and developing policies to support effective tree seeds and seedlings supply. It has supported better decision making through building information platforms to support tree planting choices and tree seed system operations; designing maps to guide* *tree seeds and seedlings distribution under current and future climates; and releasing statistical packages to guide appropriate tree planting* (Graudal et al., 2021).

BGCI

BGCI—a network of more than 600 institutional members in more than 100 countries—focuses on the conservation of the world's plant species. The CBD's Global Strategy for Plant Conservation, updated in 2010 and monitored by BGCI for the CBD Secretariat, highlights the importance of plants and the ecosystem services they provide for all life on earth, and aims to ensure their conservation. BGCI has a major focus on conservation of tree species as demonstrated in its ongoing Global Tree Assessment and recent State of the World's Tree report, and development of a Global System for the conservation of all known threatened tree species. The objective of the Global System is to prevent any threatened tree species from becoming extinct with all species conserved *ex situ* in either genetically diverse seed collections in seed banks or conserved in genetically diverse living collections (field gene banks) where long term seed storage is not possible. It further aims for all tree species in the most threatened categories to be in species recovery programs with all critically endangered species conserved and managed *in situ*.

Through its Global Trees Portal, BGCI provides information on the world's nearly 60,000 tree species: 2,100 tree species are critically endangered with 440 species having less than 50 individuals. BGCI members maintain mainly living collections of planted trees and shrubs, but also seed, and freely share this material among gardens and others in accordance with CBD and Nagoya protocols to better ensure its long-term conservation. Information on cultivation of tree species in botanic gardens, outside of their natural range, helps to better define each species climatic envelope and where it can be grown and likely impacts of climate change.

MSB

The Millennium Seed Bank (MSB) Partnership is built on a network of organisations around the world that share a common interest in the conservation of wild plant diversity: MSB is coordinated by Royal Botanic Gardens Kew and based at Wakehurst Place, West Sussex (UK). MSB is the world's largest and most diverse wild plant species seed collection, with over 39,000 species banked—more than 2.4 billion seeds—originating from 97 countries. The MSB prioritises plant species with orthodox seeds—that can tolerate being dried and frozen, those vulnerable to climate change—including mountain peak, dryland, coastal and island ecosystems, plants that are useful for livelihoods and economies including crop wild relatives, narrowly distributed endemics and endangered species. When seeds are required for research purposes, they may be requested from the MSB. If it has the legal permission to do so (from the donor country), then MSB can provide up to 60 seeds gratis to non-commercial organisations for the purposes of research, restoration and/or reintroduction. MSB has introduced about 420 plant species back into the wild through its global partnerships and supplied 4,600 seed samples for use in research and conservation. One of the most important activities of the MSB has been in training project collaborators in developing countries, in plant identification, seed collection, testing and storage, and equipping them to undertake collections.

National and Regional Tree Seed Centres

Many developing nations have a national tree seed centre or unit typically based in the Department of Forestry or Environment. Generally, the seed collections that are being held, are not for longer term conservation but rather active collections to be used for propagation of planting stock for tree planting programs, forest restoration and research. However, most national tree seed centres in the developing tropics are poorly resourced and their collections are of variable quality: seedlots may sometimes be misidentified, poorly stored and without a recent viability test. A major issue is intermittent power supply without a backup power source, which can result in seeds being periodically exposed to warmer ambient temperatures and reducing seed viability and storage life. Some of the seemingly more active and functional national seed centres include Burkina Faso’s Centre National de Semences Forestiéres, Ethiopia’s National Tree Seed Network, Ghana Forestry Research Institute’s National Tree Seed Centre, Kenya Forestry Research Institute Seed Centre, Rwanda’s National Tree Seed Centre, Ugandan Tree Seed Centre, and Banco de Semillas Forestales (BSF – CATIE, Costa Rica).

CSIRO’s Australian Tree Seed Centre (ATSC) maintains an active collection distributing seeds of mainly Australian and PNG trees. The extensive cultivation of eucalypts (30 M ha, Midgley et al., 2021), tropical acacia (3 M ha, Mendham & White, 2019), casuarina (c. 1 M ha, Haruthaithanasan et al., 2020), grevillea and melaleuca globally, is in part due to the their characteristics of ease of propagation, rapid growth, adaptation to infertile soils and production of in-demand wood products, but also to the effective domestication work of the ATSC and R&D partners in developing countries, involving range-wide seed collections, comprehensive field testing followed by improved seed source development. A similar approach was used by CSIRO ATSC for the SPRIG (South Pacific Regional Initiative for Forest Genetic Resources) project, resulting in the identification and increased planting of indigenous trees in Pacific Island countries including *Canarium harveyi* and *C. indicum*, *Endospermum medullosum*, *Flueggea flexuosa*, *Garcinia sessilis*, *Pandanus tectorius, Santalum austrocaledonicum* and *S. yasi*, *Terminalia catappa* and *T. richii*.

The Pacific Community's (SPC) Centre for Pacific Crops and Trees (CePACT), based in Suva Fiji, maintains and distributes tissue cultured lines of cultivars of breadfruit, banana, coconut (Figure 14) and pandanus, as well maintaining a modest seed collection of tropical tree species, mostly from Pacific Islands.

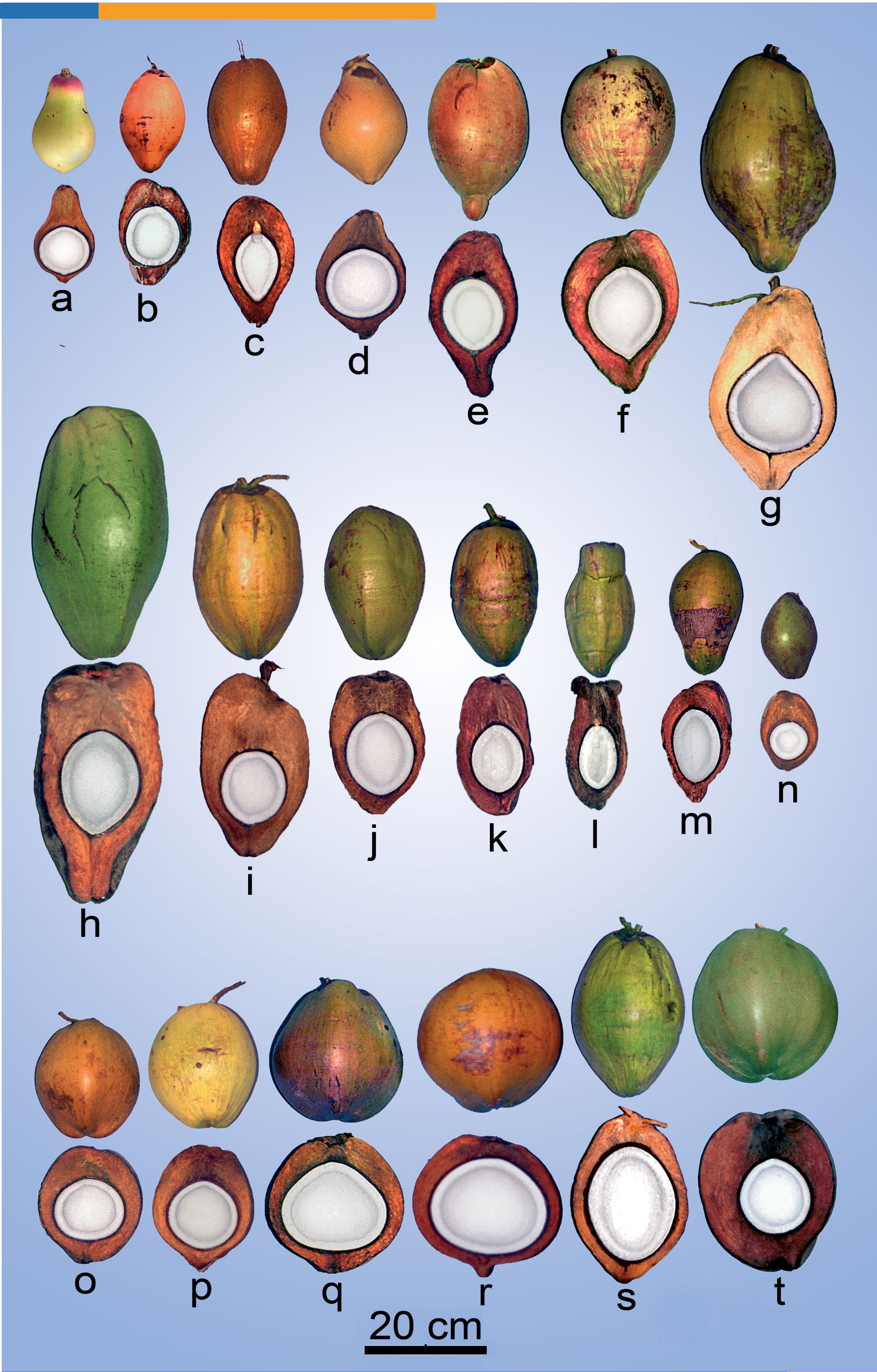

Figure 14. Cutlivar diversity in coconut (*Cocos nucifera*) for fruit shape, size, colour and proportion of husk. (Photo: Roland Bourdeix)

Svalbard Global Seed Vault

The purpose of the depository, owned by the Norwegian government and maintained by the Global Crop Diversity Trust (GCDT) and the Nordic Genetic Resources Center, is to store duplicates of all seed samples from crop collections around the world. Permafrost and thick rock ensure that, even in the case of a power cut, the seed samples will remain frozen. Duplicate samples from ICRAF are now being conserved at Svalbard, including 1,171 samples of 177 species in 104 genera.

3.2 Role for collections-based research organisations in supporting resilient landscape approaches

The respective roles and interests of the collections-based research organisations described above in supporting resilient landscape approaches—rooted upon tree diversity—will differ among organisations, depending on their objectives and level of resourcing. It is apparent that a complementary, better-coordinated and resourced approach is urgently needed to optimise conservation of tree diversity and make much more effective use of FGR in addressing major global challenges including global food insecurity and malnutrition, runaway climate change[12] and biodiversity loss as being witnessed in the planet's sixth mass extinction event (Ceballos et al., 2017). CIFOR-ICRAF, BGCI and the Alliance of Bioversity International-CIAT, are best placed to lead such a global coordination task, as well as FAO (through their Forest Management Division/FGR officer) and the MSB.

The respective roles might be:

ICRAF – continue to focus on researching, developing and conserving trees to support their effective use in maintaining livelihoods and the environment. The FGR conservation activities to be mainly through *circa situm* approaches in agroforests, interconnected with FGR throughout the landscape including primary and secondary forests and especially forest fragments and remnants ICRAFs expanded portfolio of work would essentially be an intensification of its activities with national and development partners in sub-Saharan Africa, Asia and Pacific, central and Latin America to both capitalise on its extensive experience on germplasm dissemination, species-site matching, tree domestication, value adding and development of markets for agroforestry products. ICRAF has been progressing higher quality in tree seed and seedling supply by facilitating partnerships between the public and private sectors and supporting innovation. ICRAF has also engaged directly in development projects and broader tree planting programmes to produce high-quality tree planting germplasm on a large scale and conserve forest genetic resources, such as PATSPO, but such activities need to be extended. A common limiting factor to better tree planting and reforestations projects remains the lack of high-quality germplasm – the tree seeds and seedlings of the right trees – that are needed.

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[12] The expression 'runaway climate change' is not used lightly here. It is clear for example that greenhouse gas emissions are inexorably rising, climate tipping points are being reached faster than was predicted by the climate models and the rate of sea level rise is increasing.

[13] The former DANIDA TSC programme has been maintained at the University of Copenhagen and is now largely embedded in ICRAF.

ICRAF has major advantages, compared to other organisations, in development of diverse tree germplasm for smallholder farmers and tree growers through its extensive experience and practice of linking research with and for development[13].

BGCI – continue its vital work on the Global Tree Assessment and tree conservation through its Global System for the conservation of threatened tree species. BGCI is well placed to work with its member Botanic Gardens to conserve rare and endangered species and populations of trees, arborescent monocots and woody shrubs in their living collections, seed banks and through in-country partnerships. Another focus for BGCI and botanic gardens ought to be on conservation of families and genera with one (monotypic) or few representatives. The thrust for BGCI and members needs to be on conserving sufficient diversity in each target species and each garden is best to work with a small number of species (quality of conservation over quantity of species).

It will be impossible for individual Botanic Gardens to grow the desired number of trees to effectively conserve more than a few species given that garden-bed space in BGs is almost invariably quite limited. In order to extend their impact in conservation plantings BGCI affiliates to link up with public authorities (local and provincial government, parks, forestry and water supply authorities) and community groups operating in the same area. The authorities could be approached to ascertain their interest in providing vacant or degraded lands for *ex situ* conservation-focussed plantings of rare and endangered tree species. Such plantings would also have value for research and education purposes, and act as seed sources given they would have a reasonable level of genetic diversity. BGCI is coordinating a suite of Global Conservation Consortia, which catalyse groups of institutions and experts to collaboratively develop and implement comprehensive strategies to prevent extinction of temperate and sub-tropical zone threatened plant groups including *Acer*, cycads, dipterocarps, *Erica*, *Magnolia*, *Nothofagus*, oaks, and *Rhododendron*. These consortia are carrying out integrated (*in situ*, *circa situm* and *ex situ*) conservation approaches, including genetically diverse field gene banks, for often recalcitrant or difficult orthodox seeded tree and woody shrub taxa. These Consortia groups also can act as useful models for their extension to include tropical food tree groups (their cultivars and wild relatives) such as in *Adansonia*, *Artocarpus*, *Canarium,* citrus, fehi bananas and *Mangifera,* to name but a few. Central Asia is a locus of temperate fruit tree diversity together with adjacent western China, e.g., for *Malus* (Juniper & Mabberley, 2019) with both species and cultivar diversity at risk from climate change and other threatening factors: there is a pressing need for conservation of fruit tree diversity in central Asia. In the tropics slower-growing conifers with small scale like leaves such as *Dacrydium* are especially at risk from climate change: these, often highly ornamental and valuable timber species may need to be conserved *ex situ* in living collections in botanic gardens as increasingly they are threatened and unable to regenerate in their native habitats, e.g., *Dacrydium nausoriense* in Nausori Highlands, Fiji.

In tropical developing countries, such Botanic Gardens extension activities, might also include key multipurpose and food trees for which seed is needed for plantings by Forestry Departments, NGOs, farmer associations and others for their tree plantings. In conjunction with BGCI's outstanding research and education on conservation of global tree species, and the continuing achievements of Kew Garden's Millennium Seed Bank (MSB) Partnerships, such actions would elevate the tree diversity conservation role of botanic gardens. It would place Botanical Gardens on a par with Zoological Gardens which have overhauled their objectives and operations to be a major force in wildlife conservation. Indeed, there are also opportunities to enhance the conservation value of trees being planted in Zoological Gardens, as is already happening in some places.

National Tree Seed Centres

NTSC play important roles in collecting and distributing tree germplasm both within, and sometimes beyond, their national borders. Generally, NTSCs stock active seed collections which may rapidly turn over, rather than long term storage for conservation. The seed collected by the NTSC may comprise a significant proportion of that being used for propagation and going into national tree planting and forest landscape restoration programs. Accordingly, it is essential that NTSC staff are better educated on the need to capture the genetic diversity of the species they are collecting, and how to efficiently do this. NTSCs also need to be much better equipped and resourced such that more extensive and comprehensive tree seed collecting missions can be mounted to all parts of the country, including remote areas where the genetic diversity of tree populations may be more intact and collecting much larger quantities of seed commensurate with that required.

4.0 Strategies to strengthen the integration of different approaches to tree diversity conservation

4.1 Introduction

The general strategies for conservation of forest genetic resources have often been classified as:

Ex situ – seed stored in gene banks (tree seed banks, tissue culture facilities, viz. static conservation) and as living trees outside of the natural range in field gene banks, plantations and botanical gardens.
Circa situm **-** conservation within altered agricultural landscapes outside of their natural habitats but within a species' native geographical range, e.g., agroforestry systems and home gardens.
In situ **–** conservation in the natural range in managed, natural forests and protected areas (dynamic conservation) (e.g., Boshier et al., 2004; FAO, FLD & IPGRI, 2000, 2004, 2004a; Graudal et al., 1995, 1997, 1999, 2000; Kjær et al., 2004; Young et al., 2000; Wang et al., 1993).

Often more than one of these strategies is applied to the conservation of the genetic resources of a threatened tree species. The term complementary strategies may then be applied, but with limited integration of the strategies, rather it is more safety duplication in case one strategy fails. The next section will consider how conservation strategies can be better integrated to provide more effective conservation, management and use.

For tree species with orthodox seeds (the majority of temperate and arid zone species) conservation can be efficiently achieved through seed collections stored in hermetically sealed containers at low, constant temperatures (e.g., at ±2-4°C fridge or -30°C or freezer). For tree species with recalcitrant and short-lived or difficult to store orthodox seeds—which encompasses a high proportion of tropical tree species and arborescent monocots—they will need to be stored in living collections, such as in the botanic gardens. From a genetic conservation standpoint—and especially for botanic gardens engaged in seed distribution—it is preferable to have a clumped planting or grove of minimally 15 (preferably 50 or more) genetically diverse individuals for each species conserved (see also Graudal et al., 1997). The minimum number of individuals needed to reasonably represent a rare or endangered species or subspecies will depend on breeding system and genetic diversity: ideally they will be derived from different populations unless outbreeding depression is known or considered likely (for example, if they have fixed chromosomal differences, exchanged no genes in the last 500 years, or inhabit different environments, see Frankham et al., 2011).

4.2 Strengthening integration of different conservation approaches

Some examples of where tree diversity conservation strategies can be better integrated include:

1. ***Ex situ* –** seed stored in ICRAF or BGCI partner genebank. For each seed accession an assessment ought to be made of its conservation value, taking account of both the species conservation status and the threat level to the particular population (as well as the documentation associated with the seedlot, including number of mother trees represented in the sample). The assessment ought to ideally be undertaken at the time the accession is received or collected, and then periodically repeated (if resources permit). For accessions with high conservation importance, e.g., species and/or population threatened, then a proportion of seed needs to be set aside in long-term storage in case it is required to re-establish or invigorate the species/population in the wild. Consideration also needs to be given to establishing a breeding seedling seed orchard for threatened species/populations for which there is a demand for seed for plantings.

2. ***Ex situ* –** live plants in ICRAF field genebanks. As for stored seedlots, these accessions need to be assessed for their conservation value, which will then help to inform their priority and how they can be best managed. It is observed that seed collected from ICRAF field genebanks may be of mixed provenance origin, and accordingly problematic for re-introduction back into its original collection sites (due to the potential of genetic contamination of any remaining individuals. However, seed of provenance crosses can be extremely useful for smallholder plantings and *circa situm* conservation due to the expected high levels of diversity, potential heterosis from wide provenance crosses, and opportunities for development of land races.

3. ***Ex situ* –** live plants in BGCI partner botanic gardens. Trees in botanic gardens may have limited conservation value, due to any collected seed being inbred due to small numbers of possibly related individuals, especially for monoecious species, unless seed is collected from a larger stand, e.g., seed from the 20-ha planted stand of *Swietenia macrophylla* in Lancetilla Botanic Garden and Research Centre, Honduras has exhibited excellent performance in Fiji. There will also be cases where tree species in botanic gardens are extremely valuable for conservation, i.e., in cases where the species has been extirpated or become extremely rare in the wild.

4. ***Circa situm* –** trees on smallholder farms. In many situations, there is expected to be gene flow between trees on farms and nearby wild stands of the same (or closely related) species. In addition to affecting the commercial value of planted trees, the choice of species/seed source used in smallholder tree plantings is important because of the potential impacts, both positive and negative, on wild tree populations. Where genetically appropriate and diverse seed sources are used in smallholder and reforestation plantings, then this will likely have a positive effect on the fitness of subsequent generations of local species; on the other hand, introduction of related species, which can hybridise with local species, may lead to genetic contamination of the local species, and in a worst-case scenario, their replacement with hybrids.

5. ***In situ* –** trees in protected areas and managed native forests. Increasingly, it can be difficult to obtain permits to collect tree seed from areas having an *in situ* conservation function. Whilst this is understandable, in that removal of some, or rather too much seed, can potentially impact regeneration, there may also be a need or desire to

collect seed or propagules for *ex situ* conservation and to provide for the possibility for later re-introduction or to include in mixed seed sources to restore diversity which may have been lost through habitat fragmentation, loss of habitats and overharvesting.

The examples provided here for enhancing integration of different tree genetic resources conservation strategies include those already being enacted by ICRAF, BCGI and their national partners and members. Two notable examples are:

Ecological Restoration Alliance of Botanic Gardens is an international consortium of botanic gardens, established in 2012, and actively engaged in ecological restoration. Members of the Alliance have agreed to support efforts to scale up restoration of damaged and degraded ecosystems around the world. This is in recognition of the vitally important role that botanic gardens, arboreta and seed banks can play in restoring degraded ecosystems, and ensure greater complementarity and synergies between *ex situ* and *in situ* conservation. The Alliance has now grown to 46 member botanic gardens, working to restore a variety of different ecosystems in a range of cultural contexts across six continents. Collectively, ERA members manage over 140 active restoration projects, utilising their herbarium, seed and living plant collections, and botanical and horticultural expertise to restore ecosystems. The ERA is committed to building capacity for restoration and to improving the quality and volume of science-based ecological restoration practice.

Provision of Adequate Tree Seed Portfolios (PATSPO) project, Ethiopia
The Ethiopian government has ambitious reforestation objectives and has recognised that its target of 20 million ha is best done using locally adapted, multipurpose tree species. In 2017, with funding from Norway, the Ethiopian Government contracted ICRAF to implement the PATSPO project. PATSPO is working to ensure access to high quality seeds of the most important tree species used for forest landscape restoration and tree planting activities in Ethiopia. It has established 26 breeding seedling orchards and registered over 100 existing tree seed sources, mostly of native trees, that can be used for providing high quality tree seed for planting. ICRAF has also built an integrated network of public and private partners to efficiently supply tree seeds to growers; upgraded the tree seed processing facilities of national providers; and trained over 500 tree seed collectors to improve seed quality. According to the Mid-term Review (Smith & Tadesse, 2020), PATSPO is most relevant to, and will have the greatest impact on seed supply systems, in the following order:

- Provision of high-quality exotic and indigenous seed and tools to support production and agroforestry initiatives such as Ethiopia's Climate Resilient Green Economy strategy aimed at improving livelihoods and stimulating Ethiopia's green economy.
- Provision of high-quality exotic and indigenous seed and tools to support REDD+ avoided deforestation and assisted natural regeneration initiatives by providing alternatives to cutting of natural forest through Participatory Forest Management agreements with communities.
- Provision of high-quality seed of indigenous species and tools to assist natural forest restoration components of FLR initiatives such as the Bonn Challenge, NICFI and the REDD+ partnership.

The ICRAF's Genetic Resources Unit tree seed bank is amongst the world's largest that is being actively used for tree planting, and with many accessions safely duplicated in the Svalbard Global Seed Vault. On its Global Tree Knowledge Platform, ICRAF maintains extensive databases, accurate maps and applications, tailored guidelines and detailed analysis packages that support properly targeted tree planting, making use of indigenous trees where possible (Kindt et al., 2021a).

PATSPO/ICRAF GRU provides an outstanding model for how tree germplasm supply needs can be addressed in tropical developing countries. Such work needs to take place ahead of major tree planting initiatives in order to be most effective. PATSPO well illustrates how ICRAFs GRU seed collections (*ex situ*) and associated expertise can be used to generate seed at the scale required to impact *circa situm* and *in situ* conservation of Ethiopia's forest genetic resources.

There may also be novel opportunities for public-private partnerships, including NGOs, to better conserve and sustainably manage forest genetic resources in the tropics: these could learn from and build on the excellent models of Camcore (North Carolina University and private sector) and USDA Forest Service (Jetton et al., 2017) and ICRAF's work with Unilever and partners on *Allanblackia*.

As shown in the above examples, conservation of tree species diversity typically involves different groups of participants. These include gene bank curators and scientists working in botanical gardens, as well as forestry and environmental agencies, land managers, traditional owners and private sector forestry corporations. The most important element in ensuring better integration of conservation strategies is to ensure that there is effective and regular communication between the different participants and stakeholders leading to a better coordinated effort. The consultant believes that the most effective way to ensure better integration of conservation strategies is to build on and strengthen the activities of Ecological Restoration Alliance of Botanic Gardens/BGCI and that of ICRAF and national partners as demonstrated in the PATSPO project. It may be possible to build on these to develop an on-line-platform that brings together a community of practice, researchers and practitioners for reforestation using diverse and appropriate tree germplasm and promoting integrated conservation strategies.

Furthermore, a consolidated database of *ex situ* collections of rare and threatened tree species would be a vital resource, including for making better use of *ex situ* collections for *circa situm* and *in situ* conservation and identifying gaps: however, this is a considerable undertaking both to establish and maintain, and well-deserving and requiring external financial support.

5.0 Approaches to enhancing the use of diverse tree genetic resources in agroforestry, restoration, reforestation

5.1 *Current tree planting and reforestation programs and their sources of germplasm*

Following are examples of current tree planting and reforestation programs being undertaken by different actors in developing countries, some are major global or regional initiatives such as the Bonn Challenge while others are on a smaller but locally important scale. Most of the grander scale plantings are being undertaken with a view to increasing carbon sequestration and arresting desertification (i.e., climate change mitigation and adaptation) and supplementary objectives of enhancing rural livelihoods and biodiversity conservation. These examples provide a brief overview of some current efforts, their approaches and the sources of germplasm, their strengths and achievements, as well as challenges and lessons learnt.

5.1.1 *The Great Green Wall (Sahel, sub-Saharan Africa)*

The Great Green Wall (GGW) was launched in 2007 by the African Union in a bid to arrest desertification in the Sahel. The project is being implemented in more than 20 countries and more than eight billion USD have been mobilized for the projects. The total area of the GGW initiative extends to 156 M ha, with the largest intervention zones located in Niger, Mali, Ethiopia and Eritrea. The original project which involved planting a belt of trees about 1.5 km wide across the Sahel was poorly conceived, and as predicted by forest scientists in the 1990s, was largely unsuccessful. A lesson learned is that establishing trees in arid and semi-arid zones using seedlings is an expensive and challenging exercise. Usually such large-scale, fast-tracked initiatives do not take account of the source of germplasm with the result that seed is not available of the desired species and provenances. The GGW has now morphed, at least in some areas, into a highly successful farmer managed natural regeneration project (see 2.1.1; Dawson et al., 2021).[14]

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[14] https://www.unccd.int/actions/great-green-wall-initiative;
https://www.smithsonianmag.com/science-nature/great-green-wall-stop-desertification-not-so-much-180960171/;
https://www.science.org/content/article/great-green-wall-could-save-africa-can-massive-forestry-effort-learn-past-mistakes;
https://www.youtube.com/watch?v=XLgjyOmNkgE&t=90s&ab_channel=WorldAgroforestry

5.1.2 African Forest Landscape Restoration initiative (AFR100)

The African Forest Landscape Restoration Initiative is a country-led effort to bring 100 million hectares of degraded lands in Africa into restoration by 2030. AFR10 is a partnership of 31 African governments and technical and financial partners. It contributes to the Bonn Challenge, the African Resilient Landscapes Initiative, the African Union Agenda 2063 and the Sustainable Development Goals. It adopts a landscape approach based on best practices and 10 principles. With some exceptions there seems to have little attention paid to species to be restored and sources of germplasm. ICRAF estimates that investing a mere 5% more in tree seed supply, in a campaign to plant a broader range of higher quality, locally adapted indigenous tree seed sources, would be enough to enhance the restoration of 20% of the AFR100 target area to the extent of generating over 5 billion USD of extra income for tree growers. At the same time, this extra investment in tree seed by AFR100 would sequester a further 19 million tonnes of carbon, reduce annual soil erosion by a further four million tonnes, and generate at least 80,000 more jobs in the harvesting, processing and marketing of new tree products.

5.1.3 Humbo Community Managed Reforestation (HCMR) Project, Ethiopia

After two years of planning and consultations, World Vision's HCMR Project was initiated in 2006 under the Clean Development Mechanism, and the first Land Use, Land Use Change and Forestry carbon trading initiative in Ethiopia. The project involved regeneration of 2,728 hectares of degraded native forests with indigenous, biodiverse species through community managed FMNR (Figure 15). In order to supplement the FMNR reforestation, newly established tree nurseries raised over 450,000 seedlings each year to restore the forest where no living tree stumps remained. The impact on the community has been profound – cessation of damaging flooding, greatly reduced impact of drought; provision fodder, fuelwood, carbon credits, honey, wild foods—including nine species of wild fruit trees—and traditional medicines, and improved agricultural production on surrounding farms. Key elements to the success of the project, including legally binding tree user rights and formation of forest management cooperatives, have been identified. One of the most important elements of success of HCMR was being able to fully utilise the existing locally adapted tree genetic resources, through protection and regrowth of coppice stumps, supplemented by seedling propagation of the most highly desired local trees (World Vision, 2009, 2020).

Figure 15. Humbo Community Managed Reforestation Project, Ethiopia. (Aerial view, Google Earth)

5.1.4 One million *Faidherbia albida* tree planting program, Ethiopia

An Ethiopian Government Initiative to plant one hundred million *Faidherbia albida* trees was announced by the late Prime Minister Meles Zenawi at the 2011 Climate Change Convention in Durban, South Africa. The trees were to be established on smallholder cereal croplands across the country over three years with the aim of improving food production and livelihoods. However, the *Faidherbia* project floundered due to the challenge for the Forestry Department to collect the 150 million seeds of *Faidherbia* required to propagate the seedlings for planting. On the other hand, there are already many millions *of Faidherbia* 'shrubs' already on Ethiopian farmlands. These are cut, slashed, ploughed over, grazed, burnt each year, but ready to grow into trees if protected and given a chance. This example highlights the challenges of rapidly scaling up seed collection and production for large-scale reforestation and the complementarity of seedling planting programs with farmer managed natural regeneration, in areas where coppice of original vegetation still persists.

5.1.5 Tree planting in the South Pacific Islands

The Fiji Government's 4 Million Trees in 4 Years programme (4MT4Y) was launched in 2019. This has been a generally successful project, involving community and village groups and meeting its planting targets, but utilizing only a limited diversity of native and exotic tree species; the latter mainly due to lack of resources for the Forestry Department to collect seeds and/or wildlings. The 4MT4Y planting programme can be of greater socio-economic and biodiversity benefit a with greater inclusion of seedlings of indigenous fruit and nut trees (e.g., *Dracontomelon vitiense/tarawau*, *Pometia pinnata/dawa* and *Barringtonia/vutu kana*), endangered dry forest tree species (e.g., *Cynometra falcata/cibicibi*, *Dacrydium nausoriense*/highlands yaka), indigenous timbers (e.g., *Agathis macrophylla/dakua makadre*, *Dacrycarpus imbricatus/amunu, Decussocarpus vitiensis/dakua salusalu*, *Gmelina vitiense*/rosawa) and trees for catalysing biodiversity (e.g., *Degenaria/masiratu*, *Geissois/vure*, *Koelreuteria elegans/manuwi*). A key lesson is that high quality, diverse tree germplasm needs to be assembled prior to or at the outset of planting programs.

In Samoa, the two million tree campaign (2015-2020) was designed to restore the island nation's forests after a decade of decline driven by climate change, infrastructure and the 2009 tsunami. The project was successful with more than two million native and fruit trees planted through major community involvement. A diversity of multipurpose indigenous trees were incorporated into thess plantings building on research and seed sources developed by the Forestry Division with support from the CSIRO SPRIG project (1996-2006). A key lesson from this project is the need to undertake R&D on local trees, develop seed stands for the most promising and sought-after species—including highly cyclone resistant trees such as *Terminalia richii* (*malili*), understand their seed properties, propagation characteristics and silvicultural traits.

5.1.6 China forest and grassland five-year plan 2021-2025

China has established the world's largest planted forests, raising its forest cover from 12% in the early 1980s to 23.04% in 2020. Its Grain-for-Green Program (GFGP), initiated in 1999 primarily to control soil erosion, was the largest reforestation programme ever undertaken. However, an assessment has found that GFGP forests are overwhelmingly monocultures or compositionally simple mixed forests and fall short of restoring biodiversity to levels approximating native forests (Hua et al., 2016). According to its new forest and grassland five-year plan, China aims to raise its overall forest coverage rate by 1% (23.04 to 24.1%) by the end of 2025. China will plant 36,000 km^2 of new forest per year until 2025 as a measure to combat climate change and better protect natural habitats, especially in drought-prone regions in the north and west. The plan does not state what type of trees would be planted but the strategy will rely in part on 'natural reforestation' with different types of trees planted according to the local environment. Assuming a low-medium stocking rate of 1,000 trees per ha this would imply 3.6 billion plantable seedlings propagated per year or if direct seeding is used then approximately 3,600 tonnes of seed per year will be needed. The scale of this reforestation challenge is indeed formidable, and it would seem improbable that sufficient well-matched germplasm will be able to be collected and utilised in such a short time frame. The best option will be to incorporate several different species and sources and plant in intimate mixtures and allow natural selection to take its course (as has been done elsewhere in China, see 2.1.2). Whilst the planting targets are laudable, the new planting sites are of low site quality (cold and dry) and trees will sequester carbon at much lower rates than if plantings were undertaken in the south and as agroforestry/boundary plantings in rice and other crops.[15]

5.1.7 The One Billion & Ten Billion Tree Tsunamis, Pakistan

The Ten Billion Tree Tsunami (TBTT) will run from 2018 to 2023 and builds on the momentum of the earlier One Billion Tree Tsunami (OBTT) – a forest restoration campaign in Khyber Pakhtunkhwa Province from 2014 to 2017. The earlier project planted 872 M seedlings with 89% survival and 350,000 ha reforested[16]. The pioneer chir pine (*Pinus roxburghii*) was one of the main species used in the OBTT plantings and highly successful (as was the case in Nepal, see 2.1.2). While native trees are primarily grown in naturally regenerated areas, a mix of native and non-native species will be planted in community forests: exotics are preferred for the fat growth and timber value. Finance for Biodiversity (F4B)—a novel type of debt relief in exchange for achieving nature conservation targets—is being explored to help fund the tree planting initiative. Species/site matching will be vital in the new project given the vastly different environmental conditions in the target planting areas. When the one billion tree project was announced, the available seed stock was less than 10 percent of the number of seedlings needed to be raised: in this case the seed was able to be amassed in large measure due to the high seed production of chir pine and possibly substitution of different species. Getting seed supply right will be much more challenging in the new project due to the diversity of species and seed sources which

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[15] http://www.news.cn/english/2021_08/24/c_1310146397.htm?ct=t(EMAIL_CAMPAIGN_8_15_2020_13_19_COPY_01)

[16] The project was reviewed as successful but subsequently has come under investigation by the National Accountability Bureau. See https://www.thenews.com.pk/print/591740-nab-detects-over-rs462m-loss-in-initial-inquiry-into-billion-tree-tsunami

will be needed.

5.1.8 Uttar Pradesh, India

On Earth Day 2016, India committed to spend USD 6 billion to reforest 12% of its land, bringing its total forest cover to 95 million ha by 2030, or about 29%. As part of this effort, 50 million trees were planted in a single day in the state of Uttar Pradesh by 800,000 volunteers. Seedlings of 80 different species of trees, raised in local areas, were planted along roads, railways, and on public land. The utilisation of such a large number of species will likely ensure that at least a proportion of the planted trees will be adapted to the planting environment. Community involvement is also excellent but there will likely be high mortality due to the use of overgrown planting stock and inexperienced planters and lack of followup watering and maintenance.

5.1.9 Atlantic Forest Restoration Pact, Brazil

Brazil's Atlantic Forest Restoration Pact is a national movement whose aim is to restore the biodiverse but highly degraded and fragmented Atlantic forests, while generating environmental, social and economic benefits. Established in April 2009, the Pact acts strategically linking public and private institutions, governments, companies, the scientific community and landowners to integrate their efforts and resources in generating results in the restoration and conservation of biodiversity in the 17 states with Atlantic Forest. Between 1996 and 2015 2.72 million ha of forest regenerated naturally representing an area equivalent to 8.0% of the existing remnant forest area. Prioritizing natural forest regeneration in the most suitable areas will ensure that limited funds for restoration can achieve maximum benefit. The potential for natural regeneration is greater in areas with intermediate levels of forest cover as these areas tend to have the most amount of cleared land near a remnant forest edge. It has been estimated that assisted natural regeneration could save up to USD 90.6 billion compared to a restoration scenario based on tree planting and will better ensure that local tree species and their diversity are maintained. The three main factors considered most responsible for the successful recovery of the Atlantic Forest are the development of a governance and communication strategy in 14 of the 17 states covered by the forest; the establishment of a restoration monitoring system; and the promotion of a vision and strategy to influence public policy and restoration. Prioritizing natural forest regeneration in the most suitable areas will ensure that limited funds for restoration can achieve maximum benefit (Brancalion et al., 2013; Chazdon & Guariguata, 2016; Crouzeilles et al., 2020; de Siqueira et al., 2021; Strassburg et al., 2019).

5.2 Summary of current situation for germplasm being used in tree plantings and reforestation in the developing tropics

As the above examples show, there is a serious concern that, in many recent large-scale tree planting programs in the developing tropics insufficient, indeed often minimal, attention is being paid to their sources of germplasm. This partly arises from a lack of awareness, among decision makers and planners, of the potentially disastrous consequences of using poorly adapted, sub-optimal or even worse, environmentally weedy germplasm[17]. Furthermore, those responsible for implementation of mega-tree planting projects, including the technical professionals and practitioners, may lack knowledge of what tree species/seed source to grow where, and for what purposes, and the most efficient and effective strategies for tree establishment. In some cases, expediency is also involved as it may be well-nigh impossible to assemble the requisite quantity of the desired tree germplasm at short notice.

It is clear that grand schemes entailing tree planting on a massive scale are those most deficient in considering critical issues such as species-site matching; sourcing appropriate and diverse germplasm; balancing livelihoods/carbon sequestration and biodiversity considerations; reforestation strategy and ongoing maintenance (as may be needed in early years).

Whether it be tree germplasm for smallholders or large reforestation schemes, it is extremely difficult and costly to replace sub-optimal germplasm once established in a landscape. This is because pollen and seed will continue to spread and be dispersed, including hybridising with both cultivated and wild populations (if of the same or compatible species). While a low branchy, heavy fruiting phenotype may be advantageous where fruit or seed is the main product it is usually undesirable where the product is carbon sequestration or wood/timber.

There is a widening gulf between consideration given to source and quality of germplasm used in many public and smallholder plantings, and that used in large-scale private sector forestry. In the latter case, the source of germplasm is usually given top priority[18] with most forestry corporations either having their own tree breeding programs, or allocating serious funding for procurement of highly quality seed or vegetative plantlets. Private forestry companies may also be members of cooperative breeding programs such as Camcore's *Pinus* selection and breeding, or otherwise beneficiaries of government tree breeding programs such as the Institute of Forest Genetics and Tree Breeding (IFGTG) *Casuarina* breeding programs in Coimbatore, Tamil Nadu, India (Nicodemus et al., 2020).

The lack of attention to choice of tree species and development and selection of seed stands in current reforestation efforts is contributing to the following economic and environmental problems:

- For carbon sequestration projects: the use of less-well adapted and slower growing tree species and seed sources, is likely leading to less than half of the potential rates of CO_2 sequestration. Increasingly, and as to be expected, many carbon sequestration plantings, such as those in China, are being undertaken on degraded and marginal sites for tree growth (arid, infertile, cool or hot, saline etc), which

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[17] It is important to note that not all environmental invasives are 'bad'. For example, in dry zones of Fiji, the exotic leguminous tree *Samanea saman* colonises eroded drainage lines where it acts as a green firebreak, allowing regeneration of native trees and plants and is festooned with ferns, orchids and other epiphytes.

[18] This is not always the case especially where 'get-rich-quick' and/or managed investment schemes are concerned. Graudal and Moestrup (2017) have advocated business-oriented alliances for long-term investors in teak plantings which include *genetic business plans* that aim to assure best-informed choice of highest quality planting material.

makes it all the more imperative that appropriate tree germplasm is utilised in order to obtain worthwhile levels of carbon sequestration.

- For agroforestry projects: when smallholder preferences for multi- or single purpose tree species are not able to be realised, one consequence will be mediocre livelihood outcomes and disillusionment with tree cultivation. Similarly, deployment of inferior seed sources will lead to reduced productivity, higher plantation maintenance costs and poor results.

- For tree plantings generally: *Low genetic diversity seed sources*: diversity inbred/selfed germplasm—for preferentially outcrossed tree species, i.e., most species (e.g. Bawa 1992)—will yield inferior tree performance (e.g. *Grevillea robusta*, Harwood & Owino, 1992; *Eucalyptus*, Sedgley & Griffin, 1989; Hardner & Potts, 1995; *Shorea cordifolia* and *Syzygium rubicundum*, Stacy, 2001) while plantings of tree species with narrow diversity—e.g., plantings developed of half-siblings[19]—run the distinct risk of being grossly inferior as future seed sources.

Inappropriate seed sources: Seed source needs to be given careful attention when tree germplasm is introduced into a landscape from another gene-ecological zone[20]. There is a risk that an introduced seed source will be less-well adapted than the local seed source, unless climate and soil matching is undertaken (including factoring in projected new climate regime; e.g., Leibing et al., 2013). There is also a, possibly slim, risk of outbreeding depression, although outbreeding vigour is considered more likely especially when in-bred populations are combined.

Boshier (2007, p.4) in discussing seed sources for tree improvement and genetic diversity of British and Irish broadleaved trees has aptly observed: "*However, given the evidence; i.e. clear dangers from inbreeding and loss of genetic diversity, with extensive gene flow and adaptation at a broad scale equivalent to the British or Irish provenance regions, it is more logical to apply the precautionary principle in terms of ensuring the use of genetically diverse material with the capacity to adapt to current and future conditions. There is good evidence to suggest that a very restricted view of what is 'local' will not ensure optimally adapted tree populations and is more likely to lead to the use of stock of limited genetic diversity which will in turn impose future limitations. Threats to the maintenance of genetic diversity come mainly from poor practices in seed collection. An emphasis on restricting the area of collection or poor instruction of collectors can limit the number of trees and hence genetic diversity sampled. Well managed tree improvement programmes not only help maintain the genetic diversity of native tree populations, but also increase the economic viability of woodlands and so promote their establishment.*" These same arguments will also likely apply to most tropical tree species. The planned study Boshier et al., (2015) on 'Is local best?' will give further valuable insights into selection of tree seed sources but has yet to be concluded due to lack of funding.

Inappropriate species: Too many of the current public sector and NGO tree plantings are using inappropriate tree species, often exotics, and used simply because what is used is what is available in the nursery or from trees for which seed can be easily collected. These species are considered inappropriate for several possible reasons:

- don't match with preferences of local people and smallholders;

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[19] It is unfortunately all too common practice for forestry nurseries to collect their seed from one or very few individuals which are conveniently located near the nursery or which are heavy seeders, with the resultant progeny being full and half siblings.

[20] A gene-ecological zone is an area that exhibits uniform ecological conditions and limited degrees of gene flow between surrounding regions (Møestrup *et al.*, 2006)

- maladapted/poorly suited to the planting environment; and/or
- constitute an environmental or biodiversity risk due to their invasiveness and environmental transformative potential and/or hybridisation with local endemics leading to loss of their genetic integrity.

5.3 Approaches to enhancing the use of diverse tree genetic resources

Below are some possible approaches to enhancing the use of tree genetic diveristy in agroforestry, restoration and reforestation, and addressing and overcoming the above limitations.

5.3.1 Enhancing tree diversity in agroforestry

It is recommended that ICRAF continue to take the lead in enhancing tree diversity in agroforestry systems and more broadly in forest landscape restoration[21]. Some general approaches that will enhance tree diversity, and its more effective use in farming and degraded landscapes include:

1. *Planning* - In national agroforestry strategies, and for forest landscape restoration projects, match tree species and seed sources to the local planting environments, contexts and needs, i.e., the right tree in the right place.
2. *Develop seed sources* - Identify and/or develop seed banks and seed stands and field genebanks for a wider range of agroforestry species and sources that are desired by smallholders and therefore required by their suppliers, including forestry and agriculture department and private nurseries.
3. *Deploy genetically diverse seed* - When distributing seed from seed banks to tree planting projects and nurseries, consider making up provenance bulks, in order to reduce future inbreeding and enhance opportunity for future local adaptation and development of land races[22]. This approach needs to be considered in situations where individual seed collections are known or likely to have limited genetic diversity (Note: heterosis or hybrid vigour from wide provenance crosses is considered more likely in tree species than outbreeding depression, but more studies over several generations in different species are needed to confirm this assertion).
4. *Promote multi-species systems* - Develop and promote agroforestry/landscape level approaches that incorporate greater diversity at both species and within species levels: in many cases these will more closely resemble traditional species-rich, multi-strata agroforestry systems. Dynamic, well-designed mixed tree systems will maximise yields of multiple products and provide greater sustainability and resilience, as different tree species cycle plant nutrients differently and dilute the risks from pests and diseases.
5. *Local species focus* - Focus agroforestry and landscape restoration plantings on local tree species, including ancient introductions, whilst also incorporating the most useful

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[21] Forest landscape restoration is a process *'that aims to regain ecological integrity and enhance human well-being in deforested or degraded forest landscapes'* (Maginnis & Jackson, 2007, p.10).

[22] Local, well-adapted, land races can develop rapidly, over just one or a very few generations, if the founder population(s) are genetically diverse. For example, CTFT found that in Senegal that over three generations the introduced *Acacia tumida* quickly adapted and had much greater survival.

and desired exotic tree species, as the latter are often desired by smallholders due to their fast growth and more rapid wood production.

6. *Reforest non-arable areas* - Identify those parts of the landscape which should be left uncultivated and reforested if they have been cleared. Such sites include steeply sloping land (e.g., >20-25%), other highly erodible or infertile soils, preferential groundwater recharge zones (often rocky) in landscapes at risk from salinity; riverine and drainage line buffers. Such areas would ideally be planted with local species to conserve biodiversity and provide other vital ecosystem services. If needed for food productions they might be placed under a permanent arboricultural system, e.g., fruit or nut tree orchards. There are several food tree species which grow well in riverine sites and can tolerate periodic inundation and floodwaters, and are much better suited to riverine sites, than crop

Incorporation of these approaches into national agroforestry strategies and projects will greatly enhance the conservation and use of tree diversity in smallholder farms and throughout the landscape.

Seed stocks held in tree seed banks, tissue cultured plantlets and other tree germplasm is limited and/or inappropriate for and/or unable to match the demands of large-scale tree planting projects: these are often announced without regard to the source of propagation materials. Consideration should be given to developing biodiverse multiple-purpose, food tree 'breeding seedling seed orchards'. This would involve the mixtures of 3 or 4 (or more) tree species for which diverse, improved seed is needed and/or likely to be needed. Improved vegetatively propagated food trees could also be grown in analogous plantings to provide sufficient vegetative materials for large-scale propagation, e.g., marcots and root suckers from elite breadfruit varieties; suckers for diverse banana/plantain/fehi, bamboo and *pejibaye* (peach palm) varieties. Such plantings could be undertaken in conjunction with peri-urban agroforestry on the outskirts of large cities, largely managed by the private sector (smallholders or cooperative) with surplus produce sold in local fresh food markets to provide income to defray costs on their maintenance. Such more community-based breeding is one of the linked elements in a systems approach to tree diversity breeding that has recently been advocated by Graudal et al. (2021).

The next few years and decades will be crucial for ensuring resilience of food systems which are coming under increasing pressures due to climate change, declining crop yields and an increasing human population. Accordingly, a wider adoption of the PATSPO/ICRAF approach of identifying and registering seed stands and developing seed orchards of desired food tree species is a vital response, and urgently needed to avoid human famine on an unprecedented scale and catastrophic environmental change

5.3.2 Enhancing tree diversity in forest restoration

Forest restoration is a process entailing '*actions to reinstate ecological processes, which accelerate recovery of forest structure, ecological functioning and biodiversity levels towards those typical of climax forest*' (Elliott et al., 2013, p.12). Assisted Natural Regeneration (ANR) is a cost-effective method of forest restoration that exploits the natural processes of vegetation recovery through enhanced protection practices, including from fire, grazing and illegal cutting; facilitation of the growth of existing woody species through liberation cutting of weedy trees vines and inhibition of the grass layer, and may include some enrichment plantings especially of more desired species (Thomson, 2000). ANR, including farmer managed natural regeneration (FMNR), has an advantage over conventional forest restoration of planting seedlings, in that it naturally utilises the existing local species and sources (where still present as coppice, seed banks and in fragments) long-adapted to the sites—unless substantially altered by climate change—and has major biodiversity conservation values.

A highly cost-effective and efficient approach to restoration of degraded, species-rich tropical forest is the *framework species* approach (Goosem & Tucker, 1995; Lamb et al., 1997; Tucker & Murphy, 1997; Elliott et al., 2006; Ellliott et al., 2013). The framework species approach involves identifying and planting with a subset of local species, up to 20-30 species, which have the greatest potential to catalyse forest restoration and return of biodiversity, from nearby forests and remnants. These species are easy to propagate and fast-growing with dense shading crowns that rapidly shade out competing weeds, and are attractive to seed-dispersing wildlife, especially bats and birds. The early successional species will be specific to each site but will often include members of the same genera. In northern Thailand the Forest Restoration Research Unit (FORRU) has found *Erythrina subumbrans*, *Ficus altissima*, *Gmelina arborea*, *Hovenia dulcis*, *Melia toosendan*, *Prunus cerasoides*, *Sapindus rarak* and *Spondias axillaris* to be excellent framework species for forest restoration (Elliott et al., 2006, Figure 16).

Figure 16. Framework species approach in Thailand. [A] Upper Mae Sa Valley, northern Thailand May 1998. [B] After planting framework tree species (3,100 trees/ha), left of track, 15 years old (31 species); right, 9 years old, (76 species). [C] Forest interior after 21 years—a dense understorey of recruit species (>70 species measured in 0.46 ha) has developed beneath the closed canopy. Structural diversity has recovered, including woody climbers, and carbon-storage approaches that of mature forest. (Photos: D. Hitchcock and Stephen Elliott)

The author has assessed that for intermediate rainfall zones (c. 2,500 mm per annum) in Fiji that *Alphitonia zizyphoides*, *Bischofia javanica*, *Cananga odorata*, *Elaeocarpus* spp., *Endospermum macrophyllum*, *Erythrina variegata*, *Flueggea flexuosa*, *Ficus obliqua*, *Hibiscus tiliaceus*, *Koelreuteria elegans*, *Macaranga harveyana* and *Terminalia catappa* will be amongst the most suitable framework species. In Panama (central America) the following species were considered as ideal framework species to restore forest on an area invaded by a fire-prone grass: *Anacardium excelsum*, *Bursera simaruba*, *Cedrela odorata*, *Colubrina glandulosa*, *Crescentia cujete*, *Diphysa americana*, *Dipteryx oleifera*, *Enterolobium cyclocarpum*, *Erythrina fusca*, *Gliricidia sepium*, *Guazuma ulmifolia*, *Handroanthus guayacan*, *Hura crepitans*, *Inga punctata*, *Luehea seemannii*, *Muntingi calabura*, *Ochroma pyramidale*, *Pachira quinata*, *Sapindus saponaria*, *Swietenia macrophylla*, *Tabebuia rosea* and *Terminalia Amazonia* (Boeschoten et al., 2021).

A vital tree species diversity conservation role for BGCI partners, connected to forest restoration, will be in the collection, propagation and provision of rare and endangered tree species. Such species are less likely to colonize through natural succession (Horák et al., 2019), and plantings of precious and high-cost seedling stock of rare and endangered species will have greater success when planted later in the forest restoration process, i.e., after the site has been brought under control by framework or pioneer trees with reduced weed growth, ameliorated with improved soils and microclimate, and with reduced risks from fire and grazing animals. It is recommended, when allocating the available scarce resources to conservation of rare trees in reforested areas, that species priorities be on:

- genetically distinctive species, e.g., monotypic genera and those with few other related species;
- species that play a unique role in ecosystem functioning[23];
- commercially valuable species which have been threatened due to overharvesting;
- wild food trees and their relatives (given increasing role in food trees for human nutrition); and
- species with poor dispersal, including those whose animal seed dispersers may be reduced or absent.

Furthermore, rare and endangered rainforest tree species tend to be late-successional species and contribute to the 'permanent' or long-lasting forest carbon stock due to their longevity and high wood densities (Brancalion et al., 2018).

5.3.3 Enhancing tree diversity in reforestation

Reforestation entails the re-establishment of tree cover (>10—20%) on deforested land[24]. A recent study has identified ten guiding principles for reforestation to optimize carbon sequestration and biodiversity recovery while improving livelihood benefits (Di Sacco & Hardwick et al., 2021), viz.

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[23] Rare species have been considered to typically contribute more to functional diversity than common species, but the latter may make persistent, unique contributions to functional diversity (Chapman et al., 2018)

[24] Afforestation is differentiated in that it involves planting trees to create forests in areas that haven't recently had tree cover and is generally not recommended where the area been occupied historically by a non-forested biome such as grassland, savanna, non-forested wetland or peatland (Di Sacco & Hardwick et al., 2021) due to likely losses of biodiversity and soil organic carbon (Bond et al., 2019; Friggens et al., 2020; Veldman et al., 2015).

1. Protect existing forest first;
2. Work together—involving all stakeholders;
3. Aim to maximize biodiversity recovery to meet multiple goals;
4. Select appropriate areas for restoration;
5. Use natural regeneration wherever feasible;
6. Select species to maximize biodiversity;
7. Use resilient plant material—with appropriate genetic variability and provenance;
8. Plan ahead for infrastructure, capacity and seed supply;
9. Learn by doing—using an adaptive management approach); and
10. Make it pay—ensuring the economic sustainability of the project.

The principles 3, 6, 7 and 10 are especially pertinent to this report and are now briefly discussed.

For principle 3 it is well-noted that '*Achieving high levels of biodiversity and biomass, through the native forest approach, enables multiple outcomes to be delivered simultaneously. High species and functional trait diversity enhance productivity, ecosystem resilience and the provision of forest products and ecological services to local communities*.' (Di Sacco et al., 2021, p.1334). However, in some settings the use of near-local species and even exotics may need to be considered. For example, in a humid tropical region of Brazil, exotic eucalypts, when planted in mixed plantations with native species and selectively harvested after five years, allowed the natural regeneration of native trees in the understorey and substantially defrayed restoration costs. Eucalypts have small seeds and seldom regenerate from seed outside of their native habitats (Brancalion et al., 2020).

In tropical sub-humid and humid zones, a seral community of increasingly flammable grasses—maintained by fire 1 to 2 times per year—may develop on highly degraded soils and replace secondary forest. In such situations, the use of *Acacia mangium*, *Albizia lebbeck*, *Calliandra calothyrsus*, *Casuarina equisetifolia* and other fast-growing, leguminous trees, along with their associated root symbionts, may constitute an essential step in catalysing biodiverse forest restoration. In Puerto Rico, animal-dispersed native trees including the endangered dry forest tree *Guaiacum officinale* colonised a plantation of *Albizia lebbeck,* and catalyzing native forest regeneration on a chronically degraded site (Martínez et al., 2015). Major positive impacts on soil fertility have been observed, e.g., soil carbon, nitrogen and some other plant nutrients increased under *Acacia* × *mangiformis* plantations in Vietnam (Dong et al., 2014). Indeed *Acacia mangium* (*A. auriculiformis*, *A. crassicarpa* and several other related PNG *Acacia* species) have an unrivalled capacity to spontaneously restore tropical rainforests from highly degraded bare earth, denuded old garden sites and flammable grasslands (with the caveat that original rainforest species are growing nearby, ideally within 200 m, see Crouzeilles et al., 2020); as has been observed by the author in their native habitats in Papua New Guinea, in Fiji and in SE Asia, such as RECOFT (The Center for People and Forests) acacia field trials in Thailand, and elsewhere, e.g. trials in Indonesia (*Kuusipalo* et al., *1995*) and Vietnam (McNamara et al., 2006). Appanah et al., (2016) reported that nitrogen-fixing trees can be used as nurse crops prior to planting native species: *'Nurse trees such as Acacia mangium and Acacia auriculiformis have been used to improve site conditions. When the nurse trees reach about eight years, they can be thinned and underplanted with more desirable but less-tolerant species such as Dipterocarpus alatus, Hopea odorata or Parashorea chinensis. Some species, such as members of the Meliaceae family that are often affected by shoot borers may have damage reduced via underplanting.'* These acacias are rather short-lived and will only regenerate prolifically, from soil seed bank, if the area is accidentally burnt, i.e., precisely when such pioneer trees are again needed to protect bare soil and catalyse the next rainforest regeneration cycle.

The defining elements of Principle 6 (select species to maximise biodiversity) are to plant a mixture of species, prioritize native species, favour mutualistic interactions, and exclude invasive species. *"Maximizing biodiversity depends not only on the number of species reintroduced but also on the functions they perform. Promoting mutualistic interactions, such as those involving native tree species and fungi, seed-dispersing animals, pollinators and other organisms, is crucial to achieving a resilient, biodiverse restored ecosystem* (McAlpine et al., 2016; Steidinger et al., 2019)" (Di Sacco et al., 2021, p.1334). In locations where lack of natural seed-dispersal limits recovery of tree species richness, then planting all or nearly all species that once comprised the original forest tree community may be desirable, e.g., the maximum diversity method of Goosem and Tucker (2013) and the Miyawaki method (Miyawaki, 1993).

Principle 7 is to use resilient plant material—with appropriate genetic variability and provenance. As discussed earlier, local provenance sources are desirable except where they have reduced or low genetic diversity and/or where the climate has already changed or is predicted to change. Gene-ecological or seed zone maps are useful but not available in most cases, and may not take into account future climates.

Tree species with more resilience to climate change which include those which have evolved:

- over an extensive natural distribution and/or wide altitudinal range, encompassing different climatic zones and larger climatic envelopes, notwithstanding that a variable proportion of the species overall adaptation to different climates is associated with provenance variation;
- in areas with considerable year-to-year climate variability, especially semi-arid and arid zones; and
- along drainage lines in wet/dry and semi-arid tropics, where soil moisture may show extreme variation both seasonally and between years.

There are also many tree species with narrow climatic envelopes in their nature, but which have performed well when planted in different climates outside of their natural range. One strategy to ensure restored forests have high resilience to climate change and fluctuation is to incorporate a high proportion of the above groups of species. Another somewhat contentious strategy to enhance opportunities for climate change adaptation (local landraces) and resilience is to employ composite provenancing or mixing geographic seed sources (Broadhurst et al., 2008): a key advantage of this approach is to reduce the risk of inbreeding.

Principle 10—ensuring economic sustainability—is especially pertinent for new seed orchards established for reforestation and landscape restoration purposes. It is vital that they are established such that they can be self-funding, i.e., especially through seed sales. Accordingly, mixed species orchards are preferable to produce seed of a diversity of species rather than an overly narrow focus on 1 or few species.

A further consideration is the method of establishment. Assisted natural regeneration (ANR), and farmer or community managed natural regeneration have advantages, including conservation and use of local genetic sources/species and cost efficiency. In long altered or degraded landscapes, tree rootstocks and seed sources may no longer be present, at least in sufficient quantity to enable ANR. In these situations, direct seeding has several advantages, cf. seedlings. Firstly, the seed is likely to have been derived from a larger number of trees and therefore contains more diversity. Trees established through direct seeding will generally have better root systems and have been established in the most suitable microsites. Finally, the operation of natural selection pressure during the establishment phase will act to ensure that the final crop trees are better adapted to the site. However, one of the main bottlenecks for forest restoration is inadequate supply of germplasm and propagules of indigenous trees (Di Sacco & Hardwick et al., 2021). Insufficient seed and/or planting stock of target species from appropriate sources are often critically limiting factors in reforestation (Bannister et al., 2018; Jalonen et al., 2018; León-Lobos et al., 2020; Merritt & Dixon, 2011; Whittet et al., 2016).

BGCI's GlobalTreeSearch database and *Global Tree Assessment* provide a listing of known tree species by country, and their conservation assessments, respectively, and are a useful aid to identify rare and endangered species for inclusion in reforestation projects. Consideration might be given to integrate these databases, and the information from them, with the Crop Trust-manged *Genesys*—a database of more than four million genebank accessions of crop genetic resources, including trees. This would assist genebank managers in assessing the conservation importance of their accessions, and assist in identifying gaps in collections, especially for endanaged species.

6.0 Approaches to prioritising tree species for conservation and use

The sheer scale of tree species diversity, e.g., 58,497 known species (Beech et al., 2021), including 7,770 tropical trees documented as providing human food, and with 17,500 tree species globally threatened with extinction (Global Tree Assessment) make prioritization of species (and subspecies) for conservation, improvement a crucially important activity. Different approaches and criteria for prioritising tree species for conservation and use, will need to be employed by different collections-based agencies and others, and these are discussed in turn.

6.1 ICRAF – especially multipurpose and food trees for smallholders

Smith et al., (2015, p.23) found that "*ICRAF's germplasm collections need to be maintained and progressively expanded to fill critical gaps in the conservation and sustainable use of genetic diversity in multipurpose tree species for agroforestry systems. Currently ICRAF has satisfactorily conserved collections for a number of African multipurpose tree species but the global scope and geographic coverage of agroforestry species needs to be expanded to better fulfil its stated mandate and deliver more substantially to ex situ conservation of agroforestry tree species*". Noteworthy and internationally important collections of African food, fruit trees and food security support species (fertilizer trees) in the ICRAF genebanks include *Adansonia digitata*, *Dacryoides edulis*, *Faidherbia albida*, *Irvingia gabonensis* and *I. wombolu*, *Prosopis africana*, *Ricinodendron heudelotii*, *Sclerocarya birrea*, *Sesbania sesban*, *Strychnos cocculoides*, *Tamarindus indica*, *Upaca kirkiana*, *Vangueria infausta* and *Ziziphus mauritiana*.

ICRAF has also inherited a globally vital, extremely valuable, and well-documented germplasm collection of 3,270 accessions of principally nitrogen-fixing multipurpose tree species from Latin America, including *Calliandra calothyrsus*, *Gliricidia sepium* and *Leucaena* spp. Other important ICRAF collections from outside Africa include *Docynia indica* (Vietnamese fruit tree), *Calycophyllum spruceanum* and *Guazuma cinita* (Peruvian timber species), as well as a commercially important Peruvian landrace of peach palm (*Bactris gasipaes*).

Given that globally there are several thousand tropical tree species included in smallholder agroforestry systems the need for ICRAF to carefully prioritise new additions to its gene bank, and through its networks with national institutions, is paramount. ICRAF has long been active, indeed a global leader, in assessing tree species priorities for collection, research, conservation and domestication. Farmer preferences, market opportunities and amenability to be researched are key issues in species priority setting by ICRAF (Franzel et al., 1996, 2008; Franzel & Kindt, 2012). In recent years, ICRAF has produced three lists of priority species, using different strategies and for somewhat different purposes as follows:

1. ICRAF-GRU Curation Strategy: ICRAF GRU (Genebank) used a curation strategy to prepare a checklist and prepared a list of 50 prioritized species based on seed request and demand from field genebank (ICRAF GRU, 2017). Thirteen priority species were identified as having collection gaps based on eco-geographic mapping: *Adansonia digitata, Dacryodes edulis, Faidherbia albida, Gliricidia sepium, Prunus africana, Sclerocarya birrea, Tamarindus indica, Uapaca kirkiana, Vachellia erioloba, V. karroo, Vitellaria paradoxa* and *Warburgia ugandensis.*

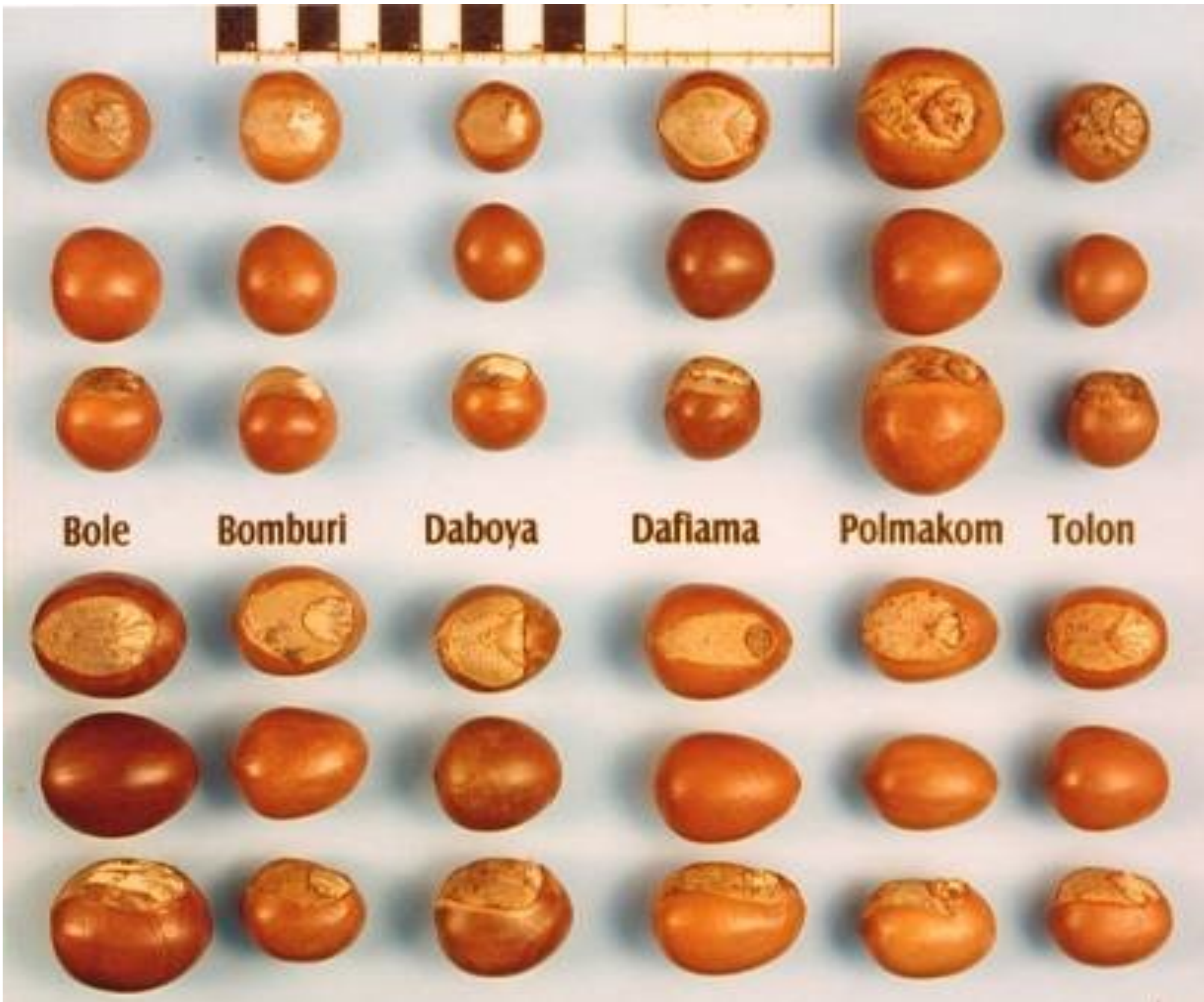

Figure 17. Variation in nuts of shea (*Vitellaria paradoxa*), an African Orphan Crops Consortium priority tree species. (Photo: Bioversity International)

2. African Orphan Crops Consortium priorities: The AOCC has prioritized orphan crops, i.e., neglected and/or underutilised crops, including 50 tree and woody shrub species for genome sequencing in order to facilitate their genetic improvement (Figure 17). This priority list was prepared by the African Union by surveying various stakeholders (farmers, academicians, researchers, industry, policy makers etc.) as discussed in Hendre et al. (2019). The outstanding work by ICRAF and AOCC collaborators in researching and improving such lesser-known and underutilised trees needs to be progressively extended, with improvement based on both advanced molecular techniques and conventional selection and

breeding. In order to be effective, breeding of underutilised multipurpose food trees need not be intensive, rather striking a balance between a level of improvement in their productivity, organoleptic and nutritional properties and maintaining germplasm diversity, and enabling opportunities for local farmer selections (e.g., Thomson, 2006).

3. Review of on-line databases: Identification of currently prioritized 100 tree species using data mining approach (Kindt et al., 2021). Twenty-three online databases encompassing 830 trees were examined to determine frequently occurring species in tropics and subtropics. The list was dominated by nitrogen-fixing trees from the family Fabaceae. These trees had wood, fuel, food and fodder and environmental services as primary use with many of them being multi-purpose. The purpose of this review was to understand which tree species are currently considered priorities for planting in the tropics and sub-tropics; accordingly, the identified species would not necessarily be priorities for ICRAF collection and/or conservation efforts.

ICRAF has well addressed the critical issues and matters in prioritising species for its work, especially in its ICRAF GRU (2017) Acquisition and Curation Strategy report and through AOCC, such as:

- Seed storage physiology, viz. recalcitrant and short-lived orthodox seeded trees are unsuited or not well-suited to storage in gene banks.
- Client demand – what tree species are being requested from the ICRAF genebank but unable to be supplied? In a similar vein, what are the highest priority tree species in demand by smallholders, but for which high quality and/or diverse germplasm is not readily available?
  Note: *These species will most often be multipurpose food trees, nitrogen-fixing trees and shrubs, and/or trees that can provide farmer income within a short period of planting (e.g., 3-5 years, maximally 15 years*).
- Important agroforestry, and typically multipurpose, tree species which have wide distributions, overlapping national borders, that require a co-ordinating role for their range-wide seed collection[25], sharing, field trials and evaluation (and which can be most effectively provided by ICRAF). It is strongly recommended for ICRAF to coordinate with national partners and complete seed collections of the 13 priority species identified in ICRAF GRU (2017).

Resources for seed collection and distribution need also to be sought for the following species:

- Tree species/cultivars which can play unique/highly specialist roles in agroforestry systems but which received inadequate attention, e.g. narrow canopy trees (including fastigiate forms) for boundary marker plantings such as *Vachellia nilotica* var. *cupressiformis* and a columnar form of *Hibiscus tiliaceus* (from Santo Vanuatu); highly cyclone resistant trees such as *Terminalia richii* (from Samoa) and *Cocos nucifera*, CV *niu leka* (from Fiji, also Lethal Yellows resistant and similar local dwarfs in other Pacific countries, including Samoa). These cyclone-resistant dwarf coconuts warrant much greater planting in cyclone (typhoon hurricane) prone coastlines in the Caribbean, Philippines/Vietnam/Hainan and Indian Ocean, especially South Asia and Madagascar.

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[25] Whilst range-wide seed collections have declined due to cost, biosecurity, A&B sharing etc., such collections provide the foundation for identifying and developing the most commercially attractive and well-adapted germplasm for local tree species: indeed that are vital making them more competitive, in the minds of smallholder tree growers, cf. exotics, and adapted to new climates.

- Another group to consider are those trees which can grow moderately fast and yet still produce naturally durable timbers. Such trees are vital for more durable and longer-lived building structures and include the widely planted and genetically diverse *Tectona grandis* (teak) (Graudal & Møestrup, 2017) and *Flueggea flexuosa* (*poumuli*). The latter is a small tree that can produce durable building poles within 6-10 years under suitable conditions. It is widely planted by farmers in Samoa and deserves to be much more extensively planted in mixed agroforestry systems in the lowland humid tropics including with teak, mahogany and other long-lived valuable timber trees. *Flueggea* is also an excellent framework species for the SE Asia-Pacific region.

- Fertiliser and bioirrigation trees: these include the legendary *Faidherbia albida* (in Africa), and many other leguminous trees, as well as *Bischofia javanica* (in Asia-Pacific) and *Acioa barteri* (in Nigeria, sub-Saharan Africa), and recently 'discovered' bioirrigation trees including *Guiera senegalensis* and *Piliostigma reticulatum* in the Sahel, as well as *Prosopis tamarugo* (in Atacama Desert, northern Chile).

- Leguminous trees – ICRAF has one of the most comprehensive seed collections of nitrogen-fixing trees and might also prioritise the gaps in its N-fixing tree seed collections especially for those from more humid zones in Africa and Asia-Pacific regions (with CSIRO ATSC having comprehensive seed collections of Australasian acacias, casuarinas and other N-fixing tree genera).

- Food tree crop wild relatives. There are so many prospective species in this category, making prioritisation imperative, but all the more challenging and necessitating integration and harmonisation with tree species conservation activities of BGCI partners, especially Kew MSB, other conservation agencies and NGOs. Given likely limited resourcing for collections of food tree crop wild relatives, it may be best for ICRAF to address just one (or two) agroforestry/ multipurpose species at a time or per year. For example, one high priority would appear to be relatives of *Adansonia digitata*, especially endangered Madagascan *Adansonia* species such as *A. perrieri* and *A. grandidieri*.

- Food tree species which can simultaneously address climate change mitigation & adaptation, food insecurity, soil erosion and land degradation. These might include starchy staples such as breadfruit, sago palm and plantain, and long lived, carbon-sequestering nut and fruit tree species such as Brazil nut, *Canarium* nuts, Tahitian chestnut, jackfruit, mango, mangosteen and durian. However, many or most of these tree species have recalcitrant or otherwise difficult-to-store seeds and are best conserved as living trees, *in situ*, *circa situm* and in mixed species breeding seedling seed orchards (akin to field gene banks), from whence seed can be harvested and used for smallholder and other plantings.

It is noted that ICRAFs field genebanks have multiple purposes, viz. including for conservation of species and genetic diversity, sources of seed as well as research. In the beginning, some of these genebanks were established as experimental trials of diverse material with considerable expenses incurred on their establishment and maintenance. Due to the very nature of perennial tree germplasm, and the time, monetary and human resources invested to continually maintain and manage this global wealth of inter- and intra-species diversity, the ICRAF leadership then classified them as field gene banks, for which ICRAF's Genetic resource strategy and the policy provide guidance. It is recommended that, wherever possible, that any future field genebanks/breeding seedling seed orchards for food trees be established near to markets where the sale of the fruits or other products can help defray the costs of their upkeep and maintenance. Operationally such field gene banks could be run by co-operatives or extended family of local people with direction from the respective national tree seed centre, and with overall guidance provided by ICRAF GRU. It is noted that many recalcitrant seeded species, for which living tree banks are appropriate, are also fruit and nut trees and would be amenable to such strategies.

Bioversity International have also been active in prioritising tree species for their work and that of partners, e.g., together with the APFORGEN network they will be shortly publishing a framework for coordinated priority setting on tree species across 20 Asian countries and involving 65 tree species (Christopher Kettle, pers. comm.).

6.2 BGCI and botanic gardens - especially rare and endangered tree species

The overall key criterion for BGCI and its members in prioritising their field activities in tree conservation will be rarity and endangeredness in the wild. BGCI, and its members and associated experts are leaders on tree species conservation including through its

- Global Trees Campaign (with Fauna & Flora International), which has assisted with the recovery of more than 400 threatened tree species over the past 15 years;
- Global Tree Assessment which is assessing the conservation status of every known tree species, and generating the most accurate and comprehensive data on global tree diversity;
- Development of a Global Biodiversity Standard, a certification system under development that is focussed on biodiversity; and through
- Technical reports such as the State of the World's Trees (BGCI, 2021).

The Global Tree Assessment has found that almost 30% of the nearly 60,000 known tree species are threatened with extinction, i.e., 17,500 species and of course many genetically distinctive subspecies, varieties and populations. It is evident that the task of conserving the world's trees is a massive undertaking, especially due to the ever-increasing threats from climate change. Without human assistance, few tree species will be able to naturally relocate to other habitats/environments to which they may be better adapted, due to the rates of climate change and lack of longer distance dispersal options. The main strategy whereby trees can survive and adapt to climate change is through their often inherently high levels of intraspecific diversity. Accordingly, it is essential that any human-mediated regeneration of trees, in agroforestry and reforestation programs, acts to simultaneously increase and conserve unique diversity rather than reduce it through poor practices, such as utilising seed from a small number of trees or through spreading exotic environmentally invasive/weedy trees.

From an evolutionary and genetic conservation viewpoint it is vital that rare tree species in the most genetically distinct genera and species are prioritised for conservation. An excellent example is the work of BCGI, Mulanje Mountain Conservation Trust and the Forestry Research Institute of Malawi, along with members of the Ecological Restoration Alliance of Botanic Gardens to conserve the highly endangered conifer Widdringtonia whytei (Mulanje cedar). Widdringtonia is a small genus (four species) and highly threatened, so the Mulanje cedar project also has enormous genetic conservation value. This project has created more than 1,000 jobs and planted 500,000 seedlings on Mulanje Mountain.

From a socio-economic and environmental perspective it is most vital to conserve the genetic resources of rare multipurpose tree species that fit well into farming systems (e.g., N-fixers, deep cyclers of nutrients), climatically-adaptable species that will be needed to address climate change, and genera/species whose rarity arises mainly from overharvesting due to their high timber, NWFP and medicinal values such as Aquilaria, Boswellia, Cryptocarya massoy, Dalbergia, Gyrinops, Santalum and Securidaca longipedunculata, to name a few.

Tree species with orthodox seeds, such as most of those in temperate and arid climates are amenable to being conserved at low, constant temperatures in hermetically-sealed containers for very long periods at a relatively low cost, as is being done in the MSB project and ICRAF GRU accessions being stored in the Svalbard Global Seed Vault. Tree species with recalcitrant and short-lived/difficult orthodox seeds, viz. majority of tropical trees, are most efficiently conserved in living collections, with *in situ* in their native habitats or *circa situm* in their native range preferred from an efficiency perspective, conserving several or many species at the same time, and from evolutionary conservation perspective which maintains genetic processes (Kjær et al., 2004). Good practices for *in situ* and on-farm (*circa situm*) conservation of tropical fruit tree species are described in Sthapit et al. (2016). Many of BGCI’s partner gardens are located and proximate, within 200 km, to global biodiversity hotspots and well positioned to contribute to conservation of tree diversity. These contributions to tree conservation are much greater than the maintenance of a few individuals in the grounds of individual botanic gardens (and not diminishing the educational and sometimes vital conservation roles played). The much greater future contributions of BCGI network to conservation of tree species and diversity will be through:

- Seed collections of rare and local species that can be used in local tree planting, both restoration and in productive systems, and in the recovery of lost and depleted species and populations,
- Knowledge of breeding systems, diversity and seed handling,
- Partnerships and alliances such as the Ecological Restoration Alliance (coordinated by BGCI) and comprising 50 organisations carrying out biodiverse ecological restoration globally and partnerships with CIFOR-ICRAF to massively enhance the socio-economic and biodiversity values of smallholder tree plantings, and associated *circa situm* conservation,
- Advocacy and actions that promote tree species diversity conservation such as through the new Global Biodiversity Standard.

The ability and desirability of collecting seed developing for general planting from remnant trees in tropical, developing world has declined markedly in recent decades due to several factors. Foremost, is that potential seed trees are more physically and genetically isolated from other trees of the same species with consequent risk of inbred progeny from harvested seed. Furthermore, there are often difficulties in obtaining permits to collect seed and being granted local permissions, along with security matters and escalating collection expedition costs. Accordingly, the importance of developing multifunctional, diverse multi-tree species plantings ASAP to serve as local seed stands cannot be over-emphasised. Such plantings need not take up a large area, e.g., 1-3 ha totalling 200 to 600 reasonably widely spaced trees[26] of 10-

20 species. They also may be undertaken on sloping or less-arable lands. It is clear that considerable numbers of such plantings will be needed to provide local seed sources in order to meet biodiversity conservation objectives (as needed and increasingly required, e.g., under the Global Biodiversity Standard.

6.3 Large-scale reforestation projects

Some large-scale reforestation projects have recently been accused of delivering perverse outcomes. Indeed, a driving consideration in establishing the Global Biodiversity Standard has been that well-intentioned solutions to climate change such as tree planting schemes are accelerating the climate and biodiversity crises by promoting the planting of non-native species. It is contended that such plantings displace and damage biodiversity, accelerating the extinction of species and potentially increasing $C0_2$ emissions. Whilst this is undoubtedly true in some cases, there are also examples of where pioneer exotic tree species, especially N-fixing trees, are vital for restoring soil carbon and N and other ecosystem functions in highly degraded landscapes, catalysing and enabling the restoration of local forest biodiversity. The important consideration is that any introduced exotic or alien tree species must be not be environmentally invasive or minimally so, and certainly not capable of environmental transformation, such as *Spathodea campanulata* (African tulip tree) and *Miconia calvescens* (Mexican velvet tree), which have invaded and take over undisturbed or minimally disturbed forest ecosystems in the Pacific Islands (Meyer, 1996). Any introduced exotics should be short-lived, incapable of regenerating from root suckers, unable to regenerate in minimally disturbed forest settings or under shade and provide useful products to local communities such that they will be harvested at maturity or earlier (and once they have performed their restoration function).

Large scale reforestation projects and tree-planting consortia such as AFR100, the Global Evergreening Alliance, Ecosia, Plan Vivo, Trillion Trees and 1t.org require vast quantities of seed of well-adapted and diverse local tree species. This highlights the imperative of rapidly developing well-designed breeding seedling seed orchards (such as in PATSPO) that can meet such urgent and on-going seed demands. Two categories of tree species, sometimes overlapping, are most vital for seed production for large scale reforestation:

1. Climatically robust species, preferably local/native, which have pioneer and/or framework species characteristics such that they can restore ecosystem function and catalyse return and restoration of local forest biodiversity.
2. Local species of high socio-economic importance to local peoples for food, animal fodder, traditional medicines and cultural uses.

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[26] Reasonably wide spacing is desired to enable good crown/canopy development and sufficient light levels to promote heavy fruit/seed production. This will also depend on the reproductive biology of included tree species, e.g., in dipterocarps different species flower in a specific sequence and pollination is done by small weak flying insects, so too wide spacing will lead to reduced or no seed production (see e.g., Lillesø, 1996).

These species will vary depending on location and increasingly decision-support systems are available to assist in selection of species, e.g., https://www.worldagroforestry.org/news/right-tree-right-place and https://www.diversityforrestoration.org/. However, information generated from such systems will need to be checked and verified with local forestry and botanical experts, including those in national forest and environmental agencies, BGCI expert network, ICRAF, CIFOR and Bioversity International.

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References

Allen MG, Bourke RM, Evans BR, Iramu E, Maemouri RK, Mullen BF, Pollard AA, Wairiu M, Watoto C, and Zotalis S, 2006. Solomon Islands Smallholder Agriculture Study. Volume 4. Provincial Reports. AusAID, Canberra, Australia.

Aide TM, Clark ML, Grau HR, López-Carr D, Levy MA, Redo D, et al., 2013. Deforestation and reforestation of Latin America and the Caribbean (2001–2010). *Biotropica* 45, 262–271. doi: 10.1111/j.1744-7429.2012.00908.x

Amaral W, Thomson LAJ, and Yanchuk A 2004. *Conservation of Genetic Resources in their Natural Environment.* Pp 1–4 in FAO, FLD, IPGRI. Forest Genetic Resources conservation and Management. Vol. 1. Overview, concepts and some systematic approaches. International Plant Genetic Resources Institute, Rome, Italy.

Appanah S, 2016. Forest landscape restoration for Asia-Pacific forests: a synthesis. In Forest landscape restoration in Asia-Pacific forests, Appanah, S. (ed.). FAO/RECOFTC, Bangkok, Thailand.

Askin DC, Boland DJ, Pinyopusarerk , 1990. Use of *Casuarina oligodon* subsp. *abbreviata* in agroforestry in the North Baliem Valley, Irian Jaya, Indonesia. Pp. 213–219 in El-Lakany M.H., Turnbull J.W., Brewbaker J.L. (eds), Proceedings of the Second International Casuarina Workshop, Cairo, Egypt. Desert Development Centre, American University in Cairo, Egypt.

Asner GP, Rudel TK, Aide TM, Defries R, and Emerson R, 2009. A contemporary assessment of change in humid tropical forests. *Conservation Biology* 23: 1386–1395. doi: 10.1111/j.1523-1739.2009.01333.x

Atchley J, and Cox PA, 1985. Breadfruit fermentation in Micronesia. *Economic Botany* 39: 326–335.

Aruwayo A, and Adeleke RA, 2019. A review of browse plants' use in the tropics and their chemical constituents. *FRSCS* 1 (3): 72–81 (a Journal of Dept. of Applied Chemistry, Federal University of Dutsin-Ma, Katsina State, Nigeria).

Ataia A, 1983. *Casuarina oligodon* in the Eastern Highlands Province - Papua New Guinea. Pp 80–88 in Midgley S.J., Turnbull J.W., Johnson R.D. (eds.), Proceedings of an International Casuarina Workshop. CSIRO: Melbourne, Australia.

Awang K, Venkateswarlu P, Nor Aini AS, Adjers G, Bhumibhamon S, Kietvuttinon B, Pan FJ, Pitpreecha K, Simsiri A, Awang K, 1994. Three year performance of international provenance trials of *Acacia auriculiformis*. *Forest Ecology and Management*, 70: 147–158.

Bankova V, Popova M, and Trusheva B, 2006. Plant sources of propolis: an update from a chemist's point of view. *Natural Product Communications* 1: 1023–1028.

Bannister JR, Vargas-Gaete R, Ovalle JF, Acevedo M, Fuentes-Ramirez A, Donoso PJ, Promis A and Smith-Ramírez C, 2018. Major bottlenecks for the restoration of natural forests in Chile. *Restoration Ecology* 26: 1039–1044. https://doi.org/10.1111/rec. 12880

Bawa KS, 1992. Mating systems, genetic differentiation and speciation in tropical rain forest plants. *Biotropica* 24: 250–255.

BGCI, 2021. State of the World's Trees. BGCI, Richmond, UK. https://www.bgci.org/wp/wp-content/uploads/2021/08/FINAL-GTAReportMedRes-1.pdf

Beech E, Rivers M, Oldfield S, and Smith PP, 2017. GlobalTreeSearch: The first complete global database of tree species and country distributions. *J. Sustain. For.* 36: 454–489. https://doi.org/10.1080/10549811.2017.1310049

Blackmore S, and Oldfield S, 2017. Mounting a fundamental defence of the plant kingdom. Pp. 1–22 in Blackmore S, & Oldfield S (Eds.), *Plant conservation science and practice; the role of botanic gardens*. Cambridge, UK: Cambridge University Press.

Birks JS, and Barnes RD, 1985. Multivariate analysis of data from international provenance trials of *Pinus oocarpa/Pinus patula* subspecies *tecunumanii*. *The Commonwealth Forestry Review* 64, 4: 367–74. http://www.jstor.org/stable/42606523

Boeschoten LE, van Breugel M, Bailon M, Balbuena J, Nuñez M, Cerezo A, and Hall JS, 2021. Framework species approach proves robust in restoring forest on fire prone invasive grass: a case study from Panama. *Journal of Sustainable Forestry* 40:2, 197–215, DOI: 10.1080/10549811.2020.1746915

Bogie NA, Bayala R, Diedhiou I, Conklin MH, Fogel ML, Dick RP and Ghezzehei TA, 2018. Hydraulic redistribution by native Sahelian shrubs: bioirrigation to resist in-season drought. Frontiers in Environmental Science 6: Article 98. URL=https://www.frontiersin.org/article/10.3389/fenvs.2018.00098.

Bond WJ, Stevens N, Midgley GF, and Lehmann CER, 2019. The trouble with trees: Afforestation plans for Africa. *Trends in Ecology & Evolution* 34: 963–965. https://doi.org/10.1016/j.tree.2019.08.003

Boshier DH, Gordon JE, and Barrance AJ, 2004. Prospects for *circa situm* tree conservation in Mesoamerican dry-forest agro-ecosystems. Pp. 210–226 in Biodiversity conservation in Costa Rica: learning the lessons in a seasonal dry forest. Frankie GW, Mata A and Vinson SB (eds), University of California Press, Berkeley, USA. https://doi.org/10.1525/9780520937772-017

Boshier DH, Broadhurst L, Cornelius J, Gallo L, Koskela J, Loo J, Petrokofsky G, and St Clair B, 2015. Is local best? Examining the evidence for local adaptation in trees and its scale. *Environmental Evidence* 4:20. DOI 10.1186/s13750-015-0046-3.

Boshier DH, 1984. The international provenance trial of *Cordia alliodora* (R & P) Oken in Costa Rica. Pp 168–185 in Provenance and genetic improvement strategies in tropical forest trees. Mutare, Zimbabwe, April 1984. Barnes, R. D., Gibson, G. L. (eds). Commonwealth Forestry Institute, Oxford, and Forest Research Center, Harare, Zimbabwe.

Bourke RM, 1985. Food, coffee and casuarina: and agroforestry system from the Papua New Guinea highlands. *Agroforestry Systems* 2: 273–279.

Bowen MR, and Whitmore TC, 1980. *A second look at Agathis*. C.F.I. Occasional papers no.13 University of Oxford, Oxford, UK.

Boyle TJB, 1996. CIFOR's research programme on conservation of tropical forest genetic resources. Working Paper No 9. Center for International Forestry Research (CIFOR), Bogor, Indonesia.

Braatz S, 2012. Building resilience for adaptation to climate change through sustainable forest management. In A. Meybeck, J. Lankoski, S. Redfern, N. Azzu & V. Gitz (eds). Building resilience for adaptation to climate change in the agriculture sector. Proceedings of a joint FAO/OECD Workshop. Rome, FAO.

Brancalion PHS , Viani RAG, Calmon M, Carrascosa H, and Rodrigues RR, 2013. How to organize a large-scale ecological restoration program? The framework developed by the Atlantic Forest Restoration Pact in Brazil, *Journal of Sustainable Forestry* 32: 728-744. http://dx.doi.org/10.1080/10549811.2013.817339.

Brewbaker JL, and Sorensson CT, 1994. Pp. 195–204 in R.R.B. Leakey, and A.C. Newton (eds) , 3–4, Tropical Trees: The Potential for Domestication and the Rebuilding of Forest Resources, HMSO, London, UK.

Broadhurst LM, Lowe A, Coates DJ, Cunningham SA, McDonald M, Vesk PA, and Yates C, 2008. Seed supply for broadscale restoration: Maximizing evolutionary potential. *Evolutionary Applications* 1: 587–597. https://doi.org/10.1111/j.1752-4571.2008.00045.x

Brown AG, 1987. Seeds of Australian trees for developing countries project. CSIRO Division of Forest Research. Canberra, Australia.

Bruijnzeel LA, Bonell M, Gilmour DA, and Lamb D, 2004. Forests, water and people in the humid tropics: an emerging view. Pp 906-925 in M. Bonell, & L. A. Bruijnzeel (eds.), Forest, Water and People in the humid Tropics. Cambridge University Press, UK.

van Bueren M, 2004. Acacia hybrids in Vietnam. Impact Assessment Series Report No. 27. ACIAR, Canberra, Australia.

van Bueren M, 2004a. Eucalypt tree improvement in China. Impact Assessment Series Report No. 30. ACIAR, Canberra, Australia.

Burley J, 1980. Selection of species for fuelwood plantations. *The Commonwealth Forestry Review*, 59(2): 133–147. http://www.jstor.org/stable/42608165.

Byrne M, Prober SM, McLean EH, Steane DA, Stock WD, Potts BM and Vaillancourt RE, 2013. *Adaptation to climate in widespread eucalypt species*. National Climate Change Adaptation Research Facility, Gold Coast, 86 pp.

Cannizzaro C, Keller A, Wilson RS, Elliott B, Newis R, Ovah R, Inae K, Kerlin DH, Bar I, Kämper W, Shapcott A, and Wallace HM, 2022. Forest landscapes increase diversity of honeybee diets in the tropics. *Forest Ecology and Management* 504, 119869. https://doi.org/10.1016/j.foreco.2021.119869.

Ceballos G, Ehrlich PR, and Dirzo R, 2017. Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. Proceedings of the National Academy of Sciences of USA, 114 (30) E6089-E6096. https://doi.org/10.1073/pnas.1704949114

Chapman ASA, Tunnicliffe V, and Bates AE, 2018. Both rare and common species make unique contributions to functional diversity in an ecosystem unaffected by human activities. *Diversity and Distributions* 24: 565–713. https://doi.org/10.1111/ddi.12712.

Chazdon RL, and Guariguata MR, 2016. Natural regeneration as a tool for large-scale forest restoration in the tropics: Prospects and challenges. *Biotropica* 48: 716–730.

Chege F, and Stewart M, 1991. Early results from trials of Australian acacias in semi-arid Kenya. Pp 201– 205 in Advances in tropical Acacia research. J.W. Turnbull (ed). Meeting held February 11– 15, 1991, Bangkok, Thailand. ACIAR Proceedings No. 35. Canberra, Australia.

Chittachumnonk P, and Sirilak S, 1991. Performance of *Acacia* species in Thailand. Pp 153– 158 in Advances in tropical Acacia research. J.W. Turnbull (ed). Meeting held February 11–15, 1991, Bangkok, Thailand. ACIAR Proceedings No. 35. Canberra, Australia.

Chomba S, Sinclair F, Savadogo P, Bourne M and Lohbeck M, 2020. Opportunities and constraints for using farmer managed natural regeneration for land restoration in sub-Saharan Africa. *Front. For. Glob. Change* 3: 571679. doi: 10.3389/ffgc.2020.571679.

Corbasson M, and Souvannavong O, 1988. *Terminalia superba* Engl. & Diels: current research on biology, physiology and breeding of *Terminalia superba. Forest Genetic Resources Information (FAO)* 16: 29–34.

Costa e Silva J, and Graudal L, 2008. Evaluation of an international series of *Pinus kesiya* provenance trials for growth and wood quality traits. *Forest Ecology and Management*, 255: 3477–3488. https://doi.org/10.1016/J.FORECO.2008.02.027

Crouzeilles R, Beyer HL, Monteiro LM, Feltran-Barbieri R, Pessôa ACM, Barros FSM, Lindenmayer DB, Lino EDSM, et al., 2020. Achieving cost-effective landscape-scale forest restoration through targeted natural regeneration. *Conservation Letters* 13(3) e12709. https://doi.org/10.1111/conl.12709

Dawson I, Harwood C, Jamnadass R, and Beniest J, 2012. Agroforestry Tree Domestication: A Primer. The World Agroforestry Centre, Nairobi, Kenya.

Dawson IK, Guariguata MR, Judy Loo J, Weber JC, Lengkeek A, Bush D, Cornelius J, Guarino L, Kindt R, Orwa C, Russell J, and Jamnadass R, 2013. What is the relevance of smallholders' agroforestry systems for conserving tropical tree species and genetic diversity in circa situm, in situ and ex situ settings? A review. *Biodivers Conserv* 22:301–324. DOI 10.1007/s10531-012-0429-5

Dawson IK, Graudal L, and Jamnadass R, 2021. *Mass tree planting: how to do it right*. The Conversation Africa, October 12, 2021. https://theconversation.com/mass-tree-planting-how-to-do-it-right-168583

Delelegn A, Sahile S, and Husen A, 2018. Water purification and antibacterial efficacy of *Moringa oleifera* Lam. *Agric. & Food Secur.* 7, 25. https://doi.org/10.1186/s40066-018-0177-

de Foresta, H, Michon G, and Kusworo A, 2000. *Complex Agroforests*. International Centre for Research in Agroforestry, Bogor, Indonesia.

de Siqueira LP, Tedesco AM, Rodrigues RR, Chaves RB, Albuquerque NCB, Corrêa FF, Santiami EL, Leandro RT, Guimarães TMG, and Brancalion PHS 2021. Engaging people for large-scale forest restoration: governance lessons from the Atlantic Forest of Brazil. In: Marques M.C.M., Grelle C.E.V. (eds) *The Atlantic Forest*. Springer, Cham. https://doi.org/10.1007/978-3-030-55322-7_18.

Di Sacco K, Hardwick A, Blakesley D, Brancalion PHS, Breman E, Rebola LC, Chomba S, Dixon K, et al., 2021. Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits *Global Change Biology* 27: 1328–1348. DOI: 10.1111/gcb.15498.

Dong TL, Doyle R, Beadle CL, Corkrey R and Quat NX, 2014. Impact of short-rotation *Acacia* hybrid plantations on soil properties of degraded lands in Central Vietnam. *Soil Research* 52: 271–281 https://doi.org/10.1071/SR13166.

Dunsdon AJ, and Simons AJ, 1996. Provenance and Progeny Trials. p. 93–118. In: J.L. Stewart, G.E. Allison, and A.J. Simons. *Gliricidia sepium*: genetic resources for farmers. Tropical Forestry Papers 33. Oxford Forestry Institute, Oxford, UK.

Elevitch CR, and Ragone DC, 2018. *Breadfruit Agroforestry Guide: Planning and implementation of regenerative organic methods.* Breadfruit Institute of the National

Tropical Botanical Garden, Kalaheo, Hawaii and Permanent Agricultural Resources, Holualoa, Hawaii, USA.

Elliott S, Blakesley D, Maxwell JF, Doust S, and Suwannaratana S, 2006. How to plant a forest: the principles and practice of restoring tropical forests. Forest Restoration Research Unit (FORRU), Biology Department, Science Faculty, Chiang Mai University, Thailand.

Elliott S, Blakesley D, and Kate Hardwick K, 2013. Restoring tropical forests: a practical guide. The University of Chicago Press, Chicago, USA.

FAO, 2000. International provenance trials of neem. Description of international provenance trials of Neem (*Azadirachta indica* A. Juss) established by collaborators of the International Neem Network. June 2000. FAO of UN, Rome, Italy.

FAO, FLD, IPGRI, 2004. Forest Genetic Resources conservation and management. Vol 1. Overview, concepts and some systematic approaches. Institute of Plant Genetic Resources, Rome, Italy.

FAO, FLD, IPGRI, 2001. Forest Genetic Resources conservation and management. Vol 2. In managed natural forests and protected areas (*in situ*). Institute of Plant Genetic Resources, Rome, Italy.

FAO, FLD, IPGRI, 2004a. Forest Genetic Resources conservation and management. Vol 3. In plantations and genebanks (*ex situ*). Institute of Plant Genetic Resources, Rome, Italy.

FAO, 2014. The State of the World's Forest Genetic Resources. Commission on Genetic Resources for Food and Agriculture, FAO of the UN, Rome, Italy.

FAO and UNEP, 2020. The State of the World's Forests 2020. Forests, biodiversity and people. Rome, Italy. https://doi.org/10.4060/ca8642en

FAO, 2020. Global Forest Resources Assessment (FRA 2020). FAO of the UN, Rome, Italy.

Fisher H, and Gordon J, 2007. Improved Australian tree species for Vietnam. ACIAR Impact Assessment Series Report No. 47. Canberra, Australia.

Fichtner A, Härdtle W, Bruelheide H, Kunz M, Li Y, and von Oheimb G, 2018. Neighbourhood interactions drive overyielding in mixed-species tree communities. *Nature Communications* 9, 1144.

Filoso S, Bezerra MO, Weiss KCB, Palmer MA 2017. Impacts of forest restoration on water yield: A systematic review. PLoS ONE 12(8): e0183210. https://doi.org/10.1371/journal.pone.0183210

Folke C, Biggs R, Norström AV, Reyers B, and Rockström J, 2016. Social-ecological resilience and biosphere-based sustainability science. *Ecology and Society* 21: 41. http://dx.doi.org/10.5751/ES-08748-210341

Forrester DI, and Bauhus J, 2016. A review of processes behind diversity-productivity relationships in forests. *Current Forestry Reports* 2: 45–61.

Foster GS, Jones N, and Kjær ED, 1995. Economics of tree improvement in development projects in the tropics. In Shen, S. & Contreras-Hermosilla, A. (eds.). *Environmental and economic issues in forestry: Selected case studies in Asia. World Bank Technical Paper No. 281*, The World Bank, Washington, DC.

Fownes JH, and Raynor WC, 1993. Seasonality and yield of breadfruit cultivars in the indigenous agroforestry system of Pohnpei, Federated States of Micronesia. *Tropical Agriculture (Trinidad)* 70: 103–109.

Frankham R, Ballou JD, Eldridge MDB, Lacy RC, Ralls K, Dudash MR, And Fenster CB, 2011. Predicting the probability of outbreeding depression. *Conservation Biology* 25: 465–75. https://doi.org/10.1111/j.1523-1739.2011.01662.x

Franzel S, and Kindt R, 2012. Species priority setting procedures. Pp 36–45 in: Dawson, I., Harwood, C., Jamnadass, R., Beniest, J. (eds.). *Agroforestry tree domestication: a primer*. Nairobi. World Agroforestry Centre ICRAF, Kenya.

Franzel S, Jaenicke H, and Janssen W, 1996. Choosing the right trees: setting priorities for multipurpose tree improvement. *ISNAR Research Report No. 8.* The Hague, The Netherlands.

Franzel S, Akinnifesi FK, and Ham C, 2008. Setting priorities among indigenous fruit tree species in Africa: examples from southern, eastern and western Africa regions. Pp 1–27 in Akinnifesi FK, Leakey RRB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds.) *Indigenous fruit trees in the tropics: domestication, utilization and commercialization*. CAB International, Wallingford, UK, in association with the World Agroforestry Centre, Nairobi, Kenya.

Friggens NL, Hester AJ, Mitchell RJ, Parker TC, Subke JA, and Wookey PA, 2020. Tree planting in organic soils does not result in net carbon sequestration on decadal timescales. *Global Change Biology* 26: 5178–5188. https://doi.org/10.1111/gcb. 15229

Gitz V, Pingault N, Meybeck A, Ickowitz A, McMullin S, Sunderland T, Vinceti B, Powell B, Termotee C, Jamnadass R, Dawson I, and Stadlmayr B, 2021. Contribution of forests and trees to food security and nutrition. CGIAR Brief. Research Program on Forests, Trees and Agroforestry. April 2021 Issue 5 DOI: 10.17528/cifor/008006

González-Orozco C, Pollock L, Thornhill A, et al., Phylogenetic approaches reveal biodiversity threats under climate change. *Nature Climate Change* 6: 1110–1114 (2016). https://doi.org/10.1038/nclimate3126

Goosem SP, and Tucker NIJ, 1995. Repairing the rainforest- theory and practise of rainforest re-establishment in north Queensland's wet tropics. Wet Tropics Management Authority, Cairns, Australia.

Graudal L, Aravanopoulos F, Bennadji Z, Changtragoon S, Fady B, Kjær ED, Loo J, Ramamonjisoa L and Vendramin GG, 2014. Global to local genetic diversity indicators of evolutionary potential in tree species within and outside forests. *Forest Ecology and Management*, 333: 35-51. https://doi.org/10.1016/j.foreco.2014.05.002

Graudal L, Baldinelli G, Loo J, Fady B, Vendramin G, Aravanopoulos FA, Bennadji,Z, Ramamonjisoa L, Changtragoon S and Kjær ED, 2020. *Indicators of the genetic diversity of trees – State, pressure, benefit and response*. State of the World's Forest Genetic Resources – Thematic study. Food and Agriculture Organization of the United Nations. https://doi.org/10.4060/cb2492en

Graudal L, Lillesø J-PB, Dawson IK, Abiyu A, Roshetko JM, Nyoka I, Tsobeng A, Kindt R, et al., 2021 (in press). Tree Seed and Seedling Systems for Resilience and Productivity. FTA Highlights of a Decade 2011-2021 series. Highlight No. 2. The CGIAR Programme on Forest, Trees and Agroforestry (FTA).

Graudal L, Thomson LAJ, and Kjær E, 2000. *Selection and management of in situ gene conservation areas for target species*. Pp 5–12 in Forest Genetic Resources Conservation and Management. Vol. 2: In managed natural forests and protected areas (*in situ*). FAO, DFSC, IPGRI, Rome, Italy.

Graudal, L. 1995. Progress in the evaluation of field trials established within the framework of the FAO project on genetic resources of arid and semi-arid zone arboreal species. *Forest Genetic Resources Information (FAO)* 23: 56-57.

Graudal L, Kjær ED, and Canger S, 1995. A systematic approach to conservation of genetic resources of trees and shrubs in Denmark. *Forest Ecology and Management* 73: 117–134

Graudal L, Kjær ED, Thomsen A, and Larsen AB, 1997. *Planning national programmes for conservation of forest genetic resources*. Technical Note No. 48. Danida Forest Seed Centre. Humlebaek, Denmark.

Graudal L, and Møestrup S, 2017. The genetic variation in natural and planted teak forests: characterisation, use and conservation for the future. Pp 19–29 in The Global Teak Study. Analysis, Evaluation and Future Potential of Teak Resources. W. Kollert & M Kleine (eds.). IUFRO World Series Volume 36. Vienna

Graudal L, Kjær ED, Suangtho V, Saardavut P, and Kaosa-ard A, 1999. *Conservation of genetic resources of teak (Tectona grandis) in Thailand.* Tech. Note No. 52, Danida Forest Seed Centre. Humlebaek, Denmark.

Graudal L, and Lillesø J-PB, 2007. *Experiences and future prospects for tree seed supply in agricultural development support: based on lessons learnt in Danida supported programmes 1965-2005*. Ministry of Foreign Affairs of Denmark. Danida, Copenhagen. https://curis.ku.dk/ws/files/33237005/Experienceandfutureprospects.pdf.

Graudal L, Dawson IK, Hale I, Powell W, Hendre P, Jamnadass R, 2022. 'Systems approach' plant breeding illustrated by trees. Trends in Plant Science (in press, available online). https://doi.org/10.1016/j.tplants.2021.09.009

Gunn BV, McDonald M, Moriarty J, 1988. 1987 Seed collections of *Acacia auriculiformis* from natural populations in Papua New Guinea and Northern Australia. Issue 4 of multipurpose tree species network research series: manual. Forestry/Fuelwood Research and Development (F/FRED) Project, USA.

Gunn BV, and Midgley SJ, 1991. Exploring and accessing the genetic resources of four selected tropical acacias. Pp. 57–63 in J.W. Turnbull (ed.) Advances in Tropical Acacia Research. ACIAR Proceedings No. 35.

Hardner CM, and Potts BM, 1995. Inbreeding depression and changes in variation after selfing in *Eucalypus globulus* ssp. *globulus*. *Silvae Genetica* 44: 46–54.

Haruthaithanasan M, Pinyopusarerk K, Nicodemus A, Bush D, and Thomson LAJ (eds.) 2020. *Casuarinas for green economy and environmental sustainability*. Proceedings of the Sixth International Casuarina Workshop held at Krabi, Thailand, 21–25 October 2019. Kasetsart Agricultural and Agro-Industrial Product Improvement Institute, Kasetsart University: Bangkok, Thailand.

Harwood CE, and Owino F, 1992. *Design of a genetic improvement strategy for Grevillea robusta*. Pp 141–150 in Harwood CE (Ed) *Grevillea robusta* in Agroforestry and Forestry. ICRAF, Nairobi, Kenya.

Hendre P, Muthemba S, Kariba R, Muchugi A, Fu Y, Chang Y, et al., 2019. African Orphan Crops Consortium (AOCC): status of developing genomic resources for African orphan crops. *Planta* 250: 989–1003. https://doi.org/10.1007/s00425-019-03156-9.

Hendre PS, Van Deynze A, 2015. How a consortium is changing Africa's food systems. http://www.africanorphancrops.org/category/resources/blog/page/3/.

Hodge GR, and Dvorak WS, 2004. The CAMCORE international provenance/progeny trials of *Gmelina arborea*: genetic parameters and potential gain. *New Forests* 28: 147–166.

Hodge GR, and Dvorak WS, 2015. Provenance variation and within-provenance genetic parameters in *Eucalyptus urophylla* across 125 test sites in Brazil, Colombia, Mexico, South Africa and Venezuela. *Tree Genetics & Genomes* 11: 57.

Hodge GR, and Dvorak WS, 2012. Growth potential and genetic parameters of four Mesoamerican pines planted in the Southern Hemisphere. *Southern Forests*, 74: 27–49.

Horák J, Brestovanská T, Mladenović S, Kout J, Bogusch P, Halda JP, and Zasadil P, 2019. Green desert? Biodiversity patterns in forest plantations. *Forest Ecology and Management* 433: 343–348. https://doi.org/10.1016/j.foreco.2018.11.019 .

Hua F, Wang X, Zheng X, Fisher B, Wang L, Zhu J, Tang Y, Yu DW, and Wilcove DS, 2016. Opportunities for biodiversity gains under the world's largest reforestation programme. *Nature Communications* 7, 12717. https://doi.org/10.1038/ncomms12717

Hughes CE, 1988. *Gliricidia sepium* seed collections for international provenance trials. *Forest Genetic Resources Information (FAO)* 16: 37–40.

ICRAF Genetic Resources Unit, 2017. Acquisition and Curation Strategy. Nairobi: World Agroforestry Centre.

Isager L, Thielade I, and Thomson LAJ, 2004. *People's participation and the role of Governments*. Pp 73–82 in FAO, FLD, IPGRI. Forest Genetic Resources conservation and Management. Vol. 1. Overview, concepts and some systematic approaches. International Plant Genetic Resources Institute, Rome, Italy.

Jalonen R, Valette M, Boshier D, Duminil J, and Thomas E, 2018. Forest and landscape restoration severely constrained by a lack of attention to the quantity and quality of tree seed: Insights from a global survey. *Conservation Letters* 11: 1–9. https://doi.org/10.1111/conl.12424

Jamnadass R, Mumm RH, Hale I, Hendre P, Muchugi A, Dawson IK, Powell W, Graudal L, Yana-Shapiro H, Simons AJ, and Van Deynze A, 2020. Enhancing African orphan crops with genomics. *Nature Genetics* 52: 356–360.

Jamnadass RH, Dawson IK, Franzel S, Leakey RRB, Mithöfer D, Akinnifesi FK, and Tchoundjeu Z, 2011. Improving livelihoods and nutrition in sub-Saharan Africa through the promotion of indigenous and exotic fruit production in smallholders' agroforestry systems: a review. The International Forestry Review, 13: 338–354. http://www.cifor.org/publications/pdf files/articles/ACIFOR1108.pdf

Jamnadass R, McMullin S, Miyuki I, Dawson I, Powell B, Termote C, Ickowitz A, Kehlenbeck K, Vinceti B, van Vliet N, et al., 2015. Understanding the roles of forests and tree-based systems in food provision. Pp 25–50 in Vira B, Wildburger C and Mansourian S. (eds.). Forests, trees and landscapes for food security and nutrition: A global assessment report. IUFRO World Series, Volume 33. Vienna, International Union of Forestry Research Organisations (IUFRO) http://www.iufro.org/science/gfep/forests-and-food-security-panel/report/

Jansen M, Guariguata MR, Raneri JE, Ickowitz A, Chiriboga-Arroyo F, Quaedvlieg J, and Kettle CJ, 2020. Food for thought: The underutilized potential of tropical tree-sourced foods for 21st century sustainable food systems. *People and Nature* 2020;2:1006–1020.

Jetton RM, Whittier WA, Dvorak, WS, Hodge GR, Crane BS, and Rhea J, 2017. Overview of the Camcore (NC State University) and USDA Forest Service cooperative gene conservation program for threatened and endangered tree species native to the southern United States. P 49 in Sniezko, RA, Man G, Hipkins V, Woeste K, Gwaze D, Kliejunas JT, McTeague BA (tech. cords). *Gene conservation of tree species—banking on the future. Proceedings of a workshop. Gen. Tech. Rep. PNW-GTR-963*. Portland, Oregon: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Johansson S, and Tuomela K, 1996. Growth of 16 provenances of *Eucalyptus microtheca* in a regularly irrigated plantation in eastern Kenya. *Forest Ecology and Management* 82: 11–18.

Jones, AMP, 2010. *Investigations into the Morphological, Agronomic, and Nutritional Diversity within Breadfruit (Artocarpus, Moraceae) as a Resource for Food Security*. PhD thesis. The University of British Columbia, Okanagan, Canada.

Jong, JJ de, 1960. Good seed doesn't cost — It pays!. *Euphytica* 9, 191–195. https://doi.org/10.1007/BF00022221

Jucker T, Bouriaud O, Avacaritei D, and Coomes DA, 2014. Stabilizing effects of diversity on aboveground wood production in forest ecosystems. Linking patterns and processes. *Ecology Letters* 17: 1560–1569.

Juniper BE, and Mabberley DJ, 2019. The extraordinary story of the apple. Second edition. Royal Botanic Gardens, Kew, Richmond, Surrey, UK.

Kalinganire A, 1999. *The reproductive biology of Grevillea robusta*. Unpublished PhD thesis. The Australian National University, Canberra, Australia.

Kanowski PJ, and Borralho NMG, 2004. Tree breeding, principles | economic returns from tree breeding. Pp 1561– 1568 in *Encyclopedia of Forest Sciences*, Elsevier, Oxford, UK.

Kindt R, Dawson IK, Lillesø J-PB, Muchugi A, Pedercini F, Roshetko JM, van Noordwijk M, Graudal L, Jamnadass R, 2021. The one hundred tree species prioritized for planting in the tropics and subtropics as indicated by database mining. Working Paper No. 312. World Agroforestry, Nairobi, Kenya. DOI http://dx.doi.org/10.5716/WP21001.PDF

Kindt R, Dawson I, Graudal L, and Jamnadass R, 2021a. Global Tree Knowledge Platform: Promoting the right tree in the right place for the right purpose. World Agroforestry Centre, Nairobi, Kenya. DOI https://worldagroforestry.org/tree-knowledge

Kjær ED, Lauridsen EB, and Wellendorf H, 1995. *Second evaluation of an international series of teak (Tectona grandis Linn.f) provenance trials*. Danida Forest Seed Centre, Humlebaek. Denmark.

Kjær ED, Amaral W, Yanchuk A, and Graudal L, 2004. Strategies for conservation of forest genetic resources. Pp 5–24 in in FAO, FLD, IPGRI. Forest Genetic Resources conservation and Management. Vol. 1. Overview, concepts and some systematic approaches. International Plant Genetic Resources Institute, Rome, Italy.

Koroveibau D, 1967. *Some Fiji Breadfruit Varieties*. Fiji Department of Agriculture, Suva, Fiji.

Labouisse J-P, 2016. Ethnobotany of Breadfruit in Vanuatu: Review and Prospects. *Ethnobiology Letters* 7: 14–23.

Lamb DJ, Parrotta J, Keenan R, and Tucker NIJ, 1997. *Rejoining habitat remnants: restoring degraded rainforest lands*. Pp 366–385 in Laurence WF, Bierrgaard Jr. RO (eds). Tropical Forest Remnants: Ecology, Management and Conservation of Fragmented Communities. University of Chicago Press, Chicago.

Lauridsen EB, and Kjær ED, 2002. Provenance research in *Gmelina arborea* Linn., Roxb. A summary of results from three decades of research and a discussion of how to use them. *International Forestry Review* 4: 1–15.

Leakey RRB, Tchoundjeu Z, Schreckenberg K, Shackleton S and Shackleton C, 2005. Agroforestry Tree Products (AFTPs): Targeting Poverty Reduction and Enhanced Livelihoods*. International Journal of Agricultural Sustainability* 3: 1–23.

Leakey RRB, Weber JC, Page T, Cornelius JP, Akinnifesi FK, Roshetko JM, Tchoundjeu Z, and Jamnadass R, 2012. Tree domestication in agroforestry: progress in the second decade (2003-2012). Pp 145-173 in Nair, P.K. Ramachandran, and Garrity, Dennis, (eds.) Agroforestry: the future of global land use. *Advances in Agroforestry*, 9. Springer, New York City, NY, USA.

Leibing C, Signer J, van Zonneveld M, Jarvis A, and Dvorak W, 2013. Selection of Provenances to Adapt Tropical Pine Forestry to Climate Change on the Basis of Climate Analogs. *Forests* 4: 155–178.

León-Lobos P, Way M, Aranda PD, and Lima-Junior M, 2012. The role of ex situ seed banks in the conservation of plant diversity and in ecological restoration in Latin America. *Plant Ecology and Diversity* 5: 245–258. https://doi.org/10.1080/17550874.2012.713402

Lillesø J-PB, 1996. *Dipterocarps. A review of literature of relevance to tree seed source programmes with emphasis on the species in Malesia*. Second, slightly revised edition. Ministry of Forestry, Indonesia Tree Seed Source Development Project. PT. Ardes Perdana/Danagro Adviser A/S.

Lillesø J-PB, Dawson IK, Graudal L, and Jamnadass R, 2021. *Quality seed for tree planting: Supporting more effective agroforestry and forest landscape restoration by learning from crop Integrated Seed System Development*. Policy Briefs, no. 54, World Agroforestry Centre. <http://outputs.worldagroforestry.org/cgi-bin/koha/opac-detail.pl?biblionumber=43573>. https://static-curis.ku.dk/portal/files/260200451/PB21003.pdf.

Liu, X. Trogisch S, He J-S, Niklaus PA, Bruelheide H, Tang Z, et al., 2018. Tree species richness increases ecosystem carbon storage in subtropical forests. *Proceedings of the Royal Society* B 285 (1885): 20181240. http://dx.doi.org/10.1098/rspb.2018.1240.

Martínez OJA, Ackerman EJM, Montiel DG, and Parrotta JA, 2015. Seed dispersal turns an experimental plantation on degraded land into a novel forest in urban northern Puerto Rico. *Forest Ecology and Management* 357: 68–75.

Macqueen DJ, 1993. *Calliandra series Racemosae: Taxonomic information; OFI seed collections; trial design.* Unpublished report. Oxford Forestry Institute, Oxford, UK.

McAlpine C, Catterall CP, Nally RM, Lindenmayer D, Reid JL, Holl KD, Bennett AF, Runting RK, et al., 2016. Integrating plant- and animal-based perspectives for more effective restoration of biodiversity. *Frontiers in Ecology and the Environment* 14: 37–45. https://doi.org/10.1002/16-0108.1

McMullin S, Njogu K, Wekesa B, Gachuiri A, Ngethe E, Stadlmayr B, Jamnadass R, and Kehlenbeck K, 2019. Developing fruit tree portfolios that link agriculture more effectively with nutrition and health: a new approach for providing year-round micronutrients to smallholder farmers. *Food Security* 11: 1355-1372.

Mendham DS, and White DA, 2019. A review of nutrient, water and organic matter dynamics of tropical acacias on mineral soils for improved management in Southeast Asia. *Australian Forestry*, 82: sup1, 45–56, DOI: 10.1080/00049158.2019.1611991

Merritt DJ, and Dixon KW, 2011. Restoration seed banks – A matter of scale. *Science* 332: 424–425. https://doi.org/10.1126/science.1203083

Meyer, J-Y 1996. Status of *Miconia calvescens* (Melastomataceae), a dominant invasive tree in the Society Island (French Polynesia). *Pacific Science* 50: 66–76.

Miyawaki A, 1993. Restoration of native forests from Japan to Malaysia. Pp 5–24 in H. Lieth and M. Lohmann (eds.), Restoration of Tropical Forest Ecosystems, Kluwer Academic Publishers, The Netherlands.

Midgley SJ, Arnold RJ, Stevens PR, Phimmavong S, Kien ND, and Chen SX, 2021. Eucalypts and acacias: smallholders' friends in Asia. Presentation to Your Forests, Our Future. 2021 IFA/AFG National Conference. 11–14 October 2021. Tasmania, Australia.

Midgley SJ, Eldridge KG, and Doran JC, 1989. Genetic resources of *Eucalyptus camaldulensis*. *The Commonwealth Forestry Review*, 68: 295–308.

Midgley SJ, and Gunn BV, 1985. *Acacia aneura* seed collections for international provenance trials. *Forest Genetic Resources Information (FAO)* 13: 21–29.

Minquan Y, and Yutian Z, 1991. *Results from a four-year-old tropical Acacia species/provenance trial on Hainan Island, China.* In J.W. Turnbull (ed.), Advances in Tropical Acacia Research: proceedings of an international workshop held in Bangkok, Thailand, 11–15 February 1991. ACIAR Proceedings No. 35. Canberra, Australia.

Møestrup S, Sloth A, and Burgess, S, 2006. *Conservation of valuable and endangered tree species in Cambodia 2001– 2006: a case study*. Hørsholm: Center for Skov, Landskab og Planlægning/Københavns Universitet. Development and Environment / Forest & Landscape, No 3.

Nicodemus A, Mayavel A, Bush D, and Pinyopusarerk K, 2020. *Increasing productivity of casuarina plantations in India through genetically improved seeds and clones*. Pp 105–116 in Proceedings of the Sixth International Casuarina Workshop: Casuarinas for Green Economy and Environmental Sustainability. Casuarina 2019, Krabi, Thailand 21– 25 October 2019. Kasetsart University, Bangkok, Thailand.

Orwa C, Mutua A, Kindt R, Jamnadass R, and Anthony S, 2009. Agroforestree Database: a tree reference and selection guide version 4.0 http://www.worldagroforestry.org/sites/treedbs/treedatabases.asp).

Paquette A, and Messier C, 2011. The effect of biodiversity on tree productivity: from temperate to boreal forests. *Glob. Ecol. Biogeogr*. 20: 170–180.

Pinho RC, Miller RP, and Alfaia SS, 2012. Agroforestry and the Improvement of Soil Fertility: A View from Amazonia. *Applied and Environmental Soil Science*, vol. 2012, Article ID 616383, 11 pages, 2012. https://doi.org/10.1155/2012/616383.

Pinyopusarerk K, Kalinganire A, Williams ER and Aken KM, 2004. Evaluation of international provenance trials of *Casuarina equisetifolia*. *ACIAR Technical Report 58*. Canberra, Australia.

Pottinger AJ, and Dunsdon AJ, 2001. Ch 6. Provenance trials. pp. 53–56 in *Calliandra calothyrsus: an agroforestry tree for the humid tropics.* J.R. Chamberlain (ed). Tropical Forestry Papers no. 40. Oxford Forestry Institute. Oxford, UK.

Purnell RC, Lundquist JE, 1986. Provenance Variation of *Eucalyptus nitens* on the Eastern Transvaal Highveld in South Africa, *South African Forestry Journal*,138:1, 23–31, DOI: 10.1080/00382167.1986.9630038.

Pye-Smith C, 2013. The Quiet Revolution: How Niger's farmers are re-greening the parklands of the Sahel; ICRAF Trees for Change no.12. World Agroforestry Centre, Nairobi, Kenya.

Qazi N, 2020. Hydrological functioning of forested catchments, Central Himalayan Region, India. *For. Ecosyst.* 7, 63. https://doi.org/10.1186/s40663-020-00275-8

Ræbild, A, Graudal LOV, and Nimbkar, N 2003. Evaluation of an *Acacia aneura* provenance trial at Phaltan, India: Trial no. 19 in the arid zone series. Results and Documentation no. 22, Danida Forest Seed Centre, Humlebaek. Denmark.

Ragone DC, 1991. Collection, Establishment, and Evaluation of a Germplasm Collection of Pacific Island Breadfruit. PhD Thesis. University of Hawai'i. Honolulu, USA.

Randall B, Walton D, Nevenimo T, Poienou M, Moxon J, Hannet G, and Wallace HM, 2018. *Canarium indicum*. Pp 73–76 in Trees for Life in Oceania: conservation and utilization of genetic diversity. Thomson LAJ, Doran J, Clarke B (eds). Australian Centre for International Agricultural Research, Canberra, Australia

Raynor WC, 1989. Structure, Production of Seasonality in an Indigenous Pacific Island Agroforestry System. A Case Example on Pohnpei Islands, F.S.M. Master of Science Thesis. University of Hawai'i, Honolulu, USA.

Redfern TN, 2007. Breadfruit improvement activities in Kiribati. *Acta Horticulturae* 757: 93–100

Redo DJ, Grau HR, Aide TM, and Clark ML, 2012. Asymmetric forest transition driven by the interaction of socioeconomic development and environmental heterogeneity in Central America. *Proc. Natl. Acad. Sci. U.S.A.* 109, 8839–8844. doi: 10.1073/pnas.1201664109

Reij C, Tappan G, and Smale M, 2009. Agro-environmental transformation in the Sahel: another kind of "Green Revolution". IFPRI Discussion Paper 00914. International Food Policy Research Institute, Washington DC., USA.

Rinaudo A, Patel P, and Thomson LAJ, 2002. Potential of Australian acacias in combating hunger in semi-arid land's. *Conservation Science Western Australia* 4: 161–169.

Rinaudo A, McKenzie S, Huynh TB, and Sterrett CL, 2021. Farmer managed natural regeneration: community driven, low cost and scalable reforestation approach for climate change mitigation and adaptation. In: Leal Filho W., Luetz J., Ayal D. (eds) Handbook of Climate Change Management. Springer, Cham. https://doi.org/10.1007/978-3-030-22759-3 281-1.

Roshetko JM, and Purnomosidhi P, 2013. Smallholder agroforestry fruit production in Lampung, Indonesia: horticultural strategies for smallholder livelihood enhancement. *Acta Hortic*. 975: 671–679. DOI: 10.17660/ActaHortic.2013.975.84.

Roshetko, JM, Dawson IK, Urquiola J, Lasco RD, Leimona B, Weber JC, Bozzano M, Lillesø JPB, Graudal L, and Jamnadass R, 2018. To what extent are genetic resources considered in environmental service provision? A case study based on trees and carbon sequestration. *Climate and Development*, 10: 755–768. https://doi.org/10.1080/17565529.2017.1334620

Roupsard O, Ferhi A, Granier A, Pallo F, Depommier D, Mallet B, Joly HI, and Dreyer E, 1999. Reverse phenology and dry-season water uptake by *Faidherbia albida* (Del.) A. Chev. in an agroforestry parkland of Sudanese west Africa. *Functional Ecology* 13: 460–472.

Rudel TK, Coomes OT, Moran E, Achard F, Angelsen A, Xu J, and Lambin E, 2005. Forest transitions: towards a global understanding of land use change. *Global Environmental Change* 15: 23–31. doi: 10.1016/j.gloenvcha.2004.11.001

Salim E, and Ullsten O, 1999. *Our Forests, Our Future: Report of the World Commission on Forests and Sustainable Development*. Cambridge University Press, Cambridge, UK.

Sacandé M, Jøker D, Dulloo ME, and Thomsen KA, 2004. Comparative storage biology of tropical tree seeds. International Plant Genetic Resources Institute, Rome, Italy.

Schmidt L, 2000. Guide to handling of tropical and subtropical forest seed. Danida Forest Seed Centre, Humlebaek, Denmark.

Schmidt MVC, Ikpeng YU, Kayabi T, Sanches RA, Ono KY, and Adams C. 2021. Indigenous knowledge and forest succession management in the Brazilian Amazon: contributions to reforestation of degraded areas. *Frontiers in forest and global change*, 4:605925. doi: 0.3389/ffgc.2021.605925.

Schmidt LH, Barsotti D, Møestrup S, Abiyu A, Graudal L, Jamnadass R, Dawson IK, and Lillesø, J-PB, 2021A. *The Resources for Tree Planting Platform: Delivering high-quality tree-planting material to growers*. World Agroforestry Centre, Nairobi, Kenya. <http://tree.worldagroforestry.org/

Scholten RC, Jandt R, Miller EA, et al., 2021. Overwintering fires in boreal forests. Nature 593, 399–404. https://doi.org/10.1038/s41586-021-03437-y

Sedgley M, and Griffin AR, 1989. *Sexual reproduction of tree crops*. Academic Press, London, UK.

Smith P, 2019. The challenge for botanic garden science. *Plants, People, Planet* 1: 38–43. https://doi.org/10.1002/ppp3.10

Smith P, and Tadesse W, 2020. Mid-Term Review Report. Provision of adequate tree seed portfolios (PATSPO). Report to Norwegian International Climate and Forest Initiative (NICFI) and Royal Norwegian Embassy in Ethiopia, Addis Ababa, Ethiopia.

Smith P, Thomson LAJ, and Dobson A, 2015. External Review of the ICRAF Genetic Resources Unit Commissioned by the Global Crop Diversity Trust. June 8–12, 2015. Nairobi, Kenya

Sloan S, 2008. Reforestation amidst deforestation: simultaneity and succession. *Global Environmental Change* 18: 425–441. doi: 10.1016/j.gloenvcha.2008.04.009

Song XP, Hansen MC, Stehman SV, Potapov PV, Tyukavina A, Vermote EF, et al., 2018. Global land change from 1982 to 2016. *Nature* 560: 639–643. doi: 10.1038/s41586-018-0411-9

Stacy EA, 2001. Cross-fertility in two tropical tree species: Evidence of inbreeding depression within populations and genetic divergence among populations. *American Journal of Botany* 88: 1041–1051.

Sthapit B, Lamers HA, Rao R, Bailey A, Sajise P and Quek P, 2016. Tropical fruit tree diversity: good practices for *in situ* and on-farm conservation. Routledge Oxfordshire, UK.

Steidinger BS, Crowther TW, Liang J, Van Nuland ME, Werner GDA, Reich PB, Nabuurs G, De-Miguel S, et al., 2019. Climatic controls of decomposition drive the global biogeography of forest-tree symbioses. *Nature*, 569 (7756), 404–408. https://doi.org/10.1038/s4158 6-019-1128-0

Stewart JL, Dunsdon AJ, and Hughes CE, 1991. Early research from a *Leucaena* species provenance trial in Honduras. *Leucaena Research Reports* 12: 101–104.

Strassburg BBN, Beyer HL, Crouzeilles R, Iribarrem A, Barros F, de Siqueira MF, Sánchez-Tapia A, Balmford A, et al., 2019. Strategic approaches to restoring ecosystems can triple conservation gains and halve costs. *Nature Ecology & Evolution* 3: 62–70.

Suangtho V, Graudal L, and Kjær ED, 1999. Genecological zonation as a tool in conservation of genetic resources of teak (*Tectona grandis*) in Thailand. In Proceedings of Teak beyond 2000 Conference, Chiang Mai, Thailand.

Tan SY, Georgousopoulou EN, Cardoso BR, Daly RM and George ES, 2021. Associations between nut intake, cognitive function and non-alcoholic fatty liver disease (NAFLD) in older adults in the United States: NHANES 2011-14. BMC Geriatrics 21, 313. https://doi.org/10.1186/s12877-021-02239-1

Termote C, Bwama Meyi M, Dhed'a Djailo B, Huybregts L, Lachat C, Kolsteren P, et al., 2012. A biodiverse rich environment does not contribute to a better diet: a case study from DR Congo. PLoS ONE 7(1): e30533. https://doi.org/10.1371/journal.pone.0030533

Thaman RR, 1989. *Agrodeforestation and the neglect of trees: Threat to the wellbeing of Pacific societies*. SPREP Occasional Paper No. 5. South Pacific Regional Environment Programme, South Pacific Commission, Noumea.

Thaman RR, 1992. *Agrodeforestation as a major threat to sustainable development*. Pp. 194–195 in Environment and development: A Pacific Island perspective. R. Thistlethwaite and G. Votaw (eds.). Asian Development Bank and South Pacific Regional Environment Programme, Manila and Apia.

Thaman RR, 2014. Agrodeforestation and the loss of agrobiodiversity in the Pacific Islands: A call for conservation. *Pacific Conservation Biology* 20: 180–192.

Thomson LAJ, and Cole EG, 1987. Woody plant seed collections in tropical, arid and semiarid Australia and recommendations for international species trials. *Forest Genetic Resources Information (FAO)* 15: 37–48.

Thomson LAJ (FAO Consultant) 1995. *Collecting Woody Perennials*. Pp 485–509 *in Collecting Plant Genetic Diversity - Technical Guidelines.* Guarino L, Ramanatha Rao V, and Reid, R, eds., Wallingford, UK: CAB International (on behalf of IPGRI, FAO, IUCN and UNEP).

Thomson LAJ, 2000. *Management of natural forests for conservation of forest genetic resources*. Pp 13–44 in Forest Genetic Resources Conservation and Management. Vol. 2: In managed natural forests and protected areas (*in situ*). FAO, DFSC, IPGRI, Rome, Italy.

Thomson LAJ, and Theilade I, 2000. *Protected areas and their role in conservation of forest genetic resources.* Pp 45–66 in Forest Genetic Resources Conservation and

Management. Vol. 2: In managed natural forests and protected areas (*in situ*). FAO, DFSC, IPGRI, Rome, Italy

Thomson L, Graudal L, and Kjær E, 2000. *Conservation of genetic resources in their natural environment.* Pp 1–4 in Forest Genetic Resources Conservation and Management. Vol. 2: In managed natural forests and protected areas (*in situ*). FAO, DFSC, IPGRI, Rome, Italy.

Thomson LAJ, 2006. *Low input breeding and genetic conservation of Pacific Islands forest tree species.* Pp 197–204 in Proceedings of the IUFRO Division 2 Joint Conference: Low Input Breeding and Conservation of Forest Genetic Resources: Antalya, Turkey, 9–13 October, 2006. Fikret Isik (ed.).

Thomson LAJ, and Evans B, 2006. *Canarium indicum* var. *indicum* and *C. harveyi* (canarium nut), ver. 2.1. In 'Species profiles for Pacific Island agroforestry: their culture, environment and use', ed. by C.R. Elevitch. Permanent Agriculture Resources: Holualoa, HI. http://agroforestry.org/free-publications/traditional-tree-profiles.

Thomson LAJ and Thaman RR, 2016. *Native forests, plantation forests and trees outside forests: their vulnerability and roles in mitigating and building resilience to climate change* pp 383–446 in M Taylor, A McGregor and B Dawson (eds) Vulnerability of Pacific Island agriculture and forestry to climate change. Pacific Community, Noumea.

Thomson LAJ, Doran J, Clarke B (eds) 2018. *Trees for Life in Oceania: conservation and utilization of genetic diversity.* Australian Centre for International Agricultural Research, Canberra, Australia.

Thomson LAJ, 2018. *Inocarpus fagifer*. Pp 140–142 in *Trees for Life in Oceania: conservation and utilization of genetic diversity.* Thomson LAJ, Doran J, Clarke B (eds). Australian Centre for International Agricultural Research, Canberra, Australia.

Thomson LAJ, Thaman RR, Guarino L, Taylor M, and Elevitch C, 2018a. *Pandanus tectorius*. Pp 179–183 in *Trees for Life in Oceania: conservation and utilization of genetic diversity.* Thomson LAJ, Doran J, Clarke B (eds). Australian Centre for International Agricultural Research, Canberra, Australia.

Thomson LAJ, and Gâteblé G 2020. *Casuarinaceae genetic resources in the Pacific Islands: enhancing their contributions to the green economy*. P 31–42 in Proceedings of the Sixth International Casuarina Workshop: Casuarinas for Green Economy and Environmental Sustainability. Casuarina 2019, Krabi, Thailand 21–25 October 2019.

Thomson LAJ, Mabberley DJ, Butaud J-F, Sardos J, Sachter-Smith GL, Wong M, Kagy V, Kepler AK, et al., 2021. *The origins and dispersal of fehi bananas (in Musa Sect. Australimusa) throughout the Pacific Islands* (in prep. J. Polynesian Soc.)

Thomson LAJ, Ragone D, Wilson W, Geraghty P, and Zerega N, 2021A. *Breadfruit in the Pacific Islands and postulated origins of cultivars in East Polynesia* (in prep. J. Polynesian Soc.)

Thomson LAJ, Turnbull JW, and Maslin BR, 1994. The utilization of Australian species of Acacia, with particular reference to those of the dry subtropics and the northern and central arid zone. *Journal of Arid Environments* 27: 279–296.

Thomson LAJ, 1992. *Australia's sub-tropical dry-zone Acacia species with human food potential.* Pp 3–36 in Australian dry-zone acacias for human food. House, A.P.N. and Harwood, C.E., ed., Canberra: Australian Tree Seed Centre, CSIRO Division of Forestry.

Tucker NIJ, and Murphy TM, 1997. The effects of ecological rehabilitation on vegetation recruitment: some observations from the wet tropics of north Queensland. *Forest Ecology and Management* 99: 133–152.

Tucker NIJ, 2000. Wildlife colonisation on restored tropical lands: what can it do, how can we hasten it and what can we expect? Pp 278–295 in: Elliot S, Kerby J, Blakesley D, Hardwick K, Woods K, Anusarnsunthorn (eds). Forest Restoration for Wildlife Conservation. Chiang Mai University, Chiang Mai, Thailand.

Turnbull JW, 2007. Development of sustainable forestry plantations in China: a review. Impact Assessment Series Report No. 45. https://www.aciar.gov.au/sites/default/files/legacy/node/2418/ias45_pdf_10747.pdf

UNESCO, 2020. Gondwana Rainforests of Australia State of Conservation update - April 2020. UNESCO, Paris, France.

Veldman JW, Overbeck GE, Negreiros D, Mahy G, Le Stradic S, Fernandes GW, Durigan G, Buisson E, Putz FE, and Bond WJ, 2015. Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *BioScience*, 65: 1011–1018. https://doi.org/10.1093/biosc i/biv118

Verheij EWM, and Coronel RE, (eds) 1992. Plant Resources of South-East Asia. No 2. Edible Fruits and Nuts. PROSEA, Bogor, Indonesia.

Vercoe T, and Clarke B, 1994. Trial growth performance of *Eucalyptus urophylla* S. T. Blake. Report to FAO Forestry Division on the growth of *Eucalyptus urophylla* in international provenance trials and other growth trials. CSIRO Division of Forestry

Vigulu VW, 2020. Mixed Species and Agroforestry System Interactions in Solomon Islands. PhD thesis, Griffith University, Queensland.

Vinceti B, Eyzaguirre P, and Johns T, 2008. The nutritional role of forest plant foods for rural communities. Pp. 63–93 in Colfer CJP (ed.) Human health and forests: a global overview of issues, practice and policy. Volume 12. London, Earthscan.

Vinceti B, Termote C, Ickowitz A, Powell B, Kehlenbeck K, and Hunter D, 2013. The contribution of forests and trees to sustainable diets. *Sustainability* 5: 4797–4824. https://doi.org/10.3390/su5114797

Vira B, Wildburger C, and Mansourian S. (eds.) 2015. Forests, trees and landscapes for food security and nutrition. IUFRO World Series, 33. http://www.iufro.org/download/file/18901/5690/ws33_pdf/

Wambugu C, Franzel S, Cordero J, and Stewart J, 2006. Fodder shrubs for dairy farmers in East Africa: making extension decisions and putting them into practice. Nairobi: World Agroforestry Centre; Oxford Forestry Institute, Oxford, UK. https://assets.publishing.service.gov.uk/media/57a08c1ced915d3cfd00118c/R6549_extension_manual.pdf

Walter A, 1989. Notes sur les cultivars d'arbre a pain dans le Nord de Vanuatu. *Journal de la Société des Océanistes* 1: 3–18.

Walter A, and Sam C, 1996. Indigenous nut trees in Vanuatu: ethnobotany and variability. Pp. 56–66 in South Pacific indigenous nuts, M.L. Stevens, R.M. Bourke and B.R. Evans (eds). ACIAR Proceedings No. 69. Australian Centre for International Agricultural Research, Canberra.

Wang BSP, Charest PJ, and Downie B, 1993. *Ex situ* storage of seeds, pollen and in vitro cultures of perennial woody plant species. FAO Forestry Paper 113. FAO, Rome, Italy.

Westcott DA, Bentrupperbäumer J, Bradford M, and McKeown A, 2005. Incorporating patterns of disperser behaviour into models of seed dispersal and its effects on estimated dispersal curves. *Oecologia*. 146: 57–67. http://dx.doi.org/10.1007/s00442-005-0178-1

Whittet R, Cottrell J, Cavers S, Pecurul M, and Ennos R, 2016. Supplying trees in an era of environmental uncertainty: Identifying challenges faced by the forest nursery sector in Great Britain. *Land Use Policy* 58: 415–426. https://doi.org/10.1016/j.landusepol.2016.07.027

Workman SW, and Stuthman J, 2015. BeeTrees: tropical and sub-tropical nectar and pollen sources. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2015-0020.

World Vision, 2009. Climate Change, Community Forestry and Development: Humbo Community Managed Forestry Project, Ethiopia. World Vision Climate Change Case Studies – June 2009.

World Vision, 2020*. LEAP Project Management Report.* World Vision Ethiopia Humbo Community Managed Natural Regeneration Project (October 1, 2019 –September 30, 2020).

Young A, Boshier D, and Boyle T (eds.) 2000. Forest Conservation Genetics: Practices and Principles. CSIRO, Collingwood, Australia.

Zhang Y, Chen HYH, Reich PB, 2012. Forest productivity increases with evenness, species richness and trait variation: a global meta-analysis. *J Ecol.* 100: 742–9.

Annex 1

Examples of food trees in/for developing countries in tropical humid, subhumid and semi-arid zones.

Tropical fruits:

Artocarpus heterophyllus (jackfruit)	*Ficus opposita* (sandpaper fig)	*Plinia cauliflora* (*jaboticaba*)
Averrhoa carambola (carambola)	*Durio zibethinus* (durian)	*Pometia pinnata* (oceanic lychee)
Bactris gasipaes (peach palm)	*Eriobotrya japonica* (loquat)	*Pouteria caimito* (*abiu*)
Boscia senegalensis (hanza)	*Garcinia mangostana* (mangosteen)	*Pouteria sapota* (mamey sapote)
Burckella obovata (*naduledule*)	*Lansium parasiticum* (*langsat*)	*Psidium guajava* (guava)
Chrysophyllum cainito (*cainito*)	*Litchi chinensis* (lychee)	*Salacca zalacca* (*salak*)
Citrus × limonia (Rangpur lime)	*Mangifera indica* (mango)	*Spondias dulcis* (*ambarella*)
Citrus maxima (pomelo)	*Melicoccus bijugatus* (mamoncillo)	*Strychnos innocua* (*inguachia*)
Cordia sinensis (*saucer berry)*	*Musa* spp. (banana)	*Syzygium malaccense* (Malay apple)
Dacryodes edulis (*safou*)	*Nephelium lappaceum* (rambutan)	*Tamarindus indica* (tamarind)
Dimocarpus longan (longan)	*Oenocarpus bacaba* (*bacaba*)	*Tricoscypha acuminata* (*amvut*)
Diospyros kaki (oriental persimmon)	*Pandanus tectorius* (beach pandanus)	*Uapaca kirkiana* (wild loquat)
Docynia indica (*mehel*)	*Phoenix dactylifera* (date palm)	*Ziziphus mauritiana* (Indian jujube)
Dracontomelon vitiense (*tarawau*)	*Pithecellobium dulce* (*camachile*)	

Nuts and seeds:

Acacia coriacea (desert oak)	*Brachychiton puopulneus* (kurrajong)	*Nypa fruticans* (nipa palm)
Acacia tumida (pindan wattle)	*Canarium* spp. (*galip, pili*)	*Pachira aquatica* (Guyana chestnut)
Adenanthera pavonia (red bean tree)	*Couepia longipendula* (egg nut)	*Pandanus julianettii* (*karuka*)
Aleurites moluccanus (*kemiri*)	*Erythrina edulis* (*basul*)	*Pangium edule* (*pangi*)
Anacardium occidentale (cashew)	*Gnetum latifolium* (*koliat*)	*Pistacia vera* (pistachio)
Anacolosa frutescens (galonut)	*Inocarpus fagifer* (Tahitian chestnut)	*Schinziophyton rautanenii (mongongo)*
Araucaria angustifolia (paraná)	*Irvingia malayana* (Malay almond)	*Sterculia spp.* (Thai chestnut)
Artocarpus camansi (breadnut)	*Lithocarpus* spp. (stone oaks)	*Terminalia catappa* (beach almond)
Barringtonia spp. (cut-nut)	*Macadamia* spp. (macadamia)	*Terminalia kaernbachii* (okari nut)
Bertholletia excelsa (Brazil nut)		

Edible oils:

Allanblackia spp. (tallow-tree)	*Diploknema butyracea* (Indian butter tree)	*Platonia insignis* (*bacuri*)
Astrocaryum vulgare (*tucuma*)	*Elaeis* spp (oil palm)	*Schinziophyton rautanenii* (*mongongo*)
Attalea speciosa (*babassu*)	*Garcinia indica* (*kokum*)	*Sclerocarya birrea* (*marula*)
Balanites aegyptica (desert date)	*Irvingia gabonensis* (*dika*)	*Terminalia solomonensis* (SI avocado)
Caryocar brasiliense (*pequi*)	*Lecythis pisonis* (sapucala nut)	*Theobroma grandiflorum* (*cupuaçu*)
Cocos nucifera (coconut)	*Persea americana* (avocado)	*Vitellaria paradoxa* (shea)

Edible gums:

Anogeissus leiocarpa (African birch)	*Guiera senegalensis* (moshi medicine)	*Sterculia urens* (*bhutyā*)
Balanites rotundifolia (*mbamba ngoma*)	*Senegalia senegal* (gum acacia)	*Vachellia seyal* (*shittah*)

Edible shoots, leaves and flowers:

Adansonia digitata (baobab)	*Dendrocalamus* spp. (bamboo)	*Metroxylon vitensis* (Fiji sago palm)
Bambusa spp. (bamboo)	*Euterpe edulis* (*juçara*)	*Moringa oleifera* (drumstick)
Bactris gasipaes (peach palm)	*Garcinia cowa* (cowa mangosteen)	*Nastus elatus* (PNG green bamboo)
Boscia salicifolia (willow-leaved shepherds tree)	*Gnetum gnemon* (*melinjo*)	*Scleichera oleosa* (Malay lac tree)
Chimonobambusa spp. (bamboo)	*Hibiscus kaute* (*kaute*)	*Sesbania grandiflora* (*katurai*)
Crateva adansonii (sacred barna)	*Maerua crassifolia* (jiga)	*Sonneratia caseolaris* (mangrove apple)

Carbohydrate, flour and other food staple uses:

Acacia colei (Cole's Wattle)	*Bruguiera gymnorrhiza* (mangrove)	*Musa* × *paradisiaca* (plantains)
Acacia victoriae (*gundabluey*)	*Caryota urens* (jaggery palm)	*Prosopis laevigata* (mesquite)
Artocarpus altilis (breadfruit)	*Ensete ventricosum (Ethiopian banana)*	*Prosopis velutina* (velvet mesquite)
Artocarpus mariannensis (*dugdug*)	*Metroxylon sagu* (sago palm)	*Treculia africana* (African breadfruit)

Nutraceuticals[27]:

Acronychia acidula (lemon aspen)		
Annona muricata (soursop)	*Malpighia emarginata* (acerola cherry)	*Musa* sect. *Australimusa* (fehi*)*
Euterpe oleracea (*açaí*)	*Manilkara zapota* (*sapodilla*)	*Myrciaria dubia* (*camu camu*)
Garcinia gummi-gutta (*cambogia*)	*Mauritia flexuosa* (*moriche* palm)	*Punica granatum* (pomegranate)
Lycium barbarum (goji berry)	*Morinda citrifolia* (*noni*)	*Terminalia ferdinandiana* (Kakadu plum)

Spices and flavouring agents:

Backhousia spp. (fragrant myrtles)	*Illicium verum* (star anise)	*Pimenta dioca* (all spice)
Cinnamomum spp. (cinnamon)	*Murraya koenigii* (curry leaf tree)	*Salvadora persica* (toothbrush tree)
Citrus hystrix (kaffir lime)	*Myristica fragrans* (nutmeg)	*Syzygium aromaticum* (clove)
Dipteryx odorata (*cumaru*)	*Pandanus amaryllifolius* (pandan)	*Tetrapleura tetraptera* (*prekese*)
Litsea cubeba (*may chang*)	*Parkia biglobosa* (African locust bean)	*Zanthoxylum limonella* (ma-khwaen)

Alkaloids/stimulants:

Artocarpus tonkinensis (*chay*)	*Coffea* spp. (coffee)	*Ilex paraguariensis* (*yerba matá*)
Catha edulis (*khat*)	*Cola* spp. (kola nut)	*Theobroma cacao* (*cacao*)

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[27] Many fruit- and nut tree species provide nutrient-dense foods which warrant consideration as nutraceuticals