

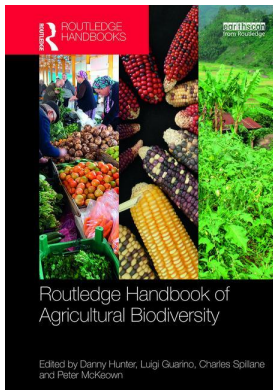
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3

FOREST AND TREE GENETIC RESOURCES

David Boshier, Judy Loo and Ian K. Dawson

Introduction

Trees show certain fundamental differences from agricultural crops in cultural, biological (life history, ecology, genetics) and economic terms, which result in differences in their use, management and conservation. Throughout the world, the varied cultural and religious values placed on woodlands, forests and even individual trees demonstrate their special place in the human psyche. In agricultural landscapes, many cultures retain forest patches as spirit/sacred groves which protect the burial places of ancestors as well as plants and animals, forming important but often overlooked components of a forest conservation network (Pungetti et al., 2012). Individual trees may be protected as sacred (e.g. Buddhist culture) or for aesthetic reasons (e.g. tree preservation orders in the United Kingdom). The elemental role of trees in the lives of rural people is also obvious from the many uses of tree products (e.g. construction, fencing, furniture, foods, medicines, fibres, fuels, forage). Forests and trees-outside-forests contribute to the livelihoods of more than 1.6 billion people worldwide (World Bank, 2008), with approximately 900 million people living in farm landscapes that have more than 10% tree cover, particularly in Southeast Asia, Central America and South America (Zomer et al., 2014).

The varying levels of dependency of communities on tree products and services has, however, often been poorly described or acknowledged (Byron and Arnold, 1999), although the situation has improved recently with initiatives such as the Poverty Environment Network (Angelsen et al., 2014; see also Ingram et al., Chapter 4 of this Handbook). Proper description has been hampered by the ubiquitous nature of tree products and services, and the complex inter-connections by which trees influence livelihoods (e.g. Turner et al., 2012). Poor characterization has also reflected the different sources of tree products and services, with forest and farmland sources often assessed differently by separately-operating and often little-communicating government forestry and agriculture departments (de Foresta et al., 2013). Thus, the positive roles and limitations of trees in supporting livelihoods are often neglected by policy makers, with poor targeting of development interventions related to managing trees in forests and farms (World Bank, 2008).

Recognizing the importance of trees and this lack of information, the first-ever report on the State of the World's Forest Genetic Resources (SOW-FGR) focused on the 'tree' component of forests and farmlands (FAO, 2014a). From 86 individual Country Reports (representing >85% of global forest cover), approximately 8,000 taxa of trees, shrubs, palms and bamboo were cited as useful, with 42%

used for timber and 41% for non-timber forest products (NTFPs), as discussed in Chapter 4 of this Handbook and also termed NWFPs (non-wood forest products; FAO, 2014a). In contrast to the limited number of agricultural crop species grown, the combined listings from the Country Reports indicated almost 2,300 tree, shrub, palm and bamboo species as national priorities for conservation and management, with economic value in the formal economy a major factor in prioritization. However, approximately 500 of those species were nominated as important for management at least in part for negative reasons related to their potential invasiveness (explored by Koskela et al., 2014).

The Country Reports show, however, that in the prioritization of species relatively little attention was given to the high value of tree products and services in informal economies. In most tropical regions, the most important use for NWFPs is shown as food (FAO, 2010); for example USD 90 billion worth of food and other NWFPs were estimated to be harvested annually from forests and trees in developing countries two decades ago (Pimentel et al., 1997). FAO's 2010 Global Forest Resources Assessment (GFRA) provides more recent, but lower, estimates of global value (based on 2005 figures), at USD 19 billion and 17 billion annually for NWFPs (including foods) and woodfuel removals, respectively (FAO, 2010). These values are likely to be gross underestimates, however, as many countries report only value for the 'top' few NWFP tree species of commercial importance. Tree commodity crops represent an exception to the limited information on the value of tree products, with export data compiled widely by national governments and assembled by FAO. Data from FAOSTAT for the five most important woody plant/palm commodity crops grown widely in the tropics – palm oil (*Elaeis guineensis*), coffee (primarily *Coffea arabica*), rubber (*Hevea brasiliensis*), cocoa (*Theobroma cacao*) and tea (primarily *Camellia sinensis*) – indicated a large export value of more than USD 80 billion in 2010, which is of the same order as total annual NWFP extractions (Dawson et al., 2014). Given the diversity of benefits from tree genetic resources, greater knowledge of these resources and the issues related to their sustainable use and conservation, both within and outside of forests, is essential.

Threats to tree genetic resources

From the preceding section, it is evident that the loss, continued degradation and fragmentation of tree populations in forests, woodlands and agroforestry landscapes is of practical concern to rural communities worldwide. Of the 8,000 tree and other perennial plant species listed as used in the SOW-FGR Country Reports, about half were also noted as threatened. The current IUCN Red List of Threatened Species¹ lists 1,200 trees and shrubs as 'critically endangered', 1,700 as 'endangered' and another 3,700 as 'vulnerable'. Although it is generally agreed that *in situ* conservation is the first line of defence, it is only in Europe that *in situ* reserves (known as dynamic genetic conservation units) have been established systematically to conserve tree genetic resources (Lefèvre et al., 2013). On the basis of the Country Reports of the SOW-FGR, at least 1,800 tree species are conserved *ex situ* in seed banks, botanic gardens and elsewhere, with approximately 600 of these species listed as priorities for conservation and management (FAO, 2014a). Data from other sources show that the actual number of tree species stored *ex situ* is much greater, as illustrated by the more than 5,800 woody perennial species listed as available globally through seed suppliers' active collections (Dawson et al., 2013; TSSD²). Active collections are, however, rarely secure in the long term, while many *ex situ* collections for long-term storage suffer from limited genetic diversity due to narrow sampling, a lack of accompanying passport data (Dawson et al., 2013) and ultimately problems associated with regeneration. Better coordination is also needed between *ex situ*, *in situ* and *circa situm* (see **Box 3.1 Conservation options for tree species**) conservation efforts.

This chapter considers the conservation-on-farm (*circa situm*) value of trees and how the nature and context of landscape, production system, forest/agriculture interface and socio-economic

Box 3.1 Conservation options for tree species

- *In situ* conservation involves the conservation of flora or fauna in the location and the ecosystem (in as natural a state as possible) in which they naturally occur. Trees may be conserved under natural conditions due to their use, or that of the ecosystem in which they are found, but *in situ* conservation may also occur for other reasons such as existence value. *In situ* refers only to location rather than motivations.
- *Ex situ* conservation involves the removal of flora or fauna from the location where they naturally occur, and their conservation either in a dormant state (e.g. as tissue or seed) or in breeding populations (e.g. in seed orchards). Seed orchards may supply germplasm for planting at the same time as conserving diversity, whereas other gene banks (either planted or *in vitro*) may be inspired solely by existence value.
- *Circa situm* conservation involves the conservation of biodiversity within its native range but under conditions highly altered by human activity. Trees are often conserved *circa situm* due to their use and consequent active retention in otherwise altered landscapes. However, many other trees persist in altered ecosystems without active protection or management, due for example to their vigour or the limited resources available to farmers to remove them. *Circa situm* refers to where the conservation is carried out, rather than its motivations.
- On-farm tree management: much discussion of the importance of trees on farms has focused on their livelihood value. In this respect, on-farm tree management is clearly a form of conservation through use, although only under certain circumstances does it contribute to the conservation of biodiversity.

Source: Modified from Barrance et al. (2009).

and cultural values influence use and conservation options. This discussion is set against a background of how basic biological differences between tree species and annual/other crops influence levels and patterns of genetic diversity, their subsequent use and conservation. Farmland trees may play important and varied roles in the long-term viability of some native species by maintaining minimum viable populations of threatened species, facilitating gene flow between patches of native forest, conserving particular genotypes not found in reserves and acting as intermediaries and alternative host habitats for pollinators and seed dispersers (Boshier et al., 2004). It is important to recognize the complementary role that maintenance of trees on farms plays to *in situ* conservation. Underestimating the capacity of many species to persist in agroforests under current practices may lead to the misdirection of limited conservation resources towards species that are not in fact under threat. The knowledge that some tree species can be conserved through existing farming practices can free resources for the conservation of more critically threatened species needing more conventional, resource-intensive approaches.

Trees are different from other crops in their basic biology

By its very nature, biodiversity is complex and multifaceted, incorporating ecosystems, habitats, species, populations and genes. Most natural resource planners recognize tree genetic diversity and the processes that underlie it as components of ecosystem and species stability, adaptability, conservation and use; rarely, however, is there any explicit attention to them in management

planning and decision-making. As many aspects of genetic diversity are hidden ('cryptic' variation), the importance of genetic diversity is easily overlooked. The value of intraspecific variation in tree species and the importance of managing this genetic variation to support rural livelihoods, have received relatively little attention from policy makers (Dawson et al., 2009), despite the benefits to rural communities that proper consideration offers (Fisher and Gordon, 2007). Resource limitations also result in genetic information being ignored or given only minor consideration in conservation or management strategies. It is far more common for ecological, social or economic criteria, alone or in combination, to drive decisions (Graudal et al., 2014).

The primary factors that shape genetic variability within tree species are, as for other plants, breeding system, natural selection, genetic drift and gene flow (Petit and Hampe, 2006). Trees have a diverse array of breeding systems (outbreeding, mixed-mating, selfing), associated incompatibility mechanisms and sexual systems (hermaphrodite, monoecy, dioecy) that influence their reproduction and levels of genetic diversity, and hence their evolutionary trajectories, current use, prospects for future adaptation and conservation. Breeding systems not only influence genetic structure but are themselves controlled genetically and may not therefore be constant, having the flexibility to respond to changing conditions. Thus, at any moment, the genetic status of a tree population results from a combination of factors such as history, spatial distribution, flowering phenology, breeding system and patterns of both pollination and seed dispersal (Petit and Hampe, 2006). Sub-population structure, inter-population variation and gene flow all effect patterns of variation and adaptation in a tree species.

In comparison to crops, trees exhibit more extreme life history traits (i.e. long-lived, late attainment of reproductive age, overlapping generations) and experience a wider variety of stresses (natural- and human-induced) during their lives, presenting different challenges for conservation and use (Petit and Hampe, 2006). Most trees are predominantly outcrossing, maintaining high levels of genetic diversity through a range of breeding systems that allows them to cope with the various conditions they experience over their lives. Their long-lived nature results in the accumulation of mutations, both somatic and in the germline, such that trees generally carry a heavy genetic load of deleterious recessive alleles (Williams and Savolainen, 1996). Consequently, any inbreeding, and in particular selfing, may lead to reduced fertility and poorer regeneration, slower growth rates, and increased susceptibility to abiotic and biotic stresses, including pests and diseases (Griffin, 1991). For trees, there is a clear need to limit the possibility and impact of inbreeding by maintaining genetic diversity. Indeed, it may be critical in seed collections for successful on-farm planting, habitat restoration, breeding or *ex situ* conservation (e.g. Thomas et al., 2014). Despite this, there is generally a lack of recognition of the importance of genetic diversity in trees and the implications for use and conservation.

For trees, knowledge of the factors influencing the spatial scale of genetic diversity and adaptation is increasingly important for conservation (e.g. determining sampling strategies for *ex situ* collections, setting priorities for genetic reserves, understanding how to source planting material for ecological restoration), production (e.g. obtaining appropriate, productive planting material for a variety of products and services) and for ensuring future adaptability to changing environmental conditions (Alfaro et al., 2014). The development of molecular markers can facilitate answers to such questions through more direct measurements of levels and patterns of genetic variation, as well as of the spatial and temporal dynamics of mating and gene flow. For trees, such research initially focussed on species of commercial interest for timber, and consequently, most early information came from coniferous taxa of northern temperate forests (e.g. Muona, 1989; Hamrick et al., 1992). In recent decades, the balance has been partially redressed by more research on tropical trees, investigating a range of taxa representative of the diversity of ecological contexts, reproductive attributes and uses (e.g. Wickneswari et al., 2014). Genomic knowledge of forest

trees lags behind that of model herbaceous species that include many of the main agricultural crops. However, for several tree species, the entire genome has been or is in the process of being sequenced (Argout et al., 2011), with novel approaches developed to link markers to important traits. Genomic or marker-assisted selection is close to being realized in some tree species, including temperate fruit trees (Muranty et al., 2015). Phenotyping and data management, however, remain considerable bottlenecks.

There is a growing understanding of the need for ‘systems-oriented’ approaches, as evidenced by recent studies that demonstrate the role of genetic variation in determining not only the performance of particular tree species but of entire ecosystems (Wymore et al., 2014). Such approaches can, directly or indirectly, provide insights into tree genetic structures, and actual and required effective population sizes across farm landscapes. However, for trees in agroecosystem dominated landscapes, specific challenges to increasing our understanding remain (**Box 3.2** *Challenges in characterizing tree genetic variation in agroecosystems*).

When establishing a species, the first generation of trees plays a key role in either subsequent natural regeneration or collection of seed for further planting. Low genetic diversity in the founder population may result in inbreeding and reduced fitness in future generations (McKay et al., 2005). Sampling of genetic diversity may also be smaller than is apparent purely from a census count, as overlapping generations reduce effective population size. In fragmented landscapes, reproductive dominance by a few large canopy trees (e.g. in pasture) can also reduce effective

Box 3.2 Challenges in characterizing tree genetic variation in agroecosystems

- The large number of species involved: a large number of tree species is found on farms in a diverse array of agroforestry systems, as well as in remnant forest patches within agricultural landscapes. Farmers are interested in practical work with a wide range of species. Analysis of genetic variation in all taxa is impractical, but can studies on a subset of tree species within a particular context provide useful information for other taxa and wider ecosystems? Is the concept of ‘model’ species – targets for research from which general recommendations for interventions can be devised – relevant or not (Atta-Krah et al., 2004; Dawson et al., 2009)?
- Difficulties in recognizing and quantifying variation: in comparison to most crops, most forest tree species have had, until recently, little or no history of domestication. As a result, genetic variation may be difficult for farmers to evaluate in agricultural landscapes, as they are not able to recognize important ‘varietal’ differences in trees in the same way as they can for traditional agricultural crops. Important variation may sometimes be invisible to the naked eye (Atta-Krah et al., 2004) and ‘surrogate’ measures of genetic variation have not been widely explored (e.g. Jennings et al., 2001; Graudal et al., 2014). This situation particularly applies when the tree propagule is not the desired product from the tree (e.g. the eventual form and growth rate of a timber tree cannot be judged from the appearance of the seed).
- Lack of recognition of problems until too late: as trees can persist in landscapes even when they are no longer reproductively active (Janzen, 1986), problems in some species related to inbreeding, lack of seed set and regeneration may not be immediately evident. By the time problems become clear, the landscape may have been modified to such a degree that it is too late to devise practical interventions.

population size, while loss of self-incompatibility alleles may also limit regeneration in small populations. A number of studies have shown that a lack of attention to these issues can lead to genetic bottlenecks in community nurseries, in natural regeneration on farms and in restoration programmes (e.g. Kettle et al., 2014).

Unlike with annual crops, the most popular planting material for trees are nursery seedlings, partly because this enhances the success rate of planting (Godefroid et al., 2011). Consequently, the possibility of using optimal species combinations and planting materials that are both adapted to site conditions and genetically diverse is often limited by what is available in nurseries. Seed collectors and nurseries that use the seed are driven by economic and practical considerations. They may avoid some species because of a lack of appropriate protocols (e.g. to break seed dormancy, store recalcitrant seed) and often minimize the number of tree species they work with because of limited accessibility and availability of seed sources, a desire to simplify nursery management and to reduce the risk of having unsold seedlings at the end of the season. Avoidance of the vagaries of both seed and seedling availability requires tree planters to be in early communication with tree nursery managers, to allow time for seed collection and seedling production of desired species with adequate genetic diversity.

Trees differ from crops in terms of domestication status

Although some 2,400 tree species are actively managed for their products and services, only about 700 are recorded as subject to improvement programmes, with mostly tree commodity crops (e.g. cocoa and coffee) and some timber species subject to more intensive domestication, while genetic parameters are described for only about 1% of all tree species (FAO, 2014a). The value placed on trees for food is, however, reflected in the ancient indigenous domestication of a number of tree species in regions such as Mesoamerica (Galindo-Tovar et al., 2008) and the Amazon (Clement et al., 2015). Indigenous domestication of tree species typically shows a progression from collection in the wild through management to active cultivation. In intermediate phases, tree crops tend to be managed *in situ*, whereas agricultural crops are brought onto farms. Running parallel to increases in management are increases in the movement of germplasm (very local, through regional to wide translocation), associated with progressions in commodity use and marketing (home consumption, through local marketing to regional and global marketing).

The boundaries between forest and farm settings are often in flux and can only be loosely defined. Forests that appear pristine may have been manipulated for millennia to produce ‘anthropogenic forests’. In the Amazon, residual effects of pre-Columbian human management are evident as high density aggregations of useful trees such as Brazil nut (*Bertholletia excelsa*) located close to anthropogenic soils known as ‘dark earths’ (Clement and Junqueira, 2010). Human movement means that tree species distributions may have expanded so that divisions between natural and exotic (through planting) distributions are now unclear. As a consequence, related, but previously allopatric (isolated), species may be brought into sympatry, with the possibility of interspecific hybridization. Anderson (1954) was among the first to point to the importance of disturbed sites, such as kitchen middens and backyard gardens, as suitable habitats where otherwise isolated plant species were brought into sympatry through cultivation.

The well-documented example of the tree genus *Leucaena* shows how prevalent and influential the casual or intentional sympatry of species in cultivation can be. The genus occurs in Mexico and Central America, with some 22 species and two named hybrids, of which the seed and pods of 13 species are used for food, with eight of these species cultivated (Hughes, 1998). Given the widespread use of the seeds and pods for food, unsurprisingly most vernacular (e.g. Mixtec) names relate to species differences in pod characteristics including size, shape, colour and season

of production. Fine intraspecific divisions indicative of intensive use and management are also recognized within widely cultivated and intensively used species, such as *L. esculenta*. Pre-domestication cultivation of *Leucaena* species resulted in extensive artificial sympatry and a complex series of geographically dispersed spontaneous hybrids and at least one, possibly more, polyploids (Hughes et al., 2007).

Such ancient processes are mirrored recently by a participatory approach to the domestication of wild indigenous fruit and nut trees into local cultivation in Central Africa. Communities' traditional knowledge of tree use and management is combined with scientific advances in germplasm collection, selection, propagation and market development (Leakey, 2010; see also Chapter 14 of this Handbook), with some success in promoting farm diversification and wider impacts on incomes and health (Jamnadass et al., 2011). The approach brings selected indigenous trees from local wild stands into farms, appearing to provide a good balance between farm-level productivity gains and landscape-level conservation of genetic resources (Leakey, 2010).

Some have argued that promoting tree domestication has negative impacts on the diversity of agricultural landscapes at both interspecific and intraspecific levels. At an intraspecific level, domestication by definition causes shifts and/or losses in underlying genetic diversity in the manipulated populations (Dawson et al., 2009). However, the extent and nature of changes depends on the domestication method, with some approaches more favourable for maintaining diversity. Model analysis of a participatory domestication project with *Bactris gasipaes* in Peru, for example, showed that the risk of genetic erosion in a regional context was low (Cornelius et al., 2006). The wide use of clonal propagation methods during participatory domestication could, however, cause longer-term challenges for intraspecific diversity, due to preferential or exclusive use of small numbers of clones, especially if substantial inter-village germplasm exchange occurs. Diversity losses may, however, be much greater if domestication for increased tree productivity were not to occur, as then farmers may not plant trees at all, but rather cultivate other plants that are (otherwise) more productive (Sunderland, 2011).

The context of trees/forests on farms and in agricultural landscapes

Throughout the world, a large number of tree species are maintained and planted on farms in a range of contexts, including home gardens, fence lines, alleys, pastures and mixed with perennial or annual crops (**Table 3.1** *Examples of tree species richness in tropical agroforestry landscapes*). These different agroforestry systems reflect the various benefits sought from trees by farmers, and the suitability of different species and systems for providing them. Farming landscapes also often integrate secondary forests and forest fragments. The scale of interactions between trees and other components in agricultural landscapes is a crucial factor in determining activities and configurations for providing different products and services (Garrity, 2004). When grown on farms, tree products are often described as agroforestry tree products (AFTPs) to differentiate them from NWFPs and wood products harvested from forests (Simons and Leakey, 2004). Gradations between natural forests, anthropogenic forests and agroforests, however, mean that there is often no clear boundary between product sources, a complicating factor in estimating relative contributions of different ecosystems to livelihoods, and in devising appropriate management options for different settings (de Foresta et al., 2013). In some cases, trees are retained/planted by farmers for the products they provide on an ongoing (e.g. fruit, medicine) or one-off (e.g. large-bore timber) basis and/or for services such as soil fertility (e.g. alley cropping) and shade (e.g. shade coffee and cocoa). Trees may also be retained because they are too difficult to remove, or although they are not used by farmers they are not overly competitive, so there is no particular reason to remove them ('benign neglect'; Schroth et al., 2011).

Table 3.1 Examples of tree species richness in tropical agroforestry landscapes (ordered by descending number of tree species identified in each study)

<i>Farming system and location</i>	<i>Description of results</i>	<i>Reference</i>
265 farm plots (each 0.5 ha) in 18 different agroecological zones, Mount Kenya, Kenya	424 woody plant species, 306 indigenous. Mean of 17 species per plot. Eight of ten most frequent species were exotic.	Kehlenbeck et al., 2011
35 smallholders' farms (60 ha total) east of Mount Kenya, Kenya	297 tree species, ~ 2/3 of which indigenous. Mean of 54 species per farm. Five most common species were exotic.	Lengkeek et al., 2005
5 cacao cabruca plantation plots (each 3 ha) in southern Bahia, Brazil ^a	293 tree species, 97% indigenous. Mean of 101 species per plot. Exotic species relatively more abundant (> individuals per species) than indigenous ones.	Sambuichi and Haridasan, 2007
126 samples in range of agroecosystems, over 4 communities in southern Honduras	241 tree and shrub species. Mean of 34.5 species per sample and 154 species per community.	Gordon et al., 2003
146 plots (each 0.063 ha) in 60 cacao agroforests from 12 villages in sub-regions of Yaoundé, Mbalmayo and Ebolowa, Cameroon	206 mostly indigenous tree species. Mean of 21 species per agroforest. High relative abundance of non-primary forest species.	Sonwa et al., 2007
24 dairy farm pastures' (237 ha total) near Monteverde, Costa Rica	190 tree species, 57% primary forest trees. Primary forest trees accounted for (only) 33% of all individuals.	Harvey and Haber, 2008
51 plots (each 0.1 ha) in three shade coffee cooperatives in Tacuba, El Salvador	123 tree species identified (46 not determined). Mean of 12 to 22 species per plot, depending on cooperative. 11 species of conservation concern based on international listings. Of 58 species considered of benefit by farmers, seven of conservation concern.	Méndez et al., 2007
Six forest gardens (2.68 ha in total) in two areas of West Kalimantan, Indonesia	> 120 identified tree species (precise number not given). Mean of 52 species per garden. Most species in gardens not planted; of these 'easily dispersed' and/or 'easily established' species were over-represented in gardens compared with forest.	Marjokorpi and Ruokolainen, 2003
124 plots (each 0.12 ha) in 15 shade coffee farms of three types (shade monoculture, SM; simple polyculture, SP; diverse polyculture, DP) in central Veracruz, Mexico	107 tree species, 83 indigenous (50 primary and 33 secondary species). Mean of 11 (SM) to 29 species (DP) per farm. Three species of international conservation concern. DP farms richer in tree species than nearby forest.	López-Gómez et al., 2008
80 plots (each 0.06 ha) in 20 cacao cabruca farms in northern Espírito Santo, Brazil ^a	105 tree species, 101 indigenous, the majority pioneer and early secondary species. Mean of 15 tree species per farm.	Rolim and Chiarello, 2004
Interviews with 68 cattle ranchers and small-scale farmers in Los Santos and Rio Hato, Panama (NB, not direct farm inventory)	99 tree species identified by farmers as used, planted or protected on their land, 3/4 of which indigenous.	Garen et al., 2011

<i>Farming system and location</i>	<i>Description of results</i>	<i>Reference</i>
60 actively managed coffee-based agroforestry plots (of variable area) in three villages in Guinée Forestière, Guinea, West Africa	94 species of mature trees, compared with 134 in natural forest. Mean of 59 tree species per village. A few species dominant in agroforests. Nine species in agroforests classified as vulnerable according to IUCN listings.	Correia et al., 2010
240 plots (each 0.2 ha) in coffee farms in Lampung province, Sumatra, Indonesia, outside and inside (120 plots each) Bukit Barisan Selatan National Park (BBS)	92 identified trees species in coffee plots outside BBS, 90 in plots inside of BBS, compared with 141 in natural forest plots (with same sample area). The most abundant species in coffee plots outside and inside BBS were exotic.	Philpott et al., 2008
0.56 ha of primary forest, 21 ha cocoa agroforests, in Ondo state, Nigeria	62 tree species in primary forest, 14 species IUCN classification. 45 tree species in agroforests, six species IUCN classification.	Oke and Odebiyi, 2007

a *Cabruca* – agroforestry system with cacao planted in cleared understorey within native forest

Source: Adapted and updated from Dawson et al. (2013).

For farmers, functional diversity is more important than high tree species diversity, such that a significant proportion of tree species diversity currently found in agricultural landscapes could probably be lost without having much effect on farm production, at least in the short- to medium-term (Kindt et al., 2006). For example, although large numbers of tree species are found in cocoa agroforests, tree species composition is distinct from, and lower in number than, that of natural forests (**Table 3.1**). Furthermore, although endangered tree species may be retained in agroforests, in many locations, there is a general transition to lower tree species diversity dominated by exotics (e.g. oil palm, mango [*Mangifera indica*], avocado [*Persea americana*], *Acacia* and *Eucalyptus* species) and local pioneers. Thus, although cocoa agroforests are diverse, they do not equate with primary forests. The sometimes negative attitudes of farmers towards the retention of timber and other trees in such systems may be related to factors such as tree tenure laws, the long period for trees to mature and the need for other income sources to augment farm income in the meantime and damage to perennial/annual crops that may accompany extraction.

Natural regeneration of tree cover may be more appropriate than planting

In Niger, the adoption of farmer-managed natural regeneration (FMNR) of indigenous leguminous trees, such as *Faidherbia albida*, rather than their direct planting, has led to the ‘regreening’ of approximately 5 million hectares since 1985 (Sendzimir et al., 2011). Such practices have increased sorghum and millet yields more widely in the Sahel region of Africa, resulting in greater dietary diversity and improvements in household incomes in some locations (Place and Binam, 2013). The success of FMNR illustrates that at sites with low to intermediate levels of degradation, where soils are largely intact and there are adequate germplasm sources (e.g. mature trees or soil seed bank), natural regeneration may be the best choice for re-establishing tree cover (Chazdon, 2008). Natural regeneration can bypass some of the maladaptation risks associated with introducing germplasm and help maintain genetic integrity. However, in sites where diverse

native seed sources are lacking or insufficient, seed sources suffer from genetic erosion and/or active planting is envisaged, the introduction of external planting material may either be advantageous or simply the only short-term solution. The main choice of what material to use lies in species selection, with native species generally preferred by farmers and for wider ecosystem restoration (Thomas et al., 2014). In ecosystem restoration, evidence is growing for the importance of choosing tree species that represent different functional groups based on adaptive traits (e.g. Aerts and Honnay, 2011). However, the use of native species and their selection requires more knowledge of traits associated with their reproductive biology, phenology, propagation and management. This knowledge gap for native species means that more readily available, better researched, but less well suited, exotic species are often chosen for restoration projects (Boshier et al., 2009; Newton, 2011).

An example is seen with *Leucaena salvadorensis*, where severe forest degradation in most of the species' natural distribution (seasonally dry Pacific slopes of El Salvador, Honduras, and Nicaragua between 200 and 800 masl) has left only a few small forest remnants on steep inaccessible slopes. The species is prized by local communities within its native range as a source of round timber, poles and firewood, being deliberately retained and protected by farmers around houses, in fields and within fence lines. The species is therefore more common in the landscape than the depleted state of natural forest cover would suggest. There is, however, little tradition of planting *L. salvadorensis*, which is an outcrossed diploid and produces few seed. Instead, the non-native, self-fertile and tetraploid *L. leucocephala*, which is more easily propagated, is promoted for cultivation, threatening the maintenance and local use of *L. salvadorensis*. Though the two species are similar in appearance as seedlings, *L. leucocephala* produces inferior quality wood and grows less well on degraded soils.

Concerns of hybridization in farm landscapes

Hybridization of introduced species with native species is particularly prevalent in certain genera (e.g. *Leucaena*, Hughes et al., 2007; *Prosopis*, Carney et al., 2000), with obvious implications for the conservation of native gene pools. Concerns have also been raised regarding the impacts of intraspecific hybridization. Where a germplasm source is not local, planted trees are likely to have a different genetic composition, such that crossing with natural stands may lead to the dilution and loss of unique genetic diversity. Wild *Coffea arabica* stands in the few remaining fragments of Ethiopian montane forest are threatened by hybridization with introduced coffee cultivars planted on neighbouring farms (Labouisse et al., 2008; Aerts et al., 2013). Planted *Inga edulis* trees in smallholders' fields in the Peruvian Amazon were found to be different in genetic composition from neighbouring wild populations, raising concerns for natural stands if there are interactions between forest and farmland trees (Dawson et al., 2008). The 'exotic planted' *Inga* had larger fruit than local wild trees, explaining why farmers had introduced them. In such circumstances, it is necessary to understand the trade-offs between connectivity, genetic dilution and the level of return farmers receive from planting.

Although the orthodox view is that wild-cultivated interactions may be detrimental to wild stands where cultivated material is genetically very different, some scientists have argued for the mixing of populations as beneficial under scenarios of rapid anthropogenic climate change, where new combinations of alleles will facilitate rapid adaptation (Weeks et al., 2011). Research is required on the extent of outbreeding depression (breakdown of co-adapted gene complexes) in tree species that may occur from such interactions, as it remains a relatively understudied issue and there is limited evidence for it, except in the case of interspecific hybridization (Ellstrand, 2003; Edmands, 2007).

Low tree densities on farmland may limit conservation benefits

Although trees and forest on farms may be important for conservation, the small size of most subsistence farms means that considering the wider scale is important in achieving potential conservation benefits. Tree species of importance from a conservation perspective are often present only at low densities in farm landscapes (Gordon et al., 2003; Dawson et al., 2013), so to bring real biodiversity benefits conservation strategies require implementation of beneficial management over a large area, and hence by large numbers of smallholders. In cocoa agroforests, for example, an emphasis on cocoa production often means that the number of cocoa plants per hectare is maximized. Consequently, cocoa agroforests although potentially rich in tree species (**Table 3.1**) typically retain lower numbers and reduced population densities of individual tree species compared with natural forest. With densities for most native tropical species of 0.05 to 0.5 trees per ha (e.g. Lengkeek et al., 2005), large areas of agroforests are required to maintain significant populations of individual species; for example, at least 10,000 ha for the lowest density species (0.05 trees/ha) to have a census population of 500 trees, while a much larger area is required for an effective population size of 500 trees. Lower tree densities may affect the reproductive capacity of individual species and levels of genetic diversity, while small forest remnants may reach a critical threshold to support forest biodiversity, due to the increased influence of surrounding land uses. Thus, the number of farmers adopting and continuing to maintain a particular production system is crucial to realizing prospective conservation benefits, and this aspect requires monitoring, given the speed with which farming practices may change.

The importance of production system and species characteristics in defining conservation prospects

As is clear from the examples given in the two previous sections, the prospects for conserving tree species diversity and maintaining other associated benefits in farmland depend on the particular production system, the intensity of management, and hence the stage and complexity of agro-ecological succession attained. While, for example, shade grown coffee and cacao are generally supportive of biodiversity, the trend to monoculture seen in ‘full sun’ cacao and coffee, and oil palm plantations, reduces conservation value and encourages dependence by growers on single crops (e.g. Schroth et al., 2011; Ruf, 2011). However, multi-strata agroforests, such as shade cocoa and coffee, may not represent stable management systems and may change gradually or quickly towards assemblages of lower conservation value, depending on commodity price fluctuations and incentives. Similarly, although traditional rubber agroforests are compatible with habitat and biodiversity conservation, they are often under pressure for conversion to more intensive and less diverse production systems (Ekadinata and Vincent, 2011). Efforts to increase the output of such systems that depend on the rehabilitation of neglected production stands, rather than increasing the area under cultivation via deforestation, need to be promoted.

In most cases, assessments of the genetic conservation benefits of agroforestry systems also require consideration of the biology of the tree species involved. Available information suggests that the following tree species types are less likely to show genetic conservation benefits from agroforestry systems: outcrossing species that are self-compatible, slow-growing species that reproduce only when they are large (the extreme case being monocarpic species, that is, those that flower only once in their life), species with poor regeneration under human disturbance, species with highly specific pollinators or seed dispersers susceptible to disturbance, rare species with low population densities, and species with highly clumped distributions. Inevitably, such generalizations will be qualified by the range of factors that have been shown to influence genetic variation in trees.

Tree genetic diversity and connectivity in agroecosystem landscapes

Molecular diversity studies of farmland and adjacent forest tree populations suggest that diversity in agricultural landscapes depends on the length and intensity of tree management, the degree of planting undertaken and the method of propagation. When species have been managed for millennia, bottlenecks can be observed in farmland (e.g. for the important fruit trees *Inga edulis* in the Peruvian Amazon, see Dawson et al., 2008 and *Spondias purpurea* in Mesoamerica, see Miller and Schaal, 2006). However, where management intensity is low, there may be little difference between farm and neighbouring natural populations (e.g. for the important fruit tree *Vitellaria paradoxa* in the Sahelian and Sudanian eco-zones of West Africa; Kelly et al., 2004). Overall, the limited molecular data from comparative studies suggest that although indigenous trees in farmland occasionally experience genetic bottlenecks, these are relatively minor, despite concerns connected with germplasm collection. Founder effects and impacts on production may be of more concern for exotic trees than indigenous ones (e.g. for the timber tree *Acacia mangium* introduced from Australia and Papua New Guinea into Southeast Asia; Harwood et al., 2004).

Studies of pollen-mediated gene flow between trees in forest and farmland demonstrate that pollen exchange is generally more frequent between nearby trees but transfers can occur over km in agroecosystem landscapes, even between physically isolated trees (e.g. Ward et al., 2005; Lander et al., 2011). Thus, for many tree species, populations and individuals, gene flow can be high across some fragmented landscapes with little apparent forest cover. The view of forest fragmentation as producing genetic isolation may be more of a human perception than a true reflection of actual gene flow, with the type of non-habitat (i.e. agroecosystem) between forest patches affecting patterns of insect and other animal dispersal, and hence seed and pollen dispersal (Lander et al., 2011). Thus, the focus of conservation management can move from questions such as ‘How much land can be set aside?’, ‘How can distance be minimized between habitat patches?’ and ‘How can habitat bridges be created?’ to measures of separation between habitat patches that incorporate variability in how easily a target organism passes through the different land-use types in the landscape (i.e. issues of permeability). Thus, farmland outside forest ceases to be just an area to pass through and is seen in terms of its own capacity to provide habitat services, as well as its ability to support or inhibit movement. The entire landscape is considered a patchwork of partial habitats of varying quality, recognizing the potential habitat services that different land uses may support, and providing a useful basis for developing landscape management strategies that integrate farm production and conservation (Lander et al., 2011).

Conclusions

The current rate of global deforestation presents significant threats to the conservation of tree species and populations *in situ* (FAO, 2014a). With *ex situ* methods for tree conservation constrained primarily by limited representation and problems of regeneration, it seems inevitable that there will be a greater reliance on the conservation of trees *circa situm* in farm landscapes. How, then, can farmland tree species diversity be maintained or enhanced over time or at least the rate of loss reduced? How can the genetic base of farmland tree populations be ensured while supporting productivity increases that encourage farmers to plant them? How can farmland trees respond to climate change?

Although there is in some cases a growing awareness of the genetic aspect to conservation, relatively little information on conservation genetics is reaching forest scientists, managers and

policy makers so that it can be translated into practice (Graudal et al., 2014). As already noted, in many cases, wider ecological, social or economic considerations may actually be the defining processes of any particular conservation strategy. The challenge for conservationists, geneticists and foresters alike, is therefore to use this information to establish the circumstances under which genetic considerations, though often unseen, may become limiting to the overall conservation goals/objectives of a particular programme. The institutional frameworks within which researchers work rarely support team-based, multidisciplinary approaches that are needed to properly assess genetic variation and then apply this knowledge through appropriately-devised management interventions. For agroforestry, the situation is acute, as 'forestry' and 'agriculture' are traditionally considered as discrete schools of research that should be treated separately, whereas aspects from both must be combined together if effective action is to be realized (Dawson et al., 2009).

The complementary benefits of different land use practices for genetic conservation must be further evaluated, recognized and promoted. There is a need to raise awareness among development professionals of the value of natural regeneration in contributing to both conservation and livelihoods. The emphasis on a limited range of tree species, often exotics, by development agencies may reduce the potential conservation (inter- and intraspecific) benefits of agroforestry systems, besides creating potential problems of invasiveness. However, there is also a need for conservation planners, more accustomed to *in situ* methods, to consider the possibility that tree populations found outside protected areas, including in farmland, have a role in biodiversity conservation (Boshier et al., 2004). This in turn requires direct involvement of development organizations in conservation, and effective interactions between them and traditional conservation organizations, to ensure both conservation and development benefits, and minimize any negative trade-offs.

A Global Plan of Action for the Conservation, Sustainable Use and Development of Forest Genetic Resources (FAO, 2014b), devised from the findings of the SOW-FGR (FAO, 2014a), identified four main action areas: (1) greater availability of information on FGR to facilitate and enable better decision making on sustainable use and management, (2) strengthening and harmonization of conservation methods to support FGR and evolutionary processes both inside and outside forests, (3) enhancing approaches to sustainably use and develop FGR to support livelihoods, and (4) developing more appropriate policies, institutions and capacity-building approaches to support successful planning in the forestry sector. Specifically there is a need to improve the availability of, and access to, information on FGR, enhance *in situ* and *ex situ* conservation and improve sustainable use and management (FAO, 2014b) of FGR. While not using the term *circa situm*, the Plan stresses the importance of tree genetic resources on-farm through strategic priority 8, 'Support and develop sustainable management and conservation of FGR on farmland' (FAO, 2014b). It is, therefore, essential to consider agricultural settings with reference to points 1 to 4.

Many of the tree species identified as priorities by the SOW-FGR, especially for local use, have received little or no research attention to their biological attributes and management options, indicating a need to associate funding with priority-setting exercises. Measures to improve small-holders' access to tree planting material and thereby enhance diversity include 'diversity fairs', training of seed collectors in appropriate germplasm sampling methods, provision of more business support to small-scale commercial tree seed and seedling enterprises to deliver germplasm sustainably and the establishment of more seed multiplication stands of key species in farmers' fields and in public lands (Dawson et al., 2009). However, some indigenous tree species of conservation concern are difficult to cultivate (López-Gómez et al., 2008) and/or are of little priority to farmers (Barrance et al., 2009). In addition, information sharing of the service and subsistence

values of trees species should not be neglected, as these can be considerable and equally or more important than commercial value, depending on circumstances (Faye et al., 2011). With ratification in 2014 of the Nagoya Protocol³ on access to genetic resources and benefit sharing, the transaction costs for sourcing tree germplasm (also materials such as leaves and bark) for research may increase, especially for trees whose natural distributions cover a large number of countries (Koskela et al., 2014). The danger is of a slowing of research when its importance in responding to climate change and other global challenges is increasing (Alfaro et al., 2014), and when new tools (e.g. genomics) could support major breakthroughs in characterization, production and adaptation (Neale and Kremer, 2011).

Forests are important sources of germplasm for ongoing and future domestication of AFTPs as well as tree commodity crops, requiring management for the characterization and maintenance of these resources (Jamnadass et al., 2011). A wider focus on indigenous trees, rather than commonly used exotics, to fulfil different production and service functions may bring conservation benefits and be more sustainable in the long term. Particular opportunities for new tree domestications were identified for Africa, where genetic diversity in a range of fruit tree species that are essentially wild has been found to be large, providing the possibility for large genetic gains under cultivation (e.g. *Allanblackia* spp., Jamnadass et al., 2010; *Sclerocarya birrea*, Thiongo and Jaenicke, 2000). Leakey et al. (2012) identified major challenges for successful tree domestication related to scaling up and out, with impact studies required to understand which domestication methods have been most effective in benefitting smallholders' incomes, food and nutritional security, and what effect different approaches have on the long-term genetic diversity of species and sustainability of production. Improved management of tree genetic resources for livelihoods requires a greater understanding of genetic processes in NTFP production and more attention to the genetic quality of tree planting material supplied to smallholders (Dawson et al., 2014).

An opportunity for understanding genetic related impacts on NTFPs may come from the growing literature on the effects of logging on timber trees, although different harvesting methods, products and growth rates mean that the ability to make generalizations may be limited. More work is also required to exploit genetic variation in wild and landrace stands of tree commodity crops to develop cultivars that perform better in more resilient and sustainable mixed-species smallholder production systems. This requires more attention to the proper valuation of tree genetic variation for breeding and production, to provide a stronger case for conservation (Geburek and Konrad, 2008).

Tree genetic resource-based responses to uncertainty in conditions related to climate change include germplasm translocation, the promotion of large effective population sizes to encourage adaptation and the use of a range of more plastic species and provenances (**Table 3.2** *Summary of smallholder constraints to tree planting*). To inform germplasm distribution strategies, new trials on indigenous trees of value to smallholders are being designed to specifically consider climate change-related traits for populations collected from different ecological zones (Alfaro et al., 2014). For such interventions to be successful, they must provide clear livelihood benefits with a focus on developing new market opportunities for local smallholders (**Table 3.2**). Current payment mechanisms for the carbon sequestration function of agroforestry trees in mitigating global environmental change are generally inefficient and further work is required if farmers are to benefit significantly (Jack et al., 2008). Even so, such payments are likely to be modest and unsustainable compared with the other products and services that trees provide (Roshetko et al., 2007). A better approach is to identify and encourage cultivation of tree species that provide both sequestration benefits and high value products.

Table 3.2 Summary of smallholder constraints to tree planting, suggested interventions under existing challenges, and specific germplasm-based opportunities to address climate change

<i>Constraint</i>	<i>Nature of constraint</i>	<i>Interventions under existing challenges</i>	<i>Specific germplasm-based opportunities under climate change</i>
Lack of access to high-quality germplasm	The tree germplasm currently easily available to smallholders is frequently of suboptimal performance and function; obtaining more optimal material carries high transaction costs	<ul style="list-style-type: none"> • Improve access to germplasm through participatory domestication, by developing local seed and seedling dealer enterprises, through enhancing local farmer-exchange networks, by establishing seed production stands • Training in managing natural regeneration in farmland • New introductions to farmers of more productive germplasm from elsewhere 	<ul style="list-style-type: none"> • Link local suppliers of tree planting material with national supply programs that can facilitate germplasm translocations at larger geographic scales, nationally and internationally, to keep pace with environmental shifts. Ensure co-migrations of organisms such as pollinators and microsymbionts that are essential for tree function and production • Introduce new farm management methods to enhance pollination services and maintain effective population sizes of tree species, and bring into cultivation new tree varieties that are less dependent on associations with particular animal vectors • Ensure new introductions of species and provenances are flexible (plastic) in responding to extreme climate change-related weather events, but do not concentrate on a small range of 'exotic' species only
Absence of well-functioning markets	Market value chains are frequently biased against smallholder involvement, or are simply not present, with few opportunities for adding value through processing, and so forth	<ul style="list-style-type: none"> • Improve access to markets through identifying new product opportunities, by sensitizing consumers, through increasing value chain transparency, and by providing business training and credit facilities for growers and local businesses • Train in simple methods for adding value during processing and introduce any necessary processing equipment 	<ul style="list-style-type: none"> • Ensure market opportunities for climate mitigation (e.g. sequestration, biofuel production) can be met through new introductions of tree species and provenances that are productive for novel functions • Ensure germplasm delivery systems are able to supply appropriate planting material of tree species that provide products able to take advantage of newly-developing markets to combat climate change health challenges (e.g. that provide medicines for disease treatment and foods to prevent malnutrition associated with climate change-related disease incidences and nutrient deficiencies) • Ensure market opportunities for other local and global challenges are fully explored, so climate change-related markets don't result in narrowing of production options, over-intensification and/or tendency to monoculture that weaken resilience to environmental change

Source: Adapted and updated from Dawson et al. (2009).

Notes

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- 1 IUCN Red List. www.iucnredlist.org (last accessed 23 May 2016)
- 2 TSSD The Tree Seed Suppliers Directory www.worldagroforestry.org/our_products/databases/tssd (last accessed 23 May 2016)
- 3 The Nagoya Protocol on Access and Benefit-sharing was adopted on 29 October 2010 in Nagoya, Japan, and entered into force on 12 October 2014; a full account is given in Engels and Rudebjer, Chapter 43 of this Handbook; www.cbd.int/abs/about/ (last accessed 23 May 2016),

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