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The management of tree genetic resources and the livelihoods of rural communities in the tropics: Non-timber forest products, smallholder agroforestry practices and tree commodity crops

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ABSTRACT

Products and services provided by trees in forests and farmland support the needs and promote the well-being of hundreds of millions of people in the tropics. Value depends on managing both the diversity of tree species present in landscapes and the genetic variation within these species. The benefits from trees and their genetic resources are, however, often not well quantified because trade is frequently outside formal markets, there is a multiplicity of species and ways in which trees are used and managed, and genetic diversity within species is frequently not given proper consideration. We review here what is known about the value of trees to rural communities through considering three production categories: non-timber products harvested from trees in natural and managed forests and woodlands; the various products and services obtained from a wide range of trees planted and/or retained in smallholders' agroforestry systems; and the commercial products harvested from cultivated tree commodity crops. Where possible, we focus on the role of intra-specific genetic variation in providing support to livelihoods, and for each of the three production categories we also consider wider conservation and sustainability issues, including the linkages between categories in terms of management. Challenges to 'conventional wisdom' on tree resource use, value and management – such as in the posited links between commercialisation, cultivation and conservation – are highlighted, and constraints and opportunities to maintain and enhance value are described.

1. Introduction

The elemental role played by trees in the lives of rural people in the tropics appears obvious through the many uses made of tree products, in construction, fencing, furniture, foods, medicines, fibres, fuels and in livestock feed, and in their cultural value. Indeed, in a World Bank report published a few years ago, forests and trees-outside-forests were reported to contribute to the livelihoods of more than 1.6 billion people worldwide (World Bank, 2008). Just how trees contribute – and the varying level of dependency of different communities on tree products and services and how this changes over time – is, however, often not well described or adequately acknowledged in the compilation of such figures (Byron and Arnold, 1997). Partly, this reflects the ubiquity of tree products and services and the complex inter-connecting pathways by which trees influence livelihoods, which are often hard to delineate (e.g., Turner et al., 2012). It also reflects the different sources – from inside and outside forests – of tree products and services. Since forest and farmland sources are assessed differently by gov-

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ernment forestry and agriculture departments, a proper synthesis of the overall value of tree products and services across these sources is hard to achieve (de Foresta et al., 2013). Complexities in quantification and a lack of proper appreciation of benefits help explain why the roles (and limitations) of trees in supporting local peoples' livelihoods have frequently been neglected by policy makers, and why rural development interventions concerned with managing trees in forests and farms have sometimes been poorly targeted (Belcher and Schreckenberg, 2007; World Bank, 2008).

From a genetic perspective, the value of intra-specific variation in tree species and the importance of managing this variation to support rural livelihoods have also received relatively little attention from policy makers (Dawson et al., 2009), despite the benefits that rural communities can gain when proper consideration is given (Fisher and Gordon, 2007). Tree genetic resources exist at different levels of domestication of both populations and species, while the landscapes within which they are located are themselves domesticated to a greater or lesser extent (Michon, 2005). A few forest landscapes can be considered completely natural, but generally some degree of human management has taken place (Clement, 1999; Clement and Junqueira, 2010). Indeed, some trees that provide foods valued by humans have been subject to domestication in forest environments for millennia in processes of 'co-domestication' (*sensu* Wiersum, 1997) of the forest and the tree. The level of domestication of the tree itself – from incipiently- to fully-domesticated (i.e., from being only unconsciously managed and selected to being dependent on humans for its continued existence; Harlan, 1975) – and of the landscape in which it is found are both crucial in understanding how rural communities currently benefit from trees, and how to optimise future value through improved management.

This review, which is derived from an analysis supporting the publication of FAO's recent global synthesis on the State of the World's Forest Genetic Resources (the SOW-FGR, as described by Loo et al., 2014, this special issue; FAO, 2014), provides information on what we know about the value of trees to rural communities in the context of both the level of tree domestication that has taken place and the management setting. Our review supports the SOW-FGR by providing an insight into livelihood issues that goes beyond the limited quantitative data available in the Country Reports used to compile the global synthesis (see Appendix A). We restrict our review to the tropics, where devising appropriate interventions to manage trees and tree genetic resources is important to meet international development goals of poverty alleviation and community resilience (FAO, 2010; Garrity, 2004).

We also restrict our consideration to three production categories: non-timber forest product (NTFP) harvesting (from natural, incipiently- and/or semi-domesticated forests and woodlands); agroforestry tree products (AFTPs) and services (provided by a wide range of mostly semi-domesticated local and exotic trees in smallholder-farm landscapes); and woody perennial commodity crops (which are often completely domesticated, exotic in major production centres, and grown in both smallholdings and larger plantations, though our concern here is only with the former). The boundaries between these production categories are not always easy to define, as evidenced, for example, by often subtle transitions in landscapes between forests and agroforests in a gradient of transformation and intensification (Balée, 2013; Michon, 2005; Wiersum, 1997). In fact, one category often depends upon another for supporting sustainability, as, for example, many AFTPs and tree commodity crops were once NTFPs, and often also still are (thus, the continued improvement of AFTP and tree commodity crop production may depend to a greater or lesser degree on accessing genetic resources maintained in natural stands; Hein and Gatzweiler, 2006; Mohan Jain and Priyadarshan, 2009; Simons and Leakey, 2004).

Our three production categories have received considerable attention for their roles in meeting development targets for small-scale harvesters and smallholder farmers in the tropics, both of which groups are the subject of our attention here (Belcher et al., 2005; Garrity, 2004; Millard, 2011). Our categories are, however, not fully exhaustive of the benefits received by tropical rural communities from trees, as we do not, for example, consider the value of commercial forest timber harvesting by local people (e.g., Menton et al., 2009). Nonetheless, the division into our three categories provides a useful way to structure the different benefits of trees to communities, to illustrate the issues faced in describing value and to determine appropriate interventions for improved management. Considering these different categories also demonstrates the importance of taking a wide view in determining where best to intervene for maximum impacts on livelihoods, for example, in minimising unintended consequences due to potentially negative interactions between different production systems (the same attention to interactions is important when promoting appropriate tree conservation interventions among a range of options, see Dawson et al., 2013).

In the following sections, each production category is taken in turn and information outlined in three sub-sections relating to: the benefits of production; the domestication and movement of germplasm; and the conservation issues associated with harvesting, management and/or cultivation to ensure sustainable use and benefits. Where possible, we focus on genetic resource management issues and highlight where 'conventional wisdom' on tree resource use, management and value needs to be challenged in order for pathways to more sustainable, resilient management systems to be developed.

2. Non-timber forest product harvesting

2.1. Benefits to rural communities

While there are many thousands of references in the literature to the importance of NTFPs, only a small proportion of publications proceed beyond general statements on use to quantify value in meaningful ways that support comparisons across products and sites. Despite this, some overall estimates of value have been attempted. Pimentel et al. (1997), for example, estimated very approximately that 90 billion USD worth of food and other NTFPs were harvested annually from forests and trees in developing countries. FAO's latest (2010) Global Forest Resources Assessment (GFRA) provides more recently estimated (based on 2005 figures) but lower worldwide values of 19 billion and 17 billion USD annually for non-wood forest product- and woodfuel-removals, respectively, but the country data compiled for the GFRA were acknowledged to be far from complete (one problem is that many countries, when they do report value for NTFPs, only do so for the 'top' few species of commercial importance; FAO, 2010). In the 2010 GFRA, in most tropical regions the most important use for non-wood forest products was indicated to be as food.

A good illustration of the discrepancy between current estimates of importance comes from comparing the value for woodfuel reported for Africa (most woodfuel is harvested from naturally-regenerating rather than planted sources in the continent) in the 2010 GFRA (1.4 billion USD annually) with the World Bank's (2011) much higher estimate of the value of the charcoal industry in the sub-Sahara region (eight billion USD annually). Several reasons have been highlighted as to why it is difficult to adequately represent NTFP value, including the multiplicity of products, informal trade and bartering that occurs in unmonitored local markets, direct household provisioning without products entering markets at all, and the fact that wild-harvested resources are excluded from

many large-scale rural household surveys (Angelsen et al., 2011; Shackleton et al., 2007, 2011).

Another difficulty in quantifying value is that availability of a resource does not necessarily imply use. A good case study in this regard is the (potential) value of tree NTFPs as foods (Arnold et al., 2011 and references therein). Tree foods such as fruit, nuts and leaves are often good potential sources of nutrients such as fat, fibre, protein, minerals and vitamins, and their consumption therefore appears attractive (Leakey, 1999). Long lists of edible NTFPs (Bharucha and Pretty, 2010) have been complied and many tree foods (especially fruits) have indeed been subject to some domestication (see Sections 2.2 and 3). Counter to the common perception, however, the presence of wild food species in local forest and woodland landscapes does not necessarily mean that these are consumed by humans. Termote et al. (2012) illustrated this with a survey around the city of Kisangani in the Democratic Republic of Congo, where a wide variety of wild food plants were found, but few contributed significantly to human diets (despite significant local dietary deficiencies).

When there is relatively low NTFP-food use in areas of dietary need, reasons can include the high labour costs involved in collection and processing, low yields, high phenotypic variability (with large proportions of non-preferred produce), and lack of knowledge in the community. Regarding the last point, in eastern Niger and northern Burkina Faso, respectively, for example, women prepare protein-rich condiments from the seeds of prosopis (*Prosopis africana*) and zanmné (*Acacia macrostachya*), but women in other parts of the Sahel (where the same trees are found) are not aware of these food values and do not harvest and manage woodlands for these species (Faye et al., 2011). Research suggests that knowledge on use is often higher among indigenous peoples than among immigrant communities (Kuhnlein et al., 2009; Moran, 1993), while within communities cultural perceptions on who should eat particular foods, and when, are also important (Balée, 2013; Hladik et al., 1993). The relationship between the availability of food and its consumption is therefore often complex, and simple surveys of absence/presence are not in themselves adequate for understanding diets (Webb and Kennedy, 2012). When collection costs, low yields and high proportions of non-preferred produce are factors inhibiting use, domestication can have an important role to play (Sections 2.2 and 3).

To support the NTFP sector on a proper evidence base without over- or under-stating value – as both these scenarios lead to inappropriate interventions – policy makers need to understand the caveats and subtleties involved in interpreting existing valuations (Sheil and Wunder, 2002). Fortunately, more appropriate methods for quantifying value, based on systematic reviews and meta-analyses, have been adopted in the last decade to allow more informed decision making (examples given in Table 1; Belcher et al., 2005). The data from these studies indicate that appropriate NTFP-policy support could preferentially benefit the most marginalised households in societies and women in particular because of the significant income benefits they receive from NTFPs. In a recent initiative, the Poverty Environment Network (PEN) gathered the most comprehensive comparative socio-economic data set to date on tropical forest use and poverty alleviation, with information collected from approximately 8,000 households in 24 low-income tropical nations (Angelsen et al., 2011; PEN, 2013). Completed syntheses of the PEN data have not yet been published, but preliminary analyses provide results that are consistent with those of earlier NTFP studies (Table 1).

2.2. Domestication and movement of germplasm

There have been many studies investigating ancient forest management practices for indigenous food plants in parts of Latin America (e.g., Levis et al., 2012; Peters, 2000) and Southeast Asia (e.g., Michon, 2005; Wiersum, 1997), but relatively few in Africa (although see, e.g., Leakey et al., 2004; Maranz and Wiesman, 2003). Ancient harvesting, managed regeneration and cultivation have, for example, led to genetic changes in many Amazonian fruit trees and palms (Clement, 1989). These include abiu (*Pouteria caimito*), Amazon tree grape (*Pourouma cecropiifolia*), araza (*Eugenia stipitata*), biriba (*Rollinia mucosa*), peach palm (*Bactris gasipaes*) and sapota (*Quararibea cordata*). In Africa, rarer reports of changes in the characteristics of fruits attributed to ancient domestications include bush mango (*Irvingia gabonensis* and *Irvingia wombolu*) and safou (*Dacryodes edulis*) (Leakey et al., 2004). Again, areca (*Areca catechu*), coconut (*Cocos nucifera*) and date (*Phoenix dactylifera*) are all palms for which changes in fruit size, in the proportion of useable product, and in the ability to be propagated, are attributed to long-past human selections (Clement, 1992), while an expand-

Table 1
Examples of systematic reviews and meta-analyses describing the importance of NTFPs for rural communities in the tropics.

Reference	Description of study	Findings
Vedeld et al. (2004)	Review of 54 case studies (15 East Africa, 18 southern Africa, 14 Asia, 7 Latin America) examining rural incomes from forest products in 17 countries	Forest 'environmental income' was on average ~20% of total household income of the population sampled. Main sources of income were woodfuel, wild foods and animal fodder, with the poorest more dependent on them. Cash income constituted ~50% of total forest environmental income
Ruiz-Pérez et al. (2004)	Comparison of 61 case studies (17 Africa, 21 Asia, 23 Latin America) of the production and trade of NTFPs from 24 countries	NTFPs are important sources of income. Commercial trade drives intensified production and household specialisation among forest-related peoples. Markets should be developed and resources sustainably managed accordingly
Kusters et al. (2006)	Expert opinion on a subset of 55 of the case studies of Ruiz-Pérez et al. (2004) (as above)	NTFP trade improves livelihoods, with the involvement of women having a positive effect on intra-household equity. However, trade sometimes increased inequality between households. Inability to make financial investments limits developments to increase product quality and quantity
Marshall et al. (2006)	Comparison of 10 different plant NTFPs harvested by 18 local communities in Bolivia and Mexico	Supply chains provide economic safety nets, spread income across time and can provide 'stepping-stones' to a non-poor life. Harvesting is one of the few cash-generating opportunities for many women. Shifting from subsistence to commercial extraction sometimes reduces access to the poorest in society, due to harder-to-negotiate controls on harvesting
Lobovikov et al. (2005)	Collection of data on bamboo from 22 countries (5 Africa, 13 Asia and the Pacific, 4 Latin America)	Total bamboo area was estimated to be >36 million ha, India having the largest resource. Almost a third of the bamboo area in Asia was reported as planted. Use is growing rapidly in L. America and Africa. The annual export market for bamboo is in billions of USD; volumes traded and used locally for building, furniture, food, fuel, etc., are much greater

ing list of global studies on ancient domestications includes many more food trees (Clement, 2004).

In perhaps the best studied case, in Amazonia, Amerindian populations declined after European colonial contact, which resulted in the erosion of the rich tree crop genetic heritage they had established (Clement, 1999). The effects of pre-Columbian forest management remain, however, including high density aggregations of useful trees close to ancient anthropogenic 'dark earth' soils (Clement and Junqueira, 2010) and in interfluvial regions (Levis et al., 2012), with Brazil nut (*Bertholletia excelsa*) being the most famous example (Shepard and Ramirez, 2011). A review of molecular genetic studies (Clement et al., 2010) suggested that current centres of genetic diversity in fruit and nut trees are generally located in the centre of the Amazon Basin along the major white water rivers where large pre-Colombian human populations developed, while the periphery of the basin has had an important role in domestication origins. This suggests that subtle differences in the focus of management programmes for conservation and genetic improvement may be required in different geographic regions of the Amazon, and indicates the importance of germplasm exchange and dispersal during ancient domestication processes. Proposed management interventions to protect such genetic resources in the future include further introduction into farmland surrounding forest, but for ancient domesticates where the evolutionary processes that have led to the development of present-day landraces are undetermined, on-farm conservation requires careful consideration of which genetic resources to include (e.g., when the origins of existing farmland introductions are unknown; Dawson et al., 2008).

2.3. Conservation and sustainable use issues

Commercialising the wild harvest of NTFPs has been widely promoted as a conservation measure, based on the assumption that an increase in resource value is an incentive for collectors to manage forests and woodlands more sustainably (FAO, 2010). Experience shows, however, that the concept of commercialisation and conservation proceeding in tandem is often illusory (Belcher and Schreckenberg, 2007), as more beneficial livelihood outcomes are generally associated with more detrimental environmental outcomes (Kusters et al., 2006). The harvest of fruit from the argan tree (*Argania spinosa*), endemic to Morocco, is a good illustration of the dilemmas involved. The oil extracted from the kernels of argan fruit is one of the most expensive edible oils in the world and development agencies have widely promoted a 'win–win' scenario for rural livelihoods and argan forest health based on further commercialisation (Lybbert et al., 2011). As Lybbert et al. showed, however, while the booming oil export market has benefited the local economy, it has also contributed to forest degradation.

In circumstances where NTFPs are over-harvested from the wild, a widely-advocated method to alleviate pressure on natural stands and support their more sustainable use has been the cultivation of additional product sources in farms and plantations (e.g., Lange, 1998; Strandby-Andersen et al., 2008). Although intuitive, there is surprisingly little clear evidence that this approach works, and some authors have suggested that cultivation may have a detrimental impact on forest and woodland NTFP populations (reviewed in Dawson et al., 2013), as planting can, for example, result in forest populations being degraded to 'stop-gap' supply status while cultivated stands mature (Clapp, 2001). Cultivation may also stimulate market development that unintentionally 'captures' forest as well as planted product sources (Cossalter and Pye-Smith, 2003). Gaining an understanding of the circumstances in which positive linkages can be achieved between cultivation and the conservation of forest and woodland NTFP populations is not straightforward, and the topic requires active research (Dawson et al., 2013). Measures that support productivity under cultivation, such as genetic selection and improved management, may better support wild stand conservation (through 'out-competition'). However, as already noted, this may result in poorer management of natural populations, and such a move may disadvantage the livelihoods of the very poor in communities who do not have access to land for planting and so can only harvest resources from the wild (Page, 2003). Such shifts in emphasis may detrimentally influence wider attitudes to forest use and management.

In most cases of NTFP extraction, the importance of factors such as the breeding system and the effective population size of the plant involved – in supporting regeneration, the persistence of stands and the sustainability of harvesting – has not been considered (Ticktin, 2004). When some thought has been given to these issues (e.g., Alexiades and Shanley, 2005), the quoted effects of harvesting on genetic structure and the associated impacts on production and persistence are generally suppositions only, with no direct confirmatory measurements. One opportunity for understanding genetic-related impacts on NTFPs may come from building on the growing literature of the effects of logging on timber trees, although different harvesting methods, products, rates of growth and reproductive biologies mean that the ability to make generalisations is limited (see below). A number of timber species have been hypothesised to undergo dysgenic selection based on only inferior individuals not being logged, which thereby contribute disproportionately to the seed crop for the establishment of subsequent generations (Pennington et al., 1981). Reductions in genetic diversity, and changes in timber tree stand structure and density that change mating patterns, can lead to inbreeding depression (Lowe et al., 2005).

Actual data on how changes in the genetic structure of logged tree populations influence production volumes, timber quality and economic value, however, are very limited, and the importance of dysgenic selection is itself disputed (Cornelius et al., 2005). Most studies of logging impacts on the genetic structure of timber trees have involved phenotypically-neutral molecular markers to measure diversity rather than measurements of growth, seed viability, etc. (Wickneswari et al., 2014, this special issue). Such research has revealed varying effects of logging on genetic structure, with diversity significantly reduced in some cases (e.g., André et al., 2008; Carneiro et al., 2011) but not in others (e.g., Cloutier et al., 2007; Fageria and Rajora, 2013). It appears that more important than losses in genetic diversity *per se* are changes in gene flow and breeding behaviour (Lowe et al., 2005). Jennings et al. (2001) suggested that logging impacts on timber trees will be limited because individuals generally set seed before they are cut and many juveniles that eventually take the place of adults are not removed during logging. NTFPs that are harvested by tree cutting at maturity could be subject to similar limited effects, while the impacts of destructive harvesting before maturity will likely be greater because fewer individuals then seed and a larger cohort can be exploited.

When the NTFP is the seed or the fruit, the effects of intensive harvesting on genetic structure may be high, especially if the seed/fruit are harvested by tree felling (Vásquez and Gentry, 1989). The harvest of fruit could lead to dysgenic selection (e.g., seed of the fruit of only the poor-tasting, non-collected individuals remain in stands to establish the next generation) or positive selection (e.g., seed are discarded from the fruit of superior, collected trees in locations suitable for germination and establishment) (Leakey et al., 2004). The human harvest of fruit could also lead to a reduction in number of animal seed dispersers, reducing genetic connectivity in populations and increasing the prospects for future inbreeding depression (Lowe et al., 2005). Where the NTFP is harvested non-destructively and is not the seed or fruit, impacts may depend more on harvesting impacts on forest regeneration dynamics generally (Ticktin, 2004).

Finally, sustainable NTFP management must also consider timber extraction activities in forests (Laird, 1998). First, timber and NTFPs are sometimes harvested from the same species, indicating competition or, occasionally, complementarity in harvesting (Shanley and Luz, 2003). Of the top timber species in Cameroon, for example, Laird (1998) indicated that several had important non-timber values, although most of the widely marketed NTFPs in the region were not important timbers. The magnitude of any conflict between the possible multiple uses of a species may be location-specific, complicating supportive policy development for livelihoods (Herrero-Jáuregui et al., 2013). Second, the management of forest for timber influences the availability of NTFPs produced by other species through controlling access to forest, enhancing or inhibiting regeneration, etc. (Rist et al., 2012). Third, aspects of both NTFP and timber harvesting are sometimes explicitly combined in multiple-use forest management plans, with more or less success, in which an important issue is not to neglect the contribution of NTFPs compared to timber extraction (Guariguata et al., 2010).

3. Smallholder agroforestry practices

3.1. Benefits to rural communities

Agroforestry practices involve the integration of trees with annual crop cultivation, livestock production and other farm activities (Garrity, 2004), and have been widely adopted globally, as illustrated by a geospatial analysis conducted by Zomer et al. (2009) that indicated approximately 560 million people living in farm landscapes with more than 10% tree cover. When grown on farms, tree products are often described as AFTPs to differentiate them from NTFPs and timber 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 AFTPs and NTFPs, a complicating factor in the estimation of relative contributions to livelihoods, and in devising management options tailored for different settings (Byron and Arnold, 1997).

One way to obtain an estimate of the value of agroforestry trees to tropical rural communities is to consider the range of species that smallholders consider important for planting and the recorded uses of these species, as illustrated in Table 2 (based on our compilation of information from the World Agroforestry Centre's Agroforestree Database, the AFTD [AFTD, 2013]). These data suggest that timber production is the most frequent function for smallholder-priority tree species, and the commercial value of timber planting in smallholdings pan-tropically is confirmed by incomplete economic data for the sector (e.g., teak [*Tectona grandis*; Roshetko et al., 2013] and acacia [*Acacia mangium* and *Acacia auriculiformis*; Fisher and Gordon, 2007] wood production by Indonesian and Vietnamese smallholders, respectively). After timber, our survey of the AFTD suggests medicine and then fuel are the next most important functions.

Most tree species listed by the AFTD are indicated to have a range of possible uses in agroforestry systems. Multiple uses illustrate the flexibility in the products and services that agroforestry trees can provide, which can help support diverse livelihoods and promote production-system resilience (Garrity, 2004). The environmental services provided by agroforests in parallel (such as erosion control and shade/shelter, as listed in Table 1, as well as global services such as carbon sequestration; Roshetko et al., 2007) with their production functions can be supported by 'payments for environmental services' (PES) (Roshetko et al., 2008). Experience shows, however, that more important in determining the tree planting and retention behaviour of farmers is the products they receive directly from trees, not PES (Roshetko et al., 2007).

A recent example of the successful adoption of improved agroforestry technologies in Africa is for soil fertility replenishment (Place et al., 2011). The planting of nitrogen-fixing 'fertiliser trees' in the south of the continent to substitute for (or enhance) mineral fertiliser application has resulted in increased staple crops yields, more stable crop production in drought years and improved crop rain-use efficiency (Sileshi et al., 2008, 2012). A recent project in Malawi, for example, encouraged more than 180,000 farmers to plant fertiliser trees, leading to improvements in maize yields, more food secure months per year and greater dietary diversity (CIE, 2011). Further approaches to improve soil fertility in Africa include farmer-managed natural regeneration (FMNR) of faidherbia (*Faidherbia albida*) and other leguminous trees, which since 1985 in Niger alone has led to the 'regreening' of approximately 5 million hectares (Sendzimir et al., 2011). FMNR in the Sahel region has resulted in increases in sorghum and millet yields, with greater dietary diversity and improvements in household incomes

Table 2
The number of tree species in the Agroforestree Database (AFTD) mentioned as providing various tree functions of importance to smallholders' livelihoods, and the known geographic distribution of these species. The percentage of references to indigenous species is given in brackets. Based on the number of mentions summed across functions compared with the total number of species (650) in the database, it is evident that many tree species perform several functions. Data illustrate that smallholders are able to use a wide range of trees.

Function[a]	Region[b]						
	Africa	Oceania	South America	South Central Asia	Southeast Asia	Western Asia and Middle East	Total (regions)
Apiculture	177 (50)	84 (31)	83 (39)	108 (31)	121 (38)	34 (47)	607 (40)
Erosion control	175 (54)	70 (29)	57 (40)	120 (48)	117 (48)	32 (53)	571 (47)
Fibre	141 (40)	93 (38)	60 (33)	133 (45)	149 (45)	32 (56)	608 (42)
Fodder	295 (55)	101 (30)	96 (45)	217 (52)	191 (47)	61 (57)	961 (49)
Food	295 (54)	124 (35)	119 (43)	220 (49)	225 (49)	62 (55)	1,045 (48)
Fuel	357 (53)	147 (35)	126 (42)	243 (45)	249 (47)	62 (56)	1,184 (47)
Medicine	390 (57)	159 (36)	144 (40)	298 (50)	314 (50)	67 (55)	1,372 (50)
Shade/shelter	281 (51)	131 (40)	104 (42)	193 (44)	202 (48)	46 (57)	957 (47)
Soil improvement	194 (51)	83 (33)	73 (45)	143 (42)	154 (45)	26 (46)	673 (45)
Timber	419 (53)	192 (38)	158 (42)	313 (49)	347 (50)	70 (51)	1,499 (48)
Total (functions)	2,724 (53)	1,184 (35)	1,020 (42)	1,988 (47)	2,069 (47)	492 (54)	9,477 (47)

[a] The AFTD is an open-access database that contains information on a wide range of products and services provided by trees that are of interest to farming communities in the tropics (AFTD, 2013). Data are presented on the number of species given in the database as used for a particular purpose that can be found in particular geographic regions.

[b] The AFTD contains global data on species distributions, summarised here into regions according to <http://en.wikipedia.org/wiki/List_of_sovereign_states_and_dependent_territories_by_continent> for Africa, Oceania and South America, and <www.nationsonline.org/oneworld/asia.htm> for South Central Asia, Southeast Asia, and Western Asia and the Middle East. A factor determining the greater number of total references to the African continent is the focus given in the AFTD to documenting species found there.

also observed in some locations (Bayala et al., 2011; Place and Binam, 2013). Unlike the wide-scale planting of exotic trees in improved fallows, FMNR is based explicitly on indigenous species, which may better support biodiversity and other associated environmental services (Haglund et al., 2011).

3.2. Domestication and movement of germplasm

Although a number of successful agroforestry technologies involving tree planting have been adopted in the tropics, in only some cases has there been significant attention to the genetic quality of the material planted. Generally, relatively little attention has been given to genetic quality in soil fertility replenishment and fodder provision technologies, as well as in the provision of environmental services, despite the gains in production and service provision that could be achieved by doing so (e.g., Heering et al., 1996; Tuwei et al., 2003). A good example is presented by the case of environmental service provision. As already noted (Section 3.1), the primary reason for smallholders to cultivate trees important for service provision is the products they receive directly from doing so rather than PES. Despite this, environmental-service promotion programmes have surprisingly frequently failed to consider the quality attributes of the trees being established. A good illustration is provided by the Latin American shrub jatropha (*Jatropha curcas*), whose fruit can produce biodiesel that could mitigate the climate change impacts of fossil fuel use, as well as provide revenues for smallholder growers and local-community processors (Achten et al., 2008). Recent wide promotion of jatropha as a biofuel in Africa has relied on seed introduced into the continental mainland (probably hundreds of years ago) through Cape Verde (Lengkeek, 2007), despite this material being of poor performance compared to provenances sampled from the native range, thus leading to low returns (e.g., for Kenya, see Iiyama et al., 2013).

In contrast, for timber and food (especially fruit) trees, many of the exotic species grown by smallholders in the tropics are also grown in large-scale commercial plantations and orchards, and more attention to genetic quality has therefore been given (e.g., Fisher and Gordon, 2007; Ray, 2002). Significant work on less globally well known local timber and fruit trees species grown by tropical smallholders has also increased in recent decades. A review by Leakey et al. (2012) of more than 400 papers on 'agroforestry tree domestication', for example, assessed the progress that has been made over the last 20 years in bringing such new tree species into cultivation. Between 1993 and 2002, there was a focus on species priority-setting, assessing species potential and the development of appropriate propagation methods for selected trees. Between 2003 and 2012, more emphasis was placed on new methods for assessing genetic variation in wild tree populations, on AFTP commercialisation, and on adoption and impact issues.

For the decade 2013–2022, Leakey et al. (2012) identified the scaling up of successful domestication practices (such as the participatory approach described in Appendix B) to be one of the major challenges. Impact studies are required to understand which of the tree domestication methods that have been applied to date have been most effective in benefiting tropical smallholders' incomes, food and nutritional security, and what effect different approaches have on the genetic diversity of species in the long term, and hence on the sustainability of production (see more in Section 3.3). Particular opportunities for new tree domestications were identified for Africa, where genetic diversity in a range of essentially wild fruits has been found to be large, providing the possibility for large genetic gains under cultivation (e.g., for allanblackia [*Allanblackia* spp.] see Jamnadass et al., 2010; for marula [*Sclerocarya birrea*] see Thiongo and Jaenicke, 2000). Forests are therefore important sources of germplasm for ongoing and future domestications, for AFTPs as well as for tree commodity crops (see Section 4.3), and this requires their management for the characterisation and maintenance of these resources (Jamnadass et al., 2011). A wider focus on indigenous trees rather than the exotics that are currently widely used to fulfil different production and service functions (as illustrated by the figures on exotic and indigenous tree usage proportions given in Table 2) may bring conservation benefits and be more sustainable in the long term (see Section 3.3).

3.3. Conservation and sustainable use issues

Agroforestry landscapes sometimes contain dozens or hundreds of tree species planted by farmers or that are remnants from forest clearance (Table 3), and tree species diversity can support crop yields and promote agricultural resilience, providing a reason to maintain diversity (Steffan-Dewenter et al., 2007). Trees in farmland can also support the conservation of natural tree stands in fragmented forest-agricultural mosaics by acting as 'stepping-stones' or 'corridors' for pollen and seed dispersal that help to maintain the critical minimum population sizes needed to support persistence and, for managed forests, productivity (Bhagwat et al., 2008). Species-diverse farming systems that provide rich alternative habitat for animal pollinators can support pollination and hence seed and fruit production in neighbouring forest, including of seed and fruit that are important NTFPs (Hagen and Kraemer, 2010).

Very high levels of tree species diversity in farmland are, however, often not sustainable, as methods of agricultural production change and as (often) exotic trees become more prevalent and replace indigenous species more important from a conservation perspective (Lengkeek et al., 2005; Sambuichi and Haridasan, 2007). On occasions, exotic trees planted in agroforestry systems invade cultivated and natural habitats, and the threat of this must be weighed carefully against the benefits of the trees' presence, which is a difficult task when the balance point varies for different sections of the human community (farmers, the non-farmer rural poor, urban dwellers, etc.; see Kull et al., 2011 for the case of Australian acacias that are widely cultivated in the tropics).

Semi-domesticated tree species in agroforestry systems frequently maintain high levels of intra-specific diversity (Dawson et al., 2013) and research on temperate trees indicates that high genetic variation helps support ecosystem functions (Whitham et al., 2006). When out-crossing indigenous trees exist only at very low densities in farmland, however, as is often the case when they are remnants from natural forest otherwise cleared for crop planting (Lengkeek et al., 2005), they are vulnerable to the absence of neighbours in the landscape to support pollination, reducing the opportunities for reproduction and potentially leading to lower seed set and inbreeding depression (Lowe et al., 2005). This is a particular concern for trees that provide fruit for human consumption, as no cross-pollination/the absence of fruit set may mean there is no reason for farmers to retain these trees in the agricultural landscape (Dawson et al., 2009). In the worst case scenario, rare, isolated trees in farm landscapes may be the 'living dead' (*sensu* Janzen, 1986; i.e., unable to pollinate and set seed) and will only survive for the current generation.

Some have argued that further promoting tree domestication has negative impacts for the diversity of agricultural landscapes at both inter- and intra-specific levels, and this is most clearly seen if it leads to clonal tree monocultures (see Section 4.3). On the other hand, without the improvements in tree yield and quality associated with domestication, farmers may choose not to plant trees at all on their land, but to cultivate other plants that are (otherwise) more productive (Sunderland, 2011). At an intra-specific level, domestication processes always cause shifts and/or losses in underlying genetic diversity in the manipulated popula-

Table 3
Examples of tree-species-rich agroforests in Africa, Asia and Latin America, with information on tree uses (with particular reference to possible human food use).

Reference	Location	Tree diversity	Tree uses
Das and Das (2005)	Barak Valley, Assam, India	87 Tree species identified in agroforestry home gardens	Farmers indicated a mean of 8 species used as edible fruit per home garden, many indigenous. Fruit trees more dominant in smaller gardens. ~5 species per garden used for timber, 2 for woodfuel
Garen et al. (2011)	Los Santos and Rio Hato, Panama	99 Tree species, 75% indigenous, utilised, planted and/or protected on farmers' land	~35% of species valued for human food. 27 mostly exotic fruits mentioned as planted. ~35% of species valued for their wood, the same proportion as living fences. >60% of species were assigned multiple uses
Kehlenbeck et al. (2011)	Surrounding Mount Kenya, Kenya	424 Woody plant species, 306 indigenous, revealed in farm plots	Farmers indicated many species used for food. 7 of the 10 most frequent exotics by across-plot occurrence were cultivated, mainly for edible fruits/nuts. The most frequent indigenous species were used primarily for timber/firewood
Lengkeek (2003)	East of Mount Kenya, Kenya	297 Tree species, ~65% indigenous, revealed in smallholdings	Farmers indicated that for >20% of species the fruits/nuts consumed by humans. The most common exotic was coffee, then timber trees
Marjokorpi and Ruokolainen (2003)	Two areas of West Kalimantan, Indonesia	>120 Tree species identified in forest gardens, most species not planted	Farmers indicated ~30% of species used for edible fruit, latex and in other non-destructive ways, ~50% used for timber and in other destructive ways. Seedlings of unused trees removed around naturally-regenerating and intentionally-planted fruit/other useful trees
Philpott et al. (2008)	Bukit Barisan Selatan Park, Lampung province, Sumatra, Indonesia	92 and 90 trees species identified in coffee farm plots outside and inside the park, respectively	>50% of farmers grew a total of 17 other products in addition to coffee, including spices, timber and, most commonly, indigenous and exotic fruits. Of these farmers, ~65% grew ⩾2 additional products. Farmers planting outside the park grew alternative products more often
Sambuichi and Haridasan (2007)	Southern Bahia, Brazil	293 Tree species, 97% indigenous, revealed in cacao plantation plots in forest understory	Many indigenous trees used for food. Seedlings favoured for retention during weeding provide edible fruit or good wood. The most abundant exotic species were edible fruits
Sonwa et al. (2007)	Yaoundé, Mbalmayo and Ebolowa sub-regions, Cameroon	206 Mostly indigenous tree species revealed in cacao agroforestry plots	Farmers indicated 17% of tree species used primarily for food, 65% of which indigenous. Excluding cacao, the 3 species (2 indigenous) with the highest across-plot occurrence were used for food. Close to urban Yaoundé, the density of food trees was higher. 22% of tree species primarily for timber, 8% for medicine

tions (Dawson et al., 2009), but the extent and nature of these changes depends on the domestication method adopted, with some approaches more favourable for maintaining diversity (Cornelius et al., 2006). The participatory domestication approach (Appendix B, Section 3.2), which is based on bringing selected indigenous trees from local wild stands into farms, appears to provide a good balance between farm-level productivity gains and the landscape-level conservation of genetic resources (Leakey, 2010). Genetic-model analysis of a participatory domestication project with peach palm 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 intra-specific diversity, especially if substantial inter-village germplasm exchange occurs (expansion of a few clones).

4. Smallholder tree commodity crop production

4.1. Benefits to rural communities

Tree commodity crops represent something of an exception to the sparse information available on the value of other tree products (as exemplified in Sections 2 and 3), as export data are compiled widely by national governments and are further assembled by FAO's Statistics Division (FAOSTAT, 2013). Data extracted from FAOSTAT for the five most important tree commodity crops grown widely in the tropics – palm oil (derived from African oil palm, *Elaeis guineensis*), coffee (primarily from *Coffea arabica*), rubber (from *Hevea brasiliensis*), cocoa (from cacao, *Theobroma cacao*) and tea (primarily from *Camellia sinensis*) – indicate that a large export value of more than 80 billion USD (including re-exports) was realised in 2010, which is of the same order as total annual NTFP extractions (Section 2.1).

Unfortunately, however, most countries where tree commodity crops are widely cultivated do not provide data on the proportion of production by smallholders compared to large-scale growers, so measuring the benefits received by the former group is not straightforward. One country that does provide this information is Indonesia, where in 2011 small farms were estimated to contribute 42%, 96%, 85%, 94% and 46% of the country's production area for palm oil, coffee, rubber, cocoa and tea, respectively (Government of Indonesia, 2013). Other illustrative data reported on a commodity-by-commodity basis also show how important small-scale tree crop production is in tropical nations: approximately 30% of oil palm-planted land in Malaysia is managed by smallholders (Basiron, 2007), while more than 65% of all coffee produced worldwide comes from small farms (ICO, 2013). The equivalent figure for cocoa is 90% (ICCO, 2013), while more than 75% of all natural rubber produced between the years 1998 and 2003 was estimated to come from land holdings smaller than 40 hectares (INFOCOMM, 2013). Again, around 75% and 50% of tea grown in Sri Lanka and Kenya, respectively, is considered to come from small farms (INFOCOMM, 2013).

The above data suggest that much of the revenues from cultivating these commodities accrue to small-scale farmers. Returning to the example of Indonesia, for example, a rough calculation can be made based on estimated production volumes (Government of Indonesia, 2013) and FAOSTAT-reported producer price data. Here, in 2011, the total farm-gate value to the country's smallholders for palm oil, cocoa and coffee must have amounted to more than two billion, 1.5 billion and one billion USD, respectively, based on our calculations. Data illustrating the significant revenues received by smallholders from growing tree commodities indicate the magnitude of the challenge in managing commodities sustainably in the context of the potentially deleterious ecological impacts of their production on agricultural and forest landscapes (Section 4.3).

4.2. Domestication and movement of germplasm

The main tree commodity crops have all been subject to formal breeding, although the efforts involved have often been *ad hoc*

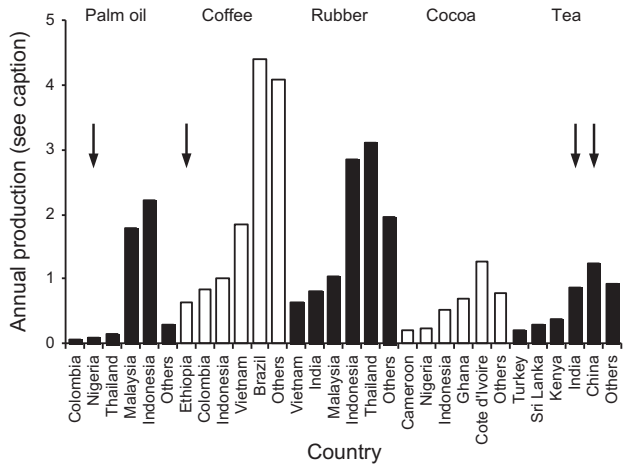

Fig. 1. Average annual production figures for five tree commodity crops for key production countries (taken from UNCTAD, 2011). Units of production are: palm oil, 10 s of millions of tonnes; coffee, 10 s of millions of 60 kg bags; rubber, cocoa and tea, millions of tonnes. Figures are based on the following years: palm oil, coffee and cocoa, 2008/2009 to 2010/2011; rubber and tea, 2007 to 2009. Note that the most important production country is outside the natural range of the crop except in the case of tea (centres of origin = West Africa, including Nigeria [4th-ranked producer], for oil palm; Ethiopia [5th-ranked producer] for coffee; Brazilian Amazonia [Brazil not ranked among the top 5 producers] for rubber; western Amazonia [no origin countries among the top 5 producers] for cacao; and Asia, including China [1st-ranked producer] and India [2nd-ranked producer], for tea). Centre of origin countries that are top-five ranked producers are indicated in the figure by an arrow. Geographic disjunctions between production locations and commodity crop origins complicate forest conservation efforts for commodity crop progenitors (see text).

based on the availability of germplasm to the breeders involved (Mohan Jain and Priyadarshan, 2009). Partly, *ad hoc* approaches reflect the fact that the main centres of production of tree commodities are spread across the tropics and are often outside their native ranges (see Fig. 1 for the five examples discussed in Section 4.1; UNCTAD, 2011). As such, tree commodities provide an excellent example of how the international transfer of plant genetic resources (both for breeding purposes and simply for planting by farmers) has been and will continue to be important for supporting smallholders' livelihoods (the importance of international tree germplasm exchange is more widely discussed by Koskela et al., 2014, this special issue).

Much of the history of movement of tree commodity crop germplasm is fairly well documented, since transfers were frequently undertaken for commercial reasons by the European powers during their period of colonial expansion (see Mohan Jain and Priyadarshan, 2009 for information on early germplasm movements for a range of tree commodities). The natural rubber industry in Southeast Asia, for example, was first based on seedlings transferred from Brazilian Amazonia via Kew Botanic Gardens in the United Kingdom to Sri Lanka and Singapore in the 1870s (Gonçalves and Fontes, 2012).

Successful early cultivation of tree commodities in exotic locations was due in part to the escape of crops from the pests and diseases that co-evolved with them in their centres of origin (Clement, 2004). However, the founder germplasm in major production centres was often introduced before much was known about genetic variation in the crops, so was often suboptimal in performance (Mohan Jain and Priyadarshan, 2009). With the importance of the production of these commodities for smallholders, further investments in genetic improvement, in the delivery of improved cultivars, and in better farm management, have wide benefits (Mohan Jain and Priyadarshan, 2009). Highly genetically-variable landrace and wild stands found outside major production centres therefore have an important role to play in future tree commodity crop development, especially with the availability and potential of modern 'genomic' breeding techniques (see, e.g., Argout et al., 2011 for cocoa's draft genome), and the conservation of these genetic resources in forest, farmland and other locations is therefore essential.

4.3. Conservation and sustainable use issues

Coffee provides an excellent example of the need for the conservation of forest stands of tree commodity crops, as only approximately 2,000 km^2 of high quality Ethiopian montane forest containing wild coffee still remains, due to forest conversion to agricultural land (Labouisse et al., 2008), while future threats also include anthropogenic climate change (Davis et al., 2012; climate change threats to tree genetic resources are explored by Alfaro et al., 2014, this special issue). Wild coffee also exemplifies some of the problems in developing a conservation strategy: in theory, the high value of cultivated coffee should provide a strong incentive to conserve wild stands in Ethiopia, but – as for other tree commodity crops – the 'disconnect' between the centre of origin of the crop and the major production centres (Brazil and Vietnam in the case of coffee, Fig. 1) causes complications because the main beneficiaries of *in situ* conservation are not the country that must engage in it.

A starting point in supporting the *in situ* conservation of tree commodity crops with extant wild or semi-wild stands is to attempt to work out what the 'option value' of this material is for breeding purposes, although this is difficult because of the many unknowns concerning both the nature of the genetic resource and future breeding requirements. In any case, Hein and Gatzweiler (2006) undertook the exercise for wild coffee based on the need to improve the yields of cultivars, to protect against three major cultivated coffee diseases and to breed some cultivars with lower natural caffeine content. Their analysis, based on a 30-year discounting period, indicated a net present value of wild coffee of 1.5 billion USD at a discount rate of 5%, 420 million USD at a discount rate of 10%. The generation of these figures assumed a 15-year period for a successful breeding programme and a 20% adoption rate for improved cultivar planting. Another assumption is that traits for improvement would be obtained from wild stands rather than existing *ex situ* field gene bank accessions of coffee, which are maintained in countries such as Brazil (i.e., we do not know to what extent extant wild stands in Ethiopia contain unique genetic resources; Reichhuber and Requate, 2007). Nevertheless, although only approximations, these figures provide a strong justification for the further protection of wild Ethiopian coffee stands and the forest around them, and should support the development of a mechanism that involves growers from elsewhere in the world in supporting such an initiative.

Although there have been some limited studies of molecular genetic diversity in wild coffee (e.g., Aerts et al., 2013), there are as of yet no comprehensive range-wide assessments to compare with current (and future predicted) forest cover in Ethiopia. Studies that combine comprehensive genetic assessment with current and future habitat niche modelling (Davis et al., 2012; Thomas et al., 2012), and with economic 'option value' analysis (Hein and Gatzweiler, 2006), are required for all important tree commodity crops that have extant wild and semi-wild stands, and similar approaches should also be applied to other trees providing valuable products. As well as estimating genetic diversity with (neutral) molecular markers, greater geo-spatial referencing of important functional diversity (disease resistance, quality traits, etc.) on forest maps would be useful; for example, by superimposing data from phenotypic evaluations of wild accessions undertaken in field trials and live gene banks.

Finally, in the context of wider conservation efforts, significant concerns exist for commodity crop cultivation, as large-scale planting may result in the wholesale conversion of natural forests and woodlands to agricultural land, and commodity crop monocultures may displace biodiversity from farms (FAO, 2012). These concerns are most obviously illustrated by oil palm cultivation, which has led to the wide-scale loss of both forests and of agrobiodiversity (Danielsen et al., 2009; Donald, 2004). Although it has often been suggested that intensive monocultures raise productivity and therefore reduce the amount of forested land that needs to be cut for crop cultivation, there are few quantitative data to support the notion that 'land sparing' is more effective than 'land sharing' as a conservation strategy (Balmford et al., 2012; Tscharntke et al., 2012). To the extent that 'land sparing' can play a role, genetic selection of more productive cultivars of commodity crops clearly has a part to play. More important, however, is an emphasis on mixed farmland production regimes that combine tree commodities with fruit trees, staple crops and/or vegetables, etc., which maintain commodity yields and promote resilience (Clough et al., 2011). In the right circumstances, the integration of tree commodity crops with other farmland trees and in forest mosaics can increase commodity production (e.g., see the case of coffee; Ricketts et al., 2004; Priess et al., 2007).

Mixed production regimes are much more amenable for some commodities (such as coffee and cocoa; SCI, 2013) than for others (such as palm oil; Donald, 2004). One option being promoted in West Africa, for example, is to incorporate 'new' tree commodity crops such as allanblackia, a tree whose seed yields edible oil with significant potential in the global food market, with cocoa production (Jamnadass et al., 2010). When allanblackia trees have matured, farmers' incomes will be distributed more evenly through the year, as allanblackia and cocoa have different production seasons (Novella Africa, 2013). To support diverse production systems, genetic selection for commodity crop cultivars that do well under shade may be of particular importance (Mohan Jain and Priyadarshan, 2009). This may require returning to wild genetic resources still found in shaded, mixed-species forest habitats.

Not only may mixed production systems be more resilient ecologically, but they may support more resilient food systems. Buying food using the income received from a single commodity crop can lead to food insecurity for farm households when payments are one-off, delayed or unpredictable in value, and as a result tree commodity crops are sometimes viewed sceptically within agricultural production-based strategies to improve nutrition (FAO, 2012). For farmers who have too little land to cultivate enough food to meet their needs, however, incomes from tree commodity crops may be the only way to obtain sufficient food (Arnold, 1990).

5. Conclusions

Tree-based production systems are often promoted because of their perceived biological, economic and social resilience in the context of anthropogenic climate change and other production challenges (Alfaro et al., 2014, this special issue; Steffan-Dewenter et al., 2007; Thorlakson and Neufeldt, 2012). It should, however, be evident that the extra resilience trees can provide should not be taken for granted or over-estimated. A number of steps are needed to support the improved management of tree genetic resources for livelihoods and sustainability (Table 4). For NTFPs, a greater understanding of the genetic aspects of production (including gene flow for sustainability) is required, perhaps building on data collected from logged timber trees. For AFTPs, a stronger emphasis on the genetic quality of the trees planted by smallholders is needed, which means paying attention both to domestication and to the systems by

Table 4
The value of trees and tree genetic resources: a summary of issues for three production categories.

Production category	Benefits to rural communities	Domestication and movement of germplasm	Conservation and sustainable use issues	Improving genetic management for livelihoods
Non-timber forest product harvesting	Important contributions to livelihoods, but in general not well quantified and fragmentary data, due to multiplicity of products, informal trade, direct provisioning, exclusion from surveys, etc.	Mostly incipient domesticates. Some ancient domestication, especially of food trees. Occasional long-distance germplasm transfers	Commercialisation is unlikely to support the conservation of natural stands. In limited cases, cultivation may support wild conservation by reducing extraction pressure	Little data available on the genetics of sustainability, but connectivity (gene flow) within populations is likely to be important, as well as possible dysgenic or positive selection in some cases. Genetic data collected from logged timber trees may be a starting point for improving management
Smallholder agroforestry practices	Not well quantified pan-tropically, but specific practices determined to be highly important. ~560 million people live in farm landscapes with >10% tree cover	Many semi-domesticates, occasionally full domesticates. Wide-scale transfer and use of several hundred 'exotic' species for timber, food, medicine, etc.	Often high tree species richness in agroforests, with high genetic diversity in indigenous trees. High diversity may, however, not be sustainable, with, e.g., displacement by exotics	More consideration to genetic quality is required in sourcing planting material for small-scale farmers. Understanding gene flow in farm landscapes will support diverse agricultural systems and enhance agroforest-forest linkages
Smallholder tree commodity crop production	Export data available on economic value, but the portion of value accrued by small producers is often not estimated	Often fully domesticated, major production centres frequently outside centres of origin	Separation of major production locations and centres of origin results in a 'disconnect' in conservation. Commodity production may result in forest clearance	Calculating the 'option value' of natural genetic resources of commodity crops is required to support their future availability for breeding. Develop cultivars that perform well in diverse farm systems (with other tree crops, annuals, etc.)

which improved germplasm is delivered to farmers (Lillesø et al., 2011). For tree commodity crops, more attention is needed on the valuation of wild and semi-wild genetic resources so that better methods for conservation that recognise value can be implemented. More work is also needed to develop cultivars that perform well in diverse farm systems.

These measures fit within a much wider context of interventions and areas for research needed to improve management and enhance access to markets for tree products and services in order to support rural livelihoods. For example, more research is required to understand the economic, environmental and other trade-offs for the different sectors of rural societies when NTFPs are converted to AFTPs (or, indeed, to new commodity crops; Dawson et al., 2013; Page, 2003), and more work is needed to ensure equitable relationships between the different participants in market supply chains (Marshall et al., 2006). The further application of incentives devised by international commodity purchasers to support diverse farm production systems is also required (Millard, 2011). For appropriate policy development, a better quantification of the relative benefits received by rural communities from different tree production categories is required, supported by an appropriate typology for characterisation (de Foresta et al., 2013). We hope that this paper will help support this initiative.

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Appendix A. A review of information on livelihoods in Country Reports of the State of the World's Forest Genetic Resources (SOW-FGR)

FAO's (2014) SOW-FGR (which this special edition of Forest Ecology and Management accompanies; see Loo et al., 2014, this issue) was compiled from information collected in Country Reports commissioned from 2010 onwards to support a global synthesis. The framework developed for country reporting indicated the importance of providing information on livelihood value. As part of our literature review for this paper, we determined to assess the level of quantitative data on livelihoods provided in the Country Reports. To do so, we chose 50 Reports (29 from Africa, 12 from the Asia-Pacific region and 9 from Latin America; see FAO, 2013) and present our findings here.

Our assessment indicated that 36 nations provided some data on livelihood value, but most of this was of very limited scope and did not specifically consider the value of genetic variation in supporting livelihoods. In addition, most contributions did not differentiate between forest, agroforest and other potential sources of tree products (although exceptions included China and Sri Lanka), and much data were based on old (>10 year-old) surveys, supporting a conclusion that little (up-to-date) quantitative information is available.

The category of use that was most commonly quantified in Country Reports was woodfuel, generally in terms of the percentage energy-dependence of countries, but rarely in terms of the economic value that this usage translates into (which would indicate the cost of substitution by other energy sources), although, e.g., in Ethiopia, woodfuel entrepreneurs earned a reported ~420 million USD per year. In Africa, reported percentages (e.g., >95% of household energy needs met be woodfuels in Malawi and Mali) indicated just how important woodfuel is as an energy source in the continent (a fact often neglected in policy discussions on 'energy futures' in Africa, which place unrealistic emphasis on 'more modern' energy sources there; Iiyama et al., 2014). For most countries included in our survey, it was evident from the interpretation of information on priority species for woodfuel production that natural rather than planted tree stands were the most important source of woodfuel. Similar percentage-dependence data were provided by a number of countries for the medicinal usage of trees.

Quantitative data given in Country Reports on rural communities' employment opportunities provided by trees were limited, but of the >300,000 tree nurseries reported for China, 95% were indicated to be individually-owned, while in Cameroon 150,000 people were suggested to be 'employed' in the informal forestry sector. Again, in, e.g., Ecuador, wood carpentry and carving together were reported to employ 96,000 people, while in the Philippines >14,000 small- and medium-size enterprises manufacturing furniture were indicated. Again, economic values are not generally attached to these figures, or the level of employment (e.g., from full to perhaps relatively marginal part-time involvement). Country Reports for Tunisia and Zimbabwe, however, indicated that the sale of NTFPs contributed 35% or more of rural household incomes in some parts of those nations, while figures for parts of Ethiopia and the marginalised Chepang communities in Nepal were >25% and 18%, respectively. The Country Report for India suggested NTFPs contributed an income equivalent of 2.7 billion USD per year.

Country Reports provided very little information on the value of tree commodity crops in USD or volume terms, although exceptions included Ethiopia (where >30% of coffee was reported to originate from wild and community-managed 'coffee forests') and the Solomon Islands (which indicated that cocoa and palm oil made up 8% and 14%, respectively, of total commodity export value).

Appendix B. Agroforestry tree domestication: the participatory approach

In the last decade, a new way of domesticating fruit and nut trees, referred to in the literature as the participatory domestication approach, has been developed as a close collaboration between scientists and farmers in Central Africa. The approach involves combining scientific advances in germplasm selection, propagation, processing, etc., with local communities' experiences to bring a range of valuable indigenous trees into cultivation (Leakey et al., 2005). Simple cloning methods such as grafting allow gains in multiple traits to be captured simultaneously, accelerate production, and provide the product uniformity required by some markets (Leakey, 2004). By supporting the domestication of a range of different trees, the approach is able to buffer production and market risks that may result from a focus on an individual species (Tchoundjeu et al., 2010). The strategy focuses initially on satisfying the domestic needs of households and then grows through producing planting material for sale to other farmers and by commercialising tree products.

When applied in the humid forest margins of Cameroon where indigenous fruit and nuts are highly valued (Degrande et al., 2006), significant improvements in access to farm inputs, incomes, diets and rural business development have been achieved (Leakey and Asaah, 2013; Tchoundjeu et al., 2010). The approach is being extended in Central Africa through rural resource centres managed

by local communities that actively encourage the involvement of women and instruct in tree propagation, farm management, etc., and provide processing facilities, business training and a venue to meet and form group associations to market tree products and obtain farm services more effectively (Asaah et al., 2011).

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