
Diversity of food trees support food security

A cornfield owned by a farmer in Buol, Central Sulawesi, Indonesia who made a mixed plantation by also planting nutmeg and cocoa.

Photo: World Agroforestry/Dienda CP Hendrawan

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CHAPTER TWO

Tree diversity as basis of agroforestry

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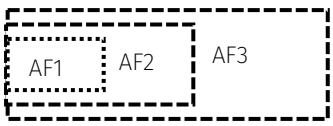
Highlights

- Of the more than 60,000 known tree species only 1% is represented in specific agroforestry databases
- Trees become part of agroforestry practices by three routes: selective retention, as volunteers and by deliberate planting (or direct seeding)
- On-farm tree diversity profiles differ between use categories and AF practices, with 1-10, 10-100 or 100-1,000 tree species depending on context
- Tree diversity transitions imply a loss of retained and volunteer trees and increase in actively managed ones
- Domesticating forest aligns with domesticating trees, with winners and losers in both

2.1 Introduction

2.1.1 Trees and three agroforestry concepts

Trees and forest relate to each other like eggs and chicken, and it is not possible to say which came first. Trees wouldn't grow as tall as they do without forest neighbours, and forests without trees exist only on paper and in a policy sense. From an agricultural perspective the trees are the most distinctive aspect of agroforestry, and similarity with forests is a secondary concept, however (Box 2.1).



In reviewing four decades of agroforestry research Chapter 1 described three 'nested' agroforestry concepts, with AF1 focused on 'trees on farm' at field and farm level, the technologies used and value chains supported, AF2 focussed on the agriculture/forest interface at landscape and livelihoods scale, and AF3 at the governance and policy aspects of the way agriculture plus forestry interact as continuum with the full spectrum of sustainable development goals. There is a logical sequence[1] of description and stock taking ('Theory of Place'), understanding of transitions, their drivers and

consequences ('Theory of Change') and transformations and leverage on drivers ('Theory of Induced Change'). This applies at each of the three AF concepts, but effectiveness of ToIC's at AF1 level may well depend on relationships included in the AF2 and AF3 concepts[2].

Box 2.1 Seeing both the trees and the agroforest

In a meeting on plant research in agroforestry in 1981, the concept of 'agroforests' with high architectural and functional similarity to natural forests in the humid tropics emerged[3,4]. It sparked empirical studies. Initially especially in Indonesia[5,6], discussions on tree architectural models suitable for agroforestry[7] and the 'ecological analogue' idea that similarity in structure supports equivalence in function[8,9]. In parallel the concept of agroforests as 'intermediate intensity' agroecosystems[10] became the basis for a segregation versus integration discussion[11] that saw similarities between debates at tree level (maintaining 'multipurpose trees' or supporting 'tree improvement' for specific functions[12]), and at (agro)forest level (maintaining multifunctionality, or specializing and intensifying agriculture segregated from nature). The equations derived for this analysis[13] were later rediscovered as basis for the land sharing versus land sparing discussion[14], that reframed the issue for broader appeal.

Plant architectural analysis, 3D-representation and models[15] were focussed on the self-similarity in developing pattern as explanation for the resulting woody branching structure of trees. After developing an impressive terminology of 'architecture types'[16] , the specification of tree growth model became so detailed and complex[17], however, that to add an extra tree species to the library required an additional 4-year PhD project. Other scientists focussed on less-architectural 'plant functional attributes'[18] and more simplified fractal branching models for the resulting woody structures, above or belowground[19].

The direct link between trees (and tree improvement, see chapter 3) and ecological understanding of agroforests became weaker in subsequent research, and the 'tree domestication' work (see Chapter 3; mostly developed as an AF1 concept) became separated from the 'forest domestication' discourse[20], that mostly focussed at the landscape/livelihoods[21] level of AF2, and the policy level of AF3 concept. A recent study for the Amazon[22], however, synthesized literature about how indigenous and traditional Amazonian peoples still manage forest resources to promote useful plant species that are mainly used as food resources in 'agroforests', and how structure and composition of forests on and near archaeological sites along four major Amazonian rivers reflect management practices such as selective retention of useful plants, attraction of non-human animal tree seed dispersers, transportation of useful plants, selection of phenotypes, fire management and soil improvement. Long-term persistence of ancient cultural practices implies that we indeed need to see both the trees and the diverse agroforest patches rich in edible perennial plants to understand either and build on this heritage for food security in Amazonia.

2.1.2 Stock taking on trees and tree diversity

Trees are the defining element of agroforestry, from an agricultural perspective. They differ from crops and livestock in important ways, and it is relevant to understand their 'temperament' or 'character' as living organisms, just as it pays off to know crops, livestock and farmers' minds if one wants to understand agriculture. Trees may be the defining element of agroforestry, but they are neither a taxonomic category, nor sharply defined[23]. Woody perennials can take the tree and shrub as life form[24], but can also be grasses, palms or ferns.

The number of tree species currently known to science[a] is 60,065 (20% of all angiosperm and gymnosperm plant species)[25], with Brazil, Colombia and Indonesia having the most tree species and nearly 58% of all tree species single-country endemics. Nearly half the tree species are found in just 10 families, with *Leguminosae*, *Rubiaceae*, and *Myrtaceae* as richest families (5405, 4827, 4330 species, respectively) and *Syzygium*, *Eugenia* and *Eucalyptus* as richest genera (1069, 884 and 747 species, respectively). Only 1% of this GlobalTreeSearch[26] diversity is currently included in the agroforestree database[27].

The 600 trees included, however, from a major share of the worlds' agrobiodiversity. Over the past 50 years national food supplies worldwide have become more similar in composition, with an increasing role for globally important cereal and oil crops, and a decline of other cereal, oil, and starchy root species[28], many of which are traditionally associated with agroforestry and more shade-tolerant than the open-field crops that replaced them. Of the 150 or so species that make up most of our plant-based food, a mere three crops (rice, wheat and maize) supply more than 50% of the world's plant-derived calories, and only 12 crop and five animal species provide 75% of the world's food[29]. Fruits and vegetables consumption are far below recommended levels to avoid micronutrient deficiency in many parts of the world, in East Africa in particular[30]. Yet, due to limited storage and processing, tree diversity is essential to guarantee year-round availability of fruits that are 'in season'[31].

Agroforestry includes non-trees, especially shade-tolerant understory species such as gingers or cardamom, but also light-demanding crops in specific spaces or temporal phases. This chapter starts with diversity found within the tree category, forming a background on the 'tree improvement' or 'tree domestication'[32] focus in chapter 3; it then considers diversity of agroforestry trees at plot- and landscape scale with implications for tree-soil-crop interactions (discussed in subsequent chapters), functions and risk at farm enterprise level. It then uses understanding of tree diversity transitions in agroforestry (as Theory of Change) as basis for the management of agroforestree diversity (as Theory of Induced Change).

2.2 Trees: functional aspects of being a woody perennial

The occurrence of trees alongside non-trees in many plant families suggests that trees as a life form have advantages, as well as disadvantages, depending on context, and that the longevity and woody stem traits could be readily switched on and off in plant evolution. Trees live longer than most other plants, and this implies that adverse conditions (such as droughts, cold spells, fire, floods) must be bridged, without the option annuals have to avoid them in well-protected propagules. Survival contributes to reproductive fitness, and temporary storage of growth resources is common in trees and their reproductive success is measured at decade rather than annual scale for long-lived species. While avoiding grazing by common herbivores due to height (once past their early growth), they are fully exposed to insects and disease-causing pathogens. To counter these threats, the long-lived trees have devised structural and physiological mechanisms such as spines and have chemical defence (secondary metabolites) that support leaf longevity and fruit production. This is more

[a] Including as-yet-undescribed species other sources estimate a total of around 80,000 or even 100,000 tree species

common in perennials (and biennials) than in annuals, as is evident from lists of plants with medicinal properties, based on the secondary metabolites that the plant formed to avoid grazing. Coevolution of hosts and pathogens has been compared to biological warfare, reaching a fragile, site-specific balance.

Among the 'woody perennials' the 'grasses', 'palms' or 'ferns' differ from the other, dicotyledonous and conifer trees in the absence of aboveground branching and, related to that, secondary stem diameter increments; their real long-term surviving component is the belowground 'clump'. Palms a have a specific 'modular' pattern of growth, in which every leaf contributes a small increment to stem (and thus tree) height, and a single bud that can become a flower bunch after a specified period of time. In some of the palms (incl. coconut and oil palm) flower buds develop at a given age of the associated leaf, in others (incl. sugar palm and sago) starch accumulates in the stem and flowering starts much later, signaling the end of the life cycle of the stem (with other shoots of the clump taking over). In this context a relevant distinction is between plants that are 'monocarpic' (flowering once; annuals, biennials[b] and some perennials) and those that are 'polycarpic'.

Woody stem

Leaving the monocarpic and non-branching woody perennials such as bamboo aside, most trees are characterized by their woody stem that keeps growing over time, as branches develop, mature, break off and their scars become covered in the 'nodes' in wood anatomy (Box 2.2). The relative size and direction of branches of trees differs between species (such that many trees can be identified in a leaf-less season from a distance by their branching pattern). Yet, this variation is bounded by narrow rules that can be understood as a combination of tree mechanics (wood strength, gravity and wind exposure), and the 'pipe-stem' theory. The latter is based on the simple logic that the transport function of woody stems is determined by the leaf area and its water needs for transpiration. Because of this, the number (and total cross-sectional area) of water-transport vessels at any point in a branched structure corresponds to the leaf area it supports. From here it is a small step to 'fractal branching' and the prediction of allometric equations that relate total tree biomass to stem diameter[33,34]. Trees growing in half-open circumstances, e.g. agroforestry, have a different allometry from those in closed stands[35].

Box 2.2 The structure and anatomy of woody stems, ring width and stable isotopes

Nearly all environments in which woody plants grow have at least some seasonal variation in circumstances, although the variation may differ from the strong yearly pattern of temperate and boreal zones. Wood growth is normally associated with this seasonal variation, which results in the formation of growth rings that are visible due to specific anatomical features (Fig 2.1.A). Other anatomical features that result from seasonal variation are vessel diameter, length, and frequency (Fig 2.1.B), all of which are features regarded as important phenotypic plastic traits that enable plants deal with changing environmental conditions[36].

[b] As an example of the policy relevance of botanical distinctions: in China's Sloping Land Conversion Program (See chapter 11) annual crops were not allowed once land was converted to trees, but biennial medicinal plants were tolerated, leading to a specific form of agroforestry

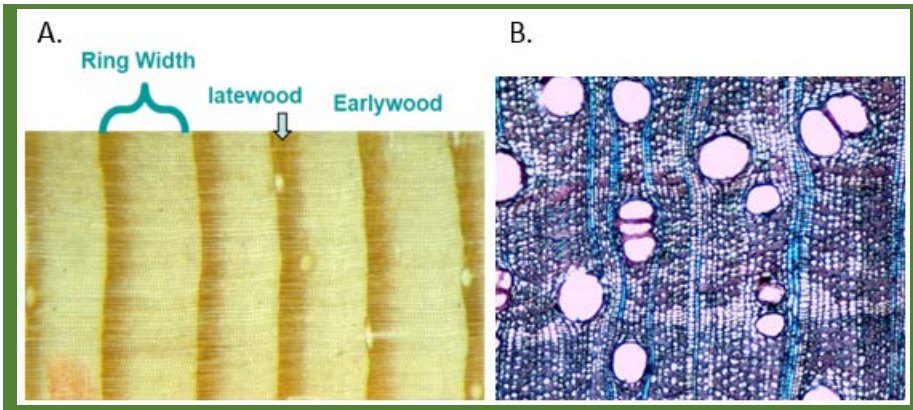


Figure 2.1 A. Illustration of earlywood and latewood, differing in colour on a cross section due to differences in vessel size and wood density; B. Vessel characteristics can be further distinguished and measured on a transverse section, such as this one of *Triplochiton scleroxylon* (African Whitewood)

Particularly, understanding density variation as a function of radial growth will facilitate greater knowledge about how to accurately estimate carbon sequestration, which could be useful for environmental mitigation strategies. Annual wood density is directly related to rates of carbon assimilation (photosynthetic rate), and inversely related to stomatal conductance[37]. Wood density within a species tends to vary within between early and late wood in a yearly (or half-yearly cycle in bimodal rainfall climates), and sites. Therefore, the inclusion of temporal and spatial variability of wood density improves substantially our knowledge to estimate carbon sequestration over time. Besides, the anatomy of xylem cells (vessels), late and early wood variations are also important variables to reconstruct past tree responses to environment because of its high intra-annual resolution and its direct link to important functional and physiological processes[36], and thereby to reconstruct past climatic conditions. Quantification of vessel traits and tracheids will also be essential for linking wood anatomy with dendrochronology.

The analysis of stable carbon and oxygen isotopes adds value to our understanding of past responses to climate, and how trees can tune their water–carbon balance. During carbon sequestration and water uptake by roots and subsequent wood formation processes, heavier isotopes may be discriminated against the lighter ones in response to a prevailing environmental condition and thus may imprint the environmental signal in tree rings[38]. For instance, variations in stable carbon isotopes ($\delta^{13}C$) in tree rings provide deeper insight into the occurrence of water stress and related changes of intrinsic water-use efficiency (iWUE). Intrinsic water use efficiency derived from tree-ring stable carbon isotope ratios ($\delta^{13}C$) has already been used as a potential proxy for past physiological responses of tropical trees to environmental changes[37]. By integrating anatomical data, ring width, and stable isotopes it is possible to address ecological aspects of plant hydraulic traits, study the long-term responses of trees to environmental changes from wood cell to the landscape, and from multi-decadal to centennial scales.

Beyond the site-specific variation and temporal patterns in wood density revealed by wood anatomical analysis (Box 2.2), an important part of tree 'temperament' at species level is reflected in its wood density. Fast-growing pioneer trees that try to get above their neighbours to capture light quickly tend to invest little in woody tissues – with a high branch turnover and sensitivity to wind as a consequence. Slow-growing trees with dense wood can ultimately become emergent above the canopy of other trees, but only in relatively stable environments.

Wood density[39] correlates with numerous morphological, mechanical, physiological, and ecological properties[40]. Wood density is relevant for allometric biomass equations[41,42] for trees; databases have been developed to allow tree diameter data to be converted to biomass and carbon stock estimates. A nested analysis of variance showed that 74% of the species-level wood density variation in a set of 2456 neotropical trees was explained at the genus level, 34% at the Angiosperm Phylogeny Group (APG) family level, and 19% at the APG order level[43]. Across available data, wood density correlates with growth rate[44], drought tolerance[45] and survival of fire[46]. The frequency with which trees of low, medium and high wood density coexist can provide a powerful way to compare agroforestry and natural vegetation (Figure 2.2).

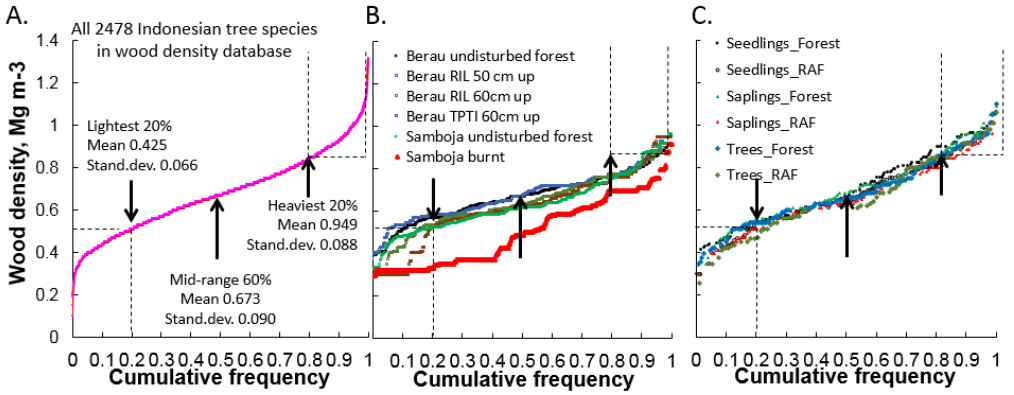


Figure 2.2 A. Wood density frequency distribution of Indonesian forest species; B. Examples for various types of forest management and post-burn forest recovery in E. Kalimantan; C. Example of wood density profiles of Indonesian rubber agroforestry (RAF) plots and remaining forests in Jambi, for seedling, sapling and pole/tree stages[47]

Wood density is important for the potential use of wood, as it relates to durability after the tree has been cut, as well as while it grows. Strength, however, is partly independent of wood density and an important characteristic for use in construction. Recent research on trees in peat swamps (compare paludiculture discussion in Chapter 14) has shown that trees with low wood density have effective gas exchange between root environment and atmosphere via their stems, leading to methane emissions[48], but likely also keeping roots supplied with the oxygen they need. For 'dendrochronological' research, woody stems are a history book, as it allows reconstruction of the conditions during the whole lifetime of the tree. When beyond growth ring diameters stable isotope signatures (especially carbon and oxygen)[49,50] long term fluctuations of rainfall can be interpreted, including for spatial correlates within 'precipitationsheds' (compare Chapter 17)[51].

Leaves and phenology

Tree leaves vary in shape and size, with large leaves of pioneer trees in humid environments with little wind grading into compound leaves that can regulate their degree of exposure to sunlight and (dry) air. An elaborate set of descriptors of leaf characteristics has been developed as part of the Plant Functional Type literature[52]. Diversity of plant functional types, which can be assessed without detailed taxonomic expertise is a reasonable proxy for taxonomic diversity, but in rainforests the latter exceeds the first by a factor two or more.

Tree leaves differ in longevity, with physical and chemical protection more pronounced in environments where leaves can function for a long time. In environments of low nutrient availability plants (including trees) tend to 'hoard' the nutrients they have taken up, hold on to their leaves and remobilize nutrients from leaves before they fall as litter. This contributes to slow litter decomposition (and ultimately peat formation in wet environments) and reinforces low nutrient availability. In contrast, where nutrient supply is more abundant litter turnover rates are higher and plants can rely on an external rather than internal way of nutrient cycling.

In seasonal environments most trees drop their leaves in dry (or cold, e.g. on mountains) seasons and flush young leaves after the rains have started. As young leaves tend to be attractive to grazers and vulnerable to insect pests and diseases, plants with sufficient access to deep soil water reserves tend to get a flush of young leaves before the actual start of the rainy season. In doing so, they can make use of the higher radiation intensity in non-clouded skies and avoid attackers. One tree that has developed such 'reverse phenology', at least in some environments, has become widely used in parkland agroforestry systems[53] (see also chapter 12) and has become a favourite role model for agroforestry that tries to combine benefits of trees with modest shading during the growing season[54]. Although early agroforestry researchers emphasized the lack of systematic data on phenology of the wide array of possible agroforestry trees[55], there still is little systematic information. It has been noted that trees in Sahelian parkland agroforestry flower more frequently than those in fallow or forest vegetation[56].

Roots

The logic of 'fractal branching' and 'pipe-stem theory' (Fig. 2.3) applies[57,58] to woody roots as much as it does aboveground, with the role of 'mechanical stress' restricted to the 'proximal root', close to the main stem. Belowground tree architecture is still largely the subject of speculation, rather than direct observation, with many 'rules of thumb' that relate expected rooting depth to tree height and lateral spread to crown diameter not valid beyond the species for which the ideas first were formed[59]. Like most plant characteristics, rooting patterns depend on both genotype and environment. The 'functional equilibrium' concept that plants synchronize below- and aboveground growth to balance water, nutrient and light capture[60] is still a good starting point to understand adaptive responses to environmental change[61] and aboveground pruning and management[62]. This includes the carbon strategy involved in the choice between keeping fine roots alive during a dry period or regrowing the quickly after the soil rewets as basis of fine root turnover[63]. Spatially and temporally dynamic adaptive fine root investment needs to be reconciled with the longer-term investment in woody transport roots[64]. In mixed vegetation, and agroforestry in particular, two complementary concepts coexist on nutrient uptake: the 'nutrient pump' (especially on weathering soils) and the 'safety-net', especially for mobile nutrients[65]. Deep roots are not only important when the tree is alive: old tree root channels may dominate soil physical conditions long after the trees have disappeared[66]. Direct measurement of water transport in roots[67] has increased the understanding and appreciation of 'hydraulic equilibration', that can under specific circumstances be a key part of 'facilitation' between trees and intercrops[68,69]. No tree can grow by itself. All depend on biota in the rhizosphere, if only to deal with potential invaders and 'rhizovores' (root-eating organisms). That poses interesting challenges for plants

in how to recognize the welcome invasion of mycorrhizal fungi[70] and nitrogen-fixing bacteria (Rhizobium, Frankia)[71,72] in specific plant families.

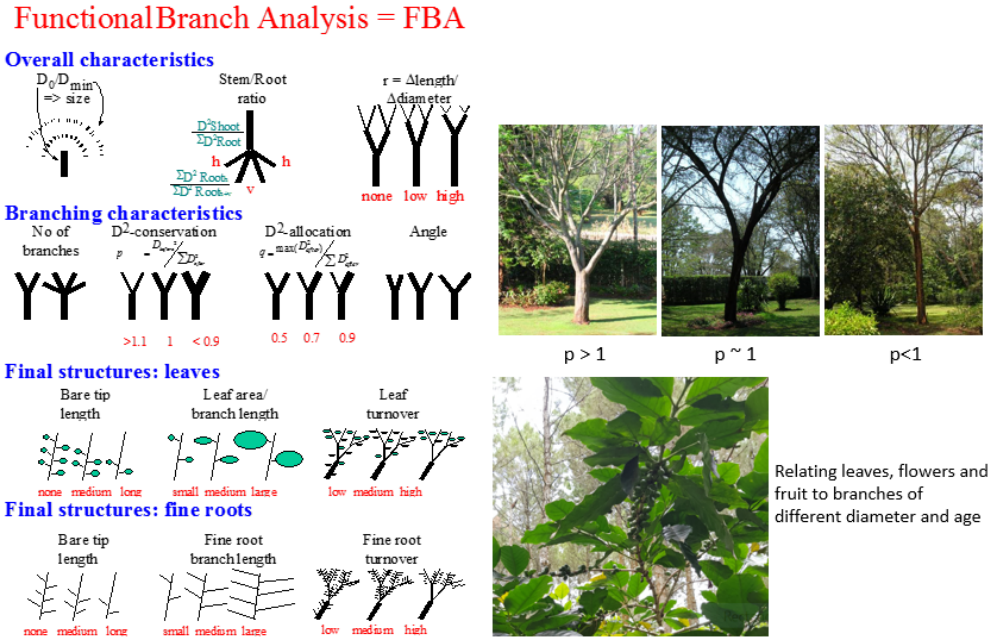


Figure 2.3 Functional branch analysis data collection as basis for fractal branching models

Flowers, pollination and dispersal

Phenology was mentioned as key aspect of the functioning of the leaf canopy, but it is also important for flowering and fruit production. Beyond the issues of avoiding specialist herbivores, trees need to coordinate (in a co-evolutionary sense) flowering and fruit ripening to the expected presence of pollinators and fruit/seed dispersal agents. Pollination strategies and associated flower (or inflorescence) morphology (Fig. 2.4) varies with environment (wind pollinators are most common in pioneer trees and harsh environments), climate and typical tree density. The low density at which the major part of rainforest trees occurs (often less than one individual per ha, linked to the high tree diversity of these habitats) helps in avoiding specialist feeders, but makes pollination a challenge. Larger-sized pollinators (birds, bats) with larger home ranges are attractive alternatives to insects for these reasons, and bat pollination is common in trees, but not possible in other life forms that lack the height and required free space around the flowers.

Fruit and seed dispersal can also be either abiotic (wind, water) or biotic (flying: birds or flying foxes; or walking: mammals), with the laxative properties of many tree fruits a functional part of inducing a suitable environment for tree seed germination.

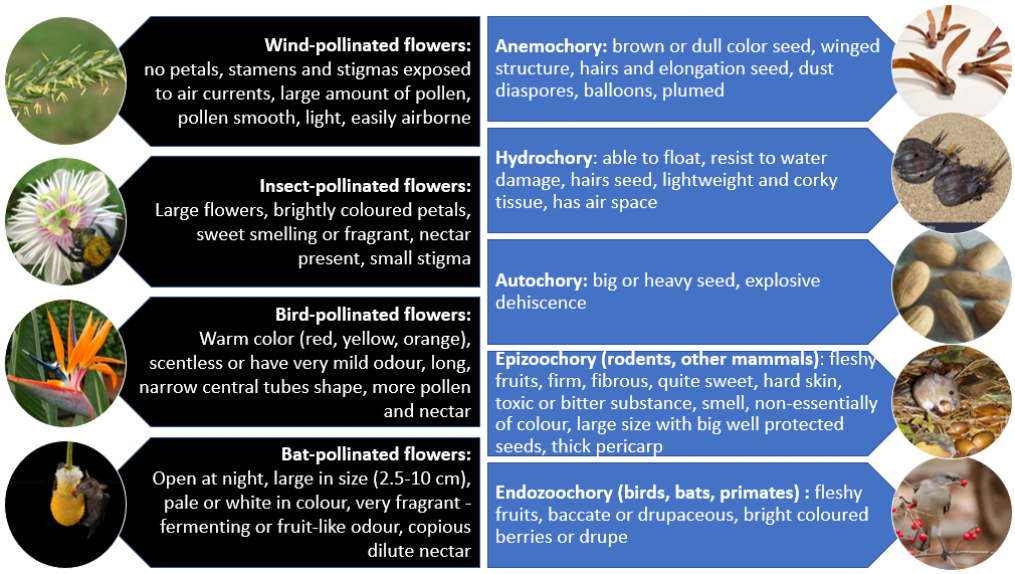


Figure 2.4 Examples of the way pollination and fruit/seed dispersal can be inferred from flower and fruit morphology, across taxonomic databases

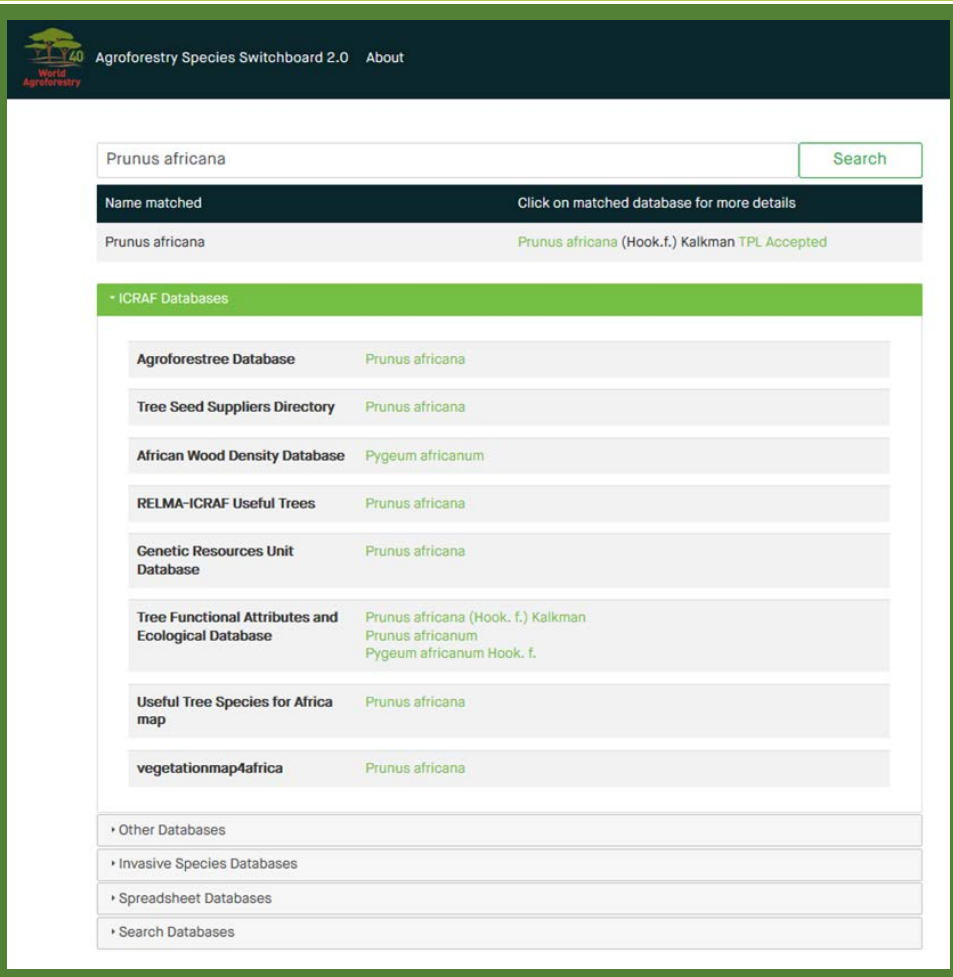
A consequence of the perennial strategy of trees is that they don't have to flower and fruit every year to have the required level of reproductive success. This aspect of the lifestyle is a challenge for the management and cashflow of agricultural production systems[73], and an argument for maintaining diverse tree portfolios rather than specialization. In some tree families (incl. *Dipterocarpaceae*) trees tend to flower with intervals of 5-10 years in a phenomenon called masting[74]. This is interpreted as a strategy to make life as difficult as possible for any organism specialized on seed predation – but it has consequences for the pollination strategy as well, as specialist pollinators cannot handle the uncertainty of resources on which they depend.

Irregular fruiting is a problem for human reliance on fruit trees, as for most the peak of production exceeds capacities of local markets to absorb fruits (in the absence of processing and conservation technology), while in in-between seasons and years other sources of nutrition and income are needed[75]. On one hand this is a key argument for retaining high diversity for portfolio risk reduction effects, on the other, one of the first issues to be addressed in 'tree domestication' (see Chapter 3) is to find management practices and genetic selections that lead to more regular and predictable fruit production.

Tree databases

Our brief overview of tree biology may have created interest in a more systematic compilation of 'functional traits' of trees that have potential use in agroforestry or are found as 'volunteer' parts of managed forests and forest landscapes. Indeed, compilation of data on trees has been an important part of agroforestry research in its first four decades. Current progress is described in Box 2.3. Several tree databases have now been connected by a 'switchboard' that avoids the taxonomic confusion that tends to plague any such comparison[76].

Box 2.3 Tree databases and plant functional traits



A completely revised version of the Agroforestry Species Switchboard was launched in May 2019[77]. The *Switchboard* currently documents the presence of 172,395 plant species across 36 web-based information sources for a total of 307,404 hyperlinks. Rather than limiting database links to tree species, all plant species documented in a particular database are listed via their current names inferred from *The Plant List*.

Only four databases have information for at least 10 percent of species listed in *GlobalTreeSearch*: the Tree Functional Attributes and Ecological Database, Useful Tropical Plants, the Global Wood Density Database and the Try Database. In many cases, the only trait that is available is wood density. Overlaps in species assemblages are generally higher for the AgroforesTree Database and the various databases listed. However, the small overlap with the European EUFORGEN database and smaller number of documented species compared to global databases such the GRIN World Economic Plants show a bias in the AFD towards tropical areas. Percentages above 50% for two invasive species databases highlight the need to check biosecurity risks when introducing typical agroforestry species into new areas.

Table 2.1 Number of species documented in databases listed in the *Switchboard* (in order of the website from where also details can be obtained for each database). GTS and AFD show the percentage of species shared with the *GlobalTreeSearch* and *Agroforestree* databases, respectively. Colours show 0-1-10-100% ranges.

Database	Species	GTS	AFD
AgroforesTree Database	616	0.9	100.0
Tree Seed Suppliers Directory	2836	3.5	60.1
African Wood Density Database	794	1.2	26.6
RELMA-ICRAF Useful Trees	661	1.0	42.7
Genetic Resources Unit Database	296	0.4	30.0
Tree Functional Attributes and Ecological Database	9606	12.9	95.6
Useful Tree Species for Africa map	436	0.6	24.7
vegetationmap4africa	1012	1.2	30.0
African Orphan Crops Consortium	97	0.1	7.1
Árboles de Centroamérica	198	0.3	9.6
Ecocrop	2338	1.7	67.9
Especies para restauración	315	0.5	11.0
EUFORGEN	105	0.2	0.8
Feedipedia	619	0.3	19.6
GRIN World Economic Plants	11438	5.6	75.3
MAPFORGEN	100	0.2	4.7
New World Fruits Database	1133	1.3	7.6
NewCROP Database	854	0.5	25.6
OPTIONs Pesticidal Plants Database	12	0.0	1.0
Pacific Island Agroforestry species	74	0.1	5.8
PROTA4U	9918	9.3	48.9
Seed Leaflets (University of Copenhagen)	172	0.3	19.3
Selection of Forages for the Tropics	172	0.0	2.8
The Tropitree Database	24	0.0	3.9
The Wood Database	311	0.5	9.7
USDA Food Composition Databases	260	0.1	8.0
Useful Tropical Plants	11575	12.6	89.1
CABI Invasive Species Compendium	9186	3.7	58.9
Global Invasive Species Database	468	0.2	8.8
Global Register of Introduced and Invasive Species	9727	2.9	54.9
eHALOPH	1374	0.4	7.0
Extrafloral nectaries	3252	2.3	15.9
Global Species Matrix	660	0.6	26.1
Global Wood Density Database	7591	11.7	69.6
GlobalTreeSearch	59649	100.0	90.1
Try Database	137308	51.0	96.8

Table 2.2 The top-40 species that were listed in a minimum of 19 databases.
* Indicates species listed for the African Orphan Crops Consortium

Species	DB	Species	DB
Albizia saman	28	*Artocarpus heterophyllus* *	20
Anacardium occidentale *	24	*Casuarina equisetifolia*	20
Ceiba pentandra	24	*Dalbergia sissoo*	20
Prosopis juliflora	24	*Hymenaea courbaril*	20
Cocos nucifera *	23	*Mangifera indica* *	20
Faidherbia albida *	23	*Psidium guajava* *	20
Gliricidia sepium	23	*Sesbania sesban*	20
Albizia lebbeck	22	*Acacia mangium*	19
Cedrela odorata	22	*Acacia melanoxylon*	19
Olea europaea	22	*Adenanthera pavonina*	19
Persea americana *	22	*Artocarpus altilis* *	19
Tamarindus indica *	22	*Azadirachta indica*	19
Ziziphus jujuba *	22	*Diospyros mespiliformis*	19
Acacia mearnsii	21	*Elaeis guineensis* *	19
Adansonia digitata *	21	*Eucalyptus camaldulensis*	19
Balanites aegyptiaca	21	*Flacourtia indica*	19
Enterolobium cyclocarpum	21	*Melia azedarach*	19
Jatropha curcas	21	*Prosopis chilensis*	19
Leucaena leucocephala	21	*Sclerocarya birrea* *	19
Moringa oleifera *	21	*Vitellaria paradoxa* *	19

Checking the number of databases where a particular species was mentioned results in top-40 ranking. Several of these species have identified as regional priority species by ICRAF's Genetic Resources collection expeditions, field genebank establishments and 15 were listed as priorities for the African Orphan Crops Consortium.

2.3 Tree diversity in agroforests and on farm

Diversity can be understood, managed and measured, analysed in multiple ways in the context of complex agroecosystems[78,79]. Beyond quantification of what trees are found where[80], analysis can include classification by 1) origin (Fig. 2.5) and seed dispersal (Fig. 2.6) of the species making up the local ensemble, 2) resulting below- and aboveground structure and phenology with consequences for microclimate, light capture, water and nutrient cycling, 3) as basis for pest and disease interactions, or 4) as providers of the range of goods and services that are desirable from a human perspective (Fig. 2.7). An important further dimension of diversity for agroforestry is the representation of trees in local knowledge and the degree of specificity of ethnobotanical knowledge, linked to culture, language and ethnicity[81].

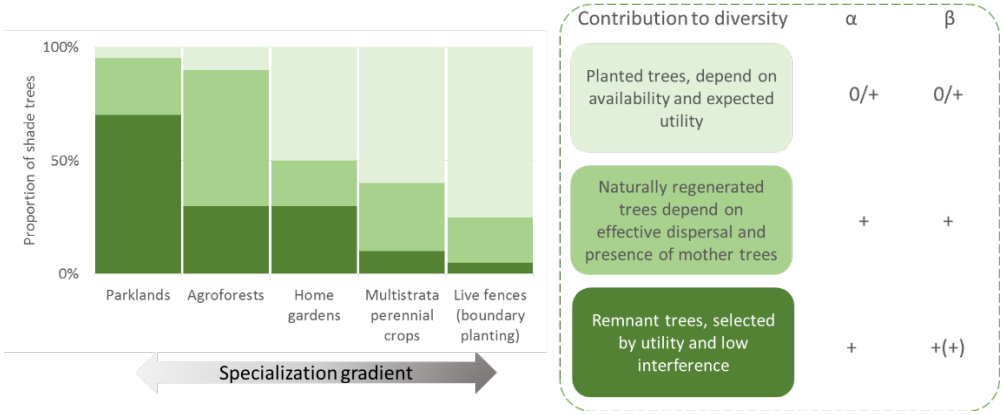


Figure 2.5 Tentative classification of trees by origin as remnant, volunteer or planted trees in various agroforestry systems[82]

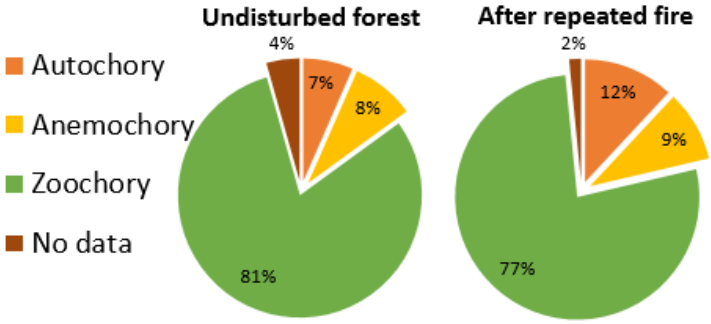


Figure 2.6 Example of the shifts in dispersal modes of trees between original forest plots and the same plots twenty-eight years after start of repeated forests fires in East Kalimantan (Indonesia), while 191 species naturally regenerated[83]

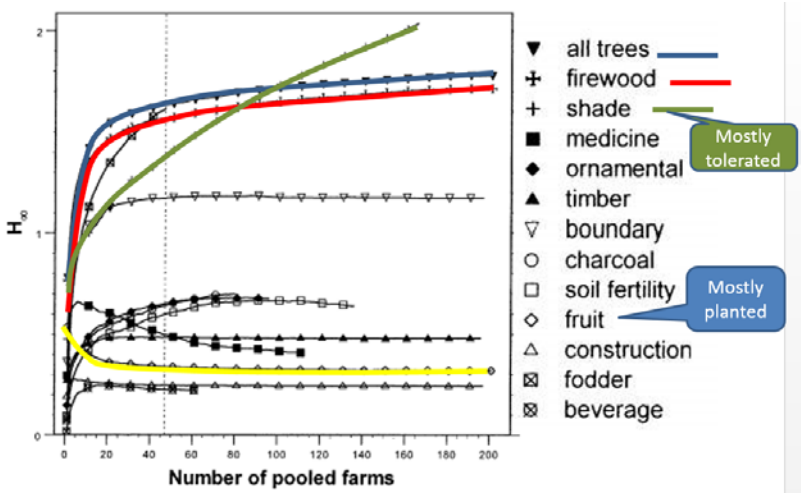


Figure 2.7 On-farm tree diversity in western Kenya in various use groups[84,85]

Similar studies have now been done in a wide range of settings, with results for total tree diversity ranging from around 10 to close to 1000 species per study. About 110 tree species

were encountered[86], including 100 indigenous species, in tree diversity surveys in 16 villages in Burkina Faso, Mali, Niger and Senegal, totalling 300 quadrats randomly sampled from the main land use categories of parklands of village fields (VF), bush fields (BF), sylvopastoral zone (SP) and forest reserves (FR). A total of 127 species with acknowledged local use value in homegardens plus coffee agroforestry systems in Southwestern Ethiopia[87].

A total of 190 tree species (≥5 cm dbh) in a study of 180 coffee agroforestry on the slopes of Mount Kenya[88]. A total of 424 woody plant species, 306 indigenous, were encountered on 265 farm plots (each 0.5 ha) in 18 different agro-ecological zones around Mount Kenya, Kenya[89], with a mean of 17 species per plot; Eight of the ten most frequent species were exotic.

Hundreds of native tree species are currently found in extensive agroforestry ecosystems in the Peruvian Amazon[90], forming an important reservoir of biodiversity. A total of 930 tree species was documented in a study[91] in Jambi (Sumatra, Indonesia) that involved 77 transects in rubber agroforest (RAF; total sampled area 2.4 ha) and 31 transects in secondary forest (total sampled area 0.9 ha) during the period 2002-2005; 405 tree species were encountered in both forest and RAF, 284 species only in forest and 241 only in RAF plots. Nearly all species in the latter still belonged to the local tree flora (with *Hevea brasiliensis* naturalized and also found in the forest plots). Some differences in dispersal profile were noted: RAF-only species were 14.9% large-seeded (autochorous) and 64.3% long-distance zoochorous, versus 4.6% and 71.1% in these categories in the forest-only data, respectively, smaller differences in other categories and intermediate results for the species found in both. The RAF plots had less trees per ha than the forest (as a result of farmer management efforts to promote rubber), but equal densities and diversities in the seedling and sapling stages. Beyond the high tree richness found, a striking feature of these data is that many tree species were found only once, and the sampling intensity was insufficient to even approximate the total richness.

The contrasts between agroforestry contexts in tree diversity also suggest differential response to the 'strong prioritization' concept[92,93] of focussing scarce resource on the 'tree improvement' programs with the highest chance of success. The higher the tree diversity, the less attractive such formalized prioritization appeared to be – with a shift in paradigm to farmer-led domestication of species with a focus on generic, replicable principles, rather than the production of 'superior germplasm (see discussion in final section of this chapter).

2.4 Consequences of tree diversity

2.4.1 Knowledge and cultural diversity

A recent study[84] of palms in 57 Neotropical indigenous communities documented local utility of 120 palm species. Communities knew on average 17.8 ± 8.4 (mean ± SD) species, with on average two specific uses per species. The study concluded that the local knowledge is as fragile as the biological aspects of tree diversity.

An exploration of 'explanatory' local knowledge of farmers with several generations of experience in managing 'complex agroforests' in Indonesia, led to a surprising conclusion: farmers manage these systems with simple concepts on light, space and opportunistic responses (allow anything that doesn't disturb trees or patches with valuable components).

Not aimed at maximizing output per ha but creating acceptable-to-good returns to labour (when compared with intensified, monoculture management), with high flexibility of response when rubber prices are down[94]. The explanatory information appeared to be simpler than that used to manage simpler forms of agroforestry elsewhere. Yet, the ethnobotanical knowledge was rich for species of direct value, while broad categories and local names are used for example for medium-quality timber trees.

Gender and religion were found to influence appreciation of sugar palm in North Sumatra (Indonesia)[95]. The centre of origin and history of human dispersal and migration helps to understand, and can sometimes be reconstructed from, intraspecific variation in and around a tree's centre of origin[96].

2.4.2 Portfolio risk reduction

One of the main advantages of tree diversity within each type of tree utility, is a reduction of risk. Risk can derive from abiotic factors (e.g. climate variability), market prices, but especially biotic relations. Specific studies on this in agroforests are lacking, but other forest-related evidence supports the hypothesis[97].

The agroforest diversity dynamics are mostly aligned in what ecologists recognize as dominant patterns in natural forest. Many tropical forests contain hundreds of tree species; some contain well over 1000. Several explanations have been discussed since decades in ecological research, without a single simple or agreed-upon answer emerging[98,99]. Empirically, the number of woody species in tropical forests tends to increase with precipitation, forest stature, soil fertility, rate of canopy turnover and time since catastrophic disturbance, and decrease with seasonality, latitude, altitude, and tree stem diameters[100]. The high tree diversity in the most productive environment can be understood from the increased importance of biotic, rather than abiotic, factors driving niche differentiation. Insects and fungi may be the primary cause of density-dependent plant mortality that favour diversity to emerge. The diversity-productivity relationship has since long been debated for the direction of causality. At the level of tree gaps as 'regeneration niche', strong recruitment (dispersal) limitations appear to control tree diversity[101].

Despite the impressive tree diversity data cited above (and similar results elsewhere)[102], it is not clear how much the agroforests contribute to long-term conservation of forest genetic resources. Tree species diversity in farmland can be high but may be transitory and dependent on the type of tree utility[103].

2.4.3 Exotic trees

There is a long-standing debate on 'Exotic' vs 'Indigenous' trees that has led to different perspectives and interpretations. First point to note is that the specific set of exotic trees that is most likely to be used is fast-growing and productive in the new environment while the 'indigenous' trees cover a wide spectrum of characteristics. Productivity in the new environment can be higher than that in the centre of origin where benefits of a temporary (unknown number of generations) escape from pests, diseases exceed costs caused by the loss of symbionts and pest control agents.

Several tree introductions to support 'restoration' have turned into ecological disasters of 'invasive' species replacing local ones that at least ecologically have higher value. The properties that appear to make an exotic tree attractive for introduction (growth rate, ease of reproduction), are now seen as primary risks for invasiveness. In selection of improved cultivars/varieties there rarely is explicit selection against invasiveness.

Part of the push for 'exotics' is an unintended consequence of efforts to protect local species from 'illegal logging' and exploitation. It is easier to show exotic trees are planted and grown on farm, than it is for local tree species, while valid conservation concerns apply only to the latter. This causes an 'exotics paradox' in policies towards on farm trees and their use.

2.5 Managing and governing tree diversity transitions in AF

The concept of a forest (or tree cover) transition has proved to be useful in both 'theory of place' and 'theory of change' type discussions[104]. However, the return of tree cover after the inflection point may be of different diversity characteristics than the tree cover that was lost in the left-hand side of the graph. Recognizing a 'tree diversity transition' curve (Fig. 2.8) may help understand the existence of four 'tipping points'.

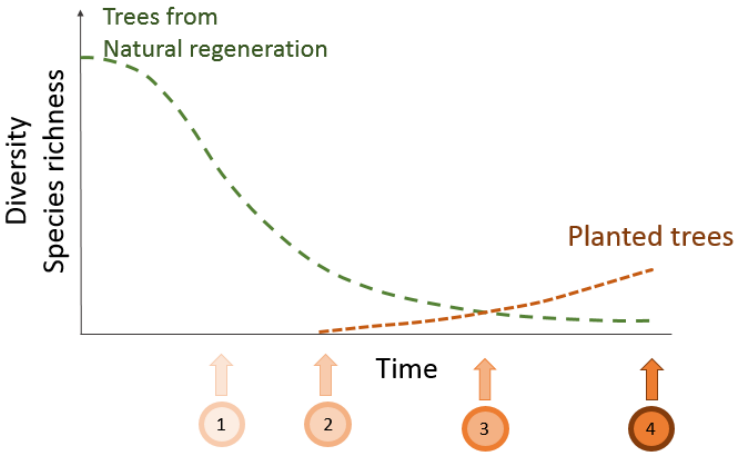


Figure 2.8 Schematic representation[84] of the 'tree diversity transitions' that may underpin 'forest transitions' in terms of tree cover, with four 'tipping points' discussed in the text

These tipping points are:

1. Seedling and sapling diversity decline as landscape-level recruitment has been affected and/or seedbanks are depleted, after the surrounding landscape lost its 'forest' status.
2. Start of tree planting, complementing managed natural regeneration and addressing local priorities[105,106]. A specific concern here can be the lack (or loss) of the required symbionts for planted trees, such as mycorrhizal fungi. This has been suggested as bottleneck for obligatory ectomycorrhizal *Dipterocarpaceae* species, for example, but field tests with *Shorea* enrichment planting in rubber agroforests in Sumatra did not show a necessity for nursery-stage inoculation[107].

3. Start of dominance of planted tree diversity over remnant and volunteer tree species, with attention shifting to germplasm collection[108], tree seed sourcing[109] and delivery mechanisms[110], quality of planting material[111], and efforts to maintain intraspecific genetic diversity[112,113,114]. Active exchange of tree germplasm is governed by several international conventions, national laws and regulations, and centre-level policies (Box 2.4).
4. Returning of the land unit to a 'forest', 'tree plantation' or 'agroforest' status, depending on locally used definition, and with consequences in the local policy context (see Chapter 8).

Box 2.4 Policies and Guidelines[115] on Genetic Resources Utilization[116]

Several international conventions, agreements and guidelines govern the use of genetic resources and the related issues of biotechnology and intellectual property rights. Research centres under the Consultative Group on International Agricultural Research (CGIAR) adhere to these international instruments and each centre develops various policy, guidelines and position statements to guide and validate their decisions regarding genetic resources. Some of the key instruments related to use and exchange of plant germplasm include:

- International Treaty on Plant Genetic Resources for Food and Agriculture **(the Treaty):** The objectives of this Treaty are the conservation and sustainable use of plant genetic resources for food and agriculture and the fair and equitable sharing of the benefits arising out of their use as expounded in the Nagoya Protocol on Access Benefit Sharing. Under the Article 15 of the Treaty, the International Agricultural Centres are guided on the conservation and exchange of germplasm held 'in trust' for international community. Such material is exchanged via the Standards Material Transfer Agreement, an agreement between the germplasm provider and recipient, developed to ensure that the provisions of the Treaty regarding the transfer of germplasm are enforceable.
- International Plant Protection Convention (IPPC) is a multilateral treaty aims to secure coordinated, effective action to prevent and control the introduction and spread of pests of plants and plant products. Under the IPPC, internationally agreed phytosanitary measures have been developed that are enforced by the National Plant Protection Organizations (NPPO). The NPPOs issue plant import permits that allow plant material entry into their countries and issue phytosanitary certificate as guarantee of cleanliness of the plant material going out of their countries. The NPPOs also list the potential invasive species and regulate their entry into the country.
- The UPOV system of Plant Variety Protection (PVP) provides and promotes an effective system of plant variety protection, with the aim of encouraging the development of new varieties of plants, for the benefit of society.

ICRAF has policies and guidelines that ensure compliance with the various international legislations relating in use of tree germplasm such as the Tree Genetic Resources Policy and the Invasive Alien Species Policy. ICRAF researchers acquire authorisation of the various host countries' NPPOs in the acquisition of agroforestry tree germplasm for research.

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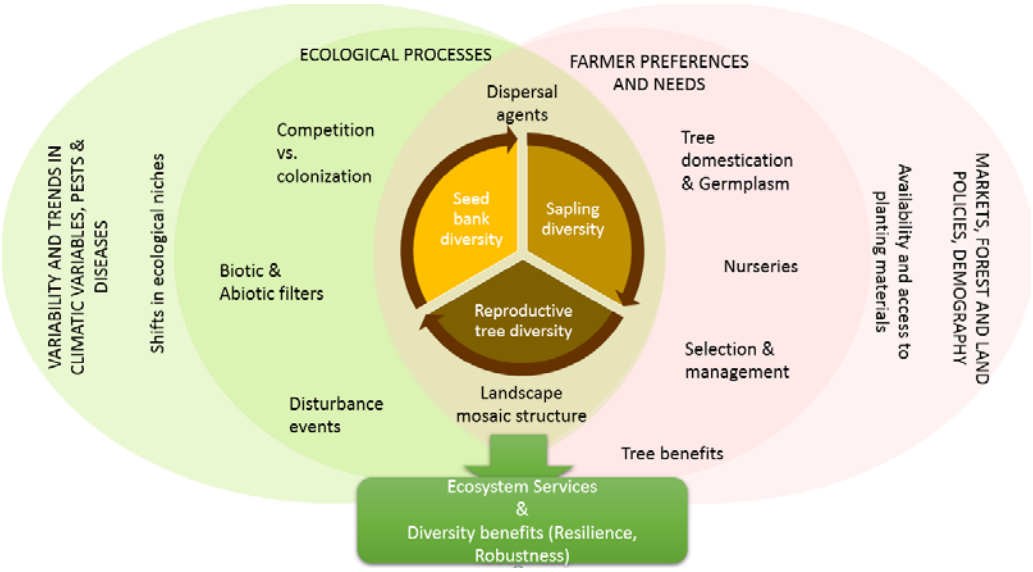

Figure 2.9 Synthesis of the ideas presented in this chapter, relating a tree life cycle perspective on natural plus anthropogenic dispersal to goods and services derived, with consequences for options to both conserve biodiversity and provide local benefits[84]

2.6 Domesticating both the tree and the agroforest

Trees and tree diversity as biological aspect of agroforestry is clearly interwoven with farmer preferences, options and opinions (Fig. 2.9), even more so than is understood for annual crops and livestock. One consequence is that the 'domestication' paradigm for trees is more complex. Box 2.1 discussed the challenge of seeing both the trees and (agro)forest. The same is true for 'domestication', where human control over biology and genetics of trees, interacts with human control over land on which to plant and grow trees[117], and the value chains that start with tree products (Fig. 2.10).

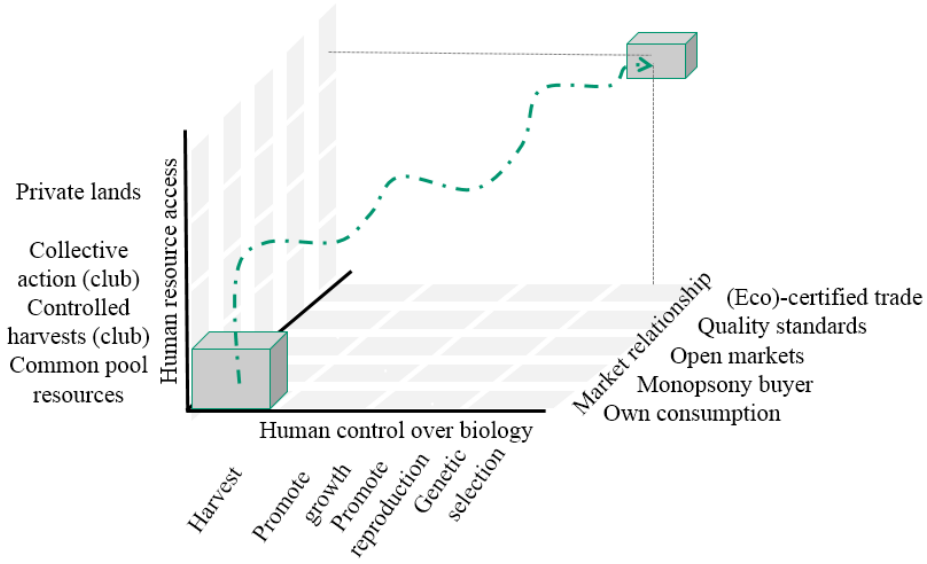

Figure 2.10 Correspondence between changes in three dimensions (human resource access, human control over biology, and market relationships) between a 'harvest of common pool resources for local consumption' and eco-certified global trade in products harvested on private lands from genetically selected' trees; the second axis has so far been the primary axis of 'tree domestication'

The general lessons for domestication of indigenous agroforestry fruit tree species learnt from 25 years of research and development efforts on peach palm[118]: 1) identify market demands, whether subsistence or market-oriented; 2) identify clients and consumers, and their perceptions of the product; 3) work on food and nutritional security aspects of the species and let entrepreneurs be attracted, rather than vice versa; 4) take up species improvement in a moderately sized effort, using a participatory approach tightly focused on clients' demands; and 5) reappraise the priorities from time to time.

Domestication of non-timber forest products such as Eaglewood can be expected to have winners and losers[119]. Domestication of other parts of the forest than trees may have faster returns and better prospects for local income enhancement[120]. Current domestication for specific environments such as tropical peats[121,122] may be driven by environmental considerations (reduced need for drainage) but challenged in its market dimension.

The shift from a laboratory-based to farmer-participatory approach[123,124] to tree domestication has built in the feedback loops to keep the complexity of Fig. 2.10 in the purview of adaptive project management (if the donors understand and accept changes that arise). Chapter 3 will discuss this issue in more depth.

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