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Mixed species plantations and their potential role in innovative production systems for forest restoration

Lessons from Latin America, sub-Saharan Africa, South and Southeast Asia

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1 Summary

Large-scale timber plantations are controversial in many parts of the world for numerous reasons, including direct and indirect land-use changes and associated impacts on a variety of ecosystem goods and services. The use of mixed-species plantations for commercial and restoration reforestation purposes is gaining interest both as an option to support the supply of wood, and to contribute to meeting international agendas on the restoration and provision of ecosystem services. Yet there are few experiences of mixed-species plantations, and those that exist are poorly documented. In this report, we review and synthesize the state of mixed-species plantations in South and Southeast Asia, Latin America and sub-Saharan Africa, as well as examine their potential role as a novel production system that supports commercial reforestation efforts, environmental and socioeconomic resilience and restoration.

For each geographic region, different scopes and depths of analysis were carried out based on information availability. For Latin America, our wide-ranging literature review encompassed primary sources, research articles and books from 2004 to 2019, found through web-based research engines and international and regional databases. From this initial search 140 potentially relevant articles were retrieved, but only 49 relevant articles were selected for further critical analysis as they directly discussed the performance of mixed plantations. The sub-Saharan Africa literature review was structured around a historical timeline of mixed plantations from 1920 to the present day and was dependent on the availability of public records. For South and Southeast Asia, the literature review included a range of literature on timber plantations published between 2004 and 2019.

In Latin America, most of the studies undertaken focused on research plots in Costa Rica, Brazil and Panama. The focus of 69% of the studies was on evaluating growth performance (i.e., height and diameter growth, survival, plot productivity) as well as site and species selection (i.e., types of combinations), together with the silvicultural management of mixed-species stands. Around 22% of the published studies examined the physiological performance and conservation value (biodiversity) of different species combinations, at either the plot or landscape level. Trends in growth productivity were identified for local native species, and specific management practices, aiming to increase survival rates among planted species, were also recorded. Generally, mixed-species plantations were considered to be among the most effective and available approaches available to restore degraded land (i.e., eroded soils, pastureland) as well as to facilitate the regrowth of forest-dependent species within agricultural landscapes (i.e., nurse species).

In sub-Saharan Africa, the Côte d'Ivoire was the country with the highest count of studies conducted on mixed plantations. Mixed-species plantations experiences were also documented in other countries including Republic of Congo, Democratic Republic of Congo, Ghana and Madagascar. The review was divided in two periods; in the first, mixed-species plantations were promoted and documented, both as part of the colonial legacy, as well as in more recent experiences

from the 1980s and 2000s. From the 1990s there was increasing focus on agroforestry systems in Africa, with less interest/published information on mixed-species plantations. The majority of studies examined research/experimental plots that, for the most part had been established in the last two decades.

In South and Southeast Asia, Indonesia and India were the countries with the biggest share of studies/reports on mixed-species plantations. Most evidence is based upon research plots, together with a few NGO-led reforestation projects.

In general, across the three geographical focus areas, we found that studies on mixed-species plantations focused on evaluating growth performance and silvicultural management of species combinations, compared to monocrops or valuable commercial species. The growth performance results of mixed plantations are varied and dependent on the species. In some cases, for example in Panama and Costa Rica, where the focus of plantations were native species, the species growing in the mixture had better growth than their counterparts growing in monocrop plantations. However, in Brazil where the focus is on commercial high-productive plantations, we found that *Eucalyptus* had greater biomass per area when growing in monocrops than in mixed plantations. In the Côte d'Ivoire, *Cedrela odorata* was reported to grow better in pure stands than in mixed (*C. odorata* and *Terminalia ivorensis*). Other studies reported on species combinations in terms of survival and growth.

Few studies reported on the financial or business case for mixed plantations versus monocrops. In Costa Rica, it was reported that mixed plantations financially outperformed monocrops with Net Present Value (NPV) of between USD 1,124 and 8,155 per hectare, and Internal Rate of Return (IRR) of between 7.7% and 15.6%, depending on the species mixture. In sub-Saharan Africa, a lack of information on species combinations, establishment costs and the benefits of mixed plantations had a negative influence on continuing research into and promotion of mixed plantations during the 1990s.

We would strongly recommend a more extensive review of the policies and incentives that are available to promote different plantation schemes, so as to increase the likelihood of meeting production, restoration and conservation goals in the three regions.

Keywords: timber plantation, native species, restoration, growth, species combinations.

2 Introduction

Planted forests are becoming an increasingly important part of the global forest estate in many parts of the world (Evans 2009; Payn et al. 2015). There are various reasons behind this trend, including a reduced supply of commercial timber from native forests, increasing demand for timber and other biomaterials from planted forests (Boucher and Elias 2013; Warman 2014; Midgley et al. 2017), and the potential role of planted forests for landscape restoration and climate change mitigation efforts (Chazdon 2008; Alexander et al. 2011). Some forty-five percent of countries' restoration pledges for the Bonn Challenge are considering the use of commercial plantations as part of their pathways for landscape restoration (Lewis and Wheeler 2019).

Reforestation, in the form of commercial forest plantations dominated by a few genera, has been one of the three approaches used to respond to forest loss and degradation across the tropics (Lamb et al 2005a). The other two approaches include: (i) the expansion of protected areas as a measure to safeguard biodiversity, and (ii) the increase of agricultural productivity in abandoned areas to improve the livelihoods of communities living in the surrounding areas (Lamb et al. 2005a).

Plantation forests – in this report referring to a planted forest managed intensively – represent approximately 3% of forest cover worldwide (FAO 2020), but this figure is expected to triple by the end of the century (Horák et al. 2019). Single species commercial plantations are favoured over other reforestation schemes mainly due to plant productivity, simplicity and well-known silviculture, however, new approaches of tree cultivation such as mixed-species systems can boost provision of ecosystem services, support climate change mitigation efforts through carbon sequestration, or reduce deforestation while complementing other existing/favoured land uses in the landscape (Paquette and Messier 2010; Barsoum et al. 2016).

Mixed-species tree plantations are not a new concept; they have been practiced successfully throughout history. In Europe, for example, it was common to mix larch (*Larix sp.*) with pine, alder (*Alnus sp.*), oak (*Quercus sp.*) and beech (*Fagus sp.*), providing early financial returns through tree thinning events (see Nichols et al. (2006) for a brief history on mixed-species plantations). The multiple benefits of mixed-species plantations to people and the environment have been acknowledged elsewhere (Kelty 2006; Nichols et al. 2006; Richards et al. 2010). Mixed plantations can expand the options of landowners/foresters when it comes to diversification, species selection (Piotto et al. 2004b, 2009; Loewe and González 2006) and their economic viability (Griess and Knoke 2010; Montagnini et al. 1995; Piotto et al. 2009). Biodiversity conservation and tree diversity are supported when native species with different life strategies are established in the mix (Redondo-Brenes et al. 2010; Brockerhoff et al. 2013; Pozo and Saumel 2018) and used with silvicultural management that is adapted to meet environmental and economic gains (Lamb et al. 2005a; Brockerhoff et al. 2013; Campoe et al. 2014).

What has been missing – and influencing negatively the adoption of mixed plantations – is available evidence of successes and failures from mixed-species combinations growing in different agroecological zones, management regimes, silvicultural practices and age structures. The lack of official statistics to record and monitor mixed-species plantations is evident throughout the tropical regions. These issues limit the possibility of supporting the scale-up of mixed plantations (Nichols et al. 2006).

The CGIAR Research Program on Forests, Trees and Agroforestry (FTA), under FP3 'Sustainable plantations and tree crop commodities', established a group of researchers to support governments (at national and subnational levels) and stakeholders to devise plantation systems that reduce harvest pressures on natural forests, while increasing the contribution of forestry and agroforestry to sustainable landscapes.

In this review, we synthesize existing evidence on the role of mixed-species plantations in three geographical regions with different biophysical, socioeconomic and political contexts. The review encompasses experiences from Latin America, sub-Saharan Africa, and South and Southeast Asia, contributing to better understanding around the potential role of mixed-species plantations on commercial reforestation efforts, environmental and socioeconomic resilience and restoration.

3 Methods

This review presents evidence on mixed-species plantations in three geographical regions. The focus and search strategy for relevant literature for each region was different and determined mainly by the availability of information. Therefore, the scope, depth and amount of information presented in the results and discussion sections will vary according to the records available. The review for the three regions encompasses a range of literature sources, including primary and secondary sources, research articles, books, conference proceedings and reviews in different languages.

For Latin America, recent and relevant literature from the period 2004 to 2019 was retrieved using different web-based search engines, including the ISI Web of Science Database, Google Scholar and other regional search engines (i.e., Redalyc, Scielo). The search string keywords used were: “mixed plantations” in combination with “management” or “productivity” or “restoration” or “biodiversity” (Figure 1). The review included literature written in Spanish, Portuguese and English. In total, 140 potentially relevant articles were retrieved. The title and abstract of each document were evaluated to identify the pool of articles to be included in the analysis. Only 49 articles were selected for review as they presented direct evidence on mixed plantations. These were then grouped into themes selected according to the attributes/processes discussed in the articles. Eight themes were identified: (1) silviculture, (2) growth performance (survival, growth), (3) physiological processes, (4) interactions (competition or complementarity), (5) support species/site selection, (6) biodiversity, (7) facilitation of restoration or succession, and (8) other (Figure 1). Cross-references from relevant papers/documents that were appropriate to our study were also examined and added to a database in EndNote. All the selected documents were screened to summarize their key findings and lessons learned from mixed plantations in Latin America.

For sub-Saharan Africa, a timeline for the promotion of the establishment of mixed-species plantations was examined, considering that most research on mixed plantations was undertaken between the 1920s and the 1980s, as a historical legacy of the former colonial technical centres in forestry and forestry departments. The literature review included documents spanning the last forty years, in both French and English. In some cases, it was not possible to retrieve the original document/report, therefore the information is provided through secondary sources (i.e., citation in more recent publications).

Relevant literature for this period was retrieved using different web-based search engines, including the ISI Web of Science Database and Google Scholar, as well as through consulting CIRAD’s own database of publications and reports (Agritrop). Most of the articles published between 1934 and 1991 had been compiled in the FAO report on mixed and pure forest plantations in the tropics and subtropics (FAO 1992). This review of more than 350 articles on forests, mixed and pure plantations compiled 58 articles and personal communications about the African context (as well as 26 for Central and South America, and 81 for Asia), of which 22 related to mixed-species plantations. Since 1992, only

11 articles on mixed-species plantations were identified and included in this review.

In the Asia-Pacific region, few mixed-species plantations have been established, or at least little information has been published, in the last two decades. The majority of plantations in this review are government research and demonstration plots, small-scale agroforestry practices and communal plantations.

This report is structured as follows – Section 3 presents a detailed description of the type of mixed plantations found in the three regions, in terms of their scale, purpose and objectives, as well as main findings and lessons learned. This information is provided in tables to facilitate and simplify the analysis of the data retrieved from the documents. Section 4 presents a discussion of those findings, considering the evidence presented in meta-analyses of papers giving a general overview of mixed plantations. Finally, Section 5 presents our conclusions and suggests a way forward.

4 Results

4.1 Latin America: Key findings

The literature retrieved included research carried out on mixed-species plantations in 14 Latin American countries, with 67% of the studies conducted across Brazil, Costa Rica and Panama. Most of the examined articles (88%) summarized information based on primary data; the remaining 14% were reviews or meta-analyses. Most of the findings/evidence of the studies were generated based on research plots (65%); with 26% of studies conducted on large- or small-scale plantations. The rest of the papers were reviews that gathered information using both research plots and large- or small-scale plantations. Most of the articles analysed focused on growth performance (69%) of the species combined/selected for the mixed stand. Species and/or site selection support, and analysis of interactions, were the second and third themes in importance. Less recurrent topics were the potential role of mixed plantations in biodiversity and physiological processes linked to productivity/use of resources (Figure 1).

Table 1a summarizes examples of species combinations, the effect on productivity, and the type of reforestation schemes found in Latin America. Overall, native species mixtures were the preferred tree species to intercrop by projects/research institutes. In general, poor growth was observed in mixtures, in comparison to more traditional tree species established in monocrops; however, mixed plantations seem to be the best option to grow valuable

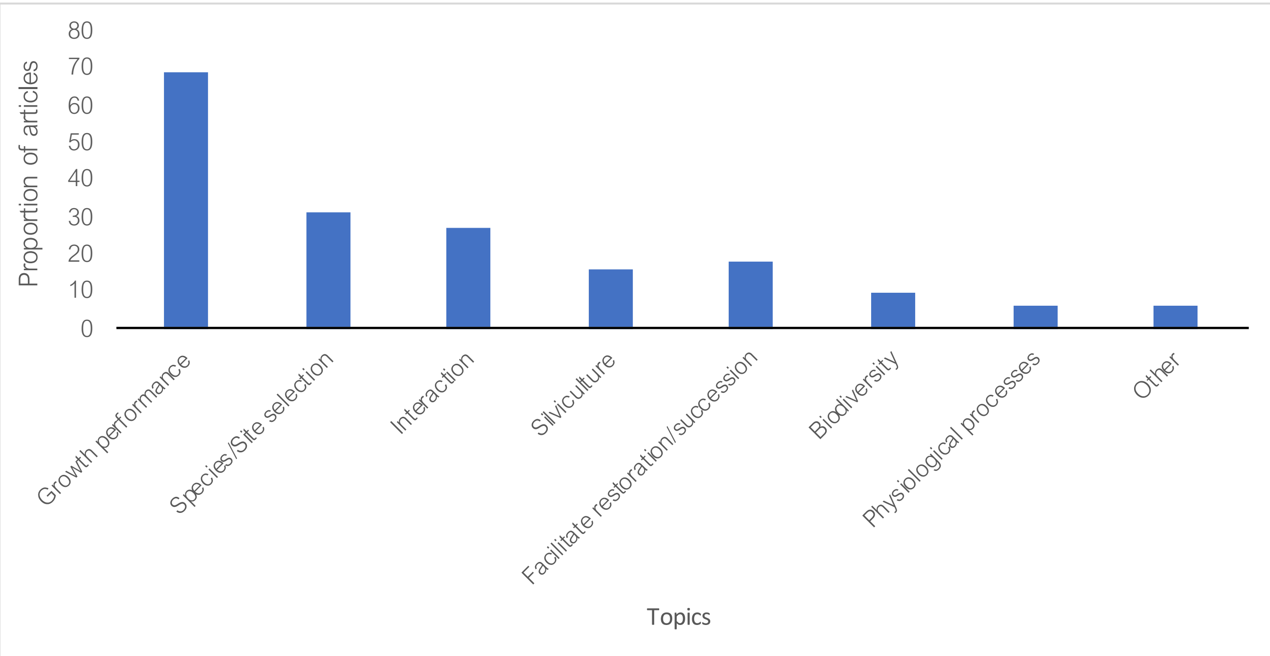

Figure 1. Topics that emerged from analysis of selected literature and used for grouping articles by theme (values in %). One manuscript can be assigned to more than one category.

Table 1a. Selected examples of species combinations, type and objective of the study, performance of mixed versus monocrops, lessons learned from mixed plantations in selected Latin American countries.

Note: The direction of response to performance is indicated with arrows. Double equal signs indicate growth performance is similar/comparable between mixed plantations and monocrops. Double dash indicates no measured/reported response for monocrops or mixed plantations.

Dimension of the study	Species combination	Country and scale of the study	Purpose of the study	Growth performance		Lessons learned	Source
				Mixed plantations	Monocrops		
Growth and productivity	*Acacia mearnsii* (A), *Eucalyptus globulus* (E)	**Brazil** Experimental research plots.	Evaluate the performance in height, diameter and wood production of Acacia mearnsii and *Eucalyptus* globulus in monocrops and mixed plantations. Length of the experiment = 8 years.	⇧ volume for Acacia ⇩ DBH for *Eucalyptus*	⇧ productivity only for *Eucalyptus*	At eight years of age, higher productivity in mixed plantations for Acacia. 50% more volume than in monoculture. *Eucalyptus* only performed better in monoculture. *Eucalyptus* experienced a decrease in diameter. DBH decrease of 17% in mixed, in comparison to monoculture.	Martins Soares et al. (2018)
Growth and Productivity	*Eucalyptus* (E) with native trees of a diverse mixed group (23–30 species)	**Brazil** Large-scale research plots in three experimental sites in a gradient of latitude, altitude, precipitation and temperature	Research on survival, productivity (wood production) and physiological performance of *Eucalyptus* in monocrops and when intercropped with a diverse group of native trees. Also, a plot with selected native trees was established.	⇩ biomass production and basal area for *Eucalyptus* and native species group. Negative effect of *Eucalyptus* on native species growth. Yield performance evaluated at 57 months of age.	⇧ for *Eucalyptus* -- for diversity group	*Eucalyptus* monoculture outperformed the high diversity mixtures in terms of biomass production. Total basal area was highest in stands of *Eucalyptus* monoculture, intermediate in mixtures (Mix of *Eucalyptus* and native tree species) and lowest in native species plots (mix of native trees of the diversity group intercropped with fast-growing, wide-canopy native tree species).	Amazonas et al. (2018a; 2018b)

Dimension of the study	Species combination	Country and scale of the study	Purpose of the study	Growth performance		Lessons learned	Source
				Mixed plantations	**Monocrops**		
Growth and productivity	Plantation model 1 *Vochysia guatemalensis*, *Jacaranda copaia*, *Calophyllum brasiliense* Plantation model 2 *Dypterix panamensis, V. koschnyi, Terminalia amazonia,* Plantation model 3 *Genipa americana, V. ferruginea, Balizia elegans, Hyeronima alchorneoides*	**Costa Rica** (humid topical lowlands) Experimental plots	Evaluate the productivity performance of native timber species growing in mixed and pure plantations on former pasturelands	== productivity (volume and basal area) Model 1: best results Evaluation 10–12 years after plantation establishment.	== productivity (volume and basal area)	The productivity performance of the species tested was similar between mixed-species and pure plantations. Plantation model 1 had the greatest figures for productivity per ha and growth and were comparable to those yielded by *V. guatemalensis* in monoculture (the species with the best performance in the whole experiment)	Alice et al. (2004)

Continued on next page

Table 1a. *Continued*

Dimension of the study	Species combination	Country and scale of the study	Purpose of the study	Growth performance		Lessons learned	Source
				Mixed plantations	Monocrops		
Growth and productivity	13 native species tested. *Platymiscium parviflorum* *Swietenia macrophylla* *Cedrela odorata* *Platymiscium pinnatum* *Astronium graveolens* *Dalbergia retusa* *Samanea saman* *Vatairea lundelli* *Terminalia oblonga* *Pseudosamanea guachapele* *Anardium excelsum* *Sterculia apetala* *Schizolobium parahyba*	**Costa Rica** (dry tropics) Experimental plots	Research on the productivity performance of native timber species	⇧ growth in DBH ⇳ growth in height (depending on the species) ⇳ for basal area (depending on the species (Evaluations at 68 months old)	⇩ growth in DBH ⇳ growth in height (depending on the species ⇳ for basal area (depending on the species) ⇧ for *T. grandis* (Evaluations at 68 months old)	*Samanea saman* and *Dalbergia retusa* top two species of the 13 native species, followed by *Astronium graveolens* and *Swietenia macrophylla*. Monocrops of *T. grandis* had greater performance for wood production commercially. Mixed plantations are an interesting option for the range of benefits that they could provide (timber production of different species in the same plot, greater survival of native species, etc.). In mixed-species plantations, a high mortality rate was reported during establishment. Certain species grew better than others. Growth of all species in mixed plantations was compared against Tectona grandis; the latter was the most productive and well adapted to the site conditions.	Piotto et al. (2004b)

Dimension of the study	Species combination	Country and scale of the study	Purpose of the study	Growth performance		Lessons learned	Source
				Mixed plantations	Monocrops		
Growth and productivity	*Prunus avium L* (cherry trees) growing in different mixed compositions/ associations. 24 combinations in six sites. *Juglans regia, Alnus glutinosa, Quillaja Saponaria, Elaeagnus angustifolia, Corylus avellane, Pyrus communis, Malus communis, Embothrium coccineum, Fabiana imbricate, Gevuina avellana*	**Chile** Experimental plots	Research on growth, pests, diseases and stem form of cherry trees under mixed plantations as a model to produce high-quality timber and limit infestation by Pseudomonas siringae pv. mors-prunorum, a common disease in cherry trees. Design of the plots included varying proportions of species combinations. Mixing was tree by tree.	⇧ growth in DBH and height	⇩ growth in DBH and height	Species associations (companion trees) and environment (soil conditions) need to be carefully studied to improve site productivity. At seven years of age cherry trees in mixed plantations performed better, had higher height (up to 28%) in 5 out of 6 sites and higher DBH (up to 34.5%) in 4 out of the 6 sites evaluated. The % of cherry trees in the mixtures ranged between 2 and 88%, depending on the complexity of the mixture.	Loewe et al. (2013)

Continued on next page

Table 1a. *Continued*

Dimension of the study	Species combination	Country and scale of the study	Purpose of the study	Growth performance		Lessons learned	Source
				Mixed plantations	Monocrops		
Growth and productivity	A mix of five species on average. Common species planted: *Pseudosamanea guachapele* *Caesalpinia eriostachys* *Samanea saman* *Simarouba amara* *Cedrela odorata* *Swietenia macrophylla* *Tabebuia rosea* *Tectona grandis* *Cordia alliodora* *Bombacopsis quinata* *Enterolobium cyclocarpum*	**Nicaragua** Smallholder forest plantations	Forest plantations for sustainable management of smallholder agricultural systems, provided as incentives via government/NGO funding/support schemes	⇧ diameter growth for some of the native species ⇩ diameter growth for majority of the species Evaluations at age 3 and 4 years old.	⇧ depending on the species	Farmers planted up to 22 different species (17 native and 5 exotic species) in different combinations and arrangements. Growth performance of the species in the mixed plantations at age 3 and 4 years was on average very low. Some species had better performance within the mixed stands than in monoculture (i.e., *Pseudosamanea guachapele, Caesalpinia eriostachys, Samanea saman*). Farmers mentioned they preferred mixed plantations because they can harvest different products and also because they are less sensitive to pest/disease attack.	(2004a)

Dimension of the study	Species combination	Country and scale of the study	Purpose of the study	Growth performance		Lessons learned	Source
				Mixed plantations	Monocrops		
Biodiversity and ecosystem function	Mixing of six tree native species planted were: *Cordia alliodora, Luehea seemannii, Anarcadium excelsum, Hura crepitans, Cedrela odorata,* and *Tabebuia rosea*	Long-term research plots established in 2001 with native species, designed for biodiversity-ecosystem function research. Plots combining three or six native species, and plots of single species representing the species in the mixtures.	Quantification of the contribution of mortality and individual growth to ecosystem function	⇧ Average basal area (ecosystem productivity) (5-year-old trees)	⇩ Average basal area (ecosystem productivity) (5-year-old trees)	The planting of mixed species could be a viable strategy to increase timber yields and preserve biodiversity in tropical tree plantations. Mixed plantations (biodiversity plots) had better results in terms of growth and productivity. Overall enhancement in individual tree height ranged between 25% and 11% respectively for three- and six-species plots compared with monocultures. Difference in tree sizes in the diversity plots evidenced first at three years of age and became more noticeable in the following years.	(2008)

Continued on next page

Table 1a. *Continued*

Dimension of the study	Species combination	Country and scale of the study	Purpose of the study	Growth performance		Lessons learned	Source
				Mixed plantations	Monocrops		
Biodiversity and ecosystem function	Unique combination of 6 native species from a pool of 18, in 4 composition combinations C1: *Anacardium excelsum, Cordia alliodora, Cedrela odorata, Hura crepitans, Luehea seemannii* and *Tabebuia rosea* C2: *Enterolobium cyclocarpum, Bursera simaruba, Calycophyllum candidissimum, Inga punctata, Erythrina fusca* and *Astronium graveolens* C3: *Ormosia macrocaly, Pseudosamanea guachapele, Guazuma ulmifolia, H. crepitans, E. fusca* and *T. rosea* C4: *A. excelsum, Spondias mombin, C. odorata, Dipteryx panamensis, Albizia adinocephala* and *T. rosea*	**Panama** Long-term research plots established in 2005 with native species and designed for biodiversity-ecosystem function research at scales relevant to forest management.	Evaluate the effect of tree composition (diversity) on plot productivity. There was no comparison with monoculture plots; this is because in previous studies carried out in the same research plots, tree species had better growth in mixed plots than in monoculture plots.	--	--	Gazuma ulmifolia, S. mombin, L. seemannii and A. excelsum performed highly and were of interest to ≥ 80% of farmers. Species were generally consistent in size between compositions. Survival rates of individuals species do not reflect composition productivity. In year 10, the mean plot basal area did not differ significantly between species compositions. Species identities were most important in determining plot productivity.	Salisbury and Potvin (2015)

Dimension of the study	Species combination	Country and scale of the study	Purpose of the study	Growth performance		Lessons learned	Source
				Mixed plantations	Monocrops		
Land restoration (former pasturelands)	Mixture of *Tabebuia rosea, Anacardium excelsum* and *Cedrela odorata* and monocrops of the same three species	**Panama** Experimental plots – pasture afforestation. Plots established in 2006.	Improve the knowledge on silvicultural management and planting schemes on degraded pasturelands, as the planting of native tree species is perceived as risky by smallholder farmers.	⇧ growth -- Survival Evaluation at 3–5 years of age	⇩ growth -- Survival	Planting schemes did not influence tree survival. Strong positive effect of mixed stands planting scheme (3-species-mixtures) combined with management practices (like insecticide application) on growth height and basal stem diameter compared to pure stands. *T. rosea* had greater rate survival and better growth. *C. odorata* had the lowest survival rate and growth.	Plath et al. (2011); Riedel et al. (2013)
Land restoration	*Pinus cembroides, P. greggii, P. devoniana* and *P. Pseudostrobus*	**Mexico** Experimental plots with different combinations of *Pinus* spp. tolerant to eroded soils and at different slope conditions	Response of selected tree species to degraded soil conditions as a measure to facilitate ecological succession and restoration of tree cover	⇧ survival rate for 3 of the 4 *Pinus* spp planted. ⇧/- for height ⇳ Year 5 of evaluation	--	Mixed plantation of *P. devoniana* y *P. greggii* good option to restore degraded soils under the conditions studied *P. greggii* can be used as a nurse species in the early stages of succession to facilitate the establishment of native species. Height performance at five years after planting: 76–332 cm	Gómez-Romero et al. (2012)

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Table 1a. *Continued*

Dimension of the study	Species combination	Country and scale of the study	Purpose of the study	Growth performance		Lessons learned	Source
				Mixed plantations	Monocrops		
Land restoration	Out of 45 species listed, 7 common native species established: Alnus acuminata *Baccharis bogotensis, Cedrela montana, Myrica, pubesens, Quercus humboltii, Sambucus nigra, Smallanthus pyramidalis*	**Ecuador** and **Colombia** 12 reforestation projects fostered by government institutes and local NGOs to restore native tree cover in degraded soils	Growth analysis of 7 common native species on 12 montane forest sites across the northern region of the tropical Andes	--	--	Combination of native species a good opportunity to restore native tree cover in degraded areas. Growth responses were attributed to soil nutrient conditions Different planting designs: multi-species plots, scattered trees. Native species can grow in a variety of soil conditions, and exhibit growth rates comparable to non-native species. Native species are site restricted.	Bare and Ashton (2015)

native timber species, as higher survival rates were reported for species growing in mixed plantations than the same species growing in monocrops (Table 1a; Piotto et al. 2004b, 2010); in some cases, growth results for native species were in the same range as non-native popular species (Table 1a; Alice et al. 2004; Potvin and Gotelli 2008).

The decision on the type of tree species to intercrop varies according to the objective of the research/project, country and plant availability. For example, in Brazil, reported species combinations were *Eucalyptus* with *Acacias*, or *Eucalyptus* with several native species, whereas in Costa Rica and Panama, mainly native species were used in the mixtures studied. Similarly, in Nicaragua and other Latin American countries, examples of mixed plantations included the combination of valuable native timber tree species with valuable exotic species (Table 1a; Piotto et al. 2004b, 2010; Campoe et al. 2014).

As we can see from the examples presented in Table 1a, mixed-species plantations have been evaluated under a range of management regimes, purposes and environmental conditions. These results provide evidence of the possibilities mixed-species plantations offer for both various reforestation plantation schemes and tree products, as well as for the acceleration of ecological succession (tree recovery) in degraded soils, and increasing tree species diversity at farm level. The combination of species used in the mixed stands was context/site dependent. In most cases, the mix provided evidence of complementarity or competition (interactions) between species in intentional mixes. In some cases, combinations included legume, multipurpose and native timber trees, or a mix of fast-growing species with slower-growing species (Table 1a, see examples in Brazil, Panama and Nicaragua). In some cases, the mixed-species systems highlighted the opportunity to use native tree species alongside valuable commercial species at the landscape level, to support the country-level restoration agendas (see Amazonas et al. 2018b) as well as to provide evidence of the suitability of new approaches (mixed stands) to produce wood-based products (Loewe et al. 2013; Amazonas et al. 2018a). In Brazil, in mixed-species stands of 50% *Eucalyptus* intercropped with a high diversity of other trees, *Eucalyptus* trees grew larger (Amazonas et al. 2018a).

In Panama and Costa Rica, the mixed-species plantations of native species grew better (in terms of stem growth performance) or had similar performance when compared to the same species growing in monocrops or when compared to valuable common tree species grown in commercial plantations (Table 1a; Alice et al. 2004; Piotto et al. 2004b). On the contrary, in Nicaragua, the native species growing in mixed-species plantations performed poorly (in stem performance and survival rates) in comparison to valuable non-native species; however, farmers expressed that mixed-species plantations were a better choice for them because they can harvest different products (diversification) and reduce the risk of pest attacks (Piotto et al. 2004a). According to Piotto et al. (2010), mixed-species plantations of native species of 15–16-year-old trees, established on degraded pasturelands at La Selva Biological Station, Costa Rica, outperformed pure plantations financially, with Net Present Value (NPV) of USD 1,124–8,155 per hectare (ha) and Internal Rate of Return (IRR) of 7.7–15.6%, depending on the species mixture. The figures reported for the most profitable pure plantations were for *Vochysia guatemalensis* which had a NPV and IRR of USD 6,035/ha and 14.3%, respectively; for *Hieronyma alchorneoides* a NPV of USD 2,654 and IRR of 10.8%; and for *Virola koschnyi*, a NPV of USD 1,906/ha and IRR of 9.22%. Unfortunately, we did not find extensive evidence on the financial aspects of mixed-species plantations, or the perceived benefits by landowners.

Mixed-species plantation approaches were also mentioned as an important practice in restoration and biodiversity conservation efforts. In Mexico, mixed plantations, combining several species of the genus *Pinus*, were used to restore eroded soils (see Gómez-Romero et al. 2012 and Table 1a). In Colombia and Ecuador, restoration projects used mixed plantation designs to restore the tree cover of important local hotspots in the tropical Andes (Bare and Ashton 2015). Similarly, Redondo-Brenes et al. (2010) in Costa Rica reported the value of multi-species plantations, both in terms of connectivity and as a buffer of remaining forest patches in the national biological corridor for tapir. In

Colombia, Castaño Villa et al. (2008) highlighted the positive effect of mixed plantations on bird communities (not shown in Table 1a).

Table 1b presents a summary of the positive reported effects of mixed plantations on processes related to restoration and biodiversity conservation. The studies presented as evidence are informative/exploratory and are not necessarily comparing the reported benefits against other land uses or pure plantations.

4.2 Sub-Sahara Africa: Key findings

There are few recent experiences of mixed plantations in Africa, even at the experimental level. Most research on mixed plantations has taken place between the 1920s and the 1980s, as a historical legacy of the former colonial technical centres in forestry and forestry departments (see Table 2b).

Côte d'Ivoire was a forerunner in this field with the establishment of several trials of mixed plantations in the early 1960s. In total 21 different mixtures of native species were tested for comparison with pure plantations in this country, by the CTFT (the former Forest Department of CIRAD). Other similar experiments have been done in Benin, Cameroon, Congo, DRC, Nigeria, Togo and Uganda. In these field experiments a wide range of species were tested and different parameters evaluated; several of these plots (Table 2a) were exploratory studies on silviculture and management, without necessarily a statistical design but with a marked interest in testing and demonstration (Marien and Mallet 2004). The main variables collected were diameter, height and mortality (Table 2b). In the case of Ghana experimentations (where *Milicia excelsa*/*Terminalia superba* mixed in different percentages were compared with *Milicia excelsa* pure plantations), neither survival nor growth was influenced by density of Milicia in a plot (Bosu et al. 2006). In other examples, in Burundi, plots of *Eucalyptus* grandis mixed with Acacia elata were established, and one of the reported results was the poor survival of *A. elata*. Similarly, in Burkina Faso, the combination of Dalbergia sissoo and *Eucalyptus* tereticornis favoured the growth of *D. retusa*.

In 1991, a FAO report (FAO 1991) compiled knowledge acquired on pure and mixed plantations, drawing heavily from a CTFT publication. The main lessons learned from this report are:

- Initial experimentation focused on reducing pathological and silvicultural issues (arrangement/configuration, pruning). Two types of plantation modalities were presented:

    1. A two-layered canopy, with a main species to be favoured during silvicultural treatments and a companion species (for example, to form an emergent tree cover/canopy, full coverage of the emergent canopy to be cut at the first thinning, or to improve stem form). This modality can be either a temporary mixture (with the expected outcome being a single species stand) or permanent (resulting in a multi-species stand).

    2. A single-layered canopy (a permanent mixture, with the expected result being a multi-species plantation). The objective here is to create a synergy

Table 1b. Overview of the reported effects of mixing species on restoration biodiversity

Process/targeted function	Reported effect	Examples
Land restoration and tree cover regeneration	Nurse trees	Barbosa et al. (2009); Salomao et al. (2014); Avendaño-Yáñez et al. (2016); Cole et al. (2011)
	Recovery of forest species via direct seeding on mixed plantations	
	Identification of species better adapted/ suitable to harsh conditions after mining	
Biodiversity	Positive for bird richness	Castaño-Villa et al. (2008)

between two (or more) species of identical silvicultural importance. In this case, both species must have similar growth patterns and silvicultural management needs, in particular for plantation density, age, intensity of thinning and rotation time. For example,, *Terminalia ivorensis* as main species with *Terminalia superba* as secondary species – however this secondary species can replace the main species if insufficient growth is reported, and a single-species stand remains. The mixture of slow-growing ***Khaya spp*** or *Entandrophragma spp* with fast-growing *Terminalia spp* or *Triplochiton scleroxylon* is therefore unlikely to be successful, while mixtures of species with similar growth rates like *Terminalia superba*, *T. ivorensis* and *T. scleroxylon* do have a chance of success (FAO 1991).

Key lessons from this West African experience are that successful mixtures for wood production depend on the careful matching of species to site, as well as a knowledge of which species are ecologically and silvicultural compatible (FAO 1991, 1992). In this case, plantation politics and strict economic imperatives led to the selection of: (i) species whose multiplication is easy and for which the financial return is good; (ii) light demanding species with high initial growth, to limit the amount of maintenance required; (iii) species with high stem volume growth and therefore medium length rotation. One of the goals of this option was to provide short-term tree products and reduce pressure on natural forests.

The need to continue research into the silviculture of mixed timber plantations was highlighted, especially for: (i) the development of growth models for the different species used in industrial reforestation, in pure and mixed stands; and (ii) installation or monitoring of complementary plots for species for which silvicultural practices are still in the experimental phase.

In the 1990s, research on mixed plantations gradually gave way to research on sustainable forest management, considered to be a cheaper and easier way to produce wood than plantations, given the high uncertainties on species combination, and the lack of economic data on installation costs and profitability. As a consequence and due to security conditions, these experimental plots have not been updated since the late 1990s.

Interest in mixed plantations with native species has recently reappeared in Africa, linked to the issues of restoring degraded land and reduced wood resources available in secondary forests. The TreeDivNet platform (https://treedivnet.ugent.be/), connecting experiments worldwide in tree diversity, is an indication of the under-representation of Africa in this network; of the 26 experiments registered in the platform, only 2 are based in Africa (https://treedivnet.ugent.be/;Verheyen et al. 2015):

- Gazi Bay (Kenya), a mangrove diversity and restoration experiment established in 2004. Three mangrove species were planted at an open, degraded site that had been a mangrove forest 35 years before. Its key goals were to study (1) the potential for mangrove restoration and (2) the effects of species richness on ecosystem recovery.
- ForestInnov (Tené Forest, in Côte d'Ivoire), is a 25 ha (49 * 0.5 ha) experiment set up in 2019. Sixteen local species are tested in monoculture and over a gradient of functional diversity (2, 4, 8, 16 species mixture).

In Table 2b are summarized recent experiences on mixed plantation established for different purposes. Topics evaluated range from nutrients in soils to fungal diseases affectations to growth and farmers preference. Combinations of species are country specific.

The CTFT, one of the institutions providing technical assistance on forest plantations in Africa between 1949 and 1991 (which then merged with the other French tropical technical institutes within CIRAD), initiated several experimentations on pure and mixed timber plantations. From the 1960s, the colonial stations and experimental plantations were progressively handed over to the newly-independent African states. During this period, the CTFT produced many technical reports (unpublished in scientific reviews), several of them remaining in paper version in the archives

Table 2a. Examples of species combinations experimented in mixed plantations between 1949 and 1999, in selected countries in sub-Saharan Africa. Blank cells = no information/data available. / =combination mixture, = models of species combination.

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
Burkina Faso	*Dalbergia sissoo/ Eucalyptus tereticornis*		Experimental plots. Established 1967	Treatments have favoured *D. sissoo*	CTFT (1991)
Burkina Faso	*Eucalyptus camaldulensis/*		Experimental plots. Established 1980		CTFT (1991)
Burundi	*Eucalyptus grandis/ Acacia elata*		Experimental plots. Established 1987	Poor survival for *A. elata*	
Cameroon	*Khaya senegalensis/ Azadirachta indica/ Dalbergia sissoo*		Experimental plots. Established 1983		CTFT (1991)
Cameroon	*Khaya senegalensis* (20%)/ *Dalbergia sissoo* (80%)	1.7 ha, 4 m x 4 m	Experimental plots. Established 1986		CTFT (1991)
Cameroon	*Khaya senegalensis/ Eucalyptus camaldulensis*		Experimental plots. Established 1983	Low survival for Khaya	CTFT (1991)
Cameroon	*Pinus elliottii* (90%)/ *Entandrophragma cylindricum* *P. elliottii* replaced by *M. altissima*		Experimental plots. Established 1975	Slow growth observed. High survival rates for *E. cylindricum*	CTFT (1991)
Republic of Congo	*Acacia auriculiformis/ Eucalyptus tereticornis*		Experimental plots. Established 1984		CTFT (1991)
Republic of Congo	*Araucaria hunsteinii/ Pinus caribaea*		Experimental plots. Established 1980	Constant height differences recorded.	CTFT (1991)
Republic of Congo	*Entandrophragma angolense/ Acacia auriculiformis/ Letestua durissima*		Experimental plots. Established 1982	Good condition but poor growth for *A. auriculiformis.*	CTFT (1991)
Republic of Congo	*Tectona grandis/ Terminalia superba*	Individual mixture	Experimental plots. Established 1988		CTFT (1991)

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
Democratic Republic of Congo (DRC)	*Eucalyptus/Pines/ Grevilia robusta/Acacia decurrens, Cupressus lusitanica/ Eucalyptus grandis/ Acacia decurrens*	Technique based on Anderson's groups (Anderson 1953)	Experimental plots. Groups of 37 plants at close (0.5m) spacing within the groups	10 m spacing between the groups in a matrix of natural bush. Measures of growth (30 months)	FAO (1992)
DRC	*Acacia auriculiformis/ Acacia mangium/ Maesopsis eminii/ Pinus caribaea*				FAO (1992)
Ethiopia	*Grevillea robusta/Eucalyptus grandis,* *Pinus radiata* (25%) with *Pinus patula* or *Cupressus lusitanica*	Line mixture	Research on management	*G. robusta* planted into a coppiced of *E. grandis* stand of low stocking – showing promise. *Grevillea* is not browsed by duiker.	FAO (1992)
Gabon	*Aucoumea klaineana* (monospecific plantation or in mixture with 25 species)	Monospecific plantation and in mixture	Experimental station of Ekouk (total of 269 ha of plantations, monospecific or in mixture)	The experimentation does not offer crucial information about *Aucoumea klaineana* development in mixture.	Marien and Mallet (2004)
Côte d'Ivoire	*Cedrela odorata/ Terminalia ivorensis*	Individual mixture	3 ha. Experimental plots in Mopri. Established 1965	Productivity of pure stands of *C. odorata* was higher than stands of *C. odorata* and *T. ivorensis* mixed.	CTFT (1990) (unpublished)
Côte d'Ivoire	*Funtumia elastica* (Pouo)/ *Entandrophragma utile* (Sipo)		Experimental plots (0.8 ha, 1964 in Anguédédou)		CTFT (1991)
Côte d'Ivoire	*Heritiera utilis* (Niangon)/ *Aucoumea klaineana* (Okoumé)		Experimental plots, Anguédédou (3 ha, 1964) and Yapo (2.5 ha, 1965)		CTFT (1991)

Continued on next page

Table 2a. *Continued*

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
Côte d'Ivoire	*Heritiera utilis* (Niangon – experimental and filling function) 75%/ *Khaya ivorensis* 25% (Acajou Bassam)	7 m x 3.5 m in Yapo, thinning at 14 years (50% of the Niangon, 33% of the Acajou). 7.15 m x 3.60 m in Anguédédou growing under poisoned undesirable secondary species	Experimental plots, Anguédédou (1 ha, 1964) and Yapo (2.5 ha, 1965)	At 28 years, DBH= 35cm for Niangon and 39cm for Acajou (65% of stems are Niangon)	Dupuy and M'bla (1993)
Côte d'Ivoire	*Heritiera utilis* (Niangon)/ *Tieghemella heckelii* (Makoré)		Experimental plots in Anguédédou (1 ha, 1964).	Incompatible growth rates	CTFT (1991)
Côte d'Ivoire	*Heritiera utilis* (Niangon)/*Khaya ivorensis* (Acajou Bassam)/ *Aucoumea klaineana* (Okoumé)		Experimental plots (2.1 ha). 1961 in Yapo.	At 18 years (250 stems/ha): Khaya D=24.5 cm, Aucoumea 32.8 cm (Abbé station).	Dupuy (1985)
Côte d'Ivoire	*Khaya ivorensis* (Acajou Bassam) with *Triplochiton scleroxylo*n (Samba) or *Tieghemella heckelii* (Makoré, 25%)	Individual mixture.	Experimental plots (1 ha for each mix). 1964 in Mopri.	Mixture to be avoided due to incompatible growth rates	Dupuy (1985)
Côte d'Ivoire	*Khaya anthotheca* (Acajou blanc)/ *Cedrela odorata* (Cedrela)		Experimental plots (0.8 ha, 1980 in Mopri).		Dupuy (1985)
Côte d'Ivoire	*Khaya ivorensis* (Acajou Bassam)/ *Nauclea diderrichii* (Badi)	200–400 stems/ha or 1,100 stems/ha.	Experimental plots (0.95 ha, 1986 in Yapo).	Both species can be planted together in both densities.	Dupuy and M'bla (1993)
Côte d'Ivoire	*Khaya ivorensis* (Acajou Bassam)/ *Triplochyton scleroxylon* (Samba)/ *Terminalia ivorensis* (Framiré)/ *Aucoumea klaineana* (Okoumé)/ *Terminalia superba* (Fraké)/ *Cedrela odorata*		Experimental plots (0.3 ha, 1979 in Yapo).	*C. odorata/T. ivorensis* must be avoided (incompatible growth rates).	Dupuy (1985)
Côte d'Ivoire	*Milicia excelsa* (Iroko)/ *Terminalia ivorensis* (Framiré)		Experimental plots (1 ha, 1967 in Sangoué).	*T. ivorensis* did not present good results with species other than *T. superba* and Teak.	Dupuy (1985)

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
Côte d'Ivoire	*Milicia excelsa* (Iroko)/ *Terminalia ivorensis* (Framiré)/ *Tectona grandis* (Teak) /*Afzelia africana* / *Pinus* sp		Experimental plots (10.5 ha, 1981 in Sangoué).	*Terminalia* (principal species, 200–300 stems/ha) can be mixed with Teak (1,000 stems/ ha). Both will be harvested all at once.	CTFT (1991)
Côte d'Ivoire	*Pericopsis elata* (Asamela)/ *Entandrophragma utile* (Sipo)		Experimental plots, Mopri (0.5 ha, 1964) and Yapo (1.5 ha, 1987)		CTFT (1991)
Côte d'Ivoire	Terminalia ivorensis (Framiré)/ *Terminalia superba* (Fraké)	1,100 stems/ha, or 412 stems/ ha. 50%/50%, 25%/75% and 6%/94%.	Experimental plots, Mopri (1 ha, 1964) and Sangoué (3.7ha, 1976)	Rate of mixture does not appear to affect growth of either species. Silvicultural methods depend on which species is to be favoured in the thinning. Final trees with annual diameter growth of 4 cm/year.	Dupuy (1989b, 1995); CTFT (1991)
Côte d'Ivoire	*Terminalia superba* (Fraké)/ *Khaya ivorensis* (Acajou Bassam)		Experimental plots, Mopri (5 ha, 1964–1965)		Dupuy (1985); Dupuy and M'bla (1993)
Côte d'Ivoire	*Terminalia ivorensis* (Framiré) with *Cedrela odorata* (Cedrela) or *Khaya ivorensis* (Acajou Bassam) or *Entandrophragma utile* (Sipo)	8 m x 8 m	Experimental plots (3 ha, 2 ha and 1 ha for each mix). 1965 in Mopri.	Terminalia does not have a better growth than in pure plantation, and the mixture extends the rotation (40–50 years for Khaya, 70 years for E. utile. Satisfactory growth of Khaya.	Dupuy (1985); Dupuy and M'bla (1993)
Côte d'Ivoire	*Tieghemella heckelii* (Makoré)/ *Entandrophragma angolense* (Tiama)		Experimental plots, 1992, Mopri (0.3ha), Yapo (1 ha)		CTFT (1991)
Côte d'Ivoire	*Gmelina arborea/ Acacia auriculiformis*	50%/50%, 25%/75% and 6%/94% were compared	Experimental plots, 1985	Rate of mixture does not appear to affect growth of either species. Silvicultural methods depend on which species is to be favoured in the thinning. Severe insect attacks.	Dupuy (1989a), cited in FAO (1992)

Continued on next page

Table 2a. *Continued*

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
Côte d'Ivoire	*Cedrela odorata/ Gmelina arborea*	Line mixture	Experimental plots, 1976, Sassandra	After 4 years, *C. odorata* was co-dominant.	CTFT (1991)
Côte d'Ivoire	*Heritiera utilis* (Niangon) in lines with other species: *Khaya spp* (Acajou), *Lophira alata* (Azobé), Dibétou, Sipo, Tiama		Plantations	More than 10,000 ha planted between 1931 and 1946. Density 200 to 400/ha.	Dupuy and Chezeaux (1994)
Côte d'Ivoire	*Heritiera utili*s (Niangon) in lines with *Khaya spp* (Acajou bassam)	High-density undergrowth plantations (2,500/ha)	Plantations	A few ha	Dupuy and Chezeaux (1994)
Côte d'Ivoire	*Heritiera utilis* (Niangon) with *Aucoumea klaineana* (Okoumé) or *Khaya spp.*	Medium-density undergrowth plantations (400–500/ha).	Plantations	1,500 ha planted between 1965 and 1975.	Dupuy and Chezeaux (1994)
Côte d'Ivoire	*Triplochiton scleroxylon* (Samba) / *Tectona grandis* (Teak)	--	Experimental plots, Sangoué (2 ha, 1966)	Measures of architectural profiles	Dauget et al. (1990)
Côte d'Ivoire	*Triplochiton scleroxylon* (Samba)/ *Cordia sp.*	--	Experimental plots, Sangoué (3.7ha, 1976)		CTFT (1991)
Côte d'Ivoire	12 species, planted in lines (5 trees, 2 m between trees).	--	Experimental plots in Korhogo (0.77 ha, 1991)	Research on seedlings development in nursery and plantation.	CTFT unpublished
Kenya	*Cupressus spp./Grevillea robusta*	Line mixture.		Trees were not compatible and as a result the cypress neighbouring the G. robusta lines developed severe butt sweep. Competes on equal terms up to the age of 15 years, but must be thinned heavily because of spreading crown causing butt sweep in the Cypress. Practice discontinued by mid 1950s.	Graham (1949), cited in FAO (1992)

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
Madagascar	*Eucalyptus robusta/ Acacia mangium*		Experimental plots. Established 1988		CTFT (1991)
Nigeria	*Acacia tortilis/ Acacia nilotica/ Balanites aegyptiaca/ Anogeissus leiocarpus/ Dalbergia sissoo*	8 plots of 25 trees, 5 trees of each species, randomly planted.	Experimental plots. Established 1984		CTFT (1991)
Nigeria	*Azidarachta indica/ Crotolaria striata, Chlorophora excelsa/ Teak,* *Cola cordifolia/Teak,* *Khaya grandifoliola/ Teak,* *K.grandifoliola/* *T. scleroxylon,* *K. senegalensis/ Dalbergia sissoo, K.senegalensis/ Teak Mansonia altissima/ Crotolaria striata*	4 m x 2.4 m	Research	*C. excelsa/Teak, C. cordifolia/ Teak* (suppressed but healthy and 80% survival, introduced to modify adverse effect on the soil). *K. grandifoliola/Teak* (at age 20 well above Teak (21 m) – a good mixture). *K. grandifoliola* overtopped by *T. scleroxylon.* Fungal attack on *D. sissoo*, heavy borer damage in *K. senegalensis.*	MacGregor (1934), cited in FAO (1992)
Nigeria	*Erythrophleum ivorense/ Nauclea diderrichii* *Lophira alata/* *Teak*			Unsuccessful	Henry (1960), cited in FAO (1992)
Nigeria	*Tectona grandis/ Cassia siamea*				Streets (1962), cited in FAO (1992)

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Table 2a. *Continued*

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
Nigeria	*Lovoa trichilioides/ Entandrophragma utile/ Nauclea diderrichii* (which can be exploited for poles at 15 years)	Taungya. 3.7 m spacing. *Nauclea* removed at 12 to 15 years of age. *Meliaceae* harvested at 60 to 70 years.	Experimental plots planted in 1960s. Research on management and economics.	The greatest success has been achieved with *Nauclea diderichii*, pure or in 5:1 mixture with *Meliaceae*. IRR for *Nauclea* in a rotation of 60 years was 4.5% whereas when it was mixed 5:1 *Meliaceae* the IRR was 4.6% (Ball 1979).	Lamb (1991) and Lowe (1991), cited in FAO (1992)
Senegal	*Eucalyptus* camaldulensis with: *Acacia holosericea, Albizia lebbek, Anacardium occidentale, Azadirachta indica, Cassia siamea, Casuarina equisetifolia, Prosopis chilensis*		Experimental plots. Established in 1979.	The only combination with normal growth is that between *E. camaldulensis* and *A. indica*.	CTFT (1991)
South Africa	*Acacia melanoxylon* with *Pinus radiata*, and with *E. diversicolor/ E. microcorys.*			Mixture with *Pinus radiata* being tried because that species was thought to have deeper rooting and was more wind stable but proved just as liable to wind throw. *Acacia/Eucalyptus* mixtures also unsuccessful, *Acacia* suppressed.	Zwaan (1981), cited in FAO (1992)
Tanzania	*Cinamomum camphora/ Juniperus procera*				Streets (1962), cited in FAO (1992)
Togo	*Eucalyptus torelliana/ E. tereticornis*	Line mixture	AFRI experimental project.	*E. tereticornis* has proved to be the more competitive of the two. Considered as a success.	Farrichon (1987)

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
Uganda	*Chlorophora excelsa* with *Eucalyptus, Cassia siamea, Vernonia amygdalina, Markhamia platycalyx*				Dawkins (1949) and Streets (1962), cited in FAO (1992)
Uganda	*Chlorophora excelsa with Artocarpus sp, Canarium schweinfurthii/ Ceara rubber/ Clausena anisata/ Cassia bicapsularis/ Euphorbia tirucalli/ Ficus spp/ Toona serrata/ T. ciliata*			Considered to be a failure for unspecified reasons.	Dawkins (1949), cited in FAO (1992)
Uganda	*Cholorophora excelsa/ Khaya grandifolia, Phyllanthus discoideus/ Gmelina arborea*			Has worked well on 'better' sites	Dawkins (1949), cited in FAO (1992)

of African institutes. These documents could be scanned to make them accessible for further analysis (Mallet unpublished).

Some of the plots established between 1930s and 1990s have suffered from the discontinuity of funding and monitoring, and have in part disappeared today. There is an urgent need to visit those that remain to assess the state of the plots, and to consider if it would be pertinent to update them (planning new inventories). A project in Côte d'Ivoire, led by CIRAD, is going to do this census during 2019–2021 (ForestInnov project cited in TreeDivNet).

4.3 South and Southeast Asia: Key findings

In recent years, there has been increasing interest in the establishment of mixed-species plantations in Asia and the Pacific. While wide-ranging mixed-species plantations are practiced by smallholder farmers, community groups, plantation companies and government authorities, the proportion of new mixed-species plantations is low relative to monoculture plantations (Nguyen et al. 2014). In many cases, native and exotic species are combined at plot or landscape scale (Table 3). China and India have greatly contributed to the development of timber plantations, predominantly monoculture, but it is difficult to differentiate the percentage of area under monoculture versus mixed-species plantation.

In many cases, especially under agroforestry plantations, trees are mixed with fruit tree species such as *Litchi chinensis, Mangifera indica* combined with *Melia azedarach*, and *Acacia mangium*, in Vietnam (Table 3). Similarly, high value timber species like *Tectona grandis* and *Swietenia macrophylla* are combined with fodder and fuel species i.e., *Leucaena leucocephala*. In the Indonesian archipelago, a wide variety of agroforestry systems exist, from those simply structured/designed with a just few species, to very complex designs which closely resemble natural forests (Foresta and Geneviève 1993). In many cases, mixed-species plantations provide a wide range of environmental benefits and a safety net to farmers in the event of poor species performance, low productivity or a drop in the market price of one species.

Examples of species combinations, associated productivity and type of reforestation schemes found in South and Southeast Asian countries are summarised in Table 3. These reforestation schemes varied between countries and the land uses intervened. The land uses commonly used for mixed-species plantations included silvopastoral systems, plantations on degraded soils, multi-strata agroforestry systems and small-scale rain-forestation. Performance in terms of growth, carbon capture and survival rates of the examples provided in this review were not compared to pure plantations; instead they are a compilation of the varied systems/land uses that can accommodate mixed-species reforestation schemes (Table 3).

In many cases, mixed-species plantations had higher values for carbon sequestration rates as well as total carbon stocks, compared to monoculture plantations (Munisamy et al. 2019). Mixed indigenous tree species also contributed more to sustainable forest management, and provided greater shelters for many faunal communities – and their associated ecosystem goods and services – than monoculture plantations.

Table 2b. Examples of recent species combinations, growth trends and type of plantation schemes of mixed plantations in selected countries in sub-Saharan Africa.

Country	Species combination	System	Type	Lessons learned	Rubber
Republic of Congo	*Acacia mangium/ Eucalyptus urophylla x E. grandis*	Line mixture	Experimental plots planted in 2004.	P availability and C stocks in Arenosols. Second study in 2012 (second cycle: *Acacia/Eucalyptus* 50:50)	Tchichelle et al. (2017a, 2017b)
Cameroon	23 species, planted in 15 × 15 m single-species blocks using 25 seedlings per species planted 3 m apart in a block.	Simple mixture, multiple species, single cohort planting	53 plots, planted between 2009 and 2014 (total 44.4 ha), under different cover index (logged enriched forest's).	Weak correlation between species performance and most functional traits. Analysis in plantations and maintenance costs (around 160 USD/tree) underlines the current financial disincentive for establishing plantations.	Doucet et al. (2016)
Ghana	*Milicia excelsia* (high-risk species)/*Terminalia superba* (companion species)	11:89, 25:75, 50:50, and 100:0% mixtures	Experimental plots (2 x 700m2). Planted in 1996.	Impact of Phytolyma. Survival and growth in moist semi-deciduous forest zone.	Nichols et al. (1999) Bosu et al. (2006)
Ghana	*Khaya grandifoliola* and *Khaya ivorensis* (key species), with *Heritieria utilis Sprague, Terminalia superba* and *Entandrophragma angolense*	*Khaya* spp densities of 100% (pure stand), 60%, 50%, 40%, 20% and 10%.	10 ha plot at the Tano-Nimiri Forest Reserve. Planted in concession for Samartex company. Results after 2 years.	Effect of different densities of mixed-species plantation on the growth of the African mahogany and attacks of Hypsipyla robusta	Opuni-Frimpong et al. (2014)
Côte d'Ivoire	16 local species planted in monoculture and over a gradient of functional diversity (2, 4, 8, 16 species mixture).	Block design	25 ha (49 * 0.5 ha) experimental plots set up in 2019.	Development of an algorithm to maximize tested levels of complementarity.	ForestInnov project cited in TreeDivNet platform
Kenya	*Avicennia marina, Bruguiera gymnorrhiza, Ceriops tagal*	Randomized block design with 8 treatments and 4 replicates of each treatment	Experimental plot (0.12 ha), set up in 2004.	Measure of AGB, BGB, root:shoot ratio. Species mixing boosts root yield in mangrove trees.	Sigi Lang'at et al. (2013)
Madagascar	80% *Eucalyptus* with 20% of *Acacia* spp (*A. dealbata, A. mangium or A. crassicarpa*)	Mixed plantations, hedges.	Development project (UE). Objective of 2200 ha of plantations for wood fuel with small farmers.	Mixed results (some farmers preferred to plant Acacia alone, for example).	ARINA Project website. Bouillet, personal communication.

Table 3. Examples of species combinations, growth trends and type of plantation schemes of mixed plantations in selected countries in Asia and the Pacific. Blank cells = no information/data available.

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
India	*Acacia nilotica, Dalbergia sissoo, Prosopis juliflora*	Silvopastoral system in highly sodic soil	Smallholders (private investment)	Biomass assessment and analysed for carbon sequestration potential for:	Tchichelle et al. (2017a, 2017b)
India	*Albizia procera, A. amara, Azadirachta indica, Acacia pendula, Dalbergia sissoo, Dichrostachys cinerea, Emblica officinalis, Eucalyptus tereticornis, Hardwickia binata, Leucaena leucocephala, Melia azaderach, Terminalia arjuna*	Simple mixture, multiple species, single cohort planting	53 plots, planted between 2009 and 2014 (total 44.4 ha), under different cover index (logged enriched forest's).	Weak correlation between species performance and most functional traits. Analysis in plantations and maintenance costs (around 160 USD/tree) underlines the current financial disincentive for establishing plantations.	Doucet et al. (2016)
India	*Acacia auriculiformis, Cassia siamea, Dalbergia sissoo, Gmelina arborea, Leucaenea leucocephala, Terminalia arjuna*	Plantation forest system in coal mine degraded land	Government-mediated projects	Mean DBH and relative density of A. auriculiformis: 14.42 cm and 15.57%, C. siamea: 16.41 cm and 37.7%, D. sissoo: 19.14 cm and 4.92%, G. arborea: 12.31 cm and 20.77%, L. leucocephala: 13.76 cm and 6.76%, T. arjuna: 6.50 cm and 2% respectively.	Mukhopadhyay et al. (2013)
China	*Pinus massoniana* and *Castanopsis hystrix*	Plantation in subtropical degraded lands	Government projects	Mean DBH of P. massoniana and Castanopsis hystrix was 24.6 cm and 24.9 cm with tree height of 17.2 m and 17.8 m, respectively.	Wang et al. (2013)
Indonesia	*Dyera polyphylla Combined with: Elaeis guineensis, Areca catechu, Coffea spp*	Agroforestry systems	Mostly undertaken by smallholders	Diameter: 1.7 cm/year	Tata et al. (2015)
Indonesia	*Citrus suhuiensis, oryza sativa*	Agroforestry systems	Mostly undertaken by smallholders		Noor et al. (2006); Nursyamsi et al. (2015)

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
Malaysia	*Elaeis guineensis, Hevea brasiliensis, Azadirachta excelsa, Tectona grandis*	Agroforestry systems and plantation systems	Smallholders	Growth rate not specified, but growth and yield mainly fall within normal distributions	Jaafar et al. (2008)
Indonesia	*Shorea spp* *Hevea brasiliensis* *Musa sp* *Capsicum spp*	Mixed tree plantation managed through agroforestry practices	Community plantation	1. Assumed Mean Annual Increment (MAI) for Shorea is 1.5 cm per year 2. Current average diameter for Shorea in tight spacing conditions (>1,000 trees/ha) is between 6.2–6.9 cm for trees aged 6–7 years 3. Diameter in wide spacing conditions for Shorea is 12.1–15.8 cm and 12.2–13.4 cm for trees aged 6–7 years	Budiningsih and Effendi (2012)

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Table 3. *Continued*

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
Indonesia	Planted in 1956, there are about 127 species of trees, bamboo, rattan and palmae. Tree species consist of: • 42 exotic species from tropical and subtropical climates (35 genus and 19 families) • 88 species from Indonesia (59 genus and 37 families. Among the species are: *Strombosia zeylanica* *Coumarana odorata* *Hopea odorata* *Azadirachta excels* *Dracontomelon dao* *Calophyllum soulatri* *Mangifera feotida* although the *Dipterocarpaceae* family dominated plantation area. Understory species include: *Cynodon dactylon* *Lycopodium cernuum* *Eupatorium pallescens* *Gleichenia linearis* *Melastoma polyanthum* *While fauna include:* *Agkistrodon rhodostoma, Python reticulates, Lariscus sp., Para-doxurus hermaphroditus, Pycnonotus aurigaster, Antreptes malacensis, Halcyon cyanoventris, Halcyon chloris, Rhipidura javanica, Picoides moluccensis, Spilornis cheela*	Mixed tree plantation for research purposes	Government	1. Assumed MAI for Shorea is 1.5 cm per year 2. Tree species varied between 2–18 m in height and 2–80 cm in diameter. Plantation forests have reached the level of complex ecosystem.	MENHLK nd Ministry of Environment and Forestry Republic of Indonesia. Forest Research and development centre

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
The Philippines (Leyte Province)	*Shade-intolerant species* *Leucaena laucocephala,* *Melia dubia,* *Gmelina arborea, Pterocymbium tinctorium,* *Tectona grandis,* *Sandoricum koetjape,* *Gymnostoma rumphianum,* *Terminalia macrocarpa,* *Samanea saman, Dracontamelon dao,* *Artocarpus heterophyllus,* *Senna siamea,* *Swietenia macrophylla,* *Vitex parviflora, Artocarpus blancoi,* *Calophyllum lancifolium, Pterocarpus indicus,* *Myrica javanica,* *Toona ciliate,* *Podocarpus rumphii* *Shade-tolerant species* *Shorea palosapis* *Shorea polysperma* *Dipterocarpus kunstleri* *Artocarpus odoratissimus* *Parashorea plicata* *Nephelium lappaceum* *Theobroma cacao* *Shorea contorta* *Agathis philippinensis* *Durio zibethinus* *Hopea plagata* *Hopea malibato*	Rain-forestation farming plantation (small holders)	Government	• 76 canopy species of trees were recorded at 80 plots across 18 sites in 2006. • In 2012, species present decreased from 76 to 65. Major mortality was for shade-intolerant species. • Substantial decline in tree density from an estimated stocking of about 5,000 trees per ha at the time of planting to 1,145 trees per ha in 2012 suggesting that mixed-species plantation elsewhere in the humid tropics should be around 1,000 trees per ha or less. • Overall, shade-intolerant species and fruit trees lost around 5% of trees each year but only suggesting that these species need to be reaccommodated. • Only 0.7% of the shade-tolerant trees were lost • By 2006 about 2% of all trees exceeded 30 cm DBH but this increased to 6.7% by 2012 • Results showed that three shade-intolerant species could reach the DBH threshold of 30 cm by the age of 10 years.	Nguyen et al. (2014)
Bangladesh	*Mangifera indica, Artocarpus heterophyllus, Litchi chinensis, Acacia mangiumm, Litsea sp*	Agroforestry systems	Private, mostly undertaken by smallholders	Growth parameters not available	Rahman et al. (2007, 2016)

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Table 3. *Continued*

Country	Species combination	System	Type	Growth parameters evaluated/ modelled (lessons learned)	Source
Vietnam	*Acacia sp, Archidendron lucidu, Wrightia tomentosa, Aporosa villosa, Ficus racemosa, Machilus bonii, Vernicia montan, Cinnamomum parthenoxylum, Ormosia balabsae, Lithocarpus gigantophyllu*	Plantation forest	Both government and private projects	Growth parameters not available	de Jong et al. (2006); Woo et al. (2011).
Vietnam	*Melia azedarach, Acacia mangium, Litchi chinensis, Mangifera indica, Docynia indica*	Agroforestry systems	Private, mostly undertaken by smallholders	Growth parameters not available	Patton (2017)

5 Discussion

In Section 3, we presented examples of mixed-species plantations occurring in three geographical areas. These examples span numerous countries, diverse purposes and scales. In our review, we found that the experiences documented provided knowledge and information on key aspects of mixed-species plantation systems (Liu et al. 2018), including species combinations and their interactions, environmental and ecological conditions where trees grow and silvicultural management. For example, in some Central America countries, different spacing, tree species combinations, spatial arrangements and silvicultural practices were tested to evaluate the interactions of the combined species and their responses in terms of growth and survival (Table 1a). Similarly, in several countries in sub-Saharan Africa, different tree combinations and spatial designs were tested (Table 2a and 2b) to evaluate the success of the mixed-species arrangements. Although most evaluated papers focused on assessing productivity, several focused on the role of mixed-species plantations in terms of promoting tree species diversity at farm level, as a mechanism for restoring degraded soils; combining species was also reported as a successful method to facilitate tree cover recovery using native species in restoration projects. Though planting nursery-raised seedlings was found to be a more effective method for rapidly establishing canopy cover and restoring larger areas, it came at a higher cost (Cole et al. 2011).

Other studies (for example, Lamb et al. 2005b; Pozo and Saumel 2018) similarly reported the potential of existing monoculture plantations (i.e., *Pinus*, *Eucalyptus*, mixed stands) to simulate the mechanism of succession, accommodating the establishment of other native species of mid and late successional stages. In this study we found evidence (see Avendaño-Yáñez et al. 2016; Table 1a) that existing pine plantations could facilitate (i.e., increase the percentage of seedling survival compared to open cultivation) the establishment of native and endangered cloud forest species (*Juglans pyriformis* and *Oreomunnea mexicana*); however further silvicultural practices (pruning and clearing) are needed to ensure the establishment of the intercropped species over time. Likewise, Parrotta (1999) reported natural regeneration of secondary forest tree and shrub species over time in both mixed-species stands and monoculture; however, abundance and diversity of woody species varied according to the canopy species. In this example, at 8.5 years, woody species abundance was significantly greater beneath Casuarina than either *Eucalyptus* or *Eucalyptus*/*Leucaena* mixed stands. Species richness and diversity were greatest beneath the stands containing *Eucalyptus* and/or *Leucaena* than in stands with *Casuarina*. Thus, increasing the ecological and biodiversity values of planted forests as well as their climate resilience (Barsoum et al. 2016).

Other environmental services attributed to mixed tree plantations schemes were reported in Coromandel Coast of southern India, where mixed-species plantations performed 1.5 times higher in terms of aboveground biomass values, and had almost double the total carbon stock compared to the monoculture plantation (Munisamy et al. 2019). Similarly, in our review, carbon sequestration potential was estimated for several species growing in plantations established in degraded pastureland, with values ranging from 0.58 Mg C ha-1 year-1 to 2.55 Mg C ha-1 year-1 (Rai et al. 2000; Table 3).

It has been acknowledged that large and protected regions surrounded by a matrix of wildlife friendly land uses and corridors are needed to promote biodiversity conservation (Kremen 2015). In the case of mixed plantations, in a meta-analysis done on the differential effects of forestry plantations on bird diversity, Castaño-Villa et al. (2019), found strong effects of plantation structure on the bird communities reported. Mixed arrangements with native species and plantations established for protection purposes had the least negative effects on bird richness and abundance in comparison with large-scale commercial plantations. Similarly, Redondo-Brenes et al. (2010) highlighted the importance of mixed plantations as connectors (i.e., corridors) with forest patches in human-dominated landscapes. Likewise, Pozo and Saumel (2018), in their studies about *Eucalyptus* plantations and the ways to increase their environmental value in Uruguay, recommended the integration of mixed native species buff strips at the edge of plantations to foster the integration of commercial plantations into the landscape and to increase their conservation value.

5.1 Monoculture versus mixed plantations

In general, when designing mixed plantations, species with complementary traits (positive interaction) are preferred, like fast-growing with slow-growing species, short-lived with long-lived species, light-demanding with shade-tolerant species, shallow-rooting with deep-rooting species, nitrogen-fixing with non-nitrogen-fixing species, or slim-crowned and height-oriented with wide-crowned and more laterally expanding species (Forrester et al. 2006; Nguyen et al. 2014; Pretzsch and Schütze 2016).

Few of the studies in our review evaluated attributes then made comparisons against pure plantations. Among the few studies we found, results were not conclusive and depended on the species and spatial arrangement of the mixed plantations. In some Latin American countries, native species had better growth when growing in mixed plantations than in pure plantations. For sub-Saharan Africa and South Asia, there were no reports comparing between mixed stand reforestation schemes and pure plantations.

Early economic returns can sometimes be obtained using mixtures when the main species is a valuable but slow-growing species. In this case, a mixture of fast-growing species with market value can make a project more economically attractive (FAO 1992). For example, in Nigeria, the establishment of *Lovoa trichilioides* and *Entandrophragma utile* with *Nauclea diderrichii* can be harvested for poles at the age of 15 years, giving early economic returns to the owner (Lamb 1991; Lowe 1991, mentioned in FAO 1992).

5.2 Mixed plantations and reforestation schemes

Even when several studies confirm the success of mixing certain timber species (Table 1a, Table 2a, Table 2b, Table 3a) (Redondo-Brenes and Montagnini 2006), mixed plantation designs are not part of existing pathways to carry out reforestation projects; they are rather a product of chance than a considered process. For instance, tree cultivation in Guatemala has been on the rise over the last 20 years, as a direct effect of government incentives to promote sustainable forest management. Despite this, mixed plantations are rarely considered. Méndez-Paiz and Serech-Van Haute (2018) characterized timber plantations established in northern Guatemala's humid lowlands, and found plantations made of up to 12 valuable timber species, managed in small-sized mixed stands (less than 10 ha) on private lands. This design was a direct consequence of the high mortality rate experienced in the first years of establishment of the pure stands and the owner's decision to intercrop standing plantations with other valuable timber species as an option to occupy the area. However, this change in management approach has never been registered in the official accounts of the Forest Service/government agencies.

Mixed-species plantations schemes are also absent from the national forest inventory monitoring system. For example, INFOR (Chile's national institute in charge of reporting the state of national forest resources) does not record the area occupied by mixed plantations. Yet Loewe and González (2006) reported the area of mixed plantations, as of 2002, as 6,125 ha[1]. In Mexico, the Secretary of Environment and Natural Resources (SERMANAT) reported accumulated reforested area, but no detail of the planting scheme is provided; as of 2018, more than 2 million ha have been reforested between 1993 and 2018 (SERMANAT 2019). There is a clear lack of strategy to effectively promote mixed-species plantations as a pathway for forest landscape restoration and wood production.

5.3 Mixed species plantations: Advantages and disadvantages

Some of the advantages and disadvantages of mixed-species plantations are summarized as below:

Advantages

- Tree diversification on farms and the opportunity to obtain early incomes and distributed benefits of harvesting tree-based products at different points in time due to maturity periods (for example, poles and biomass)
- Establishment and management of native species susceptible to pest and diseases
- Restoration of degraded lands (e.g., eroded soils, degraded pasturelands)
- Ecological succession support, through the recovery of late successional species.

1 https://ifn.infor.cl/index.php/311-plantaciones-forestales

Disadvantages:

- Good knowledge of the ecology and silviculture of the species to be mixed is necessary, to ensure plantations are successful for both people and nature
- Monitoring the survival and growth of diverse combinations and environmental conditions is required
- There is limited knowledge of the market value of species used in the mixture presented in this report
- Species must hold value for people and for restoration purposes
- A high level of technical skills is required to manage the mixed species

5.4 Silvicultural approaches

The use of improved silvicultural practices used extensively in monocrop cultivation, like fertilization, weed control, pests and disease control, can improve the outcomes of mixed-species reforestation plantations. For example, the application of pesticides during the first two years after planting proved to be beneficial for tree survival and overall tree growth performance in afforestation initiatives with native timber trees (Table 1a; Plath et al. 2011; Riedel et al. 2013).

A reforestation project (restoring degraded pastures aged 2.5 years) in Brazil, that analysed the effectiveness and responses of Atlantic forest species to a set of silvicultural practices, reported 20% greater tree survival for the tropical native species, higher aboveground biomass (up seven-fold from 13%), and a 20% increase in photosynthesis (from 15.8 µmol m-2 s-1 to 18.7 µmol m-2 s-1) when specific silvicultural practices, like fertilization and weed control, were applied during the first 2.5 years after establishment, compared to traditional silviculture practices applied by smallholder landowners (Campoe et al. 2014). The use of best practice silvicultural methods in reforestation projects not only helped in securing the survival of seedlings, but also in the overall performance of the project, increasing the trust of local stakeholders in reforestation schemes.

Mixed plantations can be established in different spatial arrangements (species mixed within the boundaries of the property or internal roads), by linear planting, or by small lots or blocks. They need more intensive management than single species plantations, requiring greater attention to planning and silvicultural management and with less room for error than monospecific plantations. Experience in West Africa concluded that a two-layered mixture is easier to manage than a one-layered mixture. In particular, mixtures involving the growth of one species under another – for example, nurse crops or ground cover – require technical skills to manage the overstorey if the shade-tolerant species is desired as the final crop (FAO 1991, 1992). However, in many tropical countries, insufficient training and experience among staff, together with a lack of financial guarantees and staff continuity, meant that successfully managing dominant mixtures was quite unlikely (FAO 1992).

5.5 Species combinations

As we have seen, there is a wide diversity of trees used for mixed-tree plantations. In many cases mixed-species plantations focus on native species, but there are several examples of combining native and exotic species. Mixes of timber with fruit or spices are common in Southeast Asia (Table 3). In Latin America, more strong emphasis was placed on mixing native species.

In Africa, plantations have associated two different species, rarely more, with complementary silvicultural characteristics, and have been mainly carried out from 1930 to 2000 in dense African rainforest (Dupuy 1995). They mainly concerned timber species of medium and long rotation:

- Species from dense African rainforests, like *Heritiera utilis, Khaya ivorensis, Terminalia ivorensis, Terminalia superba, Aucoumea klaineana, Entandrophragma utile, Entandrophragma angolense, Triplochiton scleroxylon, Thieghemella heckelli* and *Nauclea diderrichii.*
- Introduced species, like *Tectona grandis, Gmelina arborea* and *Cedrela odorata.*
- Some fast-growing exotic species (i.e., *Pines, Eucalyptus, Acacias, Leucaena, Cassia, Albizia*) have been tested in mixes (Republic of Congo, in the 2000s).

Mixed plantations can evolve towards structures with one or more strata. This evolution depends on the growth modalities of the species concerned and the silviculture implemented. The advantages and disadvantages of these mixtures are illustrated and commented on through different associations that reveal highly variable degrees of compatibility between species (Dupuy 1995).

6 Synthesis and conclusions

Mixed forest plantations have been presented as an option to reconcile wood production with the increased conservation value and ecosystem service provision of planted forests. Despite mixed plantations being on the radar of NGOs, foresters and research projects, and proved to be valuable for different purposes, they remain few. In this review we found that:

- Most of the growth and performance reports on mixed plantations come from research experiments and did not consider the social acceptability of tested models.
- Few publications have financially analysed mixed-species plantations or documented their operational costs.
- There is insufficient evidence around the mechanisms of interactions between species combinations.
- In some cases, it is not clear what the factors behind mixed-species selections were; this limits the adoption and scale-up of this approach, even when consistent results have been shown.
- There has been insufficient effort or investment to promote mixed plantations due to information scarcity and/or mixed results in the long-term performance of mixed stands.

This study reviewed mixed-species timber plantations in Latin America, sub-Saharan Africa and Asia, considering their potential to improve commercial reforestation efforts, environmental and socioeconomic resilience and restoration. Mixed-species plantations have generally focused on combining native species, but there are several examples of combining native and exotic species throughout the three geographic areas reviewed. Mixed timber and fruit species are common in Southeast Asia. In Africa, mixed plantations include native forest species and introduced fast-growing species. In Latin America, a combination of native species with introduced species is also common. Most of the evidence in this report came from experimental/research plots. Few studies demonstrated the business case of mixed plantations.

Despite the diverse studies on mixed-species plantations, there are still few ‘real life’ cases of mixed-species plantations. At this stage, therefore, the promotion of mixed-species plantations seems a risky path. However, if through participation and incentives, local and national stakeholders (i.e., landowners, communities, wood industry, public institutions, investors) were involved in promoting and advancing new reforestation schemes, growth among mixed-species plantations would be more likely.

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FTA WORKING PAPER

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Large-scale timber plantations are controversial in many parts of the world for numerous reasons, including direct and indirect land-use changes and associated impacts on a variety of ecosystem goods and services. The use of mixed-species plantations for commercial and restoration reforestation purposes is gaining interest both as an option to support the supply of wood, and to contribute to meeting international agendas on the restoration and provision of ecosystem services. This review synthesizes the state of mixed-species plantations in South and Southeast Asia, Latin America and sub-Saharan Africa, examining their potential role as a novel production system.

The CGIAR Research Program on Forests, Trees and Agroforestry (FTA) is the world's largest research for development program to enhance the role of forests, trees and agroforestry in sustainable development and food security and to address climate change. CIFOR leads FTA in partnership with ICRAF, the Alliance of Bioversity International and CIAT, CATIE, CIRAD, INBAR and TBI.

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