The great mistake of plantation programs in cocoa agroforests – Let's bet on natural regeneration to sustainably provide timber wood

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ABSTRACT

Cocoa production has been one of the main drivers of forest loss in West Africa. In the resulting post-forest landscapes, agroforestry has often been recognised as a solution to reconcile the preservation of trees and agriculture. Thus, a large number of tree plantation programs have been carried out in cocoa fields. Despite these major investments, the success of these plantations as a tool for "reforestation" of landscapes and sustainable timber production has never really been evaluated in fields where remnant trees, spontaneous trees and (trans) planted trees coexist. To quantify the current and future timber resource, we inventoried all trees in 150 cocoa fields distributed along the bioclimatic and historical gradients of the cocoa production area of Côte d'Ivoire, the world's leading producer. Our results show that (i) 19.6% of all associated trees are timber species, (ii) in plots where farmers actually introduced trees by planting, only 13.1% of trees have been (trans)planted, (iii) 69.7% of the current timber volume comes from remnant trees and (iv) spontaneous trees constitute 77% of the future timber resource. Based on our results, we propose 23 species along with their cultivation methods for the renewal of timber resource in cocoa fields. Overall, our results show the failure of plantation programs in cocoa fields and suggest to bet on natural regeneration to sustainably provide timber wood. Consequently, private companies supplying trees to farmers should focus on species that are complementary to those already present in natural regeneration. At the landscape level, remnant trees and residual forests should be preserved to maintain propagule sources. Finally, investments in reforestation of cocoa fields should be redirected towards training small farmers in silvicultural management techniques such as assisted natural regeneration and tree pruning.

1. Introduction

The alarming evidence of the strong coupling between cocoa production and deforestation in West Africa has been a growing concern over the past few decades (Mighty earth, 2023). The remaining forest cover in West Africa is at best 20% of its original extent (FAO 2010; Leach and Fairhead, 2000). In Côte d'Ivoire, the world's leading cocoa producer, more than 90% of this forest has disappeared (BNETD 2016; FAO/SEP REDD, 2017). Thus, so-called "post-forest landscapes" are becoming increasingly important for the conservation and restoration of current and future forest ecosystem services (Sanial 2019; Gibbs and Salmon, 2015; de Carvalho et al., 2015; Saqib et al., 2019; FAO, 2018). Several initiatives have been established to try to improve the place of trees in these degraded landscapes and to counteract deforestation (IDH Report, 2021; Carimentrand, 2020; Mighty Earth, 2023). Among these initiatives, one of the current priorities of politicians, environmental organizations, scientists and the agricultural sector in West Africa is to promote trees in cocoa fields. This association, known as the "cocoa agroforestry system" (*i.e.* hereafter cocoa AFS), has raised a lot of hope and is now on the political agenda as a solution to reconstitute highly degraded forest cover and reconcile agriculture with forestry in post-forest landscapes (Rice and Greenberg, 2000; Tscharntke et al., 2011; Vaast and Somarriba, 2014).

Significant investments from private companies or international

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donors have been granted for numerous tree distribution programs in West African cocoa fields with the objective of achieving sustainability in cocoa cultivation based on different standards: Rainforest Alliance, UTZ, Fairtrade, etc. (Carimentrand, 2020). In Côte d'Ivoire, more than 11 million seedlings have been distributed to cocoa farmers since 2018, through dozens of sustainability programs (IDH Report, 2021; Mighty Earth, 2023). However, while these programs have generated interest in introducing trees into cocoa fields, they have not been sufficiently evaluated with regard to their real capacity to "reforest" the country and, ultimately, produce wood (Sanial, 2019; Jagoret et al., 2020). Yet, recent assessments indicate that demand for timber is expected to continue to increase in West Africa due to population growth and real estate development (Uzu et al., 2022). In Côte d'Ivoire, where domestic and industrial timber supply will not be sufficient to meet current demand (Louppe and Ouattara, 2013), it is desirable that alternative sources of production, such as cocoa fields, help meet this high demand for timber resources.

The timber resource present in cocoa fields has different origins depending on the farmers management practices (Ordonez et al., 2014): (i) remnant trees left alive (or that survived attempts to kill them) during deforestation (N'Guessan et al., 2019) for the installation of cocoa trees, (ii) spontaneous trees that grew naturally alongside cocoa trees and that were protected over time by farmers, and (iii) planted trees from nurseries usually distributed during plantation programs (*i.e.* planted trees hereafter) or transplanted wildlings that farmers intentionally move within the field or from one field to another (*i.e.* transplanted trees hereafter). It is important, when evaluating potential timber production from cocoa agroforests, to consider trees origins (Doua-Bi et al., 2021) to better estimate (i) the current timber resource, *i.e.* all remnant, spontaneous and (trans)planted commercial trees that have reached a sufficient size to be harvested today; and (ii) the future timber resource, *i.e.* all commercial trees that are spontaneous or (trans)planted but have not yet reached a sufficient size to be harvested today (Sanial et al., 2022).

Our study aims to characterize the current and future timber resource present in Ivorian cocoa fields according to its origin (remnant, spontaneous or (trans)planted) and to draw recommendations on effective strategies for the introduction of trees in cocoa fields. Specifically, we asked the following questions: (1) What is the relative importance of timber species in the pool of trees present in cocoa fields? (2) What are the origins of the trees that constitute the current and future wood resource? (3) What are the promising species and cultivation methods for a sustainable provision of timber? The recommendations from our results should help to evaluate, and reorient, tree promotion programs in cocoa fields that currently rely almost solely on planting.

2. Materials & methods

Our study area is located in Côte d'Ivoire (West Africa) where climate varies from humid equatorial in the south to dry tropical in the north. The current main cocoa production areas of the country are located in two bioclimatic zones: the Ombrophilic zone where the evergreen forest is located and the Mesophilic zone where the semi-deciduous forest is located (Fig. 1).

2.1. Sampling design

We conducted our study on 10 plots on each of 15 sites covering a total area of 240.4 ha and representing the diverse climates, soils, and social situations in the cocoa production area (Fig. 1). These sites are located along two different gradients: (i) a South-North climate gradient (mean annual temperatures range from 22.6 °C to 26.2 °C and annual rainfall range from 1900 mm to 1100 mm) which also corresponds to a South-North vegetation gradient (from evergreen forests to semi-deciduous forests); and (ii) an East-West historical gradient, cocoa fields being more recent in the West (Ruf et al., 2020).

To capture the diversity of the cocoa fields, 3 criteria were used to select 10 cocoa plots within each site: (i) structural complexity: ranging from cocoa monocultures in almost full sun to complex cocoa agroforests; (ii) age of cocoa fields: ranging from young plots to old plots; (iii) yield of cocoa trees: ranging from less productive plots to more productive plots. We considered the entire farmer's field as a management unit corresponding to a sampling unit. These sampling units vary in size from 0.3 to 5 ha entirely managed by the farmer.

Most of our 15 sites benefited from different plantation programs of cocoa agroforests since 2010. We recorded whether there have been any tree plantings related to plantation programs down to the plot level. Only 3 sites (Biankouma, Bonon and Gueyo) had not benefited at all

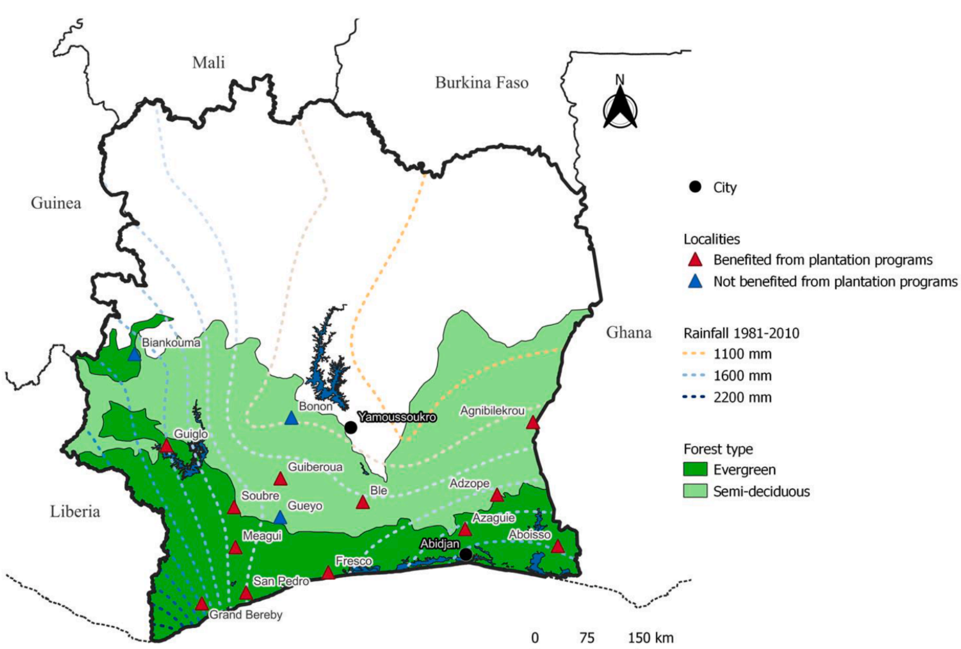

Fig. 1. Location of the 15 study sites along a climate and forest vegetation gradient.

from these programs (Fig. 1). Altogether, 81 of the 150 plots received tree seedlings from plantation programs.

2.2. Data collection

Between March 2021 and November 2022, we carried out an exhaustive inventory of all associated trees in the cocoa fields with a diameter at breast height (DBH) equal to or above 10 cm. To better assess the quality of the trees as timber resource, we recorded quantitative and qualitative data for each stem (Table 1).

Trees were identified to the species level following the Taxonomic Name Resolution Service as implemented in the BIOMASS R package (Réjou-Méchain et al., 2017). The timber species list and their Minimum Logging Diameters (MLD) were established using the current national list of timber species (Sodefor, 2017).

2.3. Characteristics and origin of the current and future timber resource

First, to be part of the timber resource, trees must be well conformed by meeting the following criteria (Table 1):

- Cylindricity $\neq 2$,
- Straightness $\neq 2$,
- Health $= 0$.

Then, trees that have reached their MLD and with a bole height of at least 5 m represent the current resource, the smaller trees represent the future resource. We assigned the minimum MLD value (50 cm) to the species with no MLD. We did not consider remnant trees in the future resource because (i) these are trees that have grown up in a forest environment and therefore have morphological characteristics linked to this environment, characteristics that are probably very difficult to reproduce in a completely open environment and (ii) there is no guarantee that these remnants, whose seeds have germinated in the forest, can regenerate in the cocoa fields.

Finally, we calculated the volume, density and basal area of the current and future resource differentiating the trees according to their origin. In the absence of local equations for the calculation of tree volume, we used the FAO formula (Magnussen and Reed, 2004):

$$Vi = 0.4 \cdot BHi \cdot DBHi$$

Where *Vi, BHi* and *DBHi* are respectively volume, bole height and diameter at breast height of stem *i*. Constant 0.4 corresponds to an average taper coefficient.

Table 1
Data collected to quantify the timber resources in our 150 study fields.

Variables	Format/Unit	Description
Diameter (DBH)	Quantitative variable in centimetres (cm)	Diameter at breast height
Bole Height (BH)	Quantitative variable in meters (m)	Height from the ground to the first living branch
Cylindricity	Ordinal variable (from 0 to 2)	Number of large bumps or flats along the trunk (0: no bump/flat; 1: one bump/flat; 2: at least two bumps/flats)
Pruning	Ordinal variable (from 0 to 2)	Number of lower branches along the trunk (0: no lower branch; 1: one lower branch; 2: at least two lower branches)
Straightness	Ordinal variable (from 0 to 2)	Number of bends along the trunk (0: no bend; 1: one bend; 2: at least two bends)
Health	Binary variable (0 or 1)	Commercially viable tree or not (0: commercially viable; 1: not commercially viable)
Origin	Nominal variable (r, s, tp)	Cocoa farmer's declaration on tree's origin (r: remnant; s: spontaneous; tp: (trans) planted)

2.4. Species and cultivation methods for a sustainable provision of timber

We established three lists of species corresponding to three strategies for the renewal of the timber resource in cocoa AFS, along with a list of non-adapted species:

- ***Naturally Regenerating Species (NR)***, species with a majority of well conformed trees and with at least 90% spontaneous individuals.
- ***Planting Species (P)***, species with a majority of well conformed trees and with at least 90% (trans)planted individuals.
- ***Species suited for both strategies (NR & P)***, species with a majority of well conformed trees and with at least 10% (trans)planted individuals and at least 10% spontaneous trees.
- ***Non-Adapted Species (NA)***, species with a majority of poorly conformed trees.

Here again, we excluded remnant trees because their conformation is the result of their development in a forest environment and is unlikely to be similar among cocoa fields. We also excluded the rare species from this analysis: only species with at least 10 individuals were considered.

3. Results

3.1. Share of timber species in the pool of trees present in cocoa AFS

Overall, 12,409 trees were inventoried, among which 2429 (19.6%) have been identified as belonging to timber species. They come from 55 species grouped in 21 families. Median timber tree density is 7.4 stems. ha^{-1}, ranging from 0 to 59.3. And median timber tree basal area is 1.5 m^2. ha^{-1}, ranging from 0 to 21.5.

Among these trees, 1175 (48.4%) are remnants, 1040 (42.8%) are spontaneous and 214 (8.8%) have been (trans)planted with the highest rate of (trans)planted trees (28.7%) observed at Agnibilekrou (Fig. 2). Looking at the sites that benefited from plantation programs, the proportion of (trans)planted trees increases from 8.8% to 10.4%; this proportion further increases to 13.1% when considering only the plots where farmers reported having benefited from plantation programs.

Most of the trees are well-conformed, regardless of their origin (Fig. 3). This is particularly true for (trans)planted trees with a total of 82.2% classified as well-conformed. Most of the trees are unpruned, regardless of their origin. Here again, this is particularly true for (trans) planted trees with a total of 65.4% of trees being unpruned.

3.2. Origin of the current and future timber resource in cocoa AFS

Overall, within the 240.4 ha inventoried, 411 trees constitute the current timber resource, with a total volume of 2176.7 m^3 and a total basal area of 281.8 m^2. Remnant trees make up most of this resource and account for 69.7% of the total volume, 65.5% of the total number of stems and 72.2% of the total basal area (Fig. 4). Following, spontaneous trees account for 29.1% of the total volume, 32.4% of the total number of stems and 26.8% of the total basal area. Finally, (trans)planted trees represent a minor part of the current resource, accounting for 1.2% of the total volume, 2.2% of the total number of stems and 1% of the total basal area.

As for the future timber resource, it consists of 725 trees with a total volume of 719.2 m^3 and a total basal area of 57.5 m^2. Spontaneous trees make up most of this resource and account for 83.7% of the total volume, 77% of the total number of stems and 82.4% of the total basal area. Here again, (trans)planted trees represent a minor part of the resource, accounting for 16.3% of the total volume, 23% of the total number of stems and 17.6% of the total basal area.

Looking at the values per hectare (Fig. 5), remnant trees again

Fig. 2. Proportion of spontaneous, remnants and (trans)planted trees among the 15 study sites. Ranked by decreasing percentage of (trans)planted. (agni: Agnibilekrou, grdb: Grand Bereby, guib: Guiberoua, azag: Azaguie, guig: Guiglo, ble: Ble, fres: Fresco, aboi: Aboisso, soub: Soubre, bono: Bonon, sanp: San Pedro, adzo: Adzope, bian: Biankouma, guey: Gueyo).

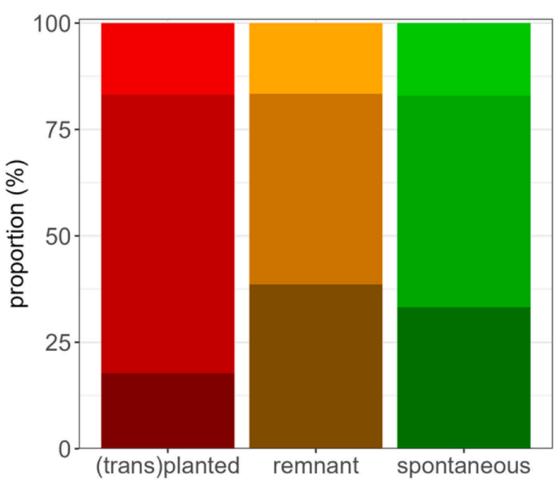

Fig. 3. Conformation and pruning condition of (trans)planted, remnant and spontaneous trees. Each origin group is distinguished into three types of conformation: well conformed - pruned (light color), well conformed - unpruned (intermediate color) and poorly conformed (dark color). Here, we do not distinguish the pruning condition of poorly conformed trees as they do not make up the current or future timber resource.

represent the majority of the current resource with a median volume of 0.9 $m^3.ha^{-1}$ [1st quartile = 0; 3rd quartile = 7.2], a median density of 0.3 trees. ha^{-1} [0; 1.6] and a median basal area of 0.1 m^2. ha^{-1} [0; 1.0]. In contrast, the median volume, median density and median basal area per hectare of spontaneous and (trans)planted trees are all equal to 0. In the future resource, spontaneous trees dominate with a median volume of 0.6 m^3. ha^{-1} [0; 2.4], a median density of 0.9 trees. ha^{-1} [0; 2.8] and a median basal area of 0.05 m^2. ha^{-1} [0; 0.2], while the median volume, median density and median basal area per hectare of (trans)planted trees are all equal to 0.

3.3. *Species and cultivation methods for a sustainable provision of timber*

We identified 23 species on which we can rely to build a sustainable strategy for the renewal of the timber resource in cocoa AFS (Table 2). Among these species, 15 are adapted for natural regeneration only (NR), 2 are adapted for plantation only (P) and 6 are well suited for both strategies (NR & P). In contrast, we identified 5 species that are not suitable for the renewal of the timber resource (NA).

4. Discussion

To our knowledge, our study is the first to (i) qualify and quantify, according to the origin of the trees, the current and future timber resource in West African cocoa agroforests, and (ii) recommend timber species and their appropriate cultivation mode (regeneration, plantation). Of the 19.6% timber trees inventoried we found that (i) even when considering only plots where tree planting was undertaken no more than 13.1% of the trees were planted, (ii) remnant trees, from the pre-existing forest, constitute 69.7% of the current timber volume, and (iii) spontaneous trees constitute 77% of the future timber resource. Furthermore, regardless of their origin, all timber trees are mostly well conformed, but with a slightly higher proportion of unpruned trees among (trans) planted trees.

4.1. *A surprisingly low rate of planted trees in cocoa AFS*

Despite significant investments in campaigns to distribute free trees, current tree promotion strategies do not seem to be working. Indeed, less than 9% of timber trees are planted in our sample. Focusing only on plots where farmers have actually planted trees, this percentage only increases to 13.1%. In Agnibilekrou, where 28.9% of the total number of trees were planted (Fig. 1, maximum site value), a complementary survey (pers. obs.) indicated that these trees are mainly the result of transplants (*i.e.,* the planting of wildlings that farmers intentionally move into their fields) and not nursery-raised trees distributed by cooperatives during 'reforestation' campaigns.

The first factor explaining the poor success of trees planted in cocoa fields is that nursery-raised seedlings very often suffer from an initial

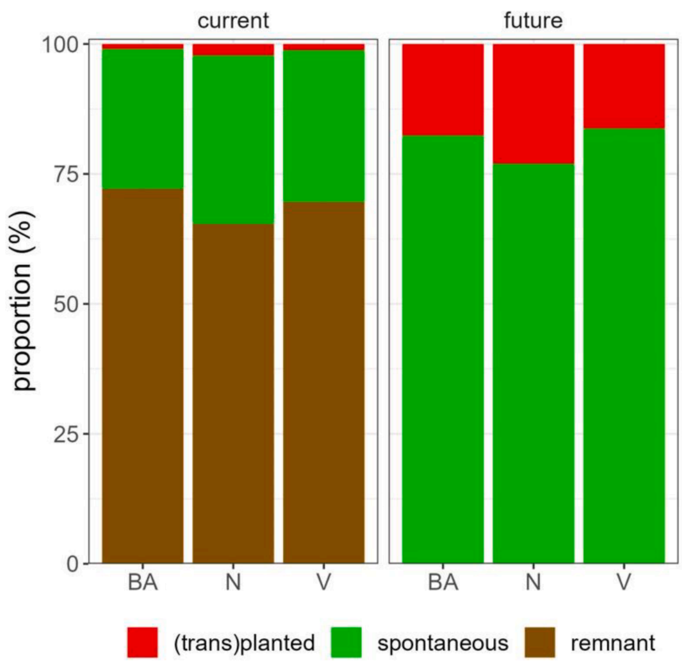

Fig. 4. Proportion of (trans)planted, remnant and spontaneous trees in the current and future timber resource. BA: basal area; N: number of stems; V: volume. A figure including remnant trees in the future resource is presented in Fig. S1 as a supplementary information.

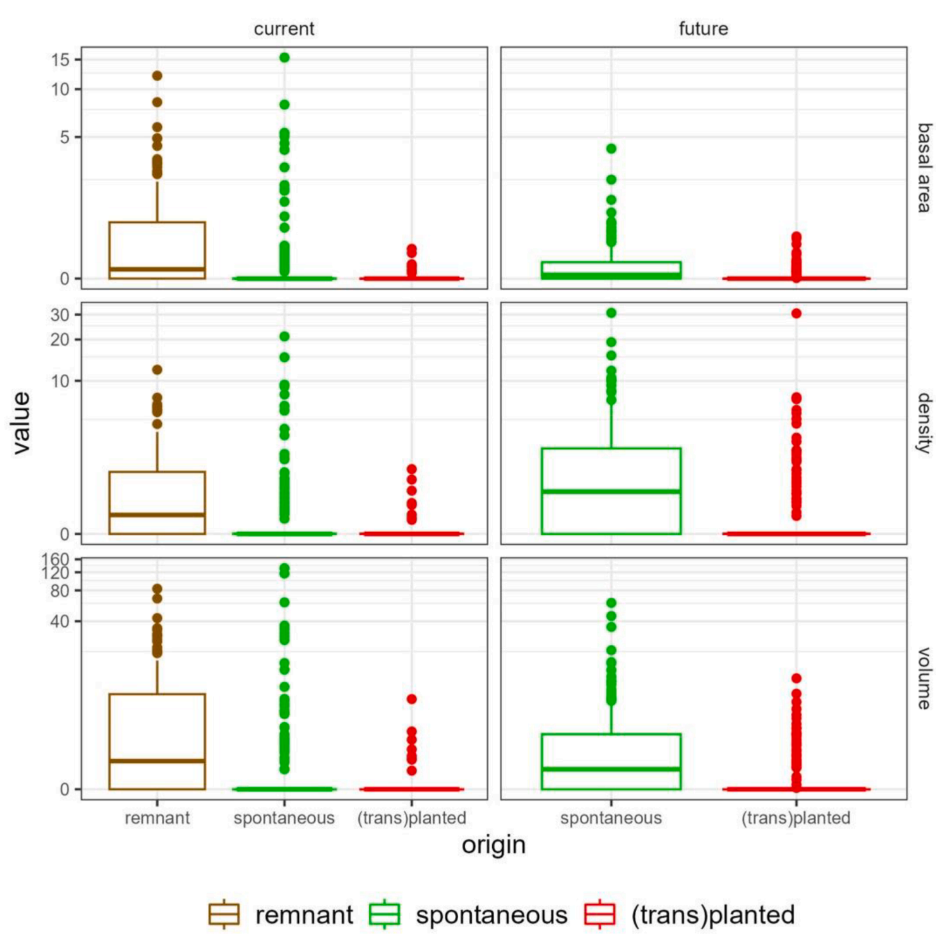

Fig. 5. Distribution (at scale log10 +1) of the volume (m^3. ha^{-1}), density (trees. ha^{-1}) and basal area (m^2.ha^{-1}) of (trans)planted, remnant (only for the current ressource) and spontaneous trees in the current and future timber resource. A figure including remnant trees in the future resource is presented in Fig. S2 as a supplementary information.

Table 2
List of species to promote or avoid for the renewal of the timber resource along with their cultivation method.

Species name	Trade name	Family	MLD (cm)	Abundance	Strategy
Alstonia boonei	EMIEN	Apocynaceae	60	59	NR
Amphimas pterocarpoides	LATI	Fabaceae	70	63	NR
Antiaris toxicaria	AKO	Moraceae	50	95	NR
Bombax brevicuspe	KONDROTI	Malvaceae	60	13	NR
Ceiba pentandra	FROMAGER	Malvaceae	80	49	NR
Celtis zenkeri	ASAN	Cannabaceae	50	10	NR
Distemonanthus benthamianus	MOVINGUI	Fabaceae	60	21	NR
Entandrophragma angolense	TIAMA	Meliaceae	60	52	NR
Funtumia africana	POUO	Apocynaceae	50	51	NR
Lannea welwitschii	LOLOTI	Anacardiaceae	60	45	NR
Milicia regia	IROKO ROUGE	Moraceae	60	22	NR
Petersianthus macrocarpus	ABALE	Lecythidaceae	50	23	NR
Piptadeniastrum africanum	DABEMA	Fabaceae	60	14	NR
Pycnanthus angolensis	ILOMBA	Myristicaceae	60	84	NR
Zanthoxylum gilletii	BAHE	Rutaceae	50	13	NR
*Cedrela odorata**	CEDRELA*	Meliaceae	50	11	P
*Gmelina arborea**	GMELINA*	Lamiaceae	50	14	P
Bombax buonopozense	OBA/KAPOKIER	Malvaceae	60	22	NR & P
Milicia excelsa	IROKO BLANC	Moraceae	60	80	NR & P
Parkia bicolor	LO	Fabaceae	50	10	NR & P
Ricinodendron heudelotii	EHO	Euphorbiaceae	60	68	NR & P
Terminalia ivorensis	FRAMIRE	Combretaceae	50	34	NR & P
Terminalia superba	FRAKE	Combretaceae	50	202	NR & P
Afzelia bella	AZODAU	Fabaceae	50	11	NA
Albizia ferruginea	IATANDZA	Fabaceae	60	13	NA
Dialium dinklagei	KROPIO	Fabaceae	50	19	NA
Irvingia gabonensis	BOBOROU	Irvingiaceae	50	12	NA
Sterculia tragacantha	PORE-PORE	Malvaceae	50	72	NA

MLD: minimum logging diameter; Abundance: number of (trans)planted or spontaneous stems inventoried with DBH > 10 cm; Strategy: cultivation methods (NR: naturally regenerating, P: planting, NA: non-adapted). (*) indicates exotic species (Ake Assi, 2001).

period of poor growth and high mortality, a phenomenon generally referred to as "planting shock" (Brown, 2004). This planting shock has multiple, non-exclusive causes: (i) Seeds used in the nursery are often collected from a narrow range of sites, with unknown but often low genetic variance. Seedlings produced in this way are extremely homogeneous and fragile, needing adequate soil and pest and disease control (Duguma et al., 2020), *i.e.* a set of care requirements that are difficult to provide in real cocoa field conditions. (ii) Nursery raised seedlings have limited root development due to the size of the container. Indeed, the roots of young seedlings need space to develop properly, to seek water and nutrients. In a plastic container (usually small), these roots pile up and cannot develop properly, which limits the growth of the plant. (iii) Planted trees do not always have the best competitive abilities, which are not as good as those of spontaneous seedlings. Indeed, while farmers are able to select, during field work, the best spontaneous seedlings, they are completely dependent on the planting material. All of these causes lead to a strong competitive disadvantage of nursery-raised seedlings compared to natural regeneration (Chazdon and Guariguata, 2016).

The 2nd factor is more related to the current context of agroforestry promotion, through free distribution of nursery trees, in Côte d'Ivoire. (i) Distribution campaigns focus solely on the distribution of seedlings to farmers without any technical support beyond planting; whereas the objective should rather be to secure the growth of trees after their introduction in the fields (Uribe-Leitz and Ruf, 2019). In particular, training in agroforestry practices for the person doing the actual work in the field *(i.e.* the tenant farmer) is almost non-existent. (ii) Project performance indicators are often the number of seedlings distributed and (more rarely) the number of them that have been planted, but almost never report on survival rate (or growth performance) at 2, 5, or 10 years. This leads to a lack of interest on the part of the farmer in these trees whose development, or lack of development, is not monitored. (iii) The focus on distributing relevant species, complementary to what farmers already find in the natural regeneration of their field, is almost non-existent (Sanial et al., 2022). Thus, even in localities that are very heavily involved in plantation programs (such as Agnibiliekrou), distributed species (such as *Terminalia superba*) are actually found in abundance in natural regeneration and thus the few planted individuals are drowned in the natural regeneration.

4.2. Remnant trees in cocoa AFS are the main timber resource today

Currently, more than 69.7% of the exploitable timber volume in Ivorian cocoa fields comes from old-growth forest remnants. This result can be explained by the post-forest location of cocoa fields in Côte d'Ivoire (Sanial, 2019). In many situations (classified forests in particular), during the (illegal) clearing of the forest for the installation of cocoa fields, a few large forest trees are spared so that clearing for cocoa will go unnoticed by the water and forest authorities (Barima et al., 2016). Once the cocoa trees are installed, the remaining trees that were initially spared are the object of numerous attempts by farmers to weaken/eliminate them (by fire, girdling or other means) so that they do not compete with the cocoa. In the end, because of these attempts, some remnant trees show a poor conformation for use as timber resource (Fig. 3).

However, remnant trees have grown in forest prior to clearing, in an environment where trees, due to competition for light (Pillet et al., 2018), tend to be slenderer (King et al., 2009). This particular life history naturally gives them better characteristics for wood production (trunk height, size, cylindricity, straightness, and health) than trees that do not grow in forests (Rutishauser et al., 2016). Consequently, under the current environmental conditions of the cocoa fields, it is not certain that the new trees (planted or spontaneous seedling) will show, in the future, the same biophysical characteristics of the remnant trees that grew in natural forest. This means that technical support for the growth of trees in cocoa fields must ensure their good conformation to produce usable timber trees in the long term.

4.3. Spontaneous trees are the key to future timber supply

Spontaneous trees constitute 77% of the future timber resource, highlighting the importance of natural regeneration in cocoa fields. These results are in agreement with several studies in the region that promote natural regeneration as a key to restoring (i) forests (Amani et al., 2021, 2022) or (ii) trees in post-forest landscapes (Sanial, 2019; Lohbeck et al., 2020). Betting on natural regeneration greatly increases the chances that saplings will belong to species capable of growing to maturity under local site conditions, as they belong to species (and ecotypes) already growing in the immediate vicinity (Brown, 2004).

Spontaneous seedlings have a more developed root system (both superficial and in-depth) than nursery-grown trees (Werden et al., 2018). This makes them more resilient under harsh climatic conditions, especially in dry seasons. Furthermore, spontaneous trees from natural regeneration show high genetic diversity, which reduces the risk of disease susceptibility (Howe, 2016; McAlpine et al., 2016). They grow more vigorously than planted trees because they are highly adapted to local plot conditions (Mirabel et al., 2019), which improves their survival (Aubry-Kientz et al., 2015). And a strong selection pressure by the local environment is experienced by spontaneous trees, which results in the survival (and selection by the farmer) of the best individual trees. The only concern is the considerable proportion of poorly conformed individuals (Fig. 3), which can be explained by uninformed selection by the farmers. Thus, technical support efforts should largely focus on this aspect.

From an ecological point of view, the immediate proximity of old-growth forests strongly favours the success of natural regeneration (Doua-bi et al., 2021). In the still recent post-forest context of Côte d'Ivoire, conserving the few remaining forests in the landscape and leaving remnant trees as an "ecological memory" in the cocoa fields or their surroundings would be very favourable to the natural regeneration of spontaneous trees (Amani et al., 2021). Concretely, care should be taken to (i) preserve some remnant trees in the immediate vicinity of cocoa fields from felling in order to improve seed banks (Hérault and Hiernaux, 2004), and (ii) renew aging timber trees from the recruitment of spontaneous trees already present in cocoa fields.

4.4. Recommended species

We have listed the species that are most promising to sustainably provide timber wood from cocoa fields (Table 2). Most of the proposed species are listed in the literature as trees that cocoa farmers traditionally use as shade trees (Nitidae, 2022; Sanial, 2018; Sonwa et al., 2014; Asare, 2005, Dumont et al., 2014, Herzog, 1994). Current strategies in plantation programs in cocoa fields are based on the free distribution of many species according to their performance in natural forest but not on their performance in cocoa fields (Cemoi, 2018, 2021; Saco, 2021; Cargill, 2021). For example, forest species such as *Heritiera utilis, Triplochiton scleroxylon, Dacryodes klaineana, Khaya spp.* or *Chrysophyllum spp.* are commonly recommended in plantation programs (Cemoi, 2018; Sodefor, 2010) but are infrequently found as adults in cocoa fields (Table S1).

Natural regeneration only (NR, Table 3) is recommended for 15 species. These species are currently not promoted as natural regenerating species even if some studies mention their importance in the traditional management practices of cocoa farmers (Sanial et al., 2022; Nitidae, 2022, Dumont et al., 2014). From a purely economic point of view, a focus on these naturally regenerating species considerably reduces costs: (i) no nurseries, (ii) no campaigns to distribute seedlings, (iii) no transport to the field, (iv) no labor for planting, and (v) less time-consuming follow-up of young trees than for planted trees, which need a careful attention to really grow.

Planting only (P, Table 3) is recommended for 2 species: *Gmelina arborea* and *Cedrela odorata*. Because of their rapid growth, these two exotic species are increasingly promoted in current plantation programs and are well accepted by farmers. However, there are high risks of biological invasion, especially for *Cedrela odorata* in the semi-deciduous zone (Van der Meersch et al., 2021), risks that lead us to recommend it in the evergreen zone only (Fig. 1).

A mixed strategy (NR & P, Table 3) is recommended for 6 species, depending on the state of local natural regeneration. Most of these species are already promoted in plantation programs but without any attention to their potential in natural regeneration. A smart strategy would therefore be, first, to verify their actual presence in cocoa fields before offering them for planting to farmers.

Finally, the other investigated species are not recommended (NA, Table 3). These species have mostly received no attention in planting programs (IDH report, 2021; Cemoi, 2018). However, *Albizia ferruginea* and *Irvingia gabonensis* are commonly promoted as shade or fruits trees. Our results show that they are unsuitable species for timber production in cocoa fields, mainly due to their poor conformation as adults.

4.5. Recommendations

Our general recommendation is to build technical guidelines that are based, first, on the protection of the spontaneous trees, and then, if necessary, to reinforce the natural regeneration by planting complementary species.

(i) For spontaneous trees, there is a need for a more rigorous selection of young plants with successive thinning that favours fast-growing individuals with good conformation. This technical guideline should be adapted to the local conditions: (i) if the natural regeneration area is not sufficiently lit, the surrounding cocoa trees should be pruned; (ii) if the area is too brightly lit, crops known to provide adequate shade for the growth of young seedlings - such as plantain - can be planted to promote a microclimate necessary for the regeneration of forest species.
(ii) For planted trees, we suggest focusing only on timber species that have proven successful in open areas (Hérault et al., 2020), that are complementary to the species already present in the field and to plant them as early as possible in the rainy season so that the plant has the entire rainy season to develop.
(iii) The growth potential of spontaneous and (trans)planted trees can be greatly improved by applying smart pruning (Amahowe et al., 2018). The branches should thus be cut at a height higher than the canopy of the cocoa trees, which allows (i) the cocoa trees not to be hindered in their biological functioning and (ii) the tree to grow taller and with a more commercially interesting bole (Blaser-Hart et al., 2021).
(iv) Integrated strategies of land management that preserve residual forests and remnant trees is a top priority to preserve the last remnant trees of the pre-existing forest that can feed the cohorts of spontaneous trees (Sanial et al., 2022).
(v) Investment in training farmers in silvicultural management in cocoa fields is a top priority for the production of quality logs, provided that (i) formal commercial contracts between farmers and timber buyers are effective and (ii) ownership of trees outside the forest (*i.e.*, land and tree rights) is secured by effective national regulations (Sanial et al., 2022)

The move from agroforestry promotion based on massive and indiscriminate distribution of saplings for planting to agroforestry promotion based on gradual and progressive selection of spontaneous seedlings in natural regeneration is a complete paradigm shift. This shift is a necessity for (i) cocoa AFS to develop effectively and get out of the spiral of failures (Mighty Earth, 2023) and (ii) to give a new lease of life to the West African timber sector. Our work suggests that realistic strategies for tree and agroforestry development in cocoa fields are possible, and at low cost, based on natural regeneration. It is up to private companies and policy makers to create the legal, financial, land and regulatory instruments to implement them.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2023.100386.

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