Suitability of large-scale tree plantation models in Africa, Asia and Latin America for forest landscape restoration objectives

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Photo 1.
Teak seedling seed orchard, Wonogiri, Central Java, Indonesia
Photo H. Baral/CIFOR.

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RÉSUMÉ

**Adéquation des modèles de plantation
à grande échelle en Afrique, en Asie et
en Amérique latine aux objectifs
de restauration des paysages forestiers**

Les plantations forestières ont aujourd'hui un rôle crucial dans l'approvisionnement en bois et en produits dérivés du bois. Elles répondent à près de la moitié de la demande mondiale, tout en assurant une diversité de services écosystémiques. Dans les zones tropicales et subtropicales, où la croissance des arbres est optimale et où de grandes étendues de terre sont disponibles, la restauration des forêts est présentée comme l'une des stratégies les plus efficaces pour atténuer le changement climatique. Pour ces raisons, les plantations forestières à grande échelle sont encouragées en Afrique, en Asie et en Amérique latine. À partir d'une revue de la littérature et des bases de données publiques sur les plantations forestières, nous avons établi une typologie des plantations à grande échelle en Amérique latine, en Afrique et en Asie à partir de quatre critères : l'objectif de gestion (production ou protection), le nombre d'espèces plantées (plantations multi- ou monospécifiques), l'origine des essences (exotique ou indigène) et le mode de gestion (entreprises industrielles, petits exploitants privés, État). Notre analyse a identifié sept principaux types de plantations et révèle que les deux types les plus courants représentent près de 60 % de la superficie totale plantée : les plantations privées monospécifiques utilisant des espèces exotiques ; les plantations publiques mono-/multispécifiques orientées vers la production et utilisant des essences indigènes. De nombreuses études expérimentales ont été menées dans les années 1950 et 1960 en appliquant un large éventail de modèles de plantations forestières. Cependant, ces modèles ont été peu adoptés par les exploitants car les taux de production et les rendements financiers étaient considérés comme faibles. Les types de plantations majoritaires ne parviennent pas à atteindre la plupart des objectifs de restauration des forêts fixés dans le cadre du Défi de Bonn (productivité, stockage du carbone, conservation de la biodiversité, moyens de subsistance des populations rurales). D'autres modèles de plantations forestières à grande échelle pourraient être favorisés en se concentrant sur les autres biens et services qu'elles peuvent fournir. Cela pourrait se réaliser à condition d'impliquer des parties prenantes plus diversifiées dans les processus de conception et de gestion des plantations et de développer des incitations techniques, financières et institutionnelles appropriées.

Mots-clés : monospécifique, modèles de plantation, typologie, plantations forestières, essences exotiques, essences indigènes, reforestation, Afrique, Asie, Amérique latine.

ABSTRACT

Suitability of large-scale tree plantation models in Africa, Asia and Latin America for forest landscape restoration objectives

Today, tree plantations play a crucial role in supplying wood and wood-based products. They supply almost half of global demand, as well as supporting a diversity of ecosystem services. In tropical and subtropical areas, where tree growth is optimum and large tracts of land are available, forest restoration is presented as one of the most effective strategies for climate change mitigation. For these reasons, large-scale tree plantations are being encouraged in Africa, Asia and Latin America. Based on a review of the literature and of public databases on forest plantations, we drew up a typology of large-scale tree plantations in Latin America, Africa and Asia using four criteria: the management objective (production versus protection), number of species planted (multi-species versus mono-species), origin of species (exotic versus indigenous) and management status (industrial companies, private smallholders, state). Our analysis identified seven main plantation types and reveals that the two most common types represent almost 60% of the total planted area: (1) private mono-species plantations using exotic species; and (2) public production-oriented mono/multi-species plantations of indigenous trees. Numerous experimental studies were conducted in the 1950s and 1960s with a wide range of tree plantation models. However, few were adopted by operators because the production rates and financial returns were considered low. The dominant tree plantation types are failing to meet most of the forest restoration objectives set out in the Bonn Challenge (i.e., productivity, carbon storage, biodiversity conservation, rural livelihoods). Alternative large-scale tree plantation models could be promoted by focusing on the other goods and services that plantations can provide. This could be achieved if more diverse stakeholders were involved in plantation design and management processes, and if appropriate technical, financial, and institutional incentives were developed.

Keywords: mono-species, plantation models, typology, tree plantations, exotic species, native species, reforestation, Africa, Asia, Latin America.

RESUMEN

Idoneidad de los modelos de plantación de árboles a gran escala en África, Asia y América Latina con objetivos de restauración del paisaje forestal

Hoy en día, las plantaciones de árboles desempeñan un papel crucial en el suministro de madera y productos derivados. Suministran casi la mitad de la demanda mundial, además de proporcionar diversos servicios ecosistémicos. En las zonas tropicales y subtropicales, donde el crecimiento de los árboles es óptimo y se dispone de grandes extensiones de terreno, la restauración de los bosques se presenta como una de las estrategias más eficaces para mitigar el cambio climático. Por ello, se están fomentando las plantaciones de árboles a gran escala en África, Asia y América Latina. A partir de una revisión de la literatura y de las bases de datos públicas sobre plantaciones forestales, elaboramos una tipología de plantaciones de árboles a gran escala en América Latina, África y Asia utilizando cuatro criterios: el objetivo de la gestión (producción o protección), el número de especies plantadas (multiespecie o monoespecie), el origen de las especies (exóticas o autóctonas) y la modalidad de la gestión (empresas industriales, pequeños propietarios privados o estado). Nuestro análisis identificó siete tipos principales de plantación y revela que los dos tipos más comunes representan casi el 60 % de la superficie total plantada: (1) plantaciones privadas monoespecie con especies exóticas; y (2) plantaciones públicas monoespecie o multiespecie de árboles autóctonos destinadas a la producción. En los años 50 y 60 se realizaron numerosos estudios experimentales con una amplia gama de modelos de plantación de árboles. Sin embargo, pocos fueron adoptados por los operadores porque los índices de producción y la rentabilidad financiera se consideraron bajos. Los tipos mayoritarios de plantaciones de árboles no logran cumplir la mayoría de los objetivos de restauración forestal establecidos en el Desafío de Bonn (esto es, productividad, almacenamiento de carbono, conservación de la biodiversidad y medio de subsistencia rural). Se podrían promover modelos alternativos de plantación de árboles a gran escala centrándose en el resto de bienes y servicios que pueden proporcionar las plantaciones. Esto podría lograrse si se implicara a partes interesadas más diversas en los procesos de diseño y gestión de las plantaciones, y si se desarrollaran incentivos técnicos, financieros e institucionales adecuados.

Palabras clave: monoespecie, modelos de plantación, tipología, plantaciones de árboles, especies exóticas, especies autóctonas, reforestación, África, Asia, América Latina.

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Introduction

In 2020, forests covered 31% of the global land area (4.06 billion hectares) and the vast majority (93%) were considered natural (FAO, 2020). There was a net decrease of 3% in the global forest area between 1990 and 2015. More specifically, the natural forest area worldwide decreased from 3,961 million hectares (M ha) in 1990 to 3,721 M ha in 2015. Most forest loss occurred in tropical regions in Central and South America, South and Southeast Asia and Africa (Keenan *et al.*, 2015). In contrast, the area of planted forests has risen from 4% of the world's total forest area in 1990 to 7% in 2020 (FAO, 2020). In absolute terms, planted forests increased from 167.5 to 294 M ha over the period 1990-2015 (Payn *et al.*, 2015; FAO, 2020). Therefore, planted forests now play a crucial role in roundwood production. They supply 47% of world demand for roundwood (including timber, woodfuel and pulp production) and provide a diversity of ecosystem services (FAO, 2017; Baral *et al.*, 2016).

In the context of climate change and biodiversity loss, well managed tree plantations can reduce pressure on natural forests, capture CO_2, enhance biodiversity conservation, restore degraded land or ecosystems, and improve food security and nutrition for rural populations, by providing a source of income, employment and economic growth (Chazdon, 2008; HLPE, 2017).

Planted forests are not a new phenomenon in Asia, Africa and Latin America. They were developed during the colonial and postcolonial eras (Szulecka *et al.*, 2014). There are various types of plantation, which depend on: (1) species composition (monoculture/mixed); (2) origin of the planted species (native/exotic); (3) plantation purpose (socio-economic and environmental); (4) plantation intended use (pulp, timber, woodfuel, non-timber forest products or ecosystem services); (5) land ownership (public and private, communal); (6) management responsibility (public and private); (7) management intensity (high-medium-low); (8) scale (large-medium-small); (9) original initiator of plantation (external and internal); and (10) level of institutional arrangements (D'Amato *et al.*, 2017; Baral *et al.*, 2016). Overall, three main approaches to planted forest emerge in the existing typologies (CIFOR, 2002; Brockerhoff *et al.*, 2008; Batra and Pirard, 2015): 1) small-scale tree plantations; 2) management of secondary forests (including enrichment); and 3) large-scale industrial plantations.

According to Bastin *et al.* (2019), "the restoration of trees remains among the most effective strategies for climate change mitigation". Thus, several international processes have been launched, such as the REDD+ process or the Bonn Challenge to support and promote tree plantations around the world, especially in Africa, Asia and Latin America. Forest restoration is also a central component of national commitments to the Paris Agreement and of the United Nations' Sustainable Development Goals and Decade on Ecosystem Restoration (2021-2030). Nowadays, planting programmes are receiving more financial, political and societal support than ever (Holl and Brancalion, 2020). These initiatives largely focus on tropical and subtropical areas (photo 1), where tree growth is faster (Lewis *et al.*, 2019) and larger tracts of land are available for tree planting (Bastin *et al.*, 2019). However, according to Chazdon and Brancalion (2019), "enormous gaps remain between high-level focus on restoration and implementation on the ground". This disconnection can be partly explained by the fact that theoretical models of forest restoration are not adapted to the real constraints – particularly economic – encountered by tree plantation managers (Lopez-Sampson *et al.*, 2021). As a matter of fact, it is from a better understanding of actual large-scale tree plantation models and their historical evolution that we can analyse their ability to evolve and apply adapted forms of forest restoration. A better understanding and characterisation of the planted forests in Africa, Asia and Latin America would allow a more detailed analysis of their functions, advantages and limitations, and finally of their suitability to support reforestation efforts in tropical countries (Batra and Pirard, 2015; Malkamäki *et al.*, 2018). In this perspective, based on a literature review, this article aims to: (1) draw up and describe a typology of large-scale tree plantations in Africa, Asia and Latin America; (2) explore the regional dynamics of large-scale tree plantations; and (3) discuss their capacity to contribute to forest restoration.

Methods

Main concepts

A forest is a "land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10%, or trees are able to reach these thresholds in situ" (FAO, 2018). The FAO (2018) defines a "Forest Plantation" as a "Planted Forest that is intensively managed and meets all the following criteria at planting and stand maturity: one or two species, even age class, and regular spacing". A planted forest is defined as a "forest composed mainly of trees established by planting and/or deliberate seeding, where planted and/or seeded trees constitute more than 50% of the mature growing stock". The FAO definition of a "Forest Plantation" is recent, and no statistics are available for this specific land-use category. Therefore, when referring to planted forests, this article does not differentiate between "planted forest", "forest plantations" or "tree plantations". We define a "large-scale tree plantation" as a tree plantation of at least 50 ha on a single plot of land or as a series of small plantations, which may add up to hundreds or thousands of hectares, spread over different plots in the same territory, as the example of the Mampu plantation in Democratic Republic of Congo (photos 2) (Bisiaux *et al.*, 2009). These large-scale plantations can be mono or pluri-specific and even-age or not.

We do not include naturally regenerating forests in our analysis as they are defined by FAO (2018) as "forest predominantly composed of trees established through natural regeneration".

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Photos 2.
The Mampu plantation, in the Democratic Republic of Congo, is mostly constituted by *Acacia auriculiformis* plots belonging to hundreds of smallholders (a) and dedicated to woodfuel and cassava production (b).
Photos A. Péroches.

Finally, forest restoration is defined as a "planned process that aims to regain ecological functionality and enhance human well-being in deforested or degraded landscapes" (Gann *et al.*, 2019). Therefore, a tree plantation is one option for forest restoration among others, such as natural regeneration, assisted natural regeneration, agroforestry, or rehabilitation/ reclamation (Chazdon, 2008). Note that according to Lewis *et al.* (2019) and Romijn *et al.* (2019) forest plantations and agroforestry systems represent 79% of forest restoration committed to by 24 countries through 2019.

Geographical scope

This study focuses on countries of Africa, Asia and Latin America. It is in these three continents that we find most of the Bonn Challenge commitments (Lewis *et al.*, 2019) and where larger tracts of land are available for tree planting (Bastin *et al.*, 2019).

Literature Review

This study is based on a review of existing literature, including peer-reviewed and grey literature from 1990 to the present. The work began with the analysis of 50 references gathered by the co-authors during their past research. This preliminary database was supplemented by additional research using Google Scholar, which yielded 189 documents. The initial database made it possible to establish a first plantation typology and an overview of different geographical situations. Then, additional research was carried out in the second phase, which made it possible to obtain more specific documents by country/geographical region and/or type of plantation and/or specific theme (e.g., yields, pests, questions about sustainability, etc.). After a preliminary reading, 109 documents were discarded because they lacked information or specific relevance to the topic. Ultimately, 79 documents were selected (48 articles, 23 technical reports, 5 conference papers and 3 books).

Choosing variables for defining a typology for large-scale tree plantations

Two steps were followed in selecting the most suitable variables to design a large-scale tree plantation typology: (i) a review of existing tree plantation typologies and a Google Scholar search to identify criteria in order to determine the different types of large-scale plantation for our database, and (ii) identification of the most relevant discriminating factors under the constraint that they can be documented for each tree plantation type.

We identified three existing typologies (CIFOR, 2002; Brockerhoff *et al.*, 2008; D'Amato *et al.*, 2017). The typology proposed by D'Amato *et al.* (2017) is the most complete and uses a coding system of 11 criteria. In comparison, the CIFOR (2002) and Brockerhoff *et al.* (2008) typologies are based on three discriminating factors. These typologies are not specific to large-scale plantations.

All three typologies use the following criteria to define plantation type: the nature of the plantation (species composition: monoculture or mixed and native or exotic), its purpose and management intensity. While the first two criteria are easy to determine, the third is less clear-cut. Consequently, we chose the nature of the plantation (tree type) and the purpose of the plantation as discriminating factors to define the typology for large-scale plantations.

Beyond these three factors, D'Amato *et al.* (2017) stress the importance of other variables, such as: (a) species composition (monoculture or mixed); (b) a plantation's intended use (provision, regulation and cultural services); (c) land ownership (public and private); (d) management responsibility (public and private); (e) scale (large-medium-small) and composition (monoculture/mixed) in landscape; (f) original initiator of plantation (external and internal); and (g) level of institutional arrangements. Criteria (a) and (d) are easy

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to evaluate and have been included in our typology, along with the nature and purpose of the plantation. Criterion (b) is already included in the typologies of CIFOR (2002) and Brockerhoff *et al*. (2008). Criteria (c), (f) and (g) are not easy to determine and were therefore excluded from our definition. Lastly, criterion (e) is not relevant because it does not relate to large-scale tree plantations.

Based on the analysis, four criteria were selected for our typology:

1. Management responsibility (or forest ownership) – The latest FRA report (FAO, 2020) and D'Amato *et al*. (2017) distinguish two main types of forest ownership: public or private. Szulecka *et al*. (2014) state that these two categories are also valid for tree plantations. Del Lungo *et al*. (2006) go further, by separating the private sector into two categories: companies and smallholders. As explained by D'Amato *et al*. (2017), the nature of "ownership and management are relevant to identifying plantation types because it can exert both positive and negative forces on local communities, for instance by influencing the status of, and access to plantation land and surrounding ecosystems and related services, and by influencing community life and relations, livelihoods, education and employment opportunities". Three categories are distinguished: public plantations, company plantations and plantations owned by smallholders. In the case of private plantations (companies or smallholders), the land may belong to the private person in charge of the plantation or to the state.

2. Planted species – In Africa, Asia and Latin America, most tree plantations are based on even-aged short rotation stands of exotic (non-indigenous) species and intensive management methods (Tassin, 2011; Jürgensen *et al*., 2014; Payn *et al*., 2015). In most cases, the main species planted are pine, eucalyptus, acacia and teak (Cossalter and Pye-Smith, 2003; Louppe, 2011; Cateau *et al*., 2018). These are fast growing exotic species, their seeds are easy to obtain, and their silvicultural techniques are known (Louppe, 2011; INDUFOR, 2017).

3. Species composition – Species can be planted as monocultures or in mixed stands, although mixed plantations are uncommon (Lopez-Sampson *et al*., 2021). This makes a significant difference in terms of biodiversity and economic returns (D'Amato *et al*., 2017).

4. Purpose of the plantation – Louppe (2011) points out that the primary objective of planting exotic species is to produce pulp or wood energy, followed by timber. Del Lungo *et al*. (2006) and Szulecka *et al*. (2014) also mentioned that some plantations have protection objectives (protection of soil and water resources, carbon storage, etc.). The fourth discriminating factor used was the objective of the plantation (i.e., timber, pulp or woodfuel production, ecosystem services-oriented or multi-purpose).

Determination of relative weight of each type of plantation

Firstly, in the cited bibliographic sources, all references to the areas covered by large-scale plantations were collected and classified by plantation type, by country and finally by continent. It is on the basis of these figures that the areas covered, and the relative weight of each type were estimated by continent. When the estimated areas were presented as a range, the middle of the class was retained. Regarding the precision of the available literature, the scale of analysis that seems the most relevant to us is the continent, even if contrasting dynamics can sometimes exist within the same continent.

Key results from the bibliographic summary

Relevant types of large-scale tree plantations in Africa, Asia and Latin America

Based on the four discriminating factors, a "decision tree" was constructed (figure 1). According to figure 1, 60 "theoretical" types of large-scale tree plantations were identified. However, most of these theoretical types do not actually exist or are negligible. The types not mentioned in the literature, or which only cover very small areas (a few thousand hectares) were considered negligible. For example, exotic multi-species stands occupied less than 0.1% of all large-scale plantations worldwide in 2006 (Nichols *et al*., 2006), and no recent source mentioning the existence of this type of tree plantations has been identified. After eliminating the non-existent theoretical types, we identified seven groups of large-scale tree plantations in Africa, Asia and Latin America (figure 1): Type 1 = Private and production-oriented plantations of monospecific exotic species; Type 2 = Private and production-oriented plantations of mono/multi-specific indigenous species; Type 3 = Public and ecosystem services-oriented plantations of monospecific exotic species; Type 4 = Public and production-oriented plantations of monospecific exotic species; Type 5 = Public and production-oriented plantations of mono/multi-specific indigenous species; Type 6 = Public and ecosystem services-oriented plantations of mono/multi-specific indigenous species; Type 7 = Production-oriented plantations of monospecific exotic species managed by smallholders. The main characteristics of these types are provided in tables I to VII.
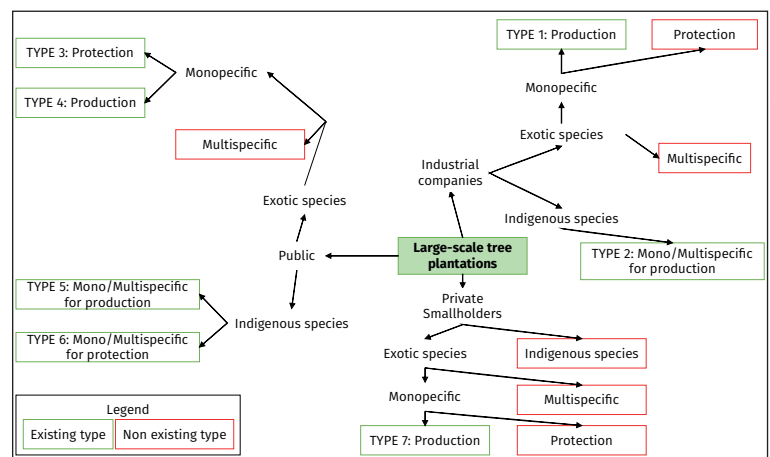

Figure 1.
Diagram of relevant types of large-scale tree plantations in Africa, Asia and Latin America.

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Table I.
Type 1: Large-scale plantation characteristics – Private and production-oriented plantations of monospecific exotic species.

Areas cultivated (in M ha)	Main geographical areas	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
25 – 32	Asia (Indonesia, Thailand, India). South America (Brazil, Chile, Argentina, Uruguay). Africa (Mainly South Africa and Congo).	Significant increase, particularly over the last 15 years. It is the dominant model in southern countries.	Most aged from 5 to 10 years, with a harvesting period ranging from 8 to 30 years.	15 – 40 m³/ha/year (Exceptionally up to 40).

Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Mainly degraded land and savanna areas. 6 to 7% of the surfaces were deforested for plantation installation. This is particularly true in Chile and Indonesia.	Eucalyptus, acacia (*mangium*, *auriculiformis* and *parkia*), pine and teak.	Significant pressure from pests and diseases linked to monoculture and the cultivation of clones outside their area of origin. For example, over 50 types of pests and diseases, which attack acacias and eucalyptus, have been listed in Vietnam alone.	Model highly criticised for its environmental and social impact: ▪ High chemical input use ▪ Low biodiversity ▪ Soil depletion ▪ Pollution and over-consumption of water ▪ Frequent conflicts with local populations, particularly over land ▪ Low job creation per hectare and increasing urban migration ▪ Considered as the secondary cause of deforestation in Southeast Asia and South America. However, this plantation type can alleviate pressure on natural forests due to its high productivity.	

References: Zobel *et al.*, 1987; Cossalter and Pye-Smith, 2003; Mugo and Ong, 2006; FAO, 2010b; Thu *et al.*, 2010; Tassin, 2011; Kollert and Cherubini, 2012; Elias and Boucher, 2014; Martin, 2014; Nambiar and Hardwood, 2014; Szulecka *et al.*, 2014; Andersson *et al.*, 2015; Payn *et al.*, 2015; WWF, 2015; Cateau *et al.*, 2018.

Table II.
Type 2: Large-scale plantation characteristics – Private and production-oriented plantations of mono/multi-specific indigenous species.

Areas cultivated (in M ha)	Main geographical areas	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
< 5	Asia. Africa.	An increase in teak plantations in Asia (particularly India), stable due to the low economic interest for other species.	15 to 25 years.	Varies according to species. Generally, relatively low (< 5 m³/ha/year) and between 10 and 20 m³/ha/year for teak.

Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Generally degraded forest areas.	Several depending on geographical areas. Largely dominated by teak (in native countries) in Asia.	Few documented. Lepidoptera attacks noticed on the genus *Khaya* in Africa.	Model highly criticised for its environmental Virtuous model in terms of environmental concerns because it could potentially reduce harvesting in the natural environment, specifically for certain species, particularly in Central Africa. Few visible impacts on local populations due to the absence of very large-scale plantations, except in the case of teak. Potential land conflicts and value-added sharing identified in the development of this model.	

References: Brunck and Mallet, 1993; Marien and Mallet, 2004; Elias and Boucher, 2014; Karsenty, 2018.

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Table III.
Type 3: Large-scale plantation characteristics – Public and ecosystem services-oriented plantations of monospecific exotic species.

Areas cultivated (in M ha)	Main geographical areas	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
= 5	Asia (Mainly China and India). Africa (Mainly Tunisia).	Significant increase in the late 1990s and 2000s, particularly with Chinese government programmes. Significant increase in Tunisia between 1990 and 2015. Still increasing in Asia and Tunisia.	15 to 15 years.	Approximately 5 m³/ha/year.

Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Areas that are degraded / threatened by desertification.	Eucalyptus, acacia, pine, poplar, teak.	In China, some indigenous and exotic forest parasites, such as pine caterpillars, fall worms, spring cankerworms, nematodes, pine mealybugs and rodents destroy large areas of plantations. In Tunisia, eucalyptus plantations are frequently attacked by four types of insects from Australia, including two species of wood borers and two species of gall insects.	Some projects compete with local populations' traditional and agricultural practices, creating tensions. This type of plantation limits biodiversity due to the monoculture of exotic species. Nevertheless, it can help restore very degraded areas and protect some soils from erosion. In addition, it contributes to carbon storage. Risks of the spread of invasive species are occasionally identified.	

References: Chokkalingam *et al.*, 2006; Del Lungo *et al.*, 2006; Dhahri and Ben Jamâa, 2008; Jacovelli, 2014; Duponnois *et al.*, 2013; Liu *et al.*, 2014; Wolosin, 2017.

Table IV.
Type 4: Large-scale plantation characteristics – Public and production-oriented plantations of monospecific exotic species.

Areas concerned (in M ha)	Main geographical areas concerned	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
6 – 8	Asia (mainly China and India) and Africa (Côte d'Ivoire, Ghana, Morocco, Ethiopia, Madagascar, etc.).	Significant growth, particularly in Asia until the 2000s. Since then, growth rate has slowed down because states generally favour the private sector for this type of plantation.	5 to 15 years.	10 – 40 m³/ha/year.

Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Degraded or agricultural areas.	Eucalyptus, acacia, pine and teak.	In China, some indigenous and exotic forest parasites, such as pine caterpillars, fall worms, spring cankerworms, nematodes, pine mealybugs, and rodents destroy large areas of plantations.	Some projects compete with local populations' traditional and agricultural practices, creating tensions. This type of plantation limits biodiversity due to the monoculture of exotic species (even if it can participate to local species recolonization). In addition, the regular export of woody material can further deplete poor soils. However, it can protect some soils from erosion, contribute to carbon storage and reduce pressure on natural forests.	

References: Barr and Cossalter, 2004; Del Lungo *et al.*, 2006; Tassin *et al.*, 2011; Kollert and Cherubini, 2012; Liu *et al.*, 2014; Wolosin, 2017; Dubiez *et al.*, 2018.

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Table V.
Type 5: Large-scale plantation characteristics – Public and production-oriented plantations of mono/multi-specific indigenous species.

Areas cultivated (in M ha)	Main geographical areas	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
≈ 20	Asia (Mainly China and India). Africa (Mainly Sudan, over a few tens of thousands of hectares in Gabon or Côte d'Ivoire).	Significant increase, particularly in China since 1990. Weak dynamics in Sudan, where most plantations are old.	15 to 30 years.	Varies according to species. Generally, relatively low (< 5 m³/ha/year).

Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Agricultural land, savanna and degraded forest areas.	Chinese fir trees, poplars, acacias from Africa, teak.	In Sudan, most damage to acacias is due to goat and camel alimentation (pruning). Parasite attacks are secondary. Quite variable depending on country and species. Monocultures are generally more sensitive.	Some projects compete with local populations' traditional and agricultural practices, creating tensions. Monospecific plantations (85% of plantations in China), limit biodiversity. Conversely, multi-species plantations have a positive impact on biodiversity. This plantation type can help restore degraded areas, provide carbon storage and provide local resources to the population.	

References: Del Lungo *et al.*, 2006; Gafaar, 2011; Marien *et al.*, 2013; Jacovelli, 2014; Wolosin, 2017; Chevalier, 2018.

Table VI.
Type 6: Large-scale plantation characteristics – Public and ecosystem services-oriented plantations of mono/multi-specific indigenous species.

Areas concerned (in M ha)	Main geographical areas concerned	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
10 – 15	Mainly East Asia (China and India).	Significant increase, particularly in China, as a result of government programmes.	Most range from 10 to 20 years.	Varies according to species. Generally, relatively low (< 5 m³/ha/year).

Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Degraded forest and/or agricultural areas.	Chinese fir tree, poplar.	This plantation type does not seem to have too many problems.	Beneficial effects on soil protection, water resource protection and carbon storage.	

References: Del Lungo *et al.*, 2006; Liu *et al.*, 2014; Wolosin, 2017.

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Table VII.
Type 7: Large-scale plantation characteristics – Production-oriented plantations of monospecific exotic species managed by smallholders.

Areas cultivated (in M ha)	Main geographical areas	Change in area over the last 30 years	Age of stands in 2020 (average)	Average yield
< 5	Africa and Asia.	Little development globally. Development is strongly correlated with the initial public, private or NGO investment.	5 to 10 years based on rotations.	10 – 20 m³/ha/year.

Previous dominant land use	Main species planted	Sensitivity to pests and diseases	Social and environmental impacts	
Degraded forests, wooded savannas.	Eucalyptus, pine and acacia.	Little documentation available.	In many cases, exporting a large part of the woody material at regular intervals can reduce soil fertility (especially in the case of woodfuel production). Given that erosion is usually the main factor involved in soil degradation, this plantation type has positive features. It generally improves the incomes of poor households.	

References: Enters *et al.*, 2004; Del Lungo *et al.*, 2006; Bisiaux *et al.*, 2009; Verhaegen *et al.*, 2014; Dubiez *et al.*, 2018.

Regional trends from 1990 to 2015 by large-scale plantation category/typology

Latin America

Today, Latin America has just over 21.5 M ha of tree plantations (FAO, 2020), of which 80-90% are planted with exotic species (Payn *et al.*, 2015; FAO, 2020). The main planted species are eucalyptus (70%) and pine (25%) (photo 3) (ITTO, 2009; Payn *et al.*, 2015). In this region, the area covered by tree plantations increased by 3.2% per year for the decade 2000-2010. This growth was driven by the private sector and supported by state land and tax policy incentives (ITTO, 2009; EFIATLANTIC *et al.*, 2013). Overall, Type 1 plantations are the most represented category of large-scale plantations.

Wood-based products obtained from South American plantations are generally exported (Cossalter and Pye-Smith, 2003; ITTO, 2009; Cateau *et al.*, 2018). Brazil and Chile have the largest areas of plantations (Jürgensen *et al.*, 2014; Payn *et al.*, 2015), which account for two-thirds of the region's total plantation area (EFIATLANTIC *et al.*, 2013; Payn *et al.*, 2015; Cateau *et al.*, 2018). In both countries, tree plantations produce greater volumes of wood-based products than natural forests (James and Del Lungo, 2005). In Chile, large-scale tree plantations were initially responsible for the deforestation of native forests. However, it seems that since 2001, a shift in tree plantation management combined with changes in forestry policy, have reduced pressure on native forests over time (Heilmayr *et al.,* 2016).

Asia

Asia is the leading continent in terms of forest plantation area, with nearly 123 M ha (EFIATLANTIC *et al.*, 2013). Unlike Latin America, in Asia, plantations of native species are the dominant model (Payn *et al.*, 2015). These native species plantations, such as industrial plantations of teak in India (a native species in the region), are managed according to the same intensive model used for exotic species (ITTO, 2009).

In Asia, historically, the development of tree plantations was based on public projects and funding. One of the main objectives of the plantations was to protect soil and water resources (EFIATLANTIC *et al.*, 2013; Wolosin, 2017). According to FAO (2010a), nearly 30% of the planted area in Asia is geared towards the protection of soil, water resources or biodiversity, more than in any other region of the world. Therefore, a significant proportion of plantations are public and correspond to plantation Types 3, 4, 5 and 6 (Enters *et al.*, 2004; Del Lungo *et al.*, 2006; Wolosin, 2017). Nevertheless, as in most southern countries, since the late 1990s and early 2000s, there has been growing interest in and a major development of industrial production-oriented plantations, particularly in Southeast Asian countries, such as Indonesia and Thailand (Michon, 2003; Enters *et al.*, 2004; Szulecka *et al.*, 2014; Wolosin, 2017). In China, the leading country in terms of planted area, the state has maintained control over plantations (Martin, 2014), which are mainly intended for protection purposes (Liu *et al.*, 2014; Wolosin, 2017).

Then, in Asia, two contrasting situations co-exist: (i) the Chinese model, mostly based on Types 3, 4, 5 and 6; and (ii) the Southeast Asian model, where Type 1 is predominant, as it is in Latin America.

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Photo 3.
Clear cutting of a *Pinus patula* plantation in Colombia.
Photo D. Torres.

Africa

Africa has 11.4 M ha of tree plantations (FAO, 2020), of which 80% are indigenous species, mainly *Acacia senegal* and *Acacia nilotica*[1] (Gafaar, 2011; Jacovelli, 2014; Payn *et al.,* 2015). The rate of increase in plantation area on the African continent is one of the lowest in the world (Payn *et al.,* 2015). Apart from the specific case of South Africa, most African plantations are state-owned (EFIATLANTIC *et al.,* 2013). Large planting campaigns in the 1970s and 1980s failed to meet expectations. Since then, there have been few planting campaigns because of a lack of interest or state withdrawal in the 1990s (Marien and Mallet, 2004; Louppe, 2011; Hamel and Dameron, 2011; Chevalier, 2018).

Sudan (and South Sudan) and South Africa are the top two countries in terms of tree plantation area (Jacovelli, 2014; Cateau *et al.,* 2018). However, their large-scale plantation strategies are very different. For example, in Sudan, tree plantations are public plantations of indigenous species to produce gum arabic (Type 5). In South Africa, private industrial plantations of exotic species (pine, eucalyptus and acacia) (Type 1) are the predominant model (Del Lungo *et al.,* 2006; Jacovelli, 2014; Cateau *et al.,* 2018). However, in this country, expansion of Type 1 plantations is limited with planted area remaining stable (Jürgensen *et al.,* 2014) because of poor soil quality, lack of water and competition with other land uses in the country. Tunisia comes in third in terms of tree plantation area, with Eucalyptus being the main species planted to reduce desertification (Type 3) (Jacovelli, 2014). The remaining African countries have less than 0.7 million hectares of plantations combined.

_____
1 Established by direct sowing and in low density.

Discussion

The typology of tree plantations established in this article is based on the state of available knowledge to provide an operational tool for classifying plantations. Nevertheless, the four criteria retained are relevant for discussing the place of these tree plantation models in relation to forest restoration objectives:

1- Management responsibility (or forest ownership) – This first criterion has indirect impacts on forest restoration objectives. The status, management and access to the plantation land and its related services (ecosystem, social, economic) have an impact on local communities' well-being (D'Amato *et al.,* 2017).

2- Planted species – The recovery of ecological functionality of an area is better in native species tree plantations than in exotic species plantations (Malkamäki *et al.,* 2018).

3- Species composition – The recovery of ecological functionality of an area is better in mixed tree plantations than in monoculture tree plantations (D'Amato *et al.,* 2017).

4- Purpose of the plantation – The four retained objectives of tree plantations (i.e., timber, pulp or woodfuel production, ecosystem services-oriented or multi-purpose) have direct impacts on biodiversity and human well-being.

Considering the three continents analysed, the dominant model for large-scale tree plantations is private industrial monospecific plantations of exotic species (eucalyptus, pine, acacia and teak in non-native areas), which corresponds to our Type 1 (figure 2). These plantations are largely dominant in Latin America and Southeast Asia. In addition, the development of these plantations has been particularly
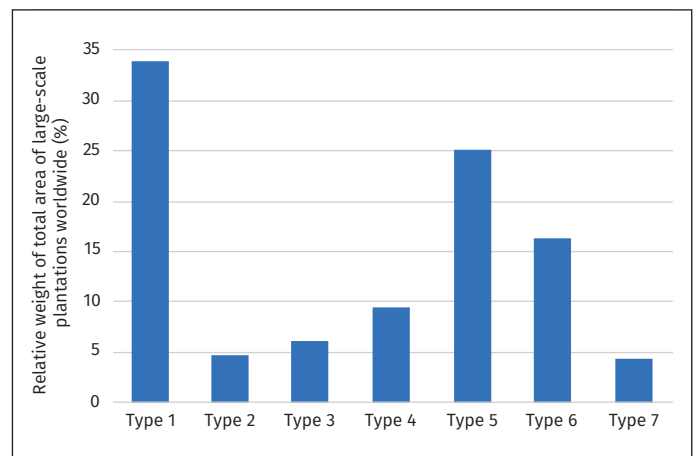

Figure 2.
Relative weight of large-scale plantation typologies worldwide (as %): Type 1 = Private and ecosystem services-oriented plantations of monospecific exotic species; Type 2 = Private and production-oriented plantations of mono/multi-specific indigenous species; Type 3 = Public and ecosystem services-oriented plantations of monospecific exotic species; Type 4 = Public and production-oriented plantations of monospecific exotic species; Type 5 = Public and production-oriented plantations of mono/multi-specific indigenous species; Type 6 = Public and ecosystem services-oriented plantations of mono/multi-specific indigenous species; Type 7 = Production-oriented plantations of monospecific exotic species managed by smallholders.

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Table VIII.
Main criticisms of Type 1 – Large-scale plantation model in Africa, Asia and Latin America.

Sustainability parameters	Weaknesses of the dominant model	References
Contribution to the preservation of biodiversity.	Monocultures and pesticide applications are harmful to biodiversity, which is low in plantations. The use of exotic species can cause imbalances (e.g., invasions) in natural biological processes. Fragmentation of natural forest stands is harmful to the survival of sensitive species. In some cases, new plantations may be responsible for the deforestation of natural forests.	Cossalter and Pye-Smith, 2003; Brockerhoff *et al.*, 2008; Chazdon, 2008; Barua *et al.*, 2014; Andersson *et al.*, 2015; Cateau *et al.*, 2018; Liu *et al.*, 2018.
Carbon storage.	Land is harvested and cleared for replanting (typically once a decade), which releases carbon as a result of decomposition of plantation waste and products (mostly paper and woodchip boards).	Lewis *et al.*, 2019.
Preservation of soil quality.	The use of pesticides and intense production methods depletes the soil over time (chemical pollution, compaction and erosion).	Barua *et al.*, 2014; Andersson *et al.*, 2015; Cateau *et al.*, 2018; Liu *et al.*, 2018; Malkamäki *et al.*, 2018.
Preservation of the quality of water resources.	The use of chemical pesticides pollutes the water resource. Water resources are overexploited in some cases to irrigate plantations, which reduces river flow rate.	Cossalter and Pye-Smith, 2003; Andersson *et al.*, 2015; Cateau *et al.*, 2018; Liu *et al.*, 2018; Malkamäki *et al.*, 2018.
Social and economic development of production areas.	Low job creation per hectare compared to other types of plantation Frequent source of social conflict, particularly relating to land issues. Displacement of local population.	Cossalter and Pye-Smith, 2003; Enters *et al.*, 2004; Van Bodegom *et al.*, 2008; Barua *et al.*, 2014; Andersson *et al.*, 2015; Cateau *et al.*, 2018; Liu *et al.*, 2018; Malkamäki *et al.*, 2018.
Maintaining production in the long term.	This type of plantation is the most susceptible to pests and diseases, which can be a problem in the medium term. This type of plantation seems to be the least resilient to climatic phenomena and, therefore, to future climate change.	Cossalter and Pye-Smith, 2003; Chazdon, 2008; Barua *et al.*, 2014; Cateau *et al.*, 2018; Liu *et al.*, 2018.

dynamic in Brazil, Southeast Asia and China over the last two decades. This plantation category has various advantages: (i) it stores carbon and produces large quantities of wood products; (ii) it can rehabilitate degraded soils; and (iii) it probably reduces pressure on natural forests – this last point being questionable according to Pirard *et al.* (2016) (Cossalter and Pye-Smith, 2003; Buongiorno and Zhu, 2014; Martin, 2014; Cateau *et al.*, 2018). However, Malkamäki *et al.* (2018) conclude, based on a few examples, that industrial exotic monoculture tree plantations often have a negative environmental and social impact. The main criticisms of this model are summed up in table VIII. Therefore, Type 1 fails to meet the necessary conditions – particularly environmental – for forest restoration objectives in accordance with recent international commitments (Bonn Challenge, UN Decade on Ecosystem Restoration or national commitments to the Paris Agreement). According to Malkamäki *et al.* (2018), these environmental and social impacts of Type 1 plantations should be studied more. This affirmation is confirmed by the study of Pirard *et al.* (2017), which

shows that in Indonesia, these plantations can be perceived as either positive or negative by local populations, and may or may not have social impacts on those populations. In the same way, Tassin *et al.* (2011) explain that planted on degraded land near to natural areas, cloned eucalyptus can facilitate the recolonization of native flora and fauna. That is why a better understanding of various situations could improve the outcomes of large-scale tree plantations on local populations and/or the environment.

This synthesis of literature also shows that regardless of the purpose of a tree plantation, all models are controversial. For example, Bremer and Farley (2010) discuss Type 3, sometimes qualifying it as "green-desert". The conclusions of their study "suggest that plantations are most likely to contribute to biodiversity when established on degraded lands rather than replacing natural ecosystems, such as forests, grasslands and shrublands, and when indigenous tree species are used rather than exotic species". Then, the debate is nearer to the one about Type 1, when dedicated to intensive wood production.

From the early 20th century until the 1980s, very diverse mixed plantation models were designed and tested in Africa, Asia and Latin America (Lopez-Sampson *et al.*, 2021). However, they were rarely adopted, primarily because they would probably give low financial returns. Financial returns are documented for exotic monocultures as *Eucalyptus* spp. or *Pinus* spp. (Cubbage *et al.*, 2014), however, financial performance and operation costs of mixed plantations are limited or absent from the literature (Lopez-Sampson *et al.* 2021). According to Cubbage *et al.* (2014), environmental regulations and land rent to governments or local populations reduce plantation investment returns. Then, to promote more socially and environmentally diverse and more efficient tree plantation models, non-financial aspects should be factored in, and the involvement of governments (in both producer and consumer countries) and other stakeholders should be encouraged.

What are the alternatives to Type 1 large-scale tree plantations?

Alternative tree plantation models may be more effective for forest restoration in Africa, Asia and Latin America. According to Brockerhoff *et al.* (2008), native species and long rotation cycles are prerequisites for sustainability. Numerous authors have demonstrated that multi-species plantations improve the sustainability performance of large-scale tree plantations. They optimise environmental resource use, increase productivity and CO_2 storage per hectare, and improve resilience to climatic and biological hazards (Erskine *et al.,* 2005, 2006; Nichols *et al.* 2006; Hung *et al.*, 2011; Louppe, 2011; Pryde *et al.*, 2015; Kelty, 2006; Liu *et al.*, 2018).

Developing alternative plantation types requires funding that will accept a higher risk factor. Funds could be provided by governments or public sources, as illustrated in China (Xu *et al.*, 2004), or by a mix of public incentives, including subsidies, tax benefits and preferential access to credit for private societies as in the Chilean example (Heilmayr *et al.*, 2020). As shown in figures 3 and 4, large-scale tree plantation types are more diverse in Asia and Africa. This can be explained partially by the fact that public funds were allocated to establish plantations. This was not the case in Latin America, where private investment is dominant. Thus, past experiences show the importance of public funds in parallel with or in addition to private investments for developing diverse models of large-scale tree plantations and for considering general interest.

However, alternative tree plantation types have also been criticised. Each type has specific advantages and disadvantages, which are summarised in table IX. Plantation types 1, 4 and 7, which are based on the monoculture of exotic species, may significantly reduce pressure on natural forests, but they are criticised for their frequent (though not systematic) negative ecological impacts, particularly on biodiversity (Holl and Brancalion, 2020). Conversely, types 2, 5 and 6 are more resilient, have fewer negative environmental impacts and promote job creation. However, they are less productive, and mechanisation and processing are more complex.

The diversity of large-scale tree plantation models shows that there are various approaches to achieving the goal of forest restoration. The choice of the appropriate model depends on the results expected from forest restoration, as well as the context. In response to the substantial development of Type 1, current international reforestation initiatives are placing greater emphasis on environmental and social considerations. We now have the knowledge to anticipate these impacts, at least generically, and better prepare new tree plantation projects (Warman, 2014). Today, the major difficulty involved in promoting sustainable tree plantations is clearly identifying the context in terms of decision making and implementation. It is important to consider stakeholders' needs and available knowledge regarding the financial, technical and institutional capacities actually available.
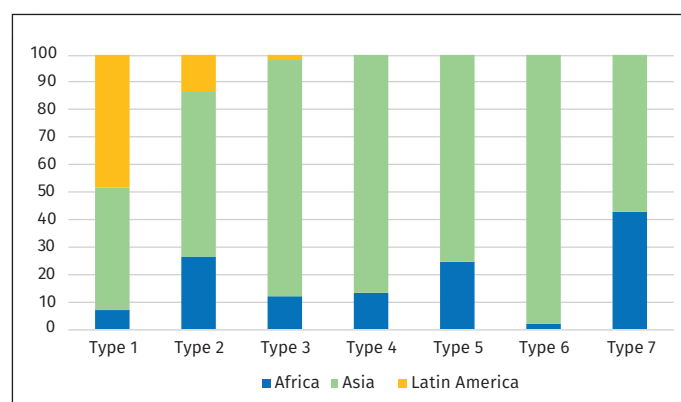

Figure 3.
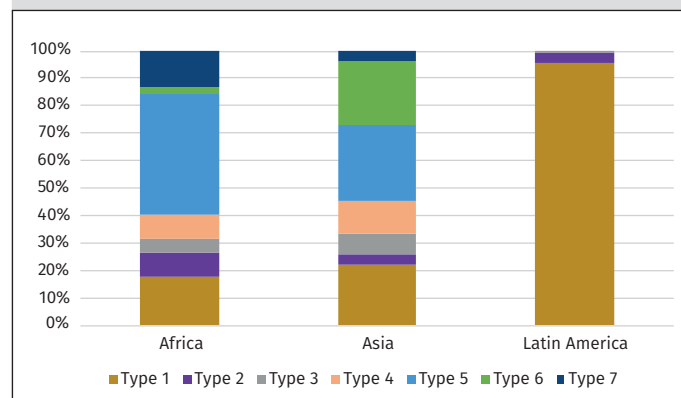Distribution of large-scale tree plantations by type by geographical areas (as %).

Figure 4.
Proportion of large-scale tree plantations by typologies by geographical areas (as %).

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Table IX.
Evaluation of positive and negative impacts of large-scale tree plantations in Africa, Asia and Latin America
(- - = very negative impact; - = negative impact; + = positive impact; ++ = very positive impact).

	Wood productivity	Carbon storage	Conservation of biodiversity	Preservation of soil quality and water resources	Resilience to climatic and biological hazards	Rural livelihoods
Type 1	+ +	+	+/-	-	- -	+/-
Type 2	+	+	+/- (1 species) or + (few species)	+/-	+/-	+/-
Type 3	- -	+ +	+/-	+ +	- -	-
Type 4	+ +	+	+/-	+/-	- -	- -
Type 5	+	+	+/- (1 species) or + + (few species)	+/-	+/-	+/-
Type 6	- -	+ +	+/- (1 species) or + + (few species)	+ +	+/- (1 species) or + + (few species)	-
Type 7	+ +	+	+/-	+	-	+ +

Type 1 = Private and ecosystem services-oriented plantations of monospecific exotic species; Type 2 = Private and production-oriented plantations of mono/multi-specific indigenous species: Type 3 = Public and ecosystem services-oriented plantations of monospecific exotic species; Type 4 = Public and production-oriented plantations of monospecific exotic species; Type 5 = Public and production-oriented plantations of mono/multi-specific indigenous species; Type 6 = Public and ecosystem services-oriented plantations of mono/multi-specific indigenous species; Type 7 = Production-oriented plantations of monospecific exotic species managed by smallholders.

Conclusion

In Africa, Asia and Latin America, large-scale tree plantations are developed in order to: (i) produce forest products (ligneous or non-ligneous); (ii) preserve ecosystems and biodiversity; (iii) act as carbon sinks; and (iv) play a positive social, economic and cultural role, which includes equitable income distribution between the various stakeholders (Cossalter and Pye-Smith, 2003; Louppe, 2011; Payn et al., 2015; Pryde et al., 2015; HLPE, 2017; Cateau et al., 2018; Malkamäki et al., 2018; Bastin et al., 2019; Lewis et al., 2019). None of the existing large-scale tree plantation models can meet these objectives simultaneously, because as Holl and Brancalion (2020) explain "a single tree planting project may achieve multiple goals, but it is rarely possible to simultaneously maximize them all because goals often conflict, and prioritizing one goal may result in other undesirable outcomes". For instance, the dominant plantation models – private monospecific plantations with exotic species – contribute significantly to roundwood production, but probably generate negative ecological and social externalities in many cases (Malkamäki et al., 2018). Conversely, less intensive models have low yields and financial returns. As Chazdon (2008) and Holl and Brancalion (2020) recall, the choice of a tree plantation model depends not only on the plantation's main goal, but also on the degree of degradation of the forest ecosystem, the local population's needs, the available financial and technical resources, and access to land.

Various existing tree plantation management schemes can improve the social, economic, and environmental integration of large-scale tree plantations in landscapes (Pirard et al., 2017). In addition, selecting the most appropriate tree plantation model will be possible if better knowledge about all plantation types is available. For types 1, 3, 4 and 7, studies should be conducted on their social and environmental impacts (Malkamäki et al., 2018), and for the remaining types, more studies are needed on technical and financial performance (Lopez-Sampson et al., 2021).

Rather than focusing on high performance plantations, a change of scale is also possible. Developing mixed-species plantations and including them in multifunctional forest landscapes offer an increasingly popular framework, which combines different types of tree plantations, strengthens their synergies and trade-offs, and involves a broader range of stakeholders, including smallholders (Brockerhoff et al., 2008; Chazdon, 2008; Barua et al., 2014; Payn et al., 2015; WWF, 2015; Lewis et al., 2019). This approach is still difficult to implement because it requires complex institutional planning and organisation (Holl and Brancalion, 2020). However, if tree plantations, and more particularly, large-scale tree plantations, are not integrated at landscape scale, they will continue to respond only to market signals (Pirard et al., 2016) and fail to contribute in forest restoration goals.

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