The role of plantations in managing the world's forests in the Anthropocene

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The public view of tree plantations is somewhat ambiguous. While planting a single tree is generally considered good for the environment, planting a million trees raises concerns in some circles. Although plantations are often used to compensate for bad forestry practices, to willingly simplify otherwise complex forest ecosystems, or as a strategy for allowing the current petroleum-based economy to continue on its course, we believe plantations have a legitimate place in the sustainable management of forests. Multi-purpose plantations, designed to meet a wide variety of social, economic, and environmental objectives, can provide key ecosystem services, help preserve the world's remaining primary forests, and sequester an important proportion of the atmospheric carbon released by humans over the past 300 years.

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The Earth is currently undergoing an unprecedented period of profound global change as a result of human activity; many now refer to this as the Anthropocene (Zalasiewicz *et al.* 2008). The transformation of the world's ecosystems during this period has had serious impacts on biodiversity and important consequences for resource management (Hobbs *et al.* 2006). The pressure on the world's forests to deliver economic, social, and environmental services has reached unsustainable levels in many places. This situation requires urgent implementation of novel forest management approaches (Noble and Dirzo 1997). In many regions of the world, the remaining natural or unmanaged forests will soon have to be protected from exploitation. Yet, the demand for wood products keeps increasing; indeed, wood is even promoted as an environmentally friendly building material, relative to alternatives. How can we reconcile the increasing demand for this renewable resource, while preserving our remaining natural forests?

In a nutshell:

- Forest plantations are expanding all over the world, along with the demand for wood products, whereas primary forests are in decline and in great need of protection
- Plantation forestry has acquired a bad reputation, mainly resulting from intensive, large-scale monocultures; although there is a definite place for such highly productive systems, many other options exist that could also be used to meet demand, as well as other objectives
- Plantation forests need not be "biological deserts"; many features of natural or unmanaged forest systems can be promoted in plantations
- Well-designed, multi-purposed plantations can help mitigate climate change through direct carbon sequestration or by avoiding deforestation, while simultaneously protecting remaining natural forests through increased productivity

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Forest plantations are often put forward as part of the answer to these questions, but there is still debate over their use, because plantations have a bad reputation – often well deserved – arising from their conceptualization and implementation as industrial large-scale monocultures. However, tree plantations in use today are conceptually and practically much more diverse and fulfill a variety of objectives, including, in many cases, conservation.

Plantation forestry designed to provide multiple ecosystem services can reduce pressure on natural forests, and can even restore some ecological services provided by natural forests. They can also play a key role in the fight against global warming, through carbon (C) sequestration. Here, we review the economic, social, and environmental services that plantations can provide, and make a plea for the implementation of well-conceived, diverse, multi-purpose plantations as a way to conserve forest biodiversity and ecosystem functions.

Forests and plantations today

Although the greatest part of "land dominated by trees" is still forest, much of it is now under some level of management or human use (Noble and Dirzo 1997). Of the remaining primary forest, approximately 60 000 km^2 are lost or modified annually by humans (FAO 2006). In many regions, this loss of natural forests has been offset somewhat by a rapid increase in the amount of forest land being allocated to plantations (FAO 2006). Already, over 15% of the world's wood production comes from plantations, which comprise less than 5% of forested lands (Hartley 2002; Carnus *et al.* 2006). In regions where forest industries have implemented large-scale, management-intensive monocultures of *Eucalyptus*, *Acacia*, and *Pinus*, plantations currently account for most of the wood supply (as much as 90% in countries such as Chile or New Zealand; Park and Wilson 2007). These numbers are increasing rapidly, in

Table 1. Examples of forest and plantation timber yield

Type/species	*Average timber yield ($m^3 ha^{-1} yr^{-1}$)*	*Main countries or regions*
Intensive monoculture plantations *(mostly exotic to the country)*		
Eucalyptus	5–40	Brazil, South Africa, China, India, Chile, Spain
Tropical acacias	15–30	Indonesia, China, Malaysia, Vietnam, South Africa
Pines	8–35	Venezuela, Argentina, Chile, New Zealand, Swaziland, USA, Australia
Hybrid poplars	9–37	China, India, USA, Canada, Europe
Exotic larches	5–8	Canada, Europe
Extensive plantations *(mostly reforestation with native species)*		
Conventional conifer restocking following clearcut	2–6	Canada
Intensive forestry	2–7	Scandinavia
Natural forests		
Extensively managed	1–3	North America, Europe, China, Russia
Certified forests	< 1	Worldwide

Note: adapted from published yield tables (Binkley 1997; Sedjo and Botkin 1997; Sedjo 1999; Sohngen *et al.* 1999; Cossalter and Pye-Smith 2003; Messier *et al.* 2003; Aarne and Peltola 2007; Park and Wilson 2007)

conjunction with increasing human populations, demand for wood, and the disappearance of natural forests. Internationally, it is now widely assumed that much of the future global demand for wood will, and should be, met by tree plantations, managed with varying degrees of intensity (Park and Wilson 2007).

Large-scale *Eucalyptus, Acacia, Pinus*, and other intensive monocultures produce average yields of 5–40 m^3 of usable wood per hectare per year; extensive plantations yield 2–7 m^3, and natural forests less than 3 m^3 (Table 1), depending on management intensity, latitude and site productivity, successional stage, and species composition. These figures are rough estimates, but they clearly demonstrate the potential of plantations to provide high volumes of wood from a small fraction of the available land.

Despite their relatively small extent, plantations have been the focus of much of the debate regarding forest sustainability. This has been mainly due to industrial large-scale plantations (3% of forested lands; FAO 2006), established for the sole purpose of quickly producing large amounts of timber, by planting one species over a short rotation and relying on agricultural-type practices. As Carnus *et al.* (2006) put it, "the emphasis, in the past, has been on reducing variability to improve predictive capabilities and efficiency of establishment, tending, and harvesting operations".

■ Not just fiber

While most forest plantations are established solely, yet effectively, for the production of industrial wood or to restock recently cut forests, some are planted for other purposes, including restoration and the production of ecological services. Here, we review three of the most often cited and debated roles plantations can play.

Protection of natural or unmanaged forests

That intensive plantations with demonstrated potential for high productivity (Table 1) could replace natural forests as providers of forest goods, especially commodity-grade wood for pulp and construction material, is, of course, appealing. This idea has been proposed by many, with such provocative titles as *Beautiful plantations*… (Park and Wilson 2007), or *Preserving nature through intensive plantation forestry*… (Binkley 1997). The suggestion is that world demand for industrial woods could be better met if a small fraction of the world's forest area were to be allocated to fast-growing plantations (Sedjo and Botkin 1997), thus reducing pressure on primary and old-growth forests (Sedjo 1999) and allowing their conservation, as well as the development of ecologically sensitive logging practices (eg ecosystem-based management and reduced-impact logging).

Social acceptance of fast-growing plantations is greatly improved when they are presented in a broad context of land-use planning, where increased productivity allows for more area to be protected or harvested by ecologically sensitive methods. This idea forms the basis of functional zoning, better known as the "triad" approach (Seymour and Hunter 1992).

As the name suggests, this novel approach divides the territory into three zones, each with a specific set of objectives. In the first zone, the conservation zone, the territory is fully protected from any industrial activity, for the protection of native biodiversity and ecosystem function. In the second zone, the ecosystem-based management zone, only low-intensity logging is permitted, based on the natural disturbance dynamics of the forest, and implemented with the objectives of preserving the resilience and ecological integrity of the forest (MacLean *et al.* 2009). In the third zone, the intensive management zone, land is primarily dedicated to timber production, without excluding other human activities, such as recreation, or the production of other ecological services associated with forests. Practices in the intensive zone include various types of traditional silvicultural techniques, such as thinning, vegetation management, fertilization, and planting of genetically improved (not genetically modified) native trees to achieve productivity gains. Fast-growing plantations using exotic hybrids or native species – or both – can also be included (Messier *et al.* 2003). The objective of this zone is to produce the timber "lost" from the other two zones in order to maintain, to the maximum extent possible, the current level of timber harvesting for a given territory. Although the territory is divided into three different and mutually exclusive functional zones, the triad approach should be implemented at the landscape level as a whole. Functional zoning is currently being implemented and tested on large privately and publicly owned forest lands in Canada and the US (MacLean *et al.* 2009). For example, in central Québec, Canada, the "Triad Initiative" is being carried out in a 1 million-ha forest management unit on public land (www.projettriade.ca).

Figure 1. *A clean development mechanism REDD project in Ipeti, Panama, where cattle ranching is becoming an attractive livelihood option for this Emberá community threatened by deforestation and poverty (Paquette* et al. *2009). Enrichment plantings are carried out in degraded secondary forests, to generate climate benefits through C sequestration and avoided deforestation, as well as providing incomes for the community, and to preserve biodiversity through forest amelioration and conservation. Insert: a cocobolo seedling (*Dalbergia retusa*).*

Critics argue that "proponents of plantation forestry [to save natural forests] are environmental optimists" (Clapp 2001). This may well be the case in parts of the world where, unfortunately, large plantation programs were not established in parallel with integrated programs of conservation (Carrere 2004). Without concerted conservation efforts – for example, where weak governments are unable or unwilling to enforce conservation programs – plantations are less likely to reduce pressure on natural forests. Indeed, the causal relationship between the economic advantages of plantations and the social and political conditions needed to achieve conservation is "complex, limited, and often perverse" (Clapp 2001). The key to successful conservation in a zoning-type initiative is the implementation and enforcement of rules to ensure that increased volumes from plantations are matched by corresponding increases in protected areas within the same landscape (Noble and Dirzo 1997).

Fighting climate change

Another role envisioned for plantations worldwide is in combating global warming (Canadell and Raupach 2008). Under the Kyoto Protocol, afforestation can be used to sequester C, but the potential of plantations to relieve pressure on natural forests could also soon be credited as "avoided deforestation", a process known as "Reduced Emissions from Deforestation and forest degradation in Developing countries" (REDD) – a topic much discussed at the 2007 Bali Conference of the Framework Convention on Climate Change.

Land-use changes, especially deforestation, account for roughly 25% of global greenhouse-gas emissions and represent the leading cause of species extinctions (IPCC 2001). While there is general agreement that action is needed on deforestation, how the conservation of forest cover should be credited remains uncertain. This topic was thoroughly discussed in Bali, where the parties agreed that pilot projects would be implemented. Clean Development Mechanism REDD projects are already underway in tropical degraded secondary forests, as a land-use alternative that provides opportunity for avoiding deforestation (Paquette *et al.* 2009; Figure 1).

The science to support these initiatives is maturing. For instance, Nilsson and Schopfhauser (1995) reviewed enough studies, some dating back to the 1970s, to allow credible estimates of the amount of area in plantations worldwide necessary to offset various levels of CO_2 emissions. They concluded that the area needed to meet objectives of atmospheric C stabilization was greater than the area readily available for such projects. Still, important quantities could be sequestered. Today, most published estimates present plantations as part of an integrated solution, together with other initiatives, such as alternative soil management methods in agriculture and fossil-fuel reductions (eg Jackson and Schlesinger 2004). The goal of such an integrated global effort is to stabilize CO_2 emissions over the next half-century, when most current plantations will reach maturity and when humanity is expected to have adopted the necessary technologies and lifestyle changes (Pacala and Socolow 2004).

Nevertheless, many environmentalists still see biological sequestration programs, such as plantations, as a strategy for allowing the current, petroleum-based economy to continue on its course. Specifically, issues of additionality and permanence of C sinks, as well as leakage, have been raised (Jackson and Schlesinger 2004; Panel 1). The same applies to REDD programs that could be plagued with fictitious land-use changes and schemes for displacing emissions from one part of the country to another. Clearly, effective rules and guidelines are needed to make it work. In short, every project should demonstrate that the positive effect of a given plantation is additive and is not being neutralized by activities that are simply being displaced (Panel 1).

Under current international and local market conditions, trees are worth more dead than alive – a hard fact that has undermined countless programs to protect forests (Anonymous 2008). It is a lesson that should not be forgotten, as the international community explores ways to reduce greenhouse-gas emissions due to deforestation, such as REDD, for which local populations will require appropriate compensation. To solve the problem, the international community needs to design a market system that recognizes the value of standing trees and forests, along with the ecological and social services they provide (Anonymous 2008).

Issues of credibility have also been raised, in particular regarding how plantations are created (eg afforestation of previously non-forested land versus reforestation) and managed (eg monocultures, pesticide use), and the way in which sequestration is evaluated (eg does it include soil C, especially that released as a result of site preparation techniques?). Permanence is also of concern. Anyone who has tended trees, especially in reclaimed fields, knows that planting is only the first, and perhaps the easiest and most gratifying, step in a long series of necessary operations to guarantee adequate growth (and C sequestration). Yet efforts and money often quickly fall short, leaving trees to struggle under competition and other stresses. Less diversified systems, such as monocultures, may also be less resilient to natural disturbance (Drever *et al.* 2006) or pests (Jactel and Brockerhoff 2007), factors that may be exacerbated by climate change (Woods *et al.* 2005). Finally, others have appropriately pointed out that atmospheric C is just one of many ecological challenges facing humanity, and that although intensive monocultures might reduce CO_2 levels, they may also result in other problems (Canadell and Raupach 2008; Kinzig 2008).

Panel 1. Concepts used for the evaluation of clean development mechanisms under the Kyoto Protocol (adapted from IPCC 2001)

Additionality: emission reductions would not have occurred if it were not for the incentives provided by the project.The actual net greenhouse gases sequestered by the project are greater than the removals that would have occurred in the absence of the project (ie baseline scenario).

Leakage: the displacement of emissions from one part of the country/area to another. A project can be successful in sequestering carbon within the area, but cause increases in carbon-emitting activities elsewhere, thus negating some or all of the climate benefits. This can happen, for example, when the carbon-emitting activities being replaced by the project are not compensated or accommodated appropriately.

Permanence: this issue is especially important for reforestation and avoided deforestation activities. The concerns are whether the carbon sequestered will be at risk of being re-emitted, due to either human actions or natural events, such as forest fires.

Restoration and ecological services

Not all plantations are of the industrial type. In many regions, plantations are effectively implemented to restore forest ecosystems (Parrotta *et al.* 1997). Objectives include the reintroduction of indigenous species often associated with primary forest (ie enrichment planting; Ashton *et al.* 2001), to increase local biodiversity (Carnevalea and Montagnini 2002), or to reconstruct a forest ecosystem to restore economic, social, or environmental services (Montagnini *et al.* 1997; Figure 1). There is strong evidence that plantations can facilitate the conversion of degraded lands to a forested ecosystem through the modification of physical and biological site conditions, thereby allowing forest succession to occur where it would have otherwise been greatly delayed (reviewed in Parrotta *et al.* 1997). Evidence is also growing that plantations can be effective surrogate providers of several ecosystem services, such as erosion reduction, water and nutrient retention, and the creation of habitats (Winjum and Schroeder 1997; Cawsey and Freudenberger 2008). Furthermore, ecological and socioeconomic objectives need not necessarily be at odds; increasingly, plantations are aimed at providing a wide variety of services (eg restoration and poverty alleviation projects; Noble and Dirzo 1997; Lamb *et al.* 2005; Figure 1).

However, these diverse goals are not enthusiastically shared by all. Researchers and practitioners are increasingly preoccupied by the consequences of biodiversity loss on ecosystem functioning and services, such as pollination and C sequestration (see Balvanera *et al.* 2006), and plantation forests are indeed associated with such problems. Plantations have been called "biological deserts" (Stephens and Wagner 2007) and some even argue that "plantations are not forests" (Carrere 2004). It is true that, in contrast to natural or unmanaged forests, plantations, especially the industrial type, are generally composed of one or a few genetically improved native tree species, or fast-growing exotic species, typically even-aged and uniformly spaced (FAO 2006). Such plantations generally possess low compositional, structural, and functional diversity (eg Hansen *et al.* 1991; but see Lugo *et al.* 1993). Moreover, most of these plantations are managed on relatively short rotations that contrast sharply with the longevity that characterizes most natural forest components (Aubin *et al.* 2008).

These concerns are supported by many studies that have compared biodiversity levels in plantations with those of natural forests (reviewed in Hunter 1999). However, other studies show a different picture (see Winjum and Schroeder 1997; Hartley 2002). Plantations may harbor substantial biodiversity (eg Michelsen *et al.* 1996) and can effectively deliver important ecosystem services (Winjum and Schroeder 1997), even in the most intensive of monocultures (Updegraff *et al.* 2004). As Stephens and Wagner (2007) point out, after reviewing the literature on biodiversity in forest plantations, much of the confusion arising from reports of lower biodiversity in plantations is the result of inappropriate comparisons. Plantations are routinely compared with natural, pristine forests, when most, although not all, plantations are established on non-forested lands (afforestation) and the largest loss of natural forests is to other land uses (FAO 2006; Stephens and Wagner 2007). The benchmark, or control, should be chosen based on the plantation's objectives. If, for example, a plantation is designed to restore or improve some ecosystem function, past levels of that function should be used as a benchmark. In the absence of clear objectives, the most appropriate comparison should be with the land use it is replacing (Stephens and Wagner 2007), acknowledging that even high-yield tree monocultures are more diverse than the intensive agricultural field they may be replacing (Updegraff *et al.* 2004). Biodiversity benefit assessment methods have also been developed to help practitioners design and manage plantations for increased biodiversity (eg Cawsey and Freudenberger 2008).

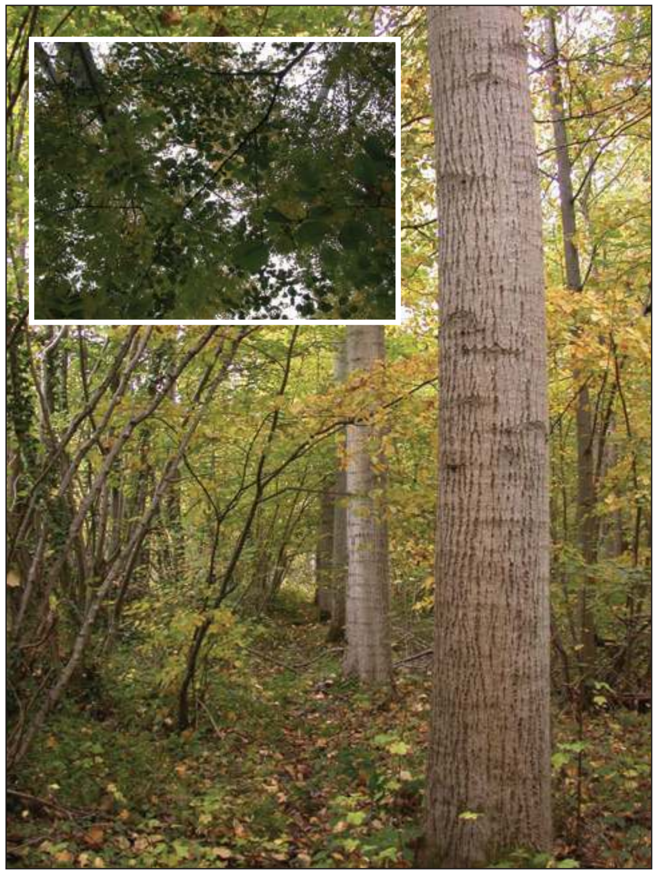

Figure 2. *Hybrid poplar plantation with a diverse understory (France). Flexibility in how intensive plantations are maintained is important for creating a more diverse ecosystem. Insert: late-season vertical structure created by the poplars (yellow foliage) and lush undergrowth.*

The need for more complex, multi-purpose plantations

How can we better design plantations to achieve multiple purposes? Can we go beyond timber and C? And can this be done without losses in productivity, so that plantations can still fulfill their role as surrogate providers of forest products? These questions point to what are probably the best prospects for plantation forestry in the Anthropocene: to proactively design plantations to produce the combination of desired outputs, such as key ecological services, while simultaneously delivering many other important social and economic benefits.

Plantations, including monocultures, can be improved in several ways. Snags and live trees from the previous stand can be retained during harvest (Hartley 2002). Appropriate site preparation can decrease soil disturbance and increase the retention of nutrients, soil organic content (thus also limiting C emissions), and coarse woody debris (Hartley 2002; Carnus *et al.* 2006). Low-intensity site preparation and tending operations – including greater tolerance of competing vegetation, especially once the plantation has established – combined with the proximity of natural forests, can maintain or help establish a diverse and lush understory (Lamb 1998; Aubin *et al.* 2008; Figure 2). Like natural or unmanaged forests, plantations typically diversify structurally and compositionally and hold greater biodiversity as they age, suggesting that within a managed landscape, some plantations should be allowed to age beyond their intended economically optimal rotation (Lamb 1998; Hartley 2002).

The larger spatial context in which the plantation is managed is very important (Hartley 2002), as illustrated by studies on faunal diversity in plantations (Díaz *et al* 1998). The maintenance of landscape-scale diversity can be accomplished in many ways, including, for instance, the use of intensive plantations that involve a mosaic of monocultures of different species, or by leaving buffer strips of natural vegetation scattered among the rows of planted trees (Lamb 1998). Plantations or natural regeneration can act as corridors along streams or hedgerows, connecting plantations with natural or unmanaged forests (Carnus *et al.* 2006). The diversity of the surrounding landscape has demonstrable effects in both natural (Cappuccino *et al.* 1998) and planted (Jactel *et al.* 2002) single-species stands. In summary, managers should maintain or enhance structural and functional complexity at all scales, both within and between plantations, because complexity is an impor-

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Figure 3. *Examples of intensive mixed-species and two-storied plantations. (a) White ash (*Fraxinus americana *– center front) and black walnut (*Juglans nigra *– behind ash) interplanted between fast-growing hybrid poplars (Québec, Canada; Paquette* et al. *2008). This plantation is also an agroforestry experimental site: soybeans are grown in the rows to the left, whereas a control is kept free of competition on the right. (b) Hybrid poplar stand underplanted with Norway spruce (*Picea abies*; Québec, Canada).*

tant determinant of biodiversity and resilience (Parrotta *et al.* 1997).

Species choice is also important for maintaining or enhancing local biodiversity. In monocultures, native species should be used in place of exotics wherever possible (Lamb 1998; Hartley 2002). Growing support exists for maintaining or enhancing stand-level diversity by using mixed-species plantations, or polycultures (Figure 3). Well-planned, mixed plantations can emulate natural stand structural development, possibly making plantations less vulnerable to insect outbreaks or disease (Jactel and Brockerhoff 2007), and reducing risks (Hartley 2002) in accordance with the "insurance hypothesis" (Yachi and Loreau 1999), in which more susceptible species may be replaced by less susceptible species with little or no loss in productivity.

Polycultures could also be more productive than monocultures, by allowing an optimal use of resources (Erskine *et al.* 2006). Theoretical models predict that greater plant diversity will lead to greater primary productivity (overyielding), and many field experiments, mostly involving herbaceous communities, have confirmed this hypothesis (Balvanera *et al.* 2006). Recently, field experiments using trees have started to produce results that confirm the positive effect of diversity on productivity (Potvin and Gotelli 2008).

Unfortunately, despite continuing calls from a wide range of advocates for mixed-species plantations, only $< 0.1\%$ of present industrial plantations are polycultures (Nichols *et al.* 2006). Mixed-species plantations are often considered to be non-viable, operationally or economically, by many in the forestry industry. Long-term trials that are well replicated in time and space (Srivastava and Vellend 2005) and operational-scale demonstration sites that collect economic, social, and environmental data – as well as conventional productivity data – are greatly needed (Nichols *et al.* 2006). At the moment, the design of mixed-species plantations still poses considerable operational challenges and research opportunities; for example, it is not known how many species or traits are necessary to have sufficient diversity to deliver functional benefits, or what species mixtures are best able to form stable and productive stands (Lamb *et al.* 2005).

Other experiments have focused on the delayed distribution of species in time on the same unit of land, mostly according to their successional state or shade tolerance. This mimics natural succession, creating conditions favorable for the development of a cohort of shade-tolerant trees growing under a nurse crop (Paquette *et al.* 2008; Figure 3). For example, conifers have been successfully planted within fast-growing, hybrid poplar stands (Park and Wilson 2007), emulating the way spruce naturally grows beneath pioneer aspen stands in boreal forests. With care and careful planning, these stands can be harvested in multiple steps instead of the traditional single-cut operation, thereby supporting permanent forest cover (Rojo and Orois 2005).

■ Conclusions

Given the proper incentives, awareness, or mandates, tree plantations can provide many of the ecosystem services we have come to expect from forests. Two important fields of research inquiry may help in designing multi-purpose, complex plantations. First, the use of functional traits to guide the choice of species and favor the complementary use of resources needs research attention. For example, species adapted to different light regimes, forming functional groups based on successional traits or shade tolerance, could promote the optimal use of resources through niche partitioning. Second, more work is necessary to understand the effective distribution of species in space and time within polycultures (Parrotta *et al.* 1997). Because of the challenges involved in working with large, long-lived organisms like trees, few experimental sites around the world have been established to test complementarity effects among tree species, the spatial scale at which these occur, and thus the optimal distribution of individuals to promote such effects (but see Scherer-Lorenzen *et al.* 2007; Potvin and Gotelli 2008). Although many spatial distribution patterns for experimental designs have been proposed, only a few have been tested. Such tests are needed, not only for theoretical reasons, but also to address practical questions, given that designs for plantations must be operationally viable if plantations are to be implemented at large scales.

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