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Role of eucalypt and other planted forests in biodiversity conservation and the provision of biodiversity-related ecosystem services

Eckehard G. Brockerhoff [a,*], Hervé Jactel [b,e,f], John A. Parrotta [c], Silvio F.B. Ferraz [d]

[a] Scion (New Zealand Forest Research Institute), PO Box 29237, Christchurch 8540, New Zealand
[b] Laboratory of Forest Entomology & Biodiversity, UMR BIOGECO, INRA, 69, Route d'Arcachon, 33612 Cestas cedex, France
[c] U.S. Forest Service, Research & Development, 4th Floor, RP-C, 1601 North Kent Street, Arlington, VA 22209, USA
[d] Luiz de Queiroz College of Agriculture (ESALQ/USP), Av. Padua Dias, 11, Piracicaba, SP 13418-900, Brazil
[e] INRA, BIOGECO, UMR1202, 69 Route d'Arcachon, F-33610 Cestas, France
[f] Université Bordeaux, BIOGECO, UMR1202, F-33400 Talence, France

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ABSTRACT

Forests provide important habitat for much of the world's biodiversity, and the continuing global deforestation is one of our greatest environmental concerns. Planted forests represent an increasing proportion of the global forest area and partly compensate for the loss of natural forest in terms of forest area, habitat for biodiversity and ecological function. At current rates, over 30% of the remaining natural forest area will be lost by the end of the century and planted forests would then represent over 20% of the total forest area. This places a greater demand on planted forests to contribute to the conservation of biodiversity and their provision of biodiversity-dependent ecosystem services. We reviewed recent trends of deforestation, afforestation and reforestation to evaluate the effects on forest biodiversity and the provision of ecosystem services. We placed particular emphasis on eucalypt plantations which continue to expand in numerous countries, especially in Brazil where rapid plantation expansion is creating the largest area of cultivated eucalypt forest worldwide. While government policies to associate plantation establishment with the protection and restoration of natural forests appear to be effective in the highly fragmented Atlantic forest, deforestation continues in Amazonia, mainly due to forest conversion associated with agricultural expansion. We conclude by reviewing methods for conserving biodiversity in planted forests at the stand- and landscape scales and with a view to enhancing the provision of biodiversity-related ecosystem services.

1. Introduction

Forests are vitally important as habitats for a major part of the world's biodiversity. The ongoing loss, fragmentation and degradation of forests (FAO, 2006) cause much concern about the resulting decline in biodiversity (Brook et al., 2003; Fearnside, 2005; Lindenmayer, 2009). As biodiversity is an important factor in ecosystem functioning and the provision of many ecosystem goods and services (Balvanera et al., 2006; Thompson et al., 2009), the decline in biodiversity is likely to have far-reaching consequences. No fewer than 25 different provisioning, cultural, supporting, and regulating ecosystem services are sensitive to changes in biodiversity (MEA, 2005), and clear relationships exist between forest biodiversity and ecosystem productivity, nutrient cycling, ecosystem resilience to disturbance, and resistance to insect herbivory (Balvanera et al., 2006; Jactel and Brockerhoff, 2007; Thompson et al., 2009).

Planted forests, which are defined as forests that are predominantly composed of trees established through planting and/or deliberate seeding (FAO, 2010), which includes more intensively managed plantation forests, are mainly composed of a few genera of fast-growing trees including pines (*Pinus*), spruces (*Picea*), poplars (*Populus*), eucalypts (*Eucalyptus*), rubber (*Hevea*), and teak (*Tectona*) (Brockerhoff et al., 2008). Most planted forests are grown primarily for efficient wood production and are typically characterised by lower levels of biodiversity than mixed natural forests (Barlow et al., 2007a; Brockerhoff et al., 2008). In addition, such forests are likely to be less capable of providing ecosystem services that are linked to biodiversity (Kelty, 2006; Thompson et al., 2009). There is evidence, for example, that forest 'mono-cultures' are more prone to damage from insect herbivores than mixed stands (Jactel and Brockerhoff, 2007). Apart from more recent considerations of effects on ecosystem function, the proximate and ultimate effects of plantation forestry on biodiversity have been debated vigorously over the last two decades. There is growing recognition that the consideration of biodiversity issues is an important element of planning and management of planted forests as well as wider considerations of biodiversity conservation across landscapes (e.g., Hartley, 2002; Carnus et al., 2006; Brockerhoff et al., 2008; Paquette and Messier, 2010).

* Corresponding author.
E-mail address: eckehard.brockerhoff@scionresearch.com (E.G. Brockerhoff).

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Planted forests (including plantation forests) currently represent about 7% of the total forest area world-wide. Contrary to the area of natural forests, which has been declining, planted forests are expanding (FAO, 2006, 2010). Forest loss varies considerably by region and is currently most severe in some tropical and subtropical regions which record forest loss of up to 0.5% annually (FAO, 2010; see also Achard et al., 2002; FAO, 2006). The main driver for forest loss is development for agriculture (Achard et al., 2002; FAO, 2010). The development of oil palm plantations (see footnote [1]) in particular has been a major cause of recent forest loss in Malaysia and Indonesia (Koh and Wilcove, 2008; Wilcove and Koh, 2010). In Australia, fire and drought were also important causes of forest loss in the last decade (FAO, 2010). While plantation forests have historically replaced natural forests in many countries (Cossalter and Pye-Smith, 2003; Lindenmayer, 2009), more recently, policies and market mechanisms to prevent natural forest loss due to conversion to plantation forests appear to be showing results (FAO, 2010). However, there is evidence that planted forest establishment is unfortunately still occurring at the expense of natural or semi-natural vegetation in some countries. In the case of carbon forestry, this can lead to perverse outcomes in terms of effects on net carbon budgets (Lindenmayer et al., 2012).

Assessment of the net effects of plantation forestry on biodiversity is complex. Many direct and indirect factors need to be considered, including the causes for land use change, conservation value of alternative land uses, the use of native or introduced tree species, and numerous other considerations (e.g., Brockerhoff et al., 2008; Paquette and Messier, 2010).

Efforts to mitigate climate change have led to various afforestation and reforestation incentives to increase carbon storage in forests, which is likely to stimulate the establishment of planted forests for this purpose (Canadell and Raupach, 2008; Lindenmayer, 2009). The increasing interest in using wood for the production of biofuels (Kole et al., 2012) may also lead to further planted forest establishment using species that are suitable for this purpose (Sims, 2003). Therefore, the trend of increasing planted forest area is likely to continue, while the decline of natural forests may not be reversed for some time. Consequently, the planted forests of the future will increasingly need to provide important environmental benefits, including biodiversity conservation and associated ecosystem goods and services (see Ferraz et al., 2012, this volume), for which we currently rely primarily on natural forests.

A substantial proportion of the recently established planted forests especially in the tropics and subtropics involves eucalypts. There are more than 700 species of *Eucalyptus* all of which are native to Australia or, to a lesser extent, adjacent areas of Southeast Asia (Boland et al., 2006). Despite their limited and isolated natural distribution, more than 90% of the area of planted eucalypts is outside Australia (Iglesias-Trabado and Wilstermann, 2008). Brazil alone has more than four times the area of cultivated eucalypts of Australia. Therefore, in this paper we focus particularly on Brazil because of its important status in plantation forestry, its major contribution to the world's total forest cover and the ongoing significant loss of natural forest within this country.

The objectives of this paper are (i) to give an overview of recent afforestation and deforestation rates worldwide, (ii) to evaluate the effects of plantation forestry on biodiversity within and beyond these forests, with emphasis on eucalypt plantations in Brazil, (iii) to review the role of forest diversity in the functioning of planted forest ecosystems and the provision of ecosystem goods and services, and (iv) to provide recommendations for forest planning and management with improved outcomes for biodiversity conservation and ecosystem services.

2. Forest trends and effects of planted forests on biodiversity

Forest loss varies considerably by region, with Europe and eastern Asia recording net afforestation, while Africa, South America, Oceania and southern Asia have lost forest at a rate of 0.2–0.5% annually, particularly in tropical and sub-tropical climates (FAO, 2010; see also Achard et al., 2002; FAO, 2006). While there are encouraging signs that the rate of deforestation is decreasing in some regions (FAO, 2010; Meyfroidt and Lambin, 2011), examination of changes in the combined area of natural forests (i.e., primary and secondary forests composed of native tree species, regenerated naturally) and planted forests is prone to obscure losses of natural forests. Therefore, we used the latest data from FAO's Forest Resources Assessment (FAO, 2010) to compile key data for the 10 countries with the highest reported rates of plantation establishment and the respective rates of forest loss (Table 1). As these 10 countries do not include all the major eucalypt-growing countries, we added 10 more countries, each of which has cultivated eucalypt forests exceeding 500,000 ha (Iglesias-Trabado and Wilstermann, 2008) (Table 1). Interestingly, more than half of the total area of planted eucalypt forest occurs in three countries, Brazil, India and China (Table 1). Our analysis revealed that in most of these countries, planted forests represented the larger share of increases in total forest area (Table 1). And several countries which reported a net increase in forest cover actually experienced a net loss in natural forest (Table 1). This evaluation of relative changes in planted and natural forest cover is informative and indeed relevant for the protection of forest biodiversity (see below), but it should not be interpreted as evidence that the establishment of planted forests *causes* loss of natural forest. In fact, today these two processes primarily occur most often on different sites or landscapes with no direct connection (see, for example, the case study on Brazil, below). Further, it is widely understood that the main cause of deforestation is land use change associated with forest conversion to agricultural land (Achard et al., 2002; FAO, 2010). Nonetheless, we recognise that the establishment of planted forests still involves clearing of natural forests in certain areas, but that this is becoming less prevalent.

In considering the information presented in Table 1, it is important to recognise some caveats related to the FAO's Forest Resources Assessment (FAO, 2010) from which these data are derived. It is acknowledged that the sums of reported forest area figures for individual countries do not necessarily give a correct estimate of the total global trends, due to incomplete or missing data sets for some countries. The best current estimate of total global forest cover is 4.033 billion ha (FAO, 2010, p. 10). Between 2000 and 2010, the rate of forest loss was estimated to be approximately 13 million ha per year (c. 0.35% per year) (FAO 2010, p. 10) and planted forest establishment was estimated to be approximately 5 million ha per year (FAO, 2010, p. 27). An extrapolation of the current trends of natural forest loss and planted forest establishment suggests that, if current trends continue, over 30% of the remaining natural forest area will be lost by the end of the century, with planted forests then representing more than 20% of the total forest area (Fig. 1). While there is some uncertainty regarding these projections, the growing demand for wood, including round wood, pulp, fuel wood, and as a feedstock for other forms of bioenergy (Meyfroidt and Lambin, 2011; Kole et al., 2012), combined with ongoing human population growth and a finite amount of land available for food production, suggest that these predictions are plausible.

What then are the likely implications of these fundamental changes, further substantial loss of natural forest and a

[1] Note that we consider oil palm plantations to be more of an agricultural than a forest system because of the intensity of their management and because palm oil is primarily used as a food product.

Table 1
The ten countries with the highest amount of establishment of planted forest per year between 2005 and 2010, and corresponding changes in the combined area of natural forests (i.e., forests composed of native tree species, regenerated naturally) and planted forest, based on FAO's (2010) Global Forest Resources Assessment 2010, and the total area of cultivated eucalypt forest in these countries and other countries with substantial cultivated eucalypt forests.

Country	Reported area of new planted forest establishment per year (1000 ha/yr)	Net forest area change of natural and planted forest (1000 ha/yr)	Approximate net change in natural forest area (1000 ha/year)	Total area of cultivated eucalypt forest (1000 ha)[a]
China	1988	2763 (1.39%)	775	2610
Brazil	331	−2194 (−0.42%)	−2525	3752
USA	188	383 (0.13%)	195	33
Canada	183	0	183	0
Mexico	162	−155 (−0.24%)	−317	100
Turkey	160	119 (1.08%)	−41	20
India	145	145 (0.21%)	0	3943
Viet Nam	144	144 (1.08%)	0	586
Thailand	108	15 (0.08%)	−93	500
Mali	65	−79 (−0.62%)	−144	?
Australia	55	−924 (−0.61%)	−979	875
Argentina	38	−240 (−0.80%)	−278	330
Chile	64	38 (0.23%)	−26	652
Morocco	12	10 (0.20%)	−2	215
Peru	48	−150 (−0.22%)	−198	480
Portugal	7	4 (0.11%)	−3	647
Spain	26	176 (1.00%)	150	640
South Africa	3	0	−3	568
Sudan	43	−54 (−0.08%)	−97	540
Uruguay	42	45 (2.79%)	3	676
World total	ca 4209[b]	−5581 (−0.14%)	−9790[b]	19,610

[a] The total area of cultivated eucalypt forest is according to Iglesias-Trabado and Wilstermann (2008). Note, in the text we also report an updated area assessment for Brazil only.
[b] Note that due to incomplete or missing data for some countries, the global sums obtained from adding individual country reports are lower than the global total planted forest establishment of ca. 5 million ha per year and forest loss of ca. 13 million ha per year reported by FAO (2010). However, data for the individual countries shown here are thought to be complete. See text for further details.

significantly increased share of planted forest? We suggest that these changes in planted and natural forest cover are indeed highly relevant for forest biodiversity and need urgent consideration regarding its future protection, as we discuss below.

Planted forests may provide habitat for numerous species and are important for biodiversity (Hartley, 2002; Carnus et al., 2006), especially in areas that have lost much natural forest cover (Brockerhoff et al., 2008). A meta-analysis that compared species richness and abundance in planted forest and in pasture land found that birds, reptiles and amphibians, and mammals tended to be richer in plantations than in pasture lands, especially when plantations were located in areas that contained remnants of natural vegetation (Felton et al., 2010). There were no significant differences for invertebrates or plants (Felton et al., 2010). However, one could argue that such comparisons are somewhat crude without consideration of a number of other important factors. For example, on land formerly covered by forest, it is probably more important to what degree the new land cover accommodates species that have lost their local habitat (Brockerhoff et al., 2008). In the case of former forest land, although planted forests are usually less diverse than natural forests (Barlow et al., 2007a; Brockerhoff et al., 2008), forest species are more likely to find suitable habitat in planted forests than in grassland (Pawson et al., 2008), and in some cases, plantation forests may even represent important refuges for threatened species (e.g., Brockerhoff et al., 2005; Pawson et al., 2010). Conversely, on land formerly occupied by natural grasslands, afforestation is usually detrimental for biodiversity because forests are unsuitable as habitat for many grassland species, except for cleared and regenerating open areas of forest (Brockerhoff et al., 2008). It is also relevant to evaluate the habitat and food requirements of (faunal) species, in relation to their occurrence in natural and modified areas (Hsu et al., 2010).

The conservation value of planted forests also depends on the tree species planted and their origin (i.e., native vs. introduced) and to what degree conservation aspects are considered in their management (see below). Plantations of native tree species are generally preferable for forest biodiversity although plantation forests of introduced trees can also provide habitat for native plants and animals (e.g., Brockerhoff et al., 2003, 2005; Eycott et al., 2006; Pawson et al., 2010). Eucalypts are introduced species almost everywhere where they are planted. Several other factors are important when evaluating the effects of eucalypt plantations on biodiversity (Tassin et al., 2011). Overall, it is generally accepted that planted forests, especially those of introduced tree species, are typically less valuable for biodiversity than natural forests. Therefore, the trends of ongoing loss of natural forest and increasing proportion of planted forest will undoubtedly have far-reaching effects on biodiversity especially for forest-dependent species. Furthermore, as plantations will increasingly represent a major proportion of the total forest cover in many regions, the demand will grow for their contribution to the conservation of forest biodiversity and the provision of ecosystem goods and services that depend on biodiversity.

It has been often argued that planted forests contribute, indirectly, to the protection of natural forests by way of their relatively greater productivity, compared with natural forests, and because they provide an alternative source of timber and other forest products (Sedjo and Botkin, 1997; Brockerhoff et al., 2008; Paquette and Messier, 2010). This argument may be more relevant to eucalypt forests grown for timber than those grown for pulp which is not usually extracted from natural forests. There is a somewhat related ongoing debate, mainly about agricultural systems, whether net benefits for biodiversity conservation are greater when crop production and conservation occur on the same land ("land sharing") or when some land is used for more intensive production which might reduce deforestation due to conversion of forests for agriculture ("land sparing") (Phalan et al., 2011). This concept is not entirely applicable to planted forests because (i) today, in most regions deforestation is primarily caused by agricultural expansion (see above), whereas planted forests are no longer commonly

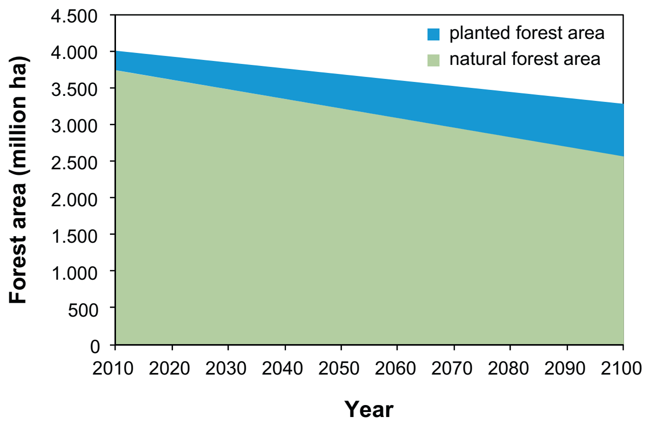

Fig. 1. Projected loss of natural forest (i.e., forests composed of native tree species, regenerated naturally) (ca. 30% loss by 2100) and expansion of planted forests from 2010–2100 (ca. 21% of total forest cover by 2100), based on extrapolation of trends given by the FAO (2010) Global Forest Resources Assessment.

established by conversion of natural forests, and (ii) protection and enhancement of biodiversity within planted forests does not necessarily lead to productivity losses (as more diverse planted forests can be as productive than less diverse forests).

3. *Eucalyptus* plantations in Brazil

Of all countries, Brazil recorded the greatest loss of forests with nearly 2.2 million ha, or about 40% of the global forest loss, for the period 2005–2010 (FAO, 2010). For the same period, Brazil recorded an increase in planted forest area of ca. 330,000 ha per year, the second highest (after China with about 2 million ha) (FAO, 2010). Most deforestation occurred, and still continues, in the Amazon region, while afforestation and reforestation are concentrated in other parts of this vast country, primarily in southern, south-eastern and north-eastern regions (ABRAF, 2012). Historically, eucalypt plantation development in Southeastern states (e.g., São Paulo, Minas Gerais) occurred to provide bioenergy where natural forests were no longer able to supply this. In the 1950s, the pulp and paper industry began to use pine and eucalypt plantations that were mostly established on pasture lands but in some cases this was done at the expense of natural forests. Since 1967, due to changes in Brazil's environmental law, plantation forests are mainly established on degraded land previously used as pasture and for agriculture, where natural forest was already extremely reduced in the past (ABRAF, 2012). This contrast at the national level of significant forest loss in some areas and substantial establishment of plantation forests in other areas is intriguing and represents a valuable case study to examine the role of plantation forestry in biodiversity conservation and the provision of biodiversity-related ecosystem goods and services. Brazil's plantations are dominated by non-native (introduced) trees, mainly eucalypts of Australian origin (ca. 4.26 million ha, see footnote [2]) and pines from North America (ca. 1.87 million ha) (ABRAF, 2012). Consequently, there are concerns that the substantial loss of natural forests in Amazonia contributes significantly to the decline in biodiversity. Planted forests of introduced species, and even restored secondary forests, can provide habitat only for some, certainly not all, species that are affected by the loss of natural forests within broad forest types and regions (e.g., Atlantic forests). They cannot compensate for biodiversity losses in other forest types and regions which may have completely different species compositions (see below). Planted forests may also be inferior in their provision of some ecosystem services (Barlow et al., 2007b). Such examples will be explored below to review measures that benefit biodiversity in plantations and fragmented natural forests.

A major study of different taxonomic groups in eucalypt and natural forest in Amazonia, found that on average 50% of primary forest species were absent in eucalypt plantations (Barlow et al., 2007a), but they still have a complementary conservation value by providing habitat for some species. This is especially important in highly fragmented landscapes. The structure and appearance of eucalypt plantations are fundamentally different from natural forest but elements of the original native forest community may be retained in the understorey of plantations, depending on the intensity of silvicultural management practises. This understorey can provide important habitat resources for wildlife species such as many birds and mammals. In a study in the Atlantic forest region, almost half of the bird and mammal species found in primary forest remnants were observed in nearby eucalypt plantation that contained a native understory, whereas none of these species were found in a eucalypt plantation without it (Stallings, 1991). This suggests that it may be possible to improve the conservation value of eucalypt plantations by modifying forest management such that it encourages the development of understorey vegetation. Another key factor influencing the biodiversity found in eucalypt plantations is the presence of native forest in the surrounding landscape. There is an extensive literature that indicates that vegetation structural complexity within plantation systems is a critical factor determining habitat diversity and niche space for native plant and animal species. This complexity is influenced by the availability of natural forest species propagules (seeds) and their dispersers (principally birds, bats and other mammals) within intact natural forests or forest fragments on the landscape (c.f. Parrotta et al., 1997; Lamb et al., 2005; Carnus et al., 2006; Brockerhoff et al., 2008). The structural complexity and species diversity of the plantation understory is likely to be the single most important factor that determines the level of mammalian biodiversity found in these plantations (Lyra-Jorge et al., 2008). Most studies focused on comparisons of birds and mammals in eucalypt plantations and native forest, but there is still a lack of information on other taxonomic groups, particularly in relation to the effects of forest management options at different spatial scales which may provide valuable information on the potential contribution of this ecosystem for conservation.

Such considerations are particularly relevant in Brazil's Atlantic Forest region, one of the global biodiversity hotspots with very high species richness and endemism, which has suffered much deforestation and fragmentation. Today it is estimated that only 11–16% of native forest remains, mostly dispersed in small fragments, protected areas and private reserves (Ribeiro et al., 2009). This situation places particular emphasis on the role of plantation forests in biodiversity conservation because most eucalypt plantation areas in Brazil are located in the Atlantic forest region.

There are two main mechanisms by which plantations can contribute to the conservation of biodiversity; (i) by providing habitat for some species within the planted area, and (ii) by contributing to the conservation and restoration of natural forest in this landscape. In the Atlantic Forest region, Brazil's environmental law requires that 30–40% of the area managed by forest plantation landscape is covered by native forest. In addition, there are state laws, the Atlantic Forest law, criteria used in assessments for certification of forest management such as FSC, and agreements between forest companies, government and NGOs that contribute to the protection and restoration of native forest in this region. One example of the potential conservation benefits offered by plantation forestry is the Veracel S.A. eucalypt plantation estate where about

[2] Note that a lower area of eucalypt forest in Brazil is reported in Table 1 as this refers to an earlier assessment for which data for many countries are available.

400 ha of forest is being restored annually and about 50% of the area managed is covered by protected native forest (Fig 2). This operation is certified by the Forest Stewardship Council (FSC Certificate: SGS-FM/COC-004383) which gives further credibility to these conservation efforts. Unfortunately, such conservation mechanisms appear not to operate in parts of Brazil's Amazonia where deforestation continues, although governance is said to increase at state and municipal levels in the region.

4. Biodiversity, ecosystem functioning and the provision of ecosystem services in planted forests

It is increasingly being recognised that biodiversity has important roles in the functioning of ecosystems. In a comprehensive meta-analysis (Balvanera et al., 2006), significant positive relationships with biodiversity have been documented for primary and higher level productivity, erosion control, nutrient cycling, regulation of biodiversity, and ecosystem stability, especially regarding resistance to consumption and invasion. In a major review specific to forests, Thompson et al. (2009) concluded that the ability of forests to resist environmental change and to recover from disturbance is related to biodiversity from genetic to landscape scales, and that plantation forests are usually less resistant and resilient than more diverse natural forests.

This observation is supported by Jactel and Brockerhoff (2007) who conducted a meta-analysis comparing pest damage in single-species forests (such as typical plantation forests) and more diverse mixed forests. They found that levels of herbivory were reduced in more diverse mixed forests, especially for oligophagous insect species which have stronger relationships with their host trees. This 'pest control effect' of forest biodiversity was strongest in mixed forests composed of taxonomically distant tree species. Such mixtures do not necessarily need to be implemented at the stand level in order to be effective. For example, Zanuncio et al. (1998) observed that lepidopterous pests in eucalypt plantations were less abundant in eucalypt strips adjacent to strips of native vegetation. Therefore, natural forest areas within the planted forest landscape may be directly beneficial to planted forests by providing free services. To our knowledge, three studies have been carried out that evaluated the effect of mixing species on damage by phytophagous insects on eucalypts. For example, Smith et al. (1989) tested the effect of inter-planting wattle species (*Acacia longifolia*) in *Eucalyptus botryoides* plantations to reduce damage by the psylid *Cardiaspina fiscella* in Western Australia. In this and two other cases (see Supplementary Material 1) a significant decrease in pest insect impact was observed in mixed eucalypt stands, with reduction of damage of between 18% and 78%, compared with the pure stands.

Such biodiversity effects on pests are highly relevant in planted eucalypt forests because eucalypts are heavily burdened by pests and diseases. This is the case in their natural range and, increasingly, in areas where eucalypts have been introduced as insect pests and diseases gradually spread around the world (Withers, 2001; Wingfield et al., 2008; Paine et al., 2011). In addition, eucalypts have begun to acquire new pests and diseases with which they have not previously been associated, and against which they often have limited resistance (Wingfield et al., 2008). If forest diversity can alleviate costly pest and disease problems then enhancing the diversity of eucalypt plantations and the surrounding landscape may be desirable.

The diversity of species in planted forests has been shown to be directly related to productivity. For example, a review of 21 studies that examined the effects of biodiversity of trees and understorey species on the productivity of forests found a positive relationship in 76% of cases (Thompson et al., 2009). Many field trials have been set up to evaluate the benefit of mixed-species plantations of *Eucalyptus* species for stand productivity, primarily in tropical regions of the USA (e.g., Parrotta, 1999; Binkley et al., 2003) and in Australia (e.g., Bauhus et al., 2004; Forrester et al., 2007, 2011). They involved many *Eucalyptus* species (*Eucalyptus cloeziana, Eucalyptus globulus*, *Eucalyptus grandis*, *Eucalyptus pellita*, *Eucalyptus nitens*, *Eucalyptus robusta*, *Eucalyptus saligna* and *Eucalyptus tereticornis*) and, in most cases, nitrogen fixing tree species of the genera *Acacia*, *Albizia*, *Casuarina*, *Enterolobium*, *Falcataria* and *Leucaena* (in only two cases, no N-fixing species of Araucariaceae or Pinaceae were involved) (see Supplementary Material 1 for a complete list of studies). Despite the wide range of species mixtures tested, these experiments produced remarkably consistent results with a global pattern of higher stem volume or biomass in mixed plantings than in pure *Eucalyptus* stands. Productivity gains were primarily attributed to above-ground niche complementation (improved use of light resources due to complementary canopy structures), higher soil fertility (increased nitrogen supply by associated species), and lower understorey competition. However these trials also showed that not all mixtures were equally more productive than pure *Eucalyptus* forests and that both, species composition, functional composition and diversity, and the spatial design of mixed-species plantations need to be considered. These results indicate that by increasing tree species diversity in planted eucalypt forests, significant productivity gains may be obtained either via enhanced growth or, indirectly, due to lower herbivory damage. Functional diversity and composition of tree assemblages are probably important factors that explain productivity and related responses.

Fig. 2. Hybrid eucalypt plantation in Bahia State, Brazil, with protected remnants of natural and restored semi-natural forest. In the Atlantic forest region of Brazil, the Government has stringent demands for forest conservation and restoration whereas deforestation is an ongoing major issue in Amazonia (Photo by Clio Luconi, Veracel).

Of potentially even greater future importance is the expectation that more diverse (mixed-species) forests are more able to withstand or adapt to climate change. This is because in mixed forests there is a greater probability that some tree species will be able to persist as climates are changing in terms of temperature, rainfall, etc., than would be the case in forests composed of a single tree species (Seppälä et al., 2009).

Consumer diversity was also found to be related to plant diversity. In a recent meta-analysis based on 320 case studies (Castagneyrol and Jactel, 2012), it has been shown that the diversity of arthropods, reptiles and amphibians, birds, and mammals significantly increases with plant diversity. Twenty-five of these correlations between plant and animal species richness involved *Eucalyptus* forests (see Fonseca et al., 2009 for examples from Brazil and Supplementary Material 1 for a complete list). These studies reveal that vertebrate diversity and arthropod diversity are positively correlated with the diversity of plants (principally understorey vegetation) associated with eucalypt plantations.

There are numerous other linkages between forest diversity and the functioning of forest ecosystems and related ecosystem goods and services that are relevant to humanity, including effects that benefit adjacent ecosystems beyond the forest (Thompson et al., 2009). For a general review of ecosystem goods and services that are provided by plantation forests, see Bauhus et al. (2010) and de Groot and van der Meer (2010).

5. Recommendations for enhancing biodiversity in planted forests and their provision of ecosystem services

Methods for conserving biodiversity in planted forest have been reviewed by several authors, emphasising different aspects and scales (e.g., Hartley, 2002; Lindenmayer and Franklin, 2002; Carnus et al., 2006; Fischer et al., 2006; Brockerhoff et al., 2008). Here our aim is to synthesise the key aspects relevant for (i) managing and enhancing biodiversity at the stand and landscape scales and (ii) increasing functional diversity (Thompson et al., 2011) for enhanced ecosystem functioning and provision of ecosystem goods and services (Table 2). Many of these recommendations are also reflected in criteria applied for certification of plantation forests such as those of the Forest Stewardship Council (FSC, 2012).

Key considerations for enhanced biodiversity outcomes can be placed within a framework encapsulated by the following questions: (1) *What is the land use prior to planted forest establishment?* The conversion of abandoned agricultural or degraded land with limited conservation value is not expected to have negative impacts on biodiversity, and it may have positive effects on biodiversity. By contrast, the conversion of natural vegetation, particularly if it contains significant vegetation or threatened species, should be avoided. (2) *Are natural areas protected?* Such areas are likely to be of high conservation value and, where possible, they should be exempt from conversion to planted forest and be set aside for protection. (3) *What management of biodiversity and, in particular, threatened species is being undertaken?* This should include surveys of biodiversity occurring in the land holding, consultation with local conservation authorities and experts, and the development and implementation of biodiversity management plans. (4) *What is the identity of the tree species planted and is it a native or introduced species?* Planted forests often involve the cultivation of introduced species. While this does not preclude opportunities for biodiversity conservation, the use of native trees typically provides better habitat for other native species. (5) *Is understorey vegetation present and are there opportunities for its enhancement?* As discussed earlier, the presence of understorey vegetation can enhance the value of planted forests as habitat for a wide range of species that benefit

Table 2
Examples of ecosystem services (sensu MEA, 2005) provided by planted forests that are likely to be sensitive to changes in biodiversity, how these (qualitatively) compare to either natural forest and to previously deforested/degraded lands (such as abandoned cropland or pasture), and management/planning practises that could enhance the provision of these services (see also Bauhus et al., 2010; de Groot and van der Meer, 2010).

Ecosystem service provided by planted forests	Provision of ecosystem service relative to		Characteristics (or management actions) that favour provision of specific ecosystem service
	Natural forests	Degraded land	
Supporting			
Soil formation	Generally lower	Generally higher	Increased diversity of planted species; decreased soil disturbance during establishment and silvicultural operations
Nutrient cycling	Generally lower	Higher	Increased diversity of planted species, encouragement of understorey vegetation
Primary production	Variable	Generally higher	Increased diversity of planted species that are compatible and complementary
Provisioning			
Habitat for forest species	Lower	Higher	Increased diversity of planted species; protection and restoration of natural vegetation areas
Food and fibre	Higher (fibre), lower (food)	Higher (fibre)	For fibre: as for 'primary production'; for food: use of canopy or understorey species that provide fruit or other food, use of agro-forestry systems
Fuel	Variable	Generally higher	Planting of species with characteristics favourable for use as firewood and/or charcoal.
Genetic resources	Lower	Variable	Increased diversity of planted species, particularly of desirable species, encouragement of understorey vegetation, protection and restoration of natural vegetation
Biochemicals, natural medicines, pharmaceuticals	Lower	Generally higher	Increased diversity of planted or naturally regenerated species of medicinal value
Fresh water (quantity)	Variable	Mostly lower	Use of species with lower water use and canopy interception, landscape mosaic management
Fresh water (quality)	Variable	Higher	Road system redesign, minimal cultivation, soil conservation techniques
Regulating			
Air quality maintenance	Variable	Higher	Planting forests or shelterbelts of suitable species within or adjacent to population centres.
Erosion control	Mostly similar	Higher	Use of deep-rooted tree species, avoidance of large-scale clearfelling
Water purification and waste treatment	Lower	Higher	Use of tree species in systems for wastewater treatment (e.g., species of known value as bioaccumulators of heavy metals)
Biological control, resistance to pest damage	Lower	?	Increased diversity of planted species, encouragement of understorey to provide habitat for natural enemies of pests
Pollination	Lower	?	Increased diversity of planted species, especially of species that support pollinators
Storm protection	Lower	Higher	Creation of "soft edges", planting of wind-resistant tree species; mangrove reforestation in appropriate coastal regions
Cultural			
For example, aesthetic values; cultural heritage values; recreation and ecotourism	Probably lower (for all cultural services)	Similar	Planting of culturally significant canopy and/or understorey species; diversification of plantation landscapes to improve aesthetic and recreation values; preservation of sites of particular cultural or recreational value within landscapes

from the increased structural complexity and the availability of resources not provided by the canopy tree species.

The following recommendations for the establishment and management of planted forests can be derived: At the stand scale, clearing natural vegetation should be avoided prior to planting; where possible, the planting of native tree species is preferable; and the introduction of structural and species diversity of canopy trees (i.e., mixed species plantings) and in the understorey (via retention of pre-existing or naturally regenerating forest species) are desirable [to the extent that this does not significantly compromise productivity of the principal tree crop]. At the landscape scale, the protection and enhancement of remnants of natural vegetation should be an explicit aim; the creation of mosaics of stand ages and tree species is recommended as this can enhance biodiversity across the landscape; as is the establishment of corridors linking habitat patches, including forest corridors, non-forest corridors, and riparian corridors. To assist with landscape management for improved conservation of biodiversity and water, a new tool, BIOINDEX, has been developed for planted forests in Brazil (Ferraz and Ferraz, 2009). This provides a set of metrics for landscape monitoring useful to assess and adjust landscape management for conservation purposes. In Brazil, this tool is now being used by one of the biggest pulp and paper companies.

Regarding management of planted forests for enhanced provision of ecosystem goods and services, there is no 'one-size-fits-all' approach. Due to the large number of different ecosystem services, the potential existence of tradeoffs among these, and site-specific and forest type-specific circumstances, recommendations need to be directed at the particular ecosystem service of interest (see Table 2). However, some generic guidance can be given. Planted forests that are well-managed with consideration of the stand- and landscape-level recommendations above, and that are composed of a greater variety of tree and understorey species, are likely to provide desired ecosystem services to a greater degree than those that are not. A careful analysis of what functional aspects of biodiversity are relevant for the provision of specific services should point towards possible solutions. Improved communication between scientists, policy makers and forest managers is a critical element for a better understanding of relationships between forest biodiversity and ecosystem services and the relevant measures that can be implemented during forest management to enhance the provision of those services most relevant and valued by society from such forests (Thompson et al., 2011).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2012.09.018.

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