Biodivers Conserv (2008) 17:925–951
DOI 10.1007/s10531-008-9380-x

ORIGINAL PAPER

Plantation forests and biodiversity: oxymoron or opportunity?

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Received: 14 September 2007 / Accepted: 19 March 2008 / Published online: 9 April 2008

Abstract Losses of natural and semi-natural forests, mostly to agriculture, are a significant concern for biodiversity. Against this trend, the area of intensively managed plantation forests increases, and there is much debate about the implications for biodiversity. We provide a comprehensive review of the function of plantation forests as habitat compared with other land cover, examine the effects on biodiversity at the landscape scale, and synthesise context-specific effects of plantation forestry on biodiversity. Natural forests are usually more suitable as habitat for a wider range of native forest species than plantation forests but there is abundant evidence that plantation forests can provide valuable habitat, even for some threatened and endangered species, and may contribute to the conservation of biodiversity by various mechanisms. In landscapes where forest is the natural land cover, plantation forests may represent a low-contrast matrix, and afforestation of agricultural land can assist conservation by providing complementary forest habitat, buffering edge effects, and

An 'oxymoron' is a figure of speech using an intended combination of two apparently contradictory terms.

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increasing connectivity. In contrast, conversion of natural forests and afforestation of natural non-forest land is detrimental. However, regional deforestation pressure for agricultural development may render plantation forestry a ‘lesser evil’ if forest managers protect indigenous vegetation remnants. We provide numerous context-specific examples and case studies to assist impact assessments of plantation forestry, and we offer a range of management recommendations. This paper also serves as an introduction and background paper to this special issue on the effects of plantation forests on biodiversity.

Keywords Afforestation · Biodiversity conservation · Certification · Context · Deforestation · Forest management · Impact assessment · Land use change · Landscape ecology

Introduction

Deforestation is a major cause of the loss of biological diversity and a significant global concern (e.g., Wilson 1988; Brook et al. 2003; Laurance 2007) as it is estimated that more than half of the known terrestrial plant and animal species live in forests (Millenium Ecosystem Assessment 2005). Globally, the area of natural and semi-natural forests decreases by some 13 million ha annually (ca. 0.3%), mostly due to conversion to agriculture (FAO 2006a, 2007). Plantation forests constitute only about 3.5% of the total forest area (ca. 140 million ha) but the area of plantation forests is increasing by about 2–3 million ha (ca. 2%) annually, against the trend of a globally falling forest cover (FAO 2006a, Table 1). According to the current Food and Agriculture Organization (FAO) and International Union of Forest Research Organisations (IUFRO) definitions (e.g., FAO 2006a), plantation forests are established through planting or seeding of one or more indigenous or introduced tree species in the process of afforestation or reforestation. Particularly in the first rotation after establishment, stands are typically of an even-aged structure with an even spacing of trees. Their main objective is often the production of timber or fuel wood (plantations provided about 35% of the global wood supply in 2000) but some are established to reduce erosion, fix carbon, or provide other environmental, economic, or social benefits. Many plantations are intensively managed including the use of improved tree varieties and silvicultural operations that may involve site preparation (e.g., ploughing, harrowing, use of fertilizers, and herbicides), thinning, and clear-cut harvesting, often with short rotations (e.g., <30 years between planting and harvesting, or as little as 5–10 years for poplars and some tropical species). Apart from such plantations, the FAO definition for “planted forests” (FAO 2006b) also includes some types of semi-natural forests that were established through planting or seeding by human intervention. In reality, it is often difficult to categorise planted forests such as those that have been established as pure stands by planting or sowing centuries ago, and have since become more diverse by natural processes, which is common in much of Europe.

The implications for the conservation of forest biodiversity of plantation forests and their continuing expansion are being debated vigorously. Although plantation forest managers increasingly recognise the need to conserve biodiversity, and many adhere to sustainable management guidelines such as those of the Forest Stewardship Council (FSC Forest Stewardship Council 2007a) or the Programme for the Endorsement of Forest Certification schemes (PEFC 2007), certification does not always benefit biodiversity conservation (Gullison 2003), and criticism of plantation forestry from some stakeholders remains strong (e.g., Cossalter and Pye-Smith 2003, and see below). Plantation forests are the focus of

Table 1 Forest cover, proportion of plantation forests, and approximate area of principle tree species used in plantation forests in selected countries with different species composition

Country	Total forest cover (million ha) and annual % change	Percentage of land area forested	Area of plantation forests (million ha) and annual % change	Percentage of forest cover in plantation forest	Approximate area of principle plantation tree species in million ha[a]	
					Conifers	Broadleaved trees
World	3952.0 −0.2%	30.3	139.8 +2.0%	3.5%		
Examples of countries with mostly exotic plantation species						
Brazil	477.7 −0.6%	57.2	5.4 +0.4%	1.1%	1.8 *Pinus spp.** (*P. taeda**, *P. caribaea**, *P. elliotii**) 0.08 *Araucaria angustifolia*	3.0 *Eucalyptus* spp.* (*E. grandis**, *E. urophylla**, *E. urograndis**)
Indonesia	88.5 −2.0%	48.8	3.4 +2.3%	3.8%	0.8 *Pinus merkusii*	3.5 *Hevea* spp.* 1.5 *Tectona* spp.* 3.4 other broadleaves
New Zealand	8.3 +0.2%	31.0	1.8 +0.9%	22.3%	1.6 *Pinus radiata** 0.1 *Pseudotsuga menziesii**	
UK	2.8 +0.4%	11.8	1.9 −0.1%	67.6%	0.8 *Picea* spp.* (*P. sitchensis**, *P. abies**) 0.3 *Pinus* spp. (*P. sylvestris*, *P. contorta**, *P. nigra**) 0.13 *Larix* spp.* 0.05 *Pseudotsuga menziesii**	
Examples of countries with mostly native plantation species						
China	197.3 +2.2%	21.2	31.4 +4.7%	15.9%	12.9 *Pinus* spp. (*P. massoniana*, *P. tabulaeformis*, *P. elliottii**) 17.2 *Cunninghamia lanceolata*/*Larix* spp.	1.3 *Eucalyptus* spp.* 11.5 *Populus* spp. and other broadleaves
France	15.6 +0.3%	28.3	2.0 +0.3%	12.7%	1.3 *Pinus* spp. (1.1 *P. pinaster*, 0.2 *P. nigra*) 0.45 *Picea abies* 0.3 *Pseudotsuga menziesii**	0.2 *Populus* spp.
USA	303.1 +0.1%	33.1	17.1 +0.9%	5.6%	15.0 *Pinus* spp. (*P. taeda*, *P. elliottii*, *P. echinata*, *P. palustris*) 1.2 *Pseudotsuga menziesii*/*Larix* spp./*Picea* spp.	

[a] Exotic species are indicated by an asterisk. Compiled from various sources, primarily FAO (2001, 2006a). Additional information, mostly about the species composition of plantation forests, for Brazil from www.itto.or.jp/newsletter/v7n2/08industrial.html (Reis MS, Industrial planted forests in tropical Latin America, accessed January 2002); for France from IFN database, Inventaire Forestier National, France (accessed January 2002 by HJ); for New Zealand from Anon. (2001a) New Zealand forest industry facts and figures. Forest Owners Association, Wellington, New Zealand; for the United Kingdom from Anon. (2001b) Forestry statistics 2001. Forestry Commission, Edinburgh, UK; and Simon Gillam (Forestry Commission, UK, pers. comm.); for the USA from W. Brad Smith (U.S. Forest Service, Washington, DC, pers. comm.). Note, for Indonesia the area of tree species in plantations is based on FAO (2001). Indonesia reported a significant drop in the total plantation area for the 2005 Forest Resources Assessment according to FAO (2006a)

widespread opposition amongst several environmental organisations (e.g., Carrere and Lohmann 1996; World Rainforest Movement 2007). The industrial scale of many plantations, their common structure as monocultures and particularly the fact that they are sometimes established on land previously covered in natural forest all serve to place them in the forefront of the concerns of environmental lobbies. FERN (2007) and the World Rainforest Movement (2007) have also expressed concern about the likely impacts of expanded use of genetically modified trees in some plantations. One recent focus of these concerns about plantations has been the debate over the extent to which, and conditions under which, plantations might be eligible for certification under the FSC. In the past, plantations were certified if they met the same basic conditions of good management that were applied to natural and semi-natural forests, along with some additional criteria specifically for plantations. Some environmental groups argued that certification by FSC implied in the minds of purchasers a natural, green product and that therefore certification should never be given to ‘monocultures’. These concerns of NGOs have recently triggered a review of the eligibility of plantation forests for certification under the Forest Stewardship Council (2004, 2007b, c).

The scientific community is equally divided over these issues (e.g., Kanowski et al. 2005), and despite an expanding body of literature on the effects of plantation forestry on biodiversity, there is no simple answer to the question of whether or not plantation forestry is compatible with biodiversity conservation goals. To answer this question, and to determine whether ‘plantation forests and biodiversity’ are indeed an oxymoron or an opportunity, it is necessary to consider the wider context of a plantation forest and to take numerous factors into account that vary substantially among locations and countries, and that ultimately determine the likely effects on biodiversity. For example, it is essential to know what kind of land use preceded the establishment of a plantation, what alternative land uses are probable at a given location, what tree species are involved, and how and for what purpose a plantation is being managed. While the majority of plantation forests are managed primarily for production purposes, substantial areas serve primarily for environmental protection and conservation, and many plantations have multiple purposes. Although these characteristics vary widely among plantation forests, assessments of their environmental effects often do not consider such factors.

The International Union of Forest Research Organizations (IUFRO), the World-Wide Fund for Nature (WWF), and several other organisations recently sponsored three conferences[1] to facilitate scientific debate on these issues. This special issue of Biodiversity and Conservation represents an account of some of these contributions of recent research that is relevant to this debate. This article serves as a background document to the topic and to give an overview of some of the key issues that need to be considered for an informed debate about plantation forestry and biodiversity. The specific objectives of this paper are:

- to provide a brief review of the value of *plantation forests as habitat*, compared with natural forests and other, mainly agricultural, land uses,
- to examine effects of plantation forests on biodiversity at the *landscape scale*,
- to *place in context the different types of plantation forests* and thereby clarify the situations in which there are positive and negative impacts of plantation forests on biodiversity, and to examine examples of various plantation forests in different countries, and
- to offer suggestions how plantations can be *managed to enhance biodiversity*.

[1] “Biodiversity and Conservation Biology in Plantation Forests.” Bordeaux, France, 27–29 April 2005. “Biodiversity and Plantation Forests—Oxymoron or Opportunity”, Technical Session at the XXII IUFRO World Congress—Brisbane, Australia, 8 August 2005. “Ecosystem Goods and Services from Planted Forests.” Bilbao, Spain, 3–7 October 2006.

Habitat or non-habitat? Is there biodiversity in plantation forests?

A common perception of plantation forests is that they are ecological deserts that do not provide habitat for valued organisms. However, numerous studies in many countries have documented that plantation forests can provide habitat for a wide range of native forest plants, animals, and fungi (Parrotta et al. 1997a; Oberhauser 1997; Humphrey et al. 2000; Brockerhoff et al. 2003; Barbaro et al. 2005; Carnus et al. 2006, and papers in this issue). Even uncommon and threatened species are increasingly recorded in plantations as more targeted surveys are being undertaken. For example, the largest population in Europe of the locally threatened hoopoe, *Upupa epops*, occurs in plantation forests in the Landes region in France (Barbaro et al. 2008—this issue). The flightless cassowary, *Casuarius casuarius*, has been recorded in *Araucaria cunninghamii* plantations in Queensland (Keenan et al. 1997). Substantial populations of the endangered brown kiwi, *Apteryx mantelli*, occur in exotic pine plantations in New Zealand (e.g., Kleinpaste 1990). The critically endangered ground beetle, *Holcaspis brevicula*, a locally endemic species, is thought to depend on a plantation forest as its only remaining habitat (Brockerhoff et al. 2005; Berndt et al. 2008—this issue).

Thus, there is abundant evidence that plantation forests themselves can be valuable as habitat. However, plantation forests are commonly being compared with biodiversity in more natural forests, often without consideration of the circumstances that define whether such comparisons are appropriate (see below). Appropriate or not, it is usually true that natural forests offer superior habitat for native forest species than plantation forests (Armstrong and van Hensbergen 1996; Moore and Allen 1999; Lindenmayer and Hobbs 2004 and references therein, du Bus de Warnaffe and Deconchat 2008—this issue). But the extent of this difference varies considerably across the range of management intensities and the degree to which plantations deviate from the tree species composition and structure of natural forests in the same area (Fig. 1). Plantation forests usually have less habitat diversity and complexity. For example, some forest bird species may not find their required food sources in plantations, or there may be a lack of overmature trees suitable for nesting (Clout and Gaze 1984). The species richness of forest specialists is often lower in plantations than in semi-natural forest, whereas the difference is less strong for generalist species (Magura et al. 2000; Raman 2006). In particular, plants and animals that are old forest specialists may not be able to colonise or reproduce in plantations with comparatively short rotations (e.g., 7–21 years for eucalypts in Brazil, ca. 27 years for *Pinus radiata* in New Zealand). In a study in California that compared species assemblages in exotic eucalypt and native *Quercus agrifolia* woodlands, Sax (2002) reported very similar species diversity for amphibians, birds, mammals, and leaf-litter invertebrates, although species composition was often dissimilar. On the other hand, longer-rotation plantation forests, especially those managed with conservation objectives, may differ little in habitat value from managed natural forests (Keenan et al. 1997; Humphrey et al. 2003; Suzuki and Olson 2008—this issue).

Nevertheless, plantations compare favorably with most other economically productive land uses. For example, in New Zealand far fewer native species are found in pastoral grasslands than in plantation forests (Brockerhoff et al. 2001; Ecroyd and Brockerhoff 2005; Pawson et al. 2008—this issue). Across the scale of management intensity and conservation value, probably all types of plantation forests have a higher conservation value than intensive agriculture land uses (Fig. 1). In the case of plantation forests that were established on agricultural land, this comparison is more appropriate than evaluating plantation forests against what would be found in a natural forest.

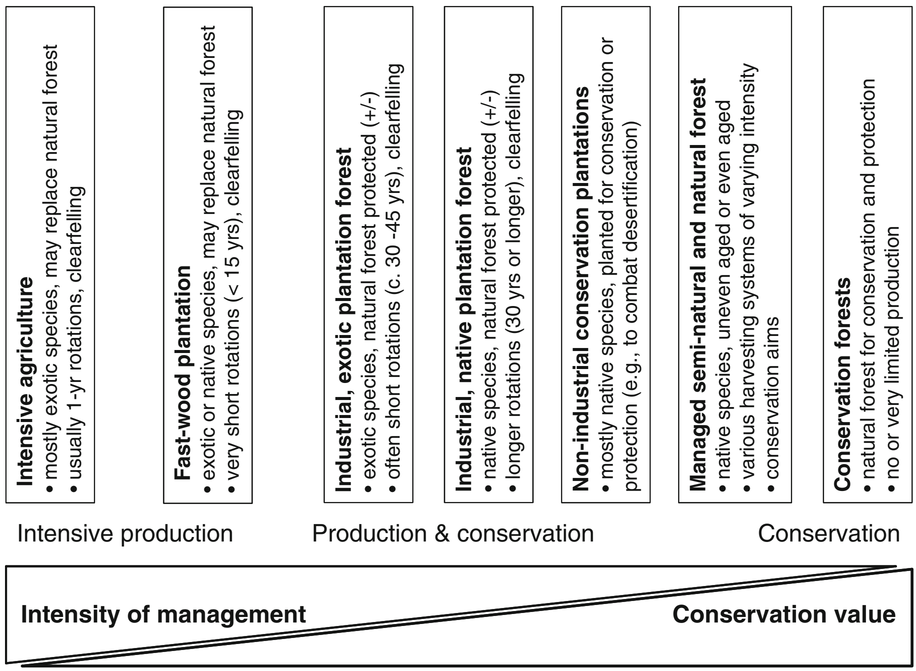

Fig. 1 Conceptual model of the relative conservation value of planted forests relative to conservation forests and agricultural land uses. Note that many plantation forests cannot be clearly assigned to one of the main categories outlined here. Some plantation forests serve multiple purposes including production, protection, and conservation on the same land. Categorisation is also difficult for some forests in Europe that have been established as pure stands by planting or sowing centuries ago, and have since become more diverse by natural processes. "Close-to-nature forests" are included in our "managed semi-natural and natural forest" category. For more details refer to the text and the case study examples provided

Successional processes strongly influence the species assemblages that occur in plantation forests and biodiversity varies considerably with stand age (i.e., time since planting). Older stands provide better habitat for forest species than young stands because of increased spatial and vertical heterogeneity, well-developed soil organic layers and associated fungal floras, increased dead wood on the forest floor, a better light environment, and inter-specific facilitation. For example, the understorey vegetation of pine plantations can show a clear successional trend toward increasing dominance by native shade-tolerant species that are typical of natural forest understories (Allen et al. 1995; Brockerhoff et al. 2003). Similar patterns have been observed for other taxonomic groups including epiphytes (see Coote et al. 2008—this issue), birds (Clout and Gaze 1984; Lopez and Moro 1997; Donald et al. 1998), and insects (Fahy and Gormally 1998; Jukes et al. 2001; Lindenmayer and Hobbs 2004; Barbaro et al. 2005; Pawson et al. 2008—this issue; du Bus de Warnaffe and Deconchat 2008—this issue). These successional processes also facilitate forest restoration on sites that were previously deforested, provided that there is a local source of propagules, dispersal agents, and a favorable climate.

There is compelling evidence that plantation forests can accelerate forest succession on previously deforested sites and abandoned agricultural areas where persistent ecological barriers to succession might otherwise preclude re-establishment of native species (see references below). This is due to the influence of the planted trees on understory microclimate conditions, vegetation structural complexity, and development of litter and humus layers during the early years of plantation growth. These changes lead to increased seed inputs from neighboring native forests by seed dispersing wildlife attracted to the plantations, suppression of grasses or other light-demanding species that normally prevent tree seed germination or seedling survival, and improved light, temperature, and moisture conditions for seedling growth. In the absence of intensive silvicultural management aimed at eliminating woody understory regeneration even mono-specific plantations are replaced by a mixed forest comprised of the planted species and an increasing number of early and late successional tree species and other floristic elements drawn from surrounding forest areas. Examples of this 'catalytic' effect of plantations of both native and exotic species, have been reported in many tropical and subtropical regions of the world (Parrotta 1993, 1999; Armstrong and van Hensbergen 1996; Fang and Peng 1997; Geldenhuys 1997; Keenan et al. 1997; Loumeto and Huttel 1997; Oberhauser 1997; Parrotta et al. 1997a, b; Zuang 1997; Yirdaw 2001; Carnevale and Montagnini 2002). These findings also suggest that populations of numerous native species that occur in plantations are viable over successive rotations.

Effects of plantation forests at the landscape scale

The loss and fragmentation of natural forests remains one of the main causes of biodiversity loss (Hunter 1990; Murcia 1995; Wigley and Roberts 1997; Didham et al. 1998; Magura 2002; Henle et al. 2004). Fragmentation reduces the available area of forest habitat (Watson et al. 2004; Benedick et al. 2006), increases the isolation of forest patches (van der Ree et al. 2004) and edge effects in these patches (Yates et al. 2004), all of which contribute to a higher risk of species extinction (Fahrig 2001; Kupfer et al. 2006). In the past, forest fragments were viewed as islands of habitat embedded in an inhospitable matrix of non-habitat. However, a growing body of evidence, referring to the "continuum model" (Fischer and Lindenmayer 2006), suggests that suitable food, shelter, or climatic conditions may be found along gradients in the matrix, allowing dispersal and survival of fragment-dwelling biota. It is now known that some matrix types can mitigate fragmentation effects (Ewers and Didham 2006; Kupfer et al. 2006). The landscape matrix can (1) supplement or complement species habitat or resources, (2) allow or even facilitate dispersal between isolated patches, and (3) its properties or configuration may dampen the effects of disturbance regimes, such as the provision of buffer zones around fragments against adverse edge effects. In contrast, some matrix habitats may act as ecological traps for native species or as sources of invasive species that can spread into remnants. Therefore, besides the conservation of large patches of native forest, there is increasing consensus that more consideration has to be given to managing the complexity of the matrix, as another important objective of biodiversity conservation in forest landscapes. As a type of forest habitat, plantation forests can greatly contribute to improve the quality of the matrix where native forest remnants are embedded (Lindenmayer and Franklin 2002; Kanowski et al. 2005; Fischer and Lindenmayer 2006), more so than alternative land uses such as intensive agriculture.

Plantations can contribute to biodiversity within landscapes through the following three mechanisms:

Habitat supplementation or complementation to forest species

Some species that survive in forest fragments may compensate for habitat loss by using resources in the matrix (Wunderle 1997; Ewers and Didham 2006; Kupfer et al. 2006,

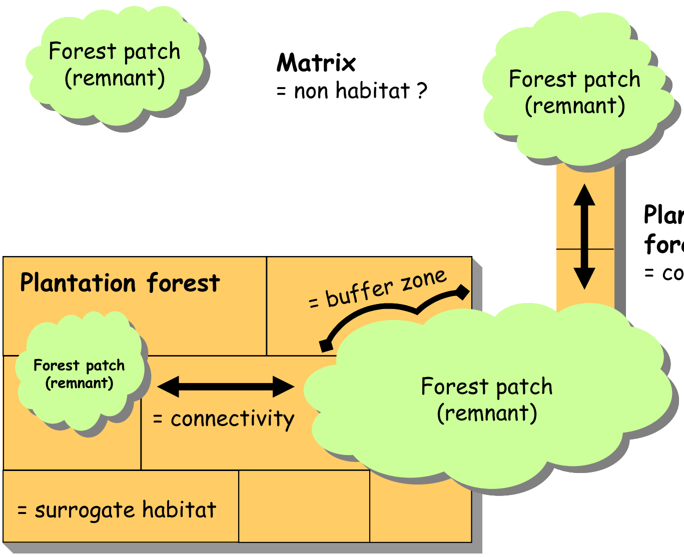

Fig. 2 The 'corridor-patch-matrix' landscape model showing a highly fragmented landscape example with ca. 85% loss of natural forest and ca. 20% plantation forest. Modified after Forman (1995) and Lindenmayer and Franklin (2002)

Fig. 2). Plantation forests can provide suitable habitats for numerous forest species. In addition to the studies mentioned above, comprehensive reviews with relevant examples are those in Gascon et al. (1999) on birds, frogs, mammals, and ants in Amazonia and those in Bernhard-Reversat (2001) on understory plants, birds, mammals, and soil invertebrates in plantations of *Acacia auriculiformis* and *Pinus caribaea* in the Congo.

Connectivity

The presence of plantation forests can enhance indigenous biodiversity by improving connectivity between indigenous forest remnants (Hampson and Peterken 1998; Norton 1998, Fig. 2). This has been demonstrated by studies on a wide range of taxa (e.g., Innes et al. 1991; Parrotta et al. 1997b; Lindenmayer et al. 1999; Wethered and Lawes 2005). For example, plantation forests facilitate the dispersal across of forest dwelling mammals such as the endangered Iberian lynx (Ferreras 2001) and various marsupials (Lindenmayer et al. 1999). Likewise, the maintenance of a network of natural forest remnants, for example along riparian areas, may assist the survival of species for which the plantation matrix is less suitable (Lamb 1998; Carnus et al 2006; Nasi et al. 2008—this issue). However, corridors of insufficient width may not be used by species that avoid edge habitats (Ewers and Didham 2007).

Buffering effects

Native forest remnant edges are characterised by altered microclimates, with edges typically experiencing higher irradiance, temperature, vapor pressure deficit, and wind speed than forest interiors, with consequential changes in biodiversity (Murcia 1995). Plantation forests may enhance the value of indigenous forest remnants by buffering remnant edges from these influences (Renjifo 2001; Fischer et al. 2006, Fig. 2). For example, Denyer et al. (2006) found that microclimate changes across native forest edges adjacent to pine plantations were half those that occurred between native forest and pasture. Furthermore, the vegetation of native forest edges was more similar to the forest interior when the edge was adjacent to plantation forest than when it was adjacent to pasture. This buffering effect is, however, disrupted by the harvesting of the plantation trees, exposing the edge temporarily to the aforementioned negative external influences (Norton 1998).

Plantations forests may also have negative effects on adjacent natural and modified land cover. Planted forests often consist of fast-growing pioneer tree species that may spread beyond the plantation and invade neighboring habitats, particularly open or disturbed habitats. Such invasive trees are also referred to as “wilding trees” (Ledgard 2001). Similar invasion processes can occur with species associated with plantations such as weeds and feral animals (Kanowski et al. 2005; Kupfer et al. 2006). Grazing animals and seed predators may also use plantations where food resources are not limited to build up their population and then cause damage in neighboring remnants (Curran et al. 1999; Lindenmayer and Hobbs 2004; Kanowski et al. 2005). Finally, responses to landscape features are often species-specific or at least dependent on particular traits of species. Generalists and species that are active dispersers are predicted to benefit more from plantation forests in the matrix than rare forest specialists, which could lead to an impoverishment of forest biota compared with native forest communities (Ewers and Didham 2006).

Plantation forests—good or bad for biodiversity? It depends on the context

To determine objectively whether plantation forests are detrimental or give net benefits for conservation is not trivial because this is context-specific and depends on multiple factors (e.g., Brockerhoff et al. 2001; Hartley 2002; Carnus et al. 2006). Essential points that need to be considered include:

1. Whether plantation forestry leads to reduced harvesting and thus improved protection of natural forests, and at what scale,
2. What was the land use or vegetation that preceded the establishment of plantation forests, and how well can the plantation forest provide substitute habitat for species of the former natural land cover (and thus what the appropriate comparison is),
3. How much time has passed since plantation establishment and thus, for example, how long have local species been able to colonise and adapt to the new habitat,
4. Whether the planted area is being managed with conservation goals in mind, whether remnants areas of natural habitat are being protected, and whether conservation goals across the wider landscape are being considered,
5. How plantation forestry compares relative to other alternative land uses that are likely to be practised on a particular piece of land.

Does plantation forestry lead to reduced harvesting and improved protection of natural forests?

Plantation forestry can benefit biodiversity (at a larger scale), if it leads to reduced harvesting of natural forests (Shepherd 1993; Hartley 2002), although this is not necessarily always the case (Clapp 2001). Intensively managed plantations can provide forest products more efficiently than natural forests, and therefore require less land, which may allow greater protection of natural forests (Carle et al. 2002). This is the case in New Zealand where the debate about a national forestry and forest conservation strategy has led to a spatial separation of production and conservation, with the agreement of all stakeholders (Shaw 1997). Over 99% of domestic forest products are obtained from plantation forests (that occupy about 7% of the land base) while there is negligible production in natural forests (that cover about 20% of the land base). This has allowed the majority of New Zealand's natural forests to be managed by the Department of Conservation for conservation and recreation. While this strategy is reasonably successful in New Zealand, a comparatively orderly and corruption-free country, this may not be the case in countries where plantation forestry is still expanding, driven by opportunities for increasing export of forest products, and where natural forests are perhaps not as well protected from conversion to plantations (e.g., Cossalter and Pye-Smith 2003). The paradigm of spatially separating production (in plantation forests) and conservation (in protected areas) is at odds with a strengthening movement in various countries, particularly in Europe, that accepts that production and conservation can occur on the same land. For example, there are efforts to introduce natural features into plantation forests, convert some plantation forests of exotic trees to semi-natural forests and to restore natural forests (e.g., Anderson 2001; Quine et al. 2004). Some of these areas are managed for both production and conservation on the same land and in some cases management is integral to maintaining their conservation value (Fuller et al. 2007). Seymour and Hunter (1999) argued for a hybrid with elements of both these approaches: ecological forestry—containing components of a landscape triad—non-intervention reserves, ecological forestry, and intensive plantations.

What land use or vegetation preceded the establishment of plantation forests, and are there affinities to the natural vegetation and fauna of the area?

The net effects of plantation forests on biodiversity conservation also strongly depend on the land cover that was or is being replaced. It is critical to distinguish if plantations forests replace or replaced natural forests or modified, agricultural land. Clearly, conversion of natural forests into plantations is detrimental to biodiversity conservation, unless deforestation is inevitable and plantation forestry is a 'lesser evil' (see below). Similarly, afforestation of non-forest ecosystems is not desirable where these represent the natural vegetation. For example, afforestation could threaten several rare bird species of open habitats that inhabit South Africa's grasslands (Allan et al. 1997). In maritime pine plantations in the Landes Forest (SW France) few forest specialist species occur even though almost 200 years and three rotations have passed since their establishment in a landscape that was originally dominated by open, moorland habitats. However, rich assemblages of open-habitat beetles, spider and bird species, including several species of conservation concern (e.g., *Harpalus rufipalpis, Carathus erratus, Lullula arborea*), occur in clear-cuts and young pine stands. This suggests that the colonization of clear-felled sites is a key process maintaining the diversity of open-habitat species in this afforested area (Barbaro et al. 2005; Van Halder et al. 2008—this issue).

On the other hand, many plantation forests were established in areas that were originally forested but have lost their natural plant and animal communities long before the plantation was established. Afforestation of intensively managed agricultural land, which is typically inhabited by a highly impoverished flora and fauna (below), usually brings conservation gains (but see Buscardo et al. 2008—this issue). This is particularly true in regions that have experienced significant losses of natural forests. In such situations plantation forests often facilitate the restoration of natural forest elements by natural succession, as outlined below (Sect. "How much time has passed since plantation establishment, and has colonisation by native species occurred?"). Plantation forests can be expected to be better equivalents of natural forests if they are composed of locally occurring native tree species, and in some cases it may be difficult to distinguish older stands from natural forests. However, even plantations of exotic tree species may have an understorey of indigenous plants and a fauna that resemble those of natural forests (e.g., Parrotta and Turnbull 1997 and references therein; Brockerhoff et al. 2003; Humphrey et al. 2003; Pawson et al. 2008—this issue). Given that land use often changes over time, it is also worth considering that plantation forests probably represent a better starting point than agriculture if restoration of natural forest becomes an objective at a later time. A good example of this are efforts in parts of the UK where some Sitka spruce plantations are gradually being restored to Atlantic oak forests and other natural forests, particularly at ancient woodland sites (Humphrey et al. 2006).

How much time has passed since plantation establishment, and has colonisation by native species occurred?

Where plantations replaced natural forests or other natural vegetation it is important to distinguish whether this happened a long time ago or whether this is still an ongoing activity. The FSC currently uses a cut-off point of 1994, and plantation establishment prior to that year is not an impediment, whereas more recent conversion of natural vegetation is not permitted (Forest Stewardship Council 2007a). An obvious benefit of this rule is that it discourages the destruction of natural vegetation. In addition, in older plantations on sites formerly occupied by natural vegetation, certification is likely to lead to improved protection of remaining natural vegetation within such plantations (see below) and it may also encourage the restoration of natural habitats in a proportion of the afforested area.

Plantation forests that were established a long time ago are also more likely to be valuable habitat for biodiversity. Plantation forest habitats become more complex over time which benefits forest species (e.g., Barlow et al. 2008—this issue). Furthermore, colonisation by forest species will have progressed more in an old plantation than in one that was established only recently, if the original vegetation was not forest. Thus, an old plantation forest is likely to be more valuable as habitat in its own right.

Are the planted area and embedded remnants of natural vegetation managed for biodiversity conservation?

The management of plantation forests increasingly meets sustainable forest management goals, particularly in the growing proportion of certified forests in many countries (Forest Stewardship Council 2007c) although many forests that are not certified may also be well managed from a biodiversity point of view. To comply with FSC criteria (Forest Stewardship Council 2007a) concerned with the various aspects of biodiversity conservation, plantation forests have to be managed in accordance with a management plan that specifies conservation goals and resulting actions, including surveys and measures for the protection of rare, threatened and endangered species, the protection of high conservation value forests and other valuable habitats (e.g., wetlands, riparian areas, natural grasslands), and critical examination of the use of pesticides and other potentially detrimental practices (Forest Stewardship Council 2007a). Consultation of a wide range of stakeholders, including

NGOs, and annual re-evaluations of certified ‘forest management units’ ensure that there is a mechanism that scrutinises whether these criteria are being met. While such processes do not transform plantation forests into biodiversity havens, in many countries FSC-certification has contributed significantly to raising the standards for consideration of biodiversity conservation goals as such issues are among the most frequently issued corrective action requests (Paulsen 2004). Forests managed in accordance with such principles, whether certified or not, clearly contribute more than others that are still managed with little or no special regard for biodiversity. It is important to note that this applies not only to the planted area but also to the often substantial areas of natural habitats that are embedded in plantation forest estates. For example, some holdings in New Zealand include as much as 30% or more of their area in natural forest remnants that are being protected and managed for conservation purposes (Hock and Hay 2003).

Some new plantations include set-aside areas of natural vegetation that are designed to maintain connectivity between these remnants. For example, in Sumatra, some *Acacia mangium* plantations retain up to 26% of the area in natural forest, and, if appropriately designed and managed, these areas can assist the conservation of primates and other species (Nasi et al. 2008—this issue). Similarly, new pine plantations in Patagonia are designed such that connectivity of forest habitats and open steppe habitats are maintained (Lantschner et al. 2008—this issue). Forest management can also contribute to the achievement of conservation goals across the wider landscape. In regions where fragmentation effects are important, plantation forests can increase connectivity between distant remnants of natural vegetation and provide additional forest habitat (Fig. 2). This will be most beneficial in cases where plantations were established in agricultural areas.

Plantation forestry compared with other ‘productive’ land uses—a ‘lesser evil’?

Illegal logging as well as the conversion of natural forests to plantation forests are undoubtedly causing the continued loss of natural vegetation (e.g., Cyranoski 2007; Nasi et al. 2008—this issue). However, land clearance for agriculture is a more significant driver of forest loss. According to the Global Forest Resources Assessment 2000 (FAO 2001) 142 million ha of natural tropical forest were lost from 1990 to 2000, and of these, 132 million ha (93%) were converted to other land uses (i.e., deforestation), whereas only 10 million ha (7%) were converted into plantation forest. Furthermore, plantation forests will provide more suitable habitat for most forest species than agriculture, as outlined above. Many plantation forests also contain substantial areas of natural vegetation in reserve areas that may not be retained if they are embedded in agricultural areas. For these reasons and because forestry companies increasingly make concessions to demands from environmental lobby groups, there is an emerging trend among such groups to accept plantation forestry as a ‘lesser evil’, and to ‘make peace with the enemy’ (Cyranoski 2007). Some ecologists believe that working with forestry companies and influencing management will ultimately provide better conservation outcomes than simply opposing plantation forestry. However, afforestation can potentially be more detrimental for biodiversity than agriculture in landscapes where the natural vegetation was not forest but a type of open vegetation, such as grassland, open shrubland, or wetland. Under such circumstances agricultural land uses may be preferable, provided that some natural elements are maintained within the landscape. However, the world wide intensification of agricultural production makes sustainability challenging (Tilman et al. 2002). If plantation forests are established in such areas their impact can be mitigated by protecting adequate areas of open natural habitats (e.g., Lantschner et al. 2008—this issue).

Plantation forests in different contexts—seven countries as case study examples

Exotic tree species are often prevalent in plantations, although in some countries plantation forests consist primarily of native species (Table 1). The desire to maximise timber production and profitability led to the widespread planting of relatively few, mostly fast-growing, tree species. Worldwide, several pine species (*Pinus* spp.) are the most widely used plantation species (ca. 20% of the total plantation area, FAO 2001). Other common plantation genera include spruces (*Picea* spp.), and poplars (*Populus* spp.) in temperate regions, eucalypts (*Eucalyptus* spp.), and rubber (*Hevea* spp.), *Acacia* spp., and teak (*Tectona* spp.) in tropical regions (Cossalter and Pye-Smith 2003; FAO 2006a). For biodiversity conservation, the use of native plantation species is generally preferable because of their higher value as habitat for native species and because of the risk of the planted species becoming invasive. However, in many situations even exotic tree species can make a considerable contribution to biodiversity conservation (below).

Regardless of the identity of the tree species, the relevance of plantation forests for biodiversity conservation in a given country or region needs to be assessed in relation to the relative forest cover and its composition. Some countries that historically had large forest areas still have a considerable cover of mostly natural forests, whereas others have little remaining forest and manage plantations also for biodiversity conservation. The following case studies were chosen as representative examples of countries where various kinds of plantation forests are significant as a land use.

Brazil

With about 478 million ha Brazil has the second largest forest area in the world (after Russia) and the most primary forest of all countries (31% of the global total), but a significant proportion of global deforestation also occurs there (FAO 2006a). Well over half of Brazil's land area is still covered in natural forests (Table 1). Plantation forests, though extensive (5.4 million ha), represent only a small proportion (Table 1) and are of comparatively minor significance for biodiversity conservation. Most of these plantations are of exotic tree species (Table 1) that are managed on very short rotations. Such plantations are also referred to as 'fast-wood plantations', and they are common in many tropical and subtropical countries (Cossalter and Pye-Smith 2003). While plantation forests sometimes replaced natural forests, particularly from the 1960s until the 1980s, their total area is small (1.6%) compared to the total forest area cleared for agriculture (FAO 2006a; IBGE 2007). In recent decades plantation establishment is increasingly occurring on lands that were deforested decades earlier for large-scale agricultural development, particularly in southern and southeastern Brazil. Although the area of plantation forests represents only about 1% of the total forest cover, plantations provide most of Brazil's forest products, according to FAO statistics. For example, 62% of Brazil's industrial roundwood comes from plantations (Carle et al. 2002). This indicates that there is much potential for substitution of wood production in natural forest by plantation forestry which may enable the protection of natural forests. Plantation forests are more valuable for biodiversity conservation than agricultural land uses because most species of conservation concern in Brazil are forest species of which some can use plantation forests as habitat (see also Barlow et al. 2008—this issue). As of mid-2007, certification of forest management under FSC covered an area of 4.8 million ha in Brazil, of which plantation forests (including mixed plantation and other forest types) contribute about 2.1 million ha (Romona Anton, FSC, pers. comm., August 2007). PEFC is also common, presently covering about 0.76 million ha (PEFC 2007).

Indonesia

Officially Indonesia has just under half of its land area in forests but much of this land has long been modified and the extent of near-natural forest is now probably below 20% of total land area (Table 1) (FAO 2006a; Indonesian Ministry of Forestry 2007). Deforestation is thought to continue at a rate of 2% annually (FAO 2006a). Teak has been extensively planted in Java and parts of Sulawezi for hundreds of years. Since the 1960s these plantations have been greatly expanded. Tropical pines have long been planted in Sumatra and throughout Indonesia vast areas are covered in smallholder managed agroforests. In the past two decades there has been a dramatic increase in establishment of fast-growing tree plantations to supply large industrial pulp mills, mainly in Sumatra. There are also significant plantations of *A. mangium* in Kalimantan (the Indonesian part of Borneo) although many of them are poorly managed and some are now abandoned. In addition, large areas have been converted to oil palm plantations which provide fewer conservation benefits than less intensively managed plantation forests. Until recently biodiversity conservation measures have focussed almost exclusively on protected areas but the potential of set-asides within industrial plantations now receives much attention. One reason for this is the realisation that deforestation rates are higher in protected areas than in managed forests—at least in Kalimantan (Curran et al 2004; Meijaard et al. 2005; Meijaard and Sheil 2007). The vast majority of plantations now being established are devoted to *A. mangium* with smaller areas of *A. auriculiformis, Paraserianthes* sp., *Pinus* spp., and *Eucalyptus* spp. Little is known of the within-stand biodiversity value of these plantations but it is likely to be low (but see Nasi et al. 2008—this volume). Despite efforts to improve the protection of natural forest habitats in Indonesia, there are reports that much plantation establishment by conversion of secondary natural forests is ongoing (Cossalter and Pye-Smith 2003), with negative impacts on biodiversity. Indonesian law requires that industrial plantation operators allocate 30% of their concessions to retaining sample areas of natural forests within the plantation matrix. Some of these areas are said to still support populations of elephants and other wildlife of conservation concern (Nasi et al. 2008—this volume) although this is not always well documented. The set aside areas are rarely given proper protection and are often subject to illegal logging or even used to supply raw material for pulp mills. However, some of these areas are extensive and under proper management would undoubtedly make a significant contribution to biodiversity conservation (Zuidema et al. 1997). Recently environmental groups have been putting pressure on these companies to observe higher levels of corporate social and environmental responsibility and there appears to have been a greater effort to give more rigorous protection to these forest enclaves within the plantation estate.

Over 0.5 million ha of mostly natural forest is FSC certified but none of the large-scale industrial pulp plantations are as yet certified, although some of the companies have stated their intention of seeking certification. WWF has recently signed an agreement with a large pulp company in Sumatra to collaborate on measures to protect biodiversity in and around the companies' concession, including the maintenance of natural forest set-asides within the plantation estate. A recent initiative, the Grand Perfect plantations, in a large-scale pulp plantation in Sarawak (a state in the Malaysian part of Borneo) has made even greater investments in maintaining biodiversity both within the planted forest and in the set asides within the plantation estate (Cyranoski 2007). Grand Perfect is sponsoring research efforts which are beginning to provide evidence that the forest mosaic and the planted forests are supporting populations of important components of the lowland forest biodiversity of Borneo.

United Kingdom

The United Kingdom is an example of a country that has lost most of its natural forests but has comparatively large areas of planted forests. Perhaps as much as 80% of the United Kingdom was once covered in natural forests but after many centuries of deforestation due to demand for timber and agricultural land, few semi-natural forest remnants were left and at the start of the 20th century only 5% of the land area was covered with trees. An extensive afforestation program during the 20th century has increased the woodland cover to 12% (Mason 2007); much of this expansion was on marginal agricultural land (especially pasture) but some (particularly pre-1980) involved the conversion of semi-natural woodland. Plantations now contribute almost 70% of the total forest area (Table 1). Because of the scarcity of natural or semi-natural forest, plantations play an important part in the conservation of forest biodiversity in the United Kingdom (e.g., Humphrey et al. 2000), despite the fact that they consist mostly of exotic species (Table 1). Recently there have been considerable efforts to improve the value of plantation forests for biodiversity and other non-wood values, and to restore natural forests (Quine et al. 2004; Humphrey 2005). On sites where plantations of the 20th century replaced former native woodland (ancient woodland), there are now substantial efforts to restore the woodland cover to native habitats. In addition, where afforestation occurred in open habitats such as blanket and raised bogs that are particularly valued today, there are activities to restore these original habitats (Anderson 2001). In both cases, the survival of elements of the former vegetation (or propagules of it, e.g., Eycott et al. 2006), makes restoration a more attractive proposition than trying to recreate such habitats from neighboring sections converted to intensive agriculture. However, there are many plantations that were established on marginal agricultural land (often upland pasture) which had not held tree cover for hundreds of years. On these sites, the benefits of forest cover, and the qualities of the new habitats are increasingly being appreciated. Several rare species are now found within these plantations of exotic tree species (Humphrey et al. 2003). Much effort is being expended on diversifying the structure (across landscapes but also within stands), to provide some of the missing structural elements that are required by native biodiversity (Humphrey 2005; Quine et al 2007). Substantial parts of the plantation area of the UK are FSC certified (Bills 2001).

New Zealand

The biodiversity of New Zealand's forests is very rich for a temperate region and characterised by a high proportion of endemic species, due to its long isolation from other land masses. New Zealand has experienced extensive loss of native forests following the colonisation by Polynesians (about 1000 years ago) and Europeans (from about 150 years ago) but natural forests remain on over 20% of the total land area (Table 1). Plantation forests represent ca. 22% of total forest cover, and the Californian *P. radiata* (radiata or Monterey pine) is the principal tree species (Table 1), managed with rotations of about 27 years and clearfell harvesting. Historically, some plantations have replaced native forests, but today almost all new plantations are on land that was previously in pasture or 'degraded land'. The Forest Accord 1991, an agreement between plantation forest managers and NGOs in effect since 1991, ensures that plantation forests are not established at the expense of natural forests or in areas recommended for protection (see also Shaw 1997), but some conversion of regenerating shrubland and native grasslands has still occurred. Until recently conservation efforts focussed almost exclusively on the publicly owned and largely protected native forests and other natural areas, which are inhabited by a unique and mostly endemic biota. Today there is a growing awareness about the value of plantations as additional habitat for native biodiversity, including several threatened species that can occur in plantations (see above). Some plantations provide particularly valuable habitat in low-lying areas where losses of natural forest were most severe. Some of these areas are now being converted into agricultural land, causing further loss of forest habitat. Approximately 700,000 ha, about 40% of the plantation area, are being managed with FSC certification (Goulding 2006; Romona Anton, FSC, pers. comm., August 2007). Certification has led to widespread biodiversity surveys in plantations, improved management of plantations and embedded remnants of natural vegetation, and it improved the general awareness of biodiversity issues among forest managers (Hock and Hay 2003; Goulding 2006). There is no PEFC certification in New Zealand (PEFC 2007).

China

China has the largest area of plantation forest of all countries, and these plantations consist mostly of native tree species (Table 1). Currently, there are massive ongoing afforestation programs with new plantings between 2000 and 2005 amounting to nearly 1.5 million ha per year, the most of any country (FAO 2006a). These programs were initiated to mitigate environmental problems resulting from the substantial loss and degradation of China's forests, in addition to increasing efforts in forest conservation and restoration of degraded forest ecosystems (Wenhua 2004). With the growth of China's population it was difficult to meet demands for wood and wood products, and this caused the overexploitation of forests and losses of biodiversity, particularly in those densely populated regions where much forest had already been lost (Wenhua 2004). The consequences for biodiversity of this forest loss are severe because China has a very rich biota; for example, there are 27,000 species of higher plants including more than 7,000 woody species. In a global assessment of biodiversity hotspots that are rich in endemic species and where threats to biodiversity are important (Myers et al. 2000), several Chinese regions were identified, along with several other regions in most of the countries covered in the case studies here. The Chinese Government has embarked on a plan to conserve biodiversity and to establish new nature reserves (Wenhua 2004). Although mixed forests are being encouraged, it appears that there are only limited efforts to integrate the expanding plantation forest estate into these biodiversity conservation activities. However, even though afforestation programmes focus on timber production and environmental benefits such as soil and water protection, several studies have shown that it also enhances the restoration of forest biodiversity (e.g., Fang and Peng 1997). Until now there has been limited uptake of FSC certification in China with only six certificates covering a total of about 0.75 million ha of plantations and other forest types (Romona Anton, FSC, pers. comm., August 2007). There is no PEFC certification of forests in China (PEFC 2007).

United States of America

The United States have the fourth largest total forest area and the second largest area of production plantation forest worldwide (FAO 2006a). Most of the plantation forests in the US consist of native tree species (Table 1). The principal areas are the intensively managed plantations of native loblolly pine (*Pinus taeda*) and slash pine (*P. elliotii*) in the south-east. These are the result of intensified management and improvement (particularly since the 1950s) of degraded natural stands that had occupied the region prior to extensive logging and large-scale conversion for agriculture (Stanturf et al. 2003). All forests in the U.S. are subject to national and state environmental regulations and the Endangered Species Act which effectively prohibit management actions that threaten listed species and their habitats. Biodiversity conservation is an important objective in the management of natural and semi-natural forests in the U.S. but less so in plantation forests. In the northwestern U.S., biodiversity conservation issues have been more prominent, and the efforts to protect spotted owls have strongly influenced forestry policy (Lindenmayer and Franklin 2002). The forestry debate has at times been polarized, whereby 'timber or biodiversity' were considered mutually exclusive. However, a compromise was reached with the Northwest Forest Plan, which set out areas assigned for forestry and others for conservation, and there is an ongoing debate about how the management of forests can be improved (e.g., Suzuki and Olson 2008—this issue). There has been considerable uptake of FSC certification in the U.S., and retail policy of some do-it-yourself chains appears to have contributed substantially to the demand for FSC-certified forest products (Hock and Hay 2003). The total area of forests with FSC-certified management exceeds 9.1 million ha although the majority of this area comprises natural forests and little plantation forest (Romona Anton, FSC, pers. comm., August 2007). Certification by Sustainable Forestry Initiative (SFI), a member system of PEFC (2007), is more widespread in the U.S. than FSC certification, and some forests are certified under both systems. In 2007, there were nearly 22 million ha of SFI-certified forests in the U.S. which included substantial areas of plantation forest (SFI 2007).

France

With forests covering over 15 million ha, France is one of the most forested countries in Europe. France has forest plantations covering 2 million ha (ranking 9th in the world in terms of plantation area) that consist mostly of native tree species and contribute ca. 13% of the total forest area (Table 1). The Landes Forest represents the largest continuous plantation forest in Europe with ca. 1 million ha of maritime pine (*Pinus pinaster*). This resulted from an afforestation program that was launched by Napoleon III in the 19th century to develop the economy of the Landes region, at that time a moorland with some deciduous trees. Seeds from the natural pine forests of the adjacent coastal area were sowed in drained soils. Although these stands have some of the lowest tree species diversity in France (Ministry of Agriculture and Fishery 2005), there are embedded semi-natural riparian forests and remnants of broadleaved forest of high biodiversity value (Barbaro et al. 2005; 2008—this issue; Van Halder et al. 2008—this issue). Contrary to some of the neighbouring countries, there is little uptake of FSC certification in France (currently only about 15,500 ha; Romona Anton, FSC, pers. comm., August 2007) but PEFC is gaining importance in plantation forests (currently about 4.3 million ha, PEFC 2007). PEFC certification of some plantation forests has led to efforts to improve both conservation and restoration of deciduous patches and hedgerows within the pine plantation matrix.

Enhancing biodiversity in plantation forests

As discussed above, many factors influence biodiversity in plantation forests and the landscapes in which they occur, and all these offer opportunities to improve forest management for the benefit of biodiversity. In a recent working paper on 'voluntary guidelines for the responsible management of planted forests', FAO (2006b) provides a comprehensive bibliography on plantation issues and some general recommendations for planners and managers to conserve biodiversity. These include "preparing baseline studies to monitor the impact of planted forest management on the maintenance of plants and animals and the conservation of genetic resources." The use of indicator species and other biodiversity indicators has been advocated for this purpose (e.g., Larsson 2001) because the assessment of a wide range of taxa is often too time consuming and expensive. In this issue a comprehensive set of such indicators is being proposed for use with plantation forest management in Ireland (Smith et al. 2008—this issue). However, such indicators have their limitations, and they have been criticised as being potentially too simplistic (e.g., Lindenmayer and Franklin 2002). Furthermore, results often vary among taxa (Barlow et al. 2007), and hence, the effects of stand and landscape-level management should ideally be examined with a wide range of taxa, if resources permit.

Management actions can broadly be divided between those that are concerned with stand-level management and those that are concerned with the spatial and landscape aspects of the entire plantation and its surroundings. Many of the following recommendations are also reflected in the criteria used for Forest Stewardship Certification of forest management.

Stand-level recommendations

A recent summary of recommendations for management at the stand level has been given by Hartley (2002). Biodiversity can be enhanced through appropriate management choices regarding composition and structure. The first approach is to consider the tree species that are being planted (e.g., du Bus de Warnaffe and Deconchat 2008—this issue). Several studies have shown that the establishment of a greater diversity of tree species will increase the range of habitat types available for native species (Lamb 1998; Norton 1998; Hartley 2002 and references therein). Planting a larger number of tree species will result in a greater diversity of habitats and thus of dependent species (Spellerberg and Sayer 1996). Moreover, mixed plantation being more resistant and resilient to natural and human disturbances (Scherer-Lorenzen et al. 2005; Jactel and Brockerhoff 2007) may provide a more stable environment for native species. Careful selection of species for these plantings could considerably improve habitat for native species, particularly if they provide food resources such as nectar and fruit and help to create understorey microclimate, soil conditions and stand structures that would favor native species (Parrotta et al. 1997a; Hartley 2002; Lindenmayer and Franklin 2002; Carnus et al. 2006). Although native species are more likely to meet these criteria, some exotics can fulfil the same role.

The amount and quality of available habitats can be influenced by a variety of stand management practices (Decocq et al. 2005; Quine et al. 2007). If possible, intensive site preparation should be avoided if the previous land cover has conservation value as it may destroy herbaceous vegetation and coarse woody debris which provide resources for many native forest species (Hartley 2002; Lindenmayer and Franklin 2002; Carnus et al. 2006). Similarly, wider tree spacing at plantation establishment and heavy pre-commercial thinning may help to maintain understorey vegetation (Moore and Allen 1999; Hartley 2002; Lindenmayer and Hobbs 2004). The age at which plantations are harvested is also often seen as a key issue for native biodiversity (Lindenmayer and Hobbs 2004). Native biodiversity is often greatest in the oldest stands, although conservation value is not always correlated with stand age. However, the trend of decreasing rotation length in many plantation areas (e.g., in New Zealand radiata pine from 40–50 years in the 1970s to 25–30 years in the 1990s) is usually a concern. An increase in rotation length has been widely advocated as a means to enhance native biodiversity in plantations (Rosoman 1994; Humphrey 2005); however, this is usually considered uneconomical because financial profitability begins to fall above a certain stand age or because of increasing environmental risks (such as wind damage) with increasing stand age. But as Peterken et al. (1992) suggested for British plantations, there can be a trade-off for increasing rotation lengths in some areas by reducing rotation lengths in other areas thus maintaining financial returns from the forest. The use of single-tree, group selection or small-coupe harvesting will result in the continued presence of mature forest at a site and this has been suggested as beneficial for native biodiversity and provides a useful alternative to the traditional forest clear-cut. Maintaining some stand structural attributes such as old trees or snags within stands will also enhance the value of plantations for biodiversity (Lindenmayer and Franklin 2002; Humphrey et al. 2006). Various stand-level management recommendations based on thinning, weed control, burning and other methods are given by Cummings and Reid (2008—this issue). These were aimed mainly at the restoration of plantations to a more natural vegetation, but many of their findings are also useful to improve the biodiversity value of production plantations.

Landscape level recommendations

General guidelines and management recommendations to increase the value of plantation forests for biodiversity have in the past focussed mostly at the stand-level. Less attention has been given to management issues at the landscape level (but see Wigley and Roberts 1997; Lamb 1998; Norton 1998; Humphrey et al. 2000; Lindenmayer and Franklin 2002). There is increasing evidence that the complexity of the landscape matrix is of great importance in maintaining biodiversity at the landscape level and that plantations forests can contribute to this complexity (Norton 1998; Lindenmayer and Franklin 2002; Fischer et al. 2006; Kupfer et al. 2006; Barbaro et al 2007).

The *structural complexity* throughout the landscape may be enhanced by juxtaposition of different plantations types, size and shapes which will in turn increase the probability of providing suitable alternative habitats to native forest species (Lamb 1998; Lamb et al. 2005). Landscape-level biodiversity issues can also be addressed by considering the spatial arrangement of different-aged plantation stands with respect to other landscape components, especially native forest remnants. Plantations in fragmented landscapes can contribute to the connectivity of native remnants, particularly when they provide corridors or stepping stones for forest specialist species (Norton 1998; Fischer et al. 2006; Nasi et al. 2008—this issue). They may also be placed side by side with native remnants to buffer adverse edge effects (Harper et al. 2005). For example, special-purpose exotic or native plantations are likely to be more beneficial when located adjacent to native forest remnants than when located distant from them (Lamb et al. 1997; Parrotta et al. 1997a; Lindenmayer and Hobbs 2004). Many forestry companies make considerable use of amenity plantings, for example along roads and around recreational amenities.

Changes in the *spatial and temporal pattern of plantation forests harvesting* offer another avenue to improve biodiversity conservation in plantation-dominated landscapes (Lamb et al. 1997; Lindenmayer and Franklin 2002; Carnus et al. 2006, see also Suzuki and Olson 2008—this issue). In Australia, Lindenmayer and Pope (2000) suggested that some advanced regrowth radiata pine plantations in the matrix should always link eucalyptus remnants to maintain connectivity for native birds. Rotational harvesting, where a core old growth remnant is surrounded by a series of managed stands that have a sufficiently long gap between harvesting to ensure that at any one time the old forest remnant is surrounded by a large proportion of mature forest, has been advocated for managing old growth Pacific northwest forests of North America (Harris 1984). A similar system has been proposed for managing upland conifer plantations in Britain (Peterken et al. 1992) involving assigning 15–20% of the plantation to long rotations surrounding permanently uncut cores. In New Zealand, Norton (1998) has suggested that a similar approach could be used for managing plantation forests around indigenous forest remnants or between remnants. For example, the native biodiversity values of plantations would be enhanced by ensuring that there is always a large area of mature forest present adjacent to the remnant, and that a continuous sequence of older plantation stands occurred between remnants (e.g., Nasi et al. 2008—this issue). Variable retention harvesting has been advocated to mitigate detrimental impacts of clear-cutting on biodiversity in large harvested areas. Residual tree patches can function as valuable refugia, at least in the short-term, for frogs (Chan-McLeod and Moy 2007), spiders and carabids (Hyvarinen et al. 2005; Matveinen-Huju et al. 2006) and birds (Vergara and Schlatter 2006). The beneficial effects of green-tree retention are expected to increase with patch size (Chan-McLeod and Moy 2007) and decrease with distance from undisturbed areas (Deans et al. 2005; Vergara and Schlatter 2006).

Plantation forests and certification

Several aspects of the current debate about the eligibility of plantation forests to be certified under the FSC involve biodiversity issues. Many of the concerns expressed by environmental NGOs are valid in some situations but generalisations about the impact of plantation forests on biodiversity are not doing justice to this complex issue (see above). It is also difficult to draw a clear line between a plantation and an intensively managed natural forest. For example, the forests covering much of Europe have all been intensively managed for centuries, many of the trees have been established by planting or sowing in pure stands (although they often became more diverse by natural succession). Should these forests therefore really be classed alongside the old growth forests of the tropics or should they be lumped together with the plantations? The different stakeholders in the FSC have been struggling with these issues for several years and do appear to be reaching a compromise that would allow certification of some plantations but under very strict conditions (Forest Stewardship Council 2006). FAO has also contributed to this debate and have recently published a voluntary code of conduct which gives a comprehensive and balanced view of the issues surrounding plantation establishment (FAO 2006b, see above).

Another complicating factor is that much criticism that has been expressed against plantation forests is concerned about social impacts of plantation forests, which are beyond the scope of the present paper. However, there are forestry companies that take longer term views of sustainability, including social sustainability (Porter and Kramer 2006) concerning the people living in the areas where these companies operate. The challenge for environmental groups is to distinguish between companies that are performing better, those that are just window dressing, their operations and those that will grab short-term profits and move on. Because certification leads to increased scrutiny of forest management, it can be expected that there are benefits for social aspects and for biodiversity conservation within plantation forests. Conversely, without certification from organisations such as FSC, there would be fewer incentives to address such concerns in the management of plantation forests. Special problems may occur in situations where plantations are established in countries with weak institutions or where corruption is widespread. In any case, blanket disapproval of plantation forests appears inappropriate given the wide range of issues and context-specific impacts of plantation forests with regard to biodiversity and other criteria.

Conclusions

Plantations can make an important contribution to the conservation of native biodiversity, but not if their establishment involves the replacement of native natural or semi-natural ecosystems—should they do so, there will indeed be a contradiction (oxymoron) in the juxtaposition of the terms plantation and biodiversity. While a plantation stand will usually support fewer native species than a native forest at the same site, plantations are increasingly replacing other human-modified ecosystems (e.g., degraded pasture) and will almost always support a greater diversity of native species. As such, plantations can play an important role in sustaining native biodiversity in production landscapes—and indeed be an opportunity for biodiversity. As well as providing habitat in their own right, plantations play particularly important roles in buffering native forest remnants and in enhancing connectivity between areas of native ecosystems, including patches of primary forests, riparian strips, and amenity plantings.

The opportunities afforded by plantations can be realised when particular attention to biodiversity informs management choices, and the objectives become multi-purpose (sustainable forest management). So, to sustain native biodiversity within plantations forest managers need to consider using a greater diversity of planted species, extending rotation lengths in some stands, and adopting a variety of harvesting approaches. Managers also have to consider plantations from a landscape perspective and the contribution that can be made by planning the spatial array of individual stands or compartments of different age and species composition as well as natural or semi-natural conservation areas. Although our understanding of such approaches is improving, there is still a need for further research on the specific requirements for the protection of biodiversity in regions that are not yet well studied. Another question that has not yet been adequately addressed is whether plantation forests composed of locally occurring native tree species are in fact providing better habitat for biodiversity than plantations of exotic tree species, and if so, how the use of native trees in plantations could be encouraged.

Tensions remain between the objectives of biodiversity conservation and plantation productivity (Lindenmayer and Hobbs 2004). The goal of higher ecosystem complexity may conflict with current trends in forest management towards increasing intensification and simplification; this is another area that requires more research. Furthermore local people, particularly in developing countries, may view biodiversity conservation as a luxury as they struggle to meet their basic food and fuel needs. Trade-offs between biodiversity conservation and improvement in human well-being are probably easier to achieve at the landscape scale where a spatial partition of forest objectives can be made, for instance by the juxtaposition of natural reserves and a productive matrix (Lamb et al. 2005). Exploration of different harvesting scenarios can be used to identify harvesting plans that provide improved biodiversity outcomes without unduly affecting economic objectives. In North America, spatial modelling tools have been used to optimise timber harvesting in native forests to meet biodiversity conservation goals, including "adjacency requirements" (Bettinger et al. 1997; Snyder and ReVelle 1997; Van Deusen 2001). Similar modelling could be used to maximise timber production and biodiversity conservation as well as ecosystem stability. The key feature of this approach is that it considers biodiversity conservation at the landscape scale rather than at the stand scale and thus removes the direct conflict between biodiversity conservation and timber production at any individual site. Thus, we suggest that the role of plantations in biodiversity conservation can be enhanced if plantations are managed in a manner in which they can contribute to biodiversity conservation across the whole landscape, rather than focusing only on the values within the plantations themselves.

Acknowledgments We would like to thank all authors for their contributions to this special issue and the three conferences or conference sessions that spawned this initiative. Many thanks also to David Hawksworth (Editor of Biodiversity and Conservation), Raphael Didham (Associate Editor), and all the staff in the Springer journal office who provided invaluable support with this special issue. This article was partly funded by the New Zealand Foundation for Research Science and Technology (contract C04X0214).

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