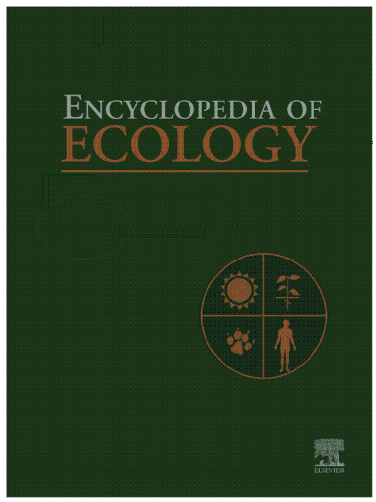

D Zhang and J Stanturf. Forest Plantations. In Sven Erik Jørgensen and Brian D. Fath (Editor-in-Chief), Ecosystems. Vol. [2] of Encyclopedia of Ecology, 5 vols. pp. [1673-1680] Oxford: Elsevier.

Mladenoff DJ (2004) LANDIS and forest landscape models. *Ecological Modelling* 180: 7–19.
Newton PF (1997) Stand density management diagrams: Review of their development and utility in stand-level management planning. *Forest Ecology and Management* 98: 251–265.
Pacala SW, Canham CD, and Silander JAJ (1993) Forest models defined by field measurements. Part I: The design of a northeastern forest simulator. *Canadian Journal of Forest Research* 23: 1980–1988.
Parton WJ, Anderson DW, Cole CV, and Stewart JWB (1983) Simulation of soil organic matter formation and mineralization in semiarid agroecosystems. In: Lowrance RR, Todd RL, Asmussen LE, and Leonard RA (eds.) *Special Publication No. 23: Nutrient Cycling in Agricultural Ecosystems*, pp. 533–550. Athens, GA: The University of Georgia, College of Agriculture Experiment Stations.
Parton WJ, Schimel DS, Cole CV, and Ojima DS (1987) Analysis of factors controlling soil organic levels of grasslands in the Great Plains. *Soil Science Society of America Journal* 51: 1173–1179.
Perttunen J, Sievänen R, and Nikinmaa E (1998) LIGNUM: A model combining the structure and the functioning of trees. *Ecological Modelling* 108: 189–198.
Pienaar LV and Turnbull KJ (1973) The Chapman–Richards generalization of Von Bertalanffy's growth model for basal area growth and yield in even-aged stands. *Forest Science* 19: 2–22.
Radtke PJ, Burk TE, and Bolstad P (2001) Estimates of the distributions of forest ecosystem model inputs for deciduous forests of eastern North America. *Tree Physiology* 21: 505–512.
Reineke LH (1933) Perfecting a stand-density index for even-aged forests. *Journal of Agriculture Research* 46: 627–638.
Reynolds JH and Ford ED (2005) Improving competition representation in theoretical models of self-thinning: A critical review. *Journal of Ecology* 93: 362–372.
Robinson AP and Ek AR (2000) The consequences of hierarchy for modeling in forest ecosystems. *Canadian Journal of Forest Research* 30: 1837–1846.
Rouvinen S and Kuuluvainen T (1997) Structure and asymmetry of tree crowns in relation to local competition in a natural mature Scots pine forest. *Canadian Journal of Forest Research* 27: 890–902.
Running SW and Coughlan JC (1988) A general model of forest ecosystem processes for regional applications. Part I: Hydrologic balance, canopy gas exchange and primary production processes. *Ecological Modelling* 42: 125–154.
Running SW and Gower ST (1991) FOREST-BGC, a general model of forest ecosystem processes for regional applications. Part II: Dynamic carbon allocation and nitrogen budgets. *Tree Physiology* 9: 147–160.
Schröder J and Gadow K von (1999) Testing a new competition index for Maritime pine in northwestern Spain. *Canadian Journal of Forest Research* 29: 280–283.
Schwalm CR and Ek AR (2001) Climate change and site: Relevant mechanisms and modeling techniques. *Forest Ecology and Management* 150: 241–257.
Shugart HH (1984) *A Theory of Forest Dynamics*. New York: Springer-Verlag.
Sievänen R, Nikinmaa E, Nygren P, Ozier-Lafontaine H, Perttunen J, and Hakula H (2000) Components of functional–structural tree models. *Annals of Forest Science* 57: 399–412.
Stadt KJ, Huston C, and Lieffers VJ (2002) *A comparison of non-spatial and spatial, empirical and resource-based competition indices for predicting the diameter growth of trees in maturing boreal mixedwood stands*. Edmonton, AB Sustainable Forest Management Network, Project Report 2002–8.
Stage AR (1973) Prognosis model for stand development, *Research Paper INT-137*. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station.
Steneker GA and Jarvis JM (1963) A preliminary study to access competition in a white spruce-trembling aspen stand. *Forestry Chronicle* 39: 334–336.
Urban DL, Bonan GB, Smith TM, and Shugart HH (1991) Spatial applications of gap models. *Forest Ecology and Management* 42: 95–110.
Vanclay JK (1994) *Modelling Forest Growth and Yield*: *Applications to Mixed Tropical Forests*. Wallingford, UK: CABI.
Vettenranta J (1999) Distance-dependent models for predicting the development of mixed coniferous forests in Finland. *Silva Fennica* 33: 51–72.
Yoda K, Kira T, Ogawa H, and Ozumi K (1963) Self-thinning in overcrowded pure stands under cultivated and natural conditions. *Journal of Biology of Osaka City University* 14: 107–129.

Relevant Website

http://www.nrel.colostate.edu – CENTURY – National Resource Ecology Laboratory, Colorado State University.

Forest Plantations

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Between the extremes of afforestation and unaided natural regeneration of natural forests, there is a range of forest conditions in which human intervention occurs. Previously, forest plantations were defined as those forest stands established by planting and/or seeding in the process of afforestation or reforestation. Within plantations, there is a gradient in conditions. At one extreme is the traditional forest plantation concept of a single introduced or indigenous species, planted at uniform density and managed as a single age class (the so-called monoculture). At the other extreme is the planted or seeded mixture of native species, managed for nonconsumptive uses such as biodiversity enhancement. To further complicate matters, many forests established as plantations come to be regarded as secondary or seminatural forests and no longer are classed as plantations. For example, European forests have long traditions of human intervention in site preparation, tree establishment, silviculture, and protection; yet they are not always defined as forest plantations.

Further refinement of the plantation concept is necessary in order to encompass the full range of actual conditions. A useful typology is based on purpose, stand structure, and composition of plantations. Thus, an industrial plantation is established to provide marketable products, which can include timber, biomass feedstock, food, or other products such as rubber. Industrial plantations usually are regularly spaced with even age classes. Home and farm plantations are managed forests but at a smaller scale than industrial plantations, producing fuelwood, fodder, orchard, and garden products but still with regular spacing and even age classes. A wide range of agroforestry systems exist, distinguishable as a complex of treed areas within a dominantly agricultural matrix. Environmental plantations are established to stabilize or improve degraded areas (commonly due to soil erosion, salinization, or dune movement) or to capture amenity values. Environmental plantations differ from industrial plantations by virtue of their purpose; they may still be characterized as regularly spaced with even age classes. Efforts to restore forest ecosystems are increasing and often utilize the technology of plantation establishment, at least initially.

Recently, FAO defined 'planted forests' as forests in which trees have been established through planting or seeding by human intervention. This definition is broader than plantations and includes some seminatural forests that are established through assisted natural regeneration, planting or seeding (as many planted forests in Europe that resembled natural forests of the same species mix) and all forest plantations which are established through planting or seeding. Planted forests of native species are classified as forest plantations if characterized by few species, straight, regularly spaced rows, and/or even-aged stands. Forest plantations may be established for different purposes and were divided by FAO into two classes: protective forest plantations which are typically unavailable for wood supply (or at least having wood production as a secondary objective only) and often consist of a mix of species managed on long rotations or under continuous cover; and productive plantation forests which are primarily for timber production purposes.

Figure 1 shows that, in 2005, some 36% of global forests (about 4 billion ha, covering 30% of total global land area) are natural forests, 53% are modified natural forests, 7% are seminatural forests, and the remaining 4% are forest plantations. Of these forest plantations, productive forest plantations account for 78% and protective forest plantations account for 22%. While natural forests and modified natural forests declined between 1990 and 2005, seminatural forests and forest plantations increased (Figure 2).

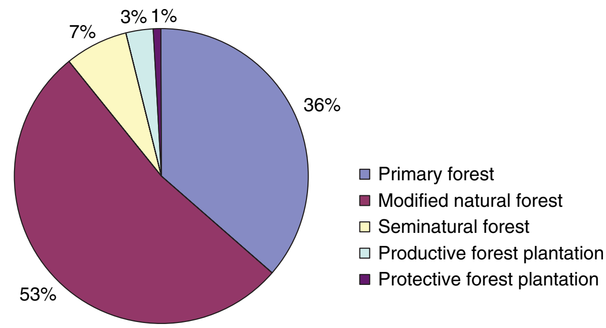

Figure 1 Global forest characteristics 2005. Modified from FAO (2005) Global forest resources assessment 2005. *FAO Forestry Paper 147*. Rome, Italy.

This article provides an overview and economic explanation of global forest plantation development. It also presents factors influencing global forest plantation development and lists the usefulness of forest plantations, including their roles in the conservation of natural forests. Finally, it summarizes the impact of forest plantations on biodiversity and other ecological functions.

An Overview and Economic Explanation of Global Forest Plantation Development

Currently, there are about 109 million ha of productive forest plantations in the world. Productive forest plantations represented 1.9% of global forest area in 1990, 2.4% in 2000, and 2.8% in 2005. The Asia region accounted for 41%; Europe 20%; North and Central America 16%; South America and Africa 10% each; and Oceania 3%.

Forest plantations have been increasing at an increased rate. The area of forest plantations increased about 14 million ha between 2000 and 2005 or about 2.8 million ha per year, 87% of which are in the productive class. The area of productive forest plantations increased by 2.0 million ha per year during 1990–2000 and by 2.5 million ha per year during 2000–05, an increase of 23% compared with the 1990–2000 period. All regions in the world showed an increase in plantation area, with the highest plantation rates found in Asia, particularly in China. The ten countries with the greatest area of productive forest plantations accounted for 79.5 million ha or 73% of the total global area of productive forest plantations (Figure 3). China, the United States, and the Russian

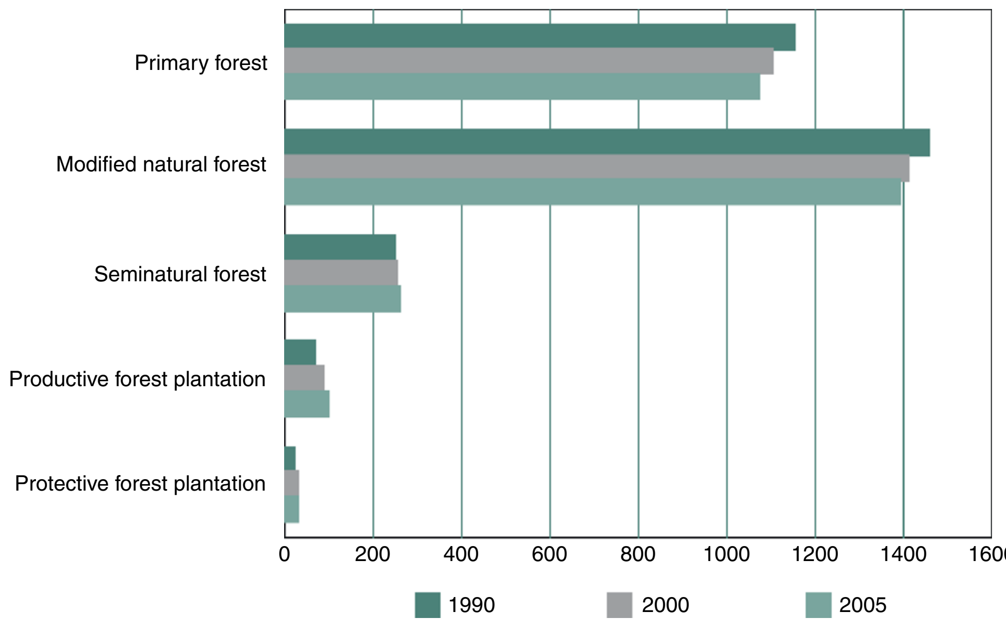

Figure 2 Global trends in forest characteristics 1990–2005 (million ha). Modified from FAO (2005) global forest resources assessment 2005. *FAO Forestry Paper 147*. Rome, Italy.

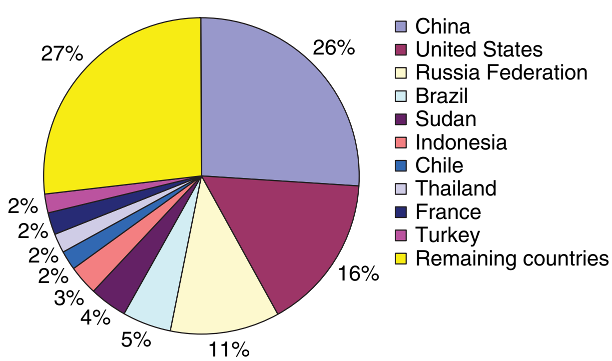

Figure 3 Ten countries with largest area of productive forest plantations in 2005. Modified from FAO (2005) Global forest resources assessment 2005. *FAO Forestry Paper 147*. Rome, Italy.

Federation together accounted for more than half of the world's productive plantations.

Forest plantations, productive or protective, develop in response to a relative scarcity of timber and other goods and services associated with forests. In the early part of modern human history, population was sparse, forests were abundant, and survival, economic development, and territorial control were the primary concerns of governments and society. As forest resources declined, assuring an adequate timber supply gradually caught the attention of rulers and planners and became state policy. Often, the very first policy implemented would be to regulate timber harvesting schedule and intensity. Society also responded by moving to frontiers farther and farther away from population centers, which in economic terms is called a shift in the extensive margin of timber production. In a nutshell, the production and consumption of forest products were all from natural forests in the early part of human history, and forest plantations were not needed.

When the increase in timber consumption caught up with the ability of a country or a region to produce timber in naturally regenerated forests, citizens and governments would become interested in tree planting. While tree planting occurred at least several thousands of years ago in the Middle East, China, and Europe, and nearly 200 years ago in the Americas, the areas planted with trees through afforestation (planting land that was formerly in a nonforest cover) and reforestation (planting land on which a former forest had been harvested) were relatively insignificant in size before AD 1800. It was only after the industrial revolution that timber consumption increased drastically, due to increasing human population and industrial use of wood – initially as charcoal, then lumber, other solid wood products including mine props and railroad ties, and pulp and paper, and finally for conservation uses – that large-scale forest plantations started to emerge in Europe, North America, Asia, and other regions in the last century, especially in the last few decades.

Thus, forest plantations develop primarily in response to economic necessity. Timber depletion drives the transition of human consumption of natural forests to artificial forests. Early in the development of North America, for example, timber prices were low, and forest lands were more valuable for other uses, especially the production of food. So trees were removed, forest lands were converted to other use, and timber inventory declined. As the standing inventory declines, timber becomes increasingly scarce and timber prices start to rise. As the prices continue to rise for timber in natural forests, the purposeful husbandry of planted forests becomes economically attractive, and productive forest plantations begin to emerge.

Further, timber depletion affects the supply and demand balance for environmental services from natural forests, whether or not these services go through formal markets. Related to this balance is the fact that the demand for most environmental services such as clean water, clean air, and esthetics, which are often produced from or protected by forests, is highly correlated with personal income. As personal income increases, society demands more environmental services from forests, as well as more wood commodities. When natural forests are depleted to the extent that they cannot adequately provide these services, protective forest plantations emerge. In some developing countries, subsistence farming requires forests to protect farming and grass land from potential flooding, dust storms, soil erosion, and desertification, and trees are thus planted for protective purposes whether or not their personal incomes actually grow over time.

Factors Influencing Forest Plantation Development

As mentioned earlier, rising timber prices, caused by timber scarcity, lead to forest plantation development. Thus, timber prices are the primary factor that influences forest plantation development. Holding everything else constant, whenever a country or a region experiences a long period of rising timber prices, forest plantations would develop quickly.

Tree planting also requires land, labor, and capital. The cost of these production factors thus influence forest plantation development. Further, high timber prices, high land costs, and high labor costs force innovation in tree-growing technologies in conventional silvicultural treatments and biotechnologies. A recent report shows that the growth rate of pine plantations in Alabama, a southern state in the US increased about 25% in a decade (from 8.20% in the period from 1982 to 1990, to 10.17% in the period of 1990–2000). This increase in growth rate is attributed to advancement in tree-growing technologies as well as an increase in management intensity.

Government policies influence forest plantation developments as well. Taxes on land and forest-related income, cash subsidies to plant trees, regulations on land use and labor, and free education and extension services to forest farmers all have an impact, positively or negatively, on tree planting. In general, the primary motivation for the private sector to plant trees is to generate financial (or other) benefits from their investment. In some cases, government policies (positive or pervasive incentives in taxes, subsidies) provide or take away a significant proportion of the financial benefits from forest plantation development. Where governments own land, they could conduct afforestation and reforestation activities directly, for purely financial reasons or for social and environmental benefits or both.

The US South is perhaps an important region in timber supply as it produces some 18% of the world's industrial round wood with just 2% of the world's forestlands and 2% of the world's forest inventory. Some 90% of forest lands in the southern US are owned by nonindustrial private and industrial owners, and timber markets are competitive. A study of tree planting showed that tree planting by both forest industry and nonindustrial private landowners was positively related to the availability (measured as previous-year harvest) and the price of land. Planting by forest industry and nonindustrial private landowners was responsive to market signals, positively to softwood pulpwood prices and negatively to planting costs and interest rates. Finally, government subsidy programs, which increase the total plantation area, might have substitution effects on nonindustrial private tree planting. The federal income tax break for reforestation expenses promoted reforestation in the southern US.

Since forests often have a long production cycle, perhaps the most important government policy in promoting forest plantation development is to provide long-term and secure property rights (private property or land tenure) to private landowners or forest farmers. Many theoretical and empirical studies substantiate that long-term and secure property rights promote tree planting activities in both developed and developing countries. For example, in British Columbia, Canada tree planting was done more often and more promptly following harvest when forest property rights were secure. In Ghana, reforestation was significantly influenced by the form of forest tenure, and more intensive resource management was fostered by more secure forms of tenure.

Forest Plantations and Conservation of Natural Forests

Plantation forests can provide most goods and services that are provided by natural forests. These include timber, nontimber forest products, protection of clean water and clean air, soil erosion control, biodiversity, esthetics, carbon sequestration, and climate control. Nonetheless, as the value of environmental services from natural forests is higher than that from forest plantations, the demand for conservation of natural forests is stronger. It is possible that a division of land, with some land specialized in timber production and other land in providing environmental services, would produce more forest-related goods and services to society. Because forest plantations grow much faster than natural forests, forest plantations are seen as an increasingly important source of timber supply. Should more forest plantations be developed, more natural forests might be saved.

In 1995, natural forests contributed some 78% of global industrial timber supply, and the remaining was from forest plantations. With growing concerns about the status and loss of natural forests, the rapid expansion of protected areas, and large areas of forest unavailable for wood supply, plantations are increasingly expected to serve as a source of timber. The general trend of the sector is for timber supply to shift from natural forests to plantations.

A simple simulation of global timber supply and demand, allowing forest plantations and their productivity to extend at the current rate, has shown that logging on natural forests could fall by half, from about 1.3 billion m^3 in 2000 to about 600 million m^3 in 2025. Thus, forest plantations will have an increasingly significant role in substituting products from natural forests, even if they cannot replace harvests from natural forests for a long period of time.

One side impact of forest plantation development is that the supply of large quantities of low-cost timber could perhaps undermine the value of natural forest stands, leading to more rapid destruction, especially where legal frameworks and law enforcement are inadequate. Therefore from a global perspective, the transition from natural forests as the primary source of timber supply to forest plantations will take a long time. Nonetheless, the transition has been completed in some countries such as New Zealand and Chile.

Direct Ecological Effects of Forest Plantation

Forest plantations have direct ecological effects in addition to the positive impact of reducing pressure on natural forests. Generalizations are difficult, however, in part because plantation management regimes are diverse and the appropriate comparison is not always to unmanaged natural forests. In worst-case scenarios, natural forests or savannas on fragile soils are converted to plantations of exotic species that lower groundwater tables, decrease biodiversity, and develop extreme nutrient deficiencies in successive rotations. While this scenario overstates the impact of plantations, their generally monoculture nature and intensive management raises concerns about the effect of plantations on biodiversity, water, long-term productivity and nutrient cycling, and susceptibility to insects and diseases.

Biodiversity illustrates the complicated ecological impact of forest plantations; although biodiversity encompasses genetic, species, structural, and functional diversity, much of the focus in discussions about diversity has been at the genetic, species, and local ecosystem levels. As has occurred in agriculture, the introduction of genetically improved exotic or native species in forestry increases productivity and carbon-fixation efficiency. In some regions, this introduction has also increased interspecies diversity at landscape and regional scales. In France, compared with 70 natural forest tree species, 30 introduced species that are commonly used in forest plantations have helped increase the interspecies genetic diversity of forests at the local level. In Europe, at least, there is no doubt that the introduction of new tree species has increased the species richness of forests. Nevertheless, exotic species, even those long naturalized species such as Douglas-fir (*Pseudotsuga menziesii*) are unacceptable in nature conservation schemes.

Exotic species can have negative impacts on native species and communities. For example, fast-growing species can replace native forest species because of their natural invasive potential, as have been observed with *Eucalyptus* in northwestern Spain and Portugal. As the introduction of exotic species has potential risks, confirmation of long-term adaptation to local environmental conditions and pest resistance is necessarily the first step for the use of exotic species in extensive plantation programs.

Plantations tend to be even-aged and managed on relatively short rotations; thus, simple stand structures are common. When repeated across a landscape, large areas of similar species and low structural complexity result in a loss of habitat for taxa that require the kind of conditions provided by naturally regenerated stands or old forests. It has been reported that the bird fauna of single-species plantation forests is less diverse than that of natural and seminatural forests. In other cases, however, bird species diversity in plantation forests is comparable with that in naturally generated stands. For example, cottonwood (*Populus deltoides*) plantations in the Mississippi River Valley in the southern United States are intensively managed (rotation lengths of 10–15 years), reaching crown closure in 2 years. In comparison to natural stands, bird species diversity and abundances are similar for all guilds except cavity nesters.

Where avian diversity is decreased in managed forests generally, loss of structure following harvest is usually the cause. In plantations, simplified structure may be exacerbated further by use of exotic species or by monoculture. Because plantations are harvested at or near economic optima, rather than at biological maturity, plantations seldom develop much beyond the stem exclusion stage of stand development and do not re-establish characteristics of old forests or complex stand structures such as snags and coarse woody debris. Strategies to compensate for the simplifying tendencies of plantations and integrate biodiversity considerations include complex plantations composed of multiple species, varying planting spacing, thinning to variable densities, and retaining uncut patches and snags after harvest. Such biological legacies should benefit invertebrates such as saproxylic beetles as well as fungi, small mammals, and birds.

Silvicultural and site management practices of site preparation, competing vegetation control, and fertilization may reduce understory and groundcover vegetation diversity, although the effects of previous land use such as agriculture may play a larger role. For example, in southern United States industrial pine plantations, understory diversity was correlated with previous land use; lower diversity of native forest species occurred in plantations established on former farmland and higher diversity in plantations on cutover forest land.

Some species can benefit from forest plantations. For example, clear-cutting and short rotations favor the occurrence of ruderal plant species over some long-lived climax species. Forest plantations accommodate edge-specialist bird species and generalist forest species such as deer. Some rare and threatened species have been found to occupy forest plantations, especially when they lost most of their habitat to agricultural and urbanized land uses. For example in the UK, the native red squirrel is out-competed in native woodlands by the gray squirrel introduced from North America but the red squirrel thrives in conifer plantations, which are poor habitat for the gray squirrel.

Spatial considerations play a role in maintaining biodiversity at the landscape scale. Landscape diversity can meet the habitat needs of wildlife and be achieved by varying the size and shape of plantations and incorporating adjacency constraints into harvest scheduling models (i.e., a plantation adjacent to a recently harvested or young stand cannot be harvested until the adjacent stand reaches a certain age or crown height). Retaining areas of naturally regenerated forest, riparian buffers, or open habitat creates a landscape mosaic that combined with prescribed burning in fire-affected ecosystems, adds to landscape diversity. Landscape connectivity that provides dispersal corridors for mobile species is fostered by careful placement of forest roads and firebreaks.

Concerns about plantations and water are as varied as the issues surrounding biodiversity but generally relate to water use, water quality, or alteration of natural drainage. Species of *Eucalyptus* planted outside their native Australia have attracted the most negative attention for their putative excessive water use, especially in Africa and India but *Populus* species have similarly been accused in China of lowering local water tables and adding to drought. Species such as *Eucalyptus camaldulensis*, *E. tereticornis*, and *E. robusta* (and hybrids of these and other eucalypts) are drought tolerant and able to transpire even under considerable moisture stress. On balance they probably do not use more water than adjacent natural forests but certainly use more of the available water than grasslands or agricultural crops. There is little evidence that they can abstract groundwater; however, there is no recharge below the root zone. In the Wheatbelt of Western Australia, removal of the deep-rooted native vegetation including eucalypts and conversion to cereal crops has caused water tables to rise with subsequent salinization of soils and surface water bodies. Plantations of oil mallee crops (*E. polybractea*, *E. kochii* subsp. *plenissima*, and *E. horistes*) are planted to restore natural hydrology and counteract salinization.

Negative effects of plantations on water quality and aquatic resources are more due to intensive management than to use of exotic species. Intensive mechanical site preparation, especially on sloping sites, can result in sediment movement into streams. Chemical herbicides are used to control competing vegetation at various stages in the plantation growth cycle, but usually for site preparation in place of mechanical treatments or early in the life of the stand to release crop species from competitors. Less intense site preparation, formulations of herbicides that are not toxic to insects or other aquatic organisms and break down in soil, careful placement of chemicals to avoid direct application to water bodies, and designation of riparian buffers all have contributed to protection of water quality.

Harvesting practices, especially placement and construction of harvest roads and layout of skidding trails, potentially can degrade water quality. In developed nations, forest practices such as site preparation, harvesting, use of herbicides, and even choice of species may be regulated to some extent. In the United States, best management practices (BMPs) to address non-point source pollution and protect water quality have been codified by state agencies and landowners follow them voluntarily. Research shows generally high rates of compliance. Certification schemes substitute the coercive power of the marketplace for that of government; the various certification bodies differ in how they regard plantations, especially with regard to the use of herbicides, exotic species, or genetically modified trees.

Use of inorganic fertilizers to overcome fertility deficiencies, promote rapid growth, and sustain biomass accumulation generally has been found to have little impact on aquatic systems unless fertilizers are applied directly to streams, lakes, rivers, or adjacent riparian zones. Greater attention has focused on nutrient removals in harvests and the potential for intensive management to reduce site fertility and cause a fall-off in productivity of subsequent rotations. Claims of later-rotation productivity declines have been hard to substantiate, however, as general improvements in seed and seedling quality, genetic makeup, site preparation and competition control, and more careful harvesting that conserves site fertility have raised, rather than lowered yields. Nevertheless, there exist documented cases of lowered fertility caused by export of nutrients in the harvested wood. These localized cases have been caused by low initial fertility, often of phosphorus, potassium, or micronutrient deficiencies inherent in the soil parent material that are easily overcome by application of inorganic fertilizers.

In the most intensive management of pine plantations for pulpwood in the southern United States, some companies routinely apply complete nutrient mixes containing all macro- and micronutrients as a precaution, despite lack of demonstrated deficiency of most nutrients except phosphorus and a responsiveness to added nitrogen. A stand may be fertilized with nitrogen up to five times in a 25-year rotation, sometimes in combination with phosphorus. These stands occur mostly on relatively infertile Ultisols and Spodosols developed on old marine sediments. On better soils (Alfisols, Entisols, and Vertisols), cottonwood plantations managed on 10-year rotations receive only an initial application of nitrogen at planting to promote rapid height growth to better compete with herbaceous competitors. Management of site nutrients in intensive plantations is critical to high yields as well as to protect long-term productivity and may require attention to retaining soil organic matter, especially on sandy soils. Factors to consider include inherent soil fertility (nutrient stocks as well as transformations and fluxes), plant demand and utilization efficiency, and nutrients export in products removed as well as leakages.

It is common wisdom that monoculture plantations are more susceptible than natural forests to insect and disease attacks, yet there is little evidence this is generally true. On the one hand, single-species stands occur naturally and some of these natural vegetation types are the product of periodic, catastrophic disturbances such as pine bark beetles or spruce budworm. On the other hand, one explanation for the often greater productivity of exotic tree species than attained in their native habitat is the lack of yield-reducing insects and diseases. But diversity in the abstract is not a guarantor of lessened risk; diverse, multiple-species stands themselves are not immune to devastating attack by introduced pests, a situation likely to increase in frequency as a result of globalization of trade in timber products.

Often the practices associated with intensive management are the causes of insect and disease problems. For example, the desire to maximize wood production may set the level of tolerable damage from native pests lower than the stable equilibrium levels for the pest; attempts to control the pest at lower levels may cause unstable population growth cycles. The potential risks of plantations stem from their uniformity: the same or a few species, planted closely together, on the same site, over large areas. Pests and pathogens adapted to the dominant species may build up quickly due to food supply and abundant sites for breeding or infection. Proximity of the branches and stems in closely spaced stands may favor buildup of species with low dispersal rates or small effective spread distances. Conversely, the same uniformity of plantations that contributed to the risks of insects and diseases also confers some advantages. Species can be chosen that have resistance to diseases, for example, the greater resistance of loblolly pine (*Pinus taeda*) compared to slash pine (*P. elliottii*) to *Cronartium* rust was one reason loblolly was favored by forest industry in the US South. The shorter rotation length of plantations relative to naturally regenerated stands means trees are fallen before they become overmature and become infected. The compact shape and uniform conditions in plantations facilitate detection and treatment of economically important pests and pathogens.

Plantations may negatively impact adjacent communities – because of invasive natural regeneration of planted trees in adjacent habitat or alteration of local and regional hydrologic cycles and poor management practices may damage aquatic systems. Plantations are certainly simpler and more uniform than naturally regenerated stands or native grasslands, and may support a less diverse flora and fauna. Nevertheless, plantations can contribute to biodiversity conservation at the landscape level by adding structural complexity to otherwise simple grasslands or agricultural landscapes and by fostering the dispersal of forest-dwelling species across these areas.

Further, comparisons of plantations to unmanaged native forests or even naturally regenerated secondary forests are not necessarily the most appropriate comparisons to make. Although the conversion of old-growth forests, native grasslands, or some other natural ecosystem to forest plantations rarely will be desirable from a biodiversity point of view, in that forest plantations often replace other land uses including degraded lands and abandoned agricultural areas. Objective assessments of the potential or actual impacts of forest plantations on biological diversity at different temporal and spatial scales require appropriate reference points. Forest plantations can have either positive or negative impacts on biodiversity at the tree, stand, or landscape level depending on the ecological context in which they found. Impacts on water quantity and quality can be minimized if sustainable practices are followed; similarly with soil resources and long-term site productivity. Both complex plantations for wood production and environmental plantations can beneficially impact local and regional environments.

Lastly, managing forest plantations to produce goods such as timber while at the same time enhancing ecological services such as biodiversity involves tradeoffs; this can be made only with a clear understanding of the ecological context of plantations in the broader landscape. Tradeoffs also require agreement among stakeholders on the desired balance of goods and ecological services from plantations. Thus, there is no single or simple answer to the question of whether forest plantations are 'good' or 'bad' for the environment.

See also: Boreal Forest; Temperate Forest; Tropical Rainforest.

Further Reading

Binkley CS (2003) Forestry in the long sweep of history. In: Teeter LD, Cashore BW, and Zhang D (eds.) *Forest Policy for Private Forestry: Global and Regional Challenges*, pp. 1–8. Wallingford: CABI Publishing.
Brown C (2000) The global outlook for future wood supply from forest plantations. *FAO Working Paper GFPOS/WP/03*. Rome, Italy.
Carnus J-M, Parrotta J, Brockerhoff E, *et al.* (2006) Planted Forests and Biodiversity. *Journal of Forestry* 104(2): 65–77.
Clawson M (1979) Forests in the long sweep of history. *Science* 204: 1168–1174.
Evans J and Turnbull JW (2004) *Plantation Forestry in the Tropics: The Role, Silviculture and Use of Planted Forests for Industrial, Social, Environmental and Agroforestry Purposes*, 3rd edn. Oxford: Oxford University Press.
FAO (2001) Global forest resources assessment 2000. *FAO Forestry Paper 140*. Rome, Italy.
FAO (2005) Global forest resources assessment 2005. *FAO Forestry Paper 147*. Rome, Italy.
Harris TG, Baldwin S, and Hopkins AJ (2004) The south's position in a global forest economy. *Forest Landowner* 63(4): 9–11.
Hartsell AJ and Brown MJ (2002) Forest statistics for Alabama, 2000. *Resource Bulletin SRS-67*, 76pp. Ashville, NC: USDA Forest Service Southern Research Station.
Li Y and Zhang D (2007) Tree planting in the US South: A panel data analysis. *Southern Journal of Applied Forestry* 31(4): 192–198.
Royer JP and Moulton RJ (1987) Reforestation incentives: Tax incentives and cost sharing in the South. *Journal of Forestry* 85(8): 45–47.
Stanturf JA (2005) What is forest restoration? In: Stanturf JA and Madsen P (eds.) *Restoration of Boreal and Temperate Forests*, pp. 3–11. Boca Raton, FL: CRC Press.
Stanturf JA, Kellison RC, Broerman FS, and Jones SB (2003) Pine productivity: Where are we and how did we get here? *Journal of Forestry* 101(3): 26–31.
Zhang D (2001) Why so much forestland in China would not grow trees? *Management World* (in Chinese) 3: 120–125.
Zhang D and Flick W (2001) Sticks, carrots, and reforestation investment. *Land Economics* 77(3): 443–56.
Zhang D and Oweridu E (2007) Land tenure, market and the establishment of forest plantations in Ghana. *Forest Policy and Economics* 9: 602–610.
Zhang D and Pearse PH (1997) The Influence of the form of tenure on reforestation in British Columbia. *Forest Ecology and Management* 98: 239–250.

Forestry Management

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Introduction

Trees are very long-lived organisms with high potential birth rates. Thus, estimating the basic birth and death parameters of tree populations is intrinsically difficult over the time duration of most ecological studies. The sizes of trees from seedling to mature tree vary over five orders of magnitude. Trees grow large enough to alter aspects of their environment as they mature. This individual–environment feedback is not usually included in traditional ecological population models. Tree interactions obtaining essential resources of light, water, and nutrients involve tree geometry in vertically for light, spatially for nutrients and water, and volumetrically for interactions among tree crowns such as crown pruning (where the branches of a tree abrade the buds from limbs of neighbor trees and change the shapes of competing trees). These geometrical aspects of tree populations are omitted in the mathematical structures of most ecological population models which, at least until recently, considered only the time dimension. Tree populations represent a modeling departure from traditional population models. Significantly, forestry models from their origins have always attempted to predict a combined response of the sizes of trees and the number of trees on a given area.

Tree population models have deep historical roots that are often not appreciated by modern population ecologists, perhaps in part because the origins of many of these forestry-based approaches are in applied fields and are focused on practical, regional results rather than the development of a general theory. For this reason, it is useful to discuss forestry models from their beginnings through the evolution to the modern approaches.