ENVIRONMENTAL IMPLICATIONS OF WOOD PRODUCTION IN INTENSIVELY MANAGED PLANTATIONS[1]

Jim L. Bowyer

Director, Forest Products Management Development Institute
Department of Wood and Paper Science
University of Minnesota
St. Paul, MN 55108

ABSTRACT

Although many of the issues raised about forest plantations are non-trivial, there are a number of significant environmental advantages of plantation establishment that appear to outweigh concerns, *if* plantation management practices can be developed to address concerns regarding sustainability. Foremost among the advantages is that establishment of highly productive forest plantations can provide large quantities of wood and fiber from relatively small land areas, raising the possibility that pressures for harvesting within natural forests can be markedly reduced. Moreover, assuming that forest plantations are carefully established and managed, they have the potential to produce a continuous, renewable stream of industrial raw materials that results in less overall environmental impact than other types of raw materials. Assessment of total environmental impacts over product life cycles shows that structural and nonstructural wood and wood fiber products made from plantation-derived raw material yield markedly lower impacts than similar products made from metallic, cementitious, petroleum-based, or other raw materials. Similarly, examination of total environmental impacts of papermaking fiber production in forest plantations versus fiber production using annual agricultural crops shows significant advantages to wood fiber. Thus, forest plantations can yield environmental benefits that extend well beyond the geographic location in which they are located.

Keywords: Environment, environmental impacts, tree plantations, forest plantations, wood, carbon sequestration, plantation productivity, wood consumption.

INTRODUCTION

As noted by Wadsworth (1997), a need for extensive forest plantations was recognized as long as a half-century ago. Champion (1949) made a case for establishing forests on millions of hectares, arguing that this would be of great benefit to society.

In the early 1990s, industrial forest plantations were estimated to occupy about 100 million hectares of land worldwide (Sutton 1993). A decade earlier, Mather (1990) estimated an increase in the planted area of approximately 1.0 to 1.2 million hectares annually. More recently, Leslie (1999) estimated new plantation establishment globally at 5–8 million hectares annually. Based on these estimates, the industrial forest plantation area globally should currently total 110 to 150 million hectares. Significant plantation development is currently underway on six of the seven continents, leading some to question whether markets in some regions will be able to absorb the large volumes of plantation wood that will soon be available (Leslie 1999; Whiteman 2000).

With increasing interest worldwide in forest plantations as a source of wood and industrial fiber, concerns about the potential environmental impacts of establishing forest plantations on a large scale are increasing as well. Specific concerns focus on potential loss of soil fertility and productivity under short harvest rotations, increasing risks of catastrophic disease and insect infestations through cultivation of monocultures, implications of replacing natural forests and associated flora and fauna with less biologically diverse plantations, and risks of introducing exotics.

This paper examines the forest plantation balance sheet from an environmental perspec-

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tive. Positive and negative aspects of plantation forests are identified and briefly examined. Particular attention is focused on life cycle impacts of wood production and use. Although given little attention in forest plantation literature to date, careful examination of environmental life cycle data for wood, and for materials that might be used as substitutes for wood, gives forest plantation establishment a new imperative.

PLANTATIONS DEFINED

The term ''plantation'' has been used by various authors to describe a number of different landscape configurations resulting from tree planting. Wadsworth (1997) outlined several silvicultural practices that lead to various forms of forest plantations. The most straightforward of these is the establishment of tree crops on deforested or cleared land, either on land previously degraded by agriculture, mining, or other activity, or on lands cleared of native vegetation specifically for the purpose of plantation establishment. Plantings may consist of one or many, native or exotic, tree species. Studies cited in this paper refer primarily to these kinds of plantations.

Other forms of plantations identified by Wadsworth are those created by planting preferred species of trees within an existing forest, often following partial cutting, in a practice known as interplanting. Variations of interplanting include gap or enrichment planting (planting in forest openings created by the felling of large canopy trees, operation of charcoal kilns, or partial failure of post-harvest regeneration), underplanting (the extensive planting of trees beneath the canopy of an existing forest), and group planting (the planting of clumps of trees, often in triangular-shaped patches, beneath an existing canopy). While there are environmental and economic implications of each variation of interplanting, these forms of plantations are not discussed herein.

WHY PLANTATIONS?

Rising raw material needs

Population growth is impacting forests in myriad ways, not the least of which are related to increasing demand for all products and services provided by forests, including wood and wood fiber. Rising demand is accentuated by steadily decreasing forest area per capita. For example, in 1800 the world population was 1 billion and there were approximately 4.5 ha of forests for each person in the world. Today the area of forests globally is about two thirds of what it was in 1800; the loss of forestland, coupled with an increase in population to just over 6 billion, has reduced the area of forest land per capita to only about 0.6 ha. Given a projected population of roughly 11 billion by the end of this century, and assuming zero loss of forests over the next 100 years, the amount of forestland for each person in the world will shrink to about 0.3 ha by the year 2100. The net effect of these trends is that it is more and more problematic as to whether it will be physically possible to meet demands placed on the world's natural forests. Plantations are clearly a part of the solution to this growing dilemma.

One of the most compelling reasons for establishment of forest plantations is that consumption of industrial wood and wood for cooking and heating is rising steadily at the same time that efforts to reduce harvesting in natural forests are also increasing (Sutton 1999). As long ago as the 1960s, Marsh (1962) observed that ''natural forests grow too slowly to meet bulk forest products demands.'' In the decade of the '90s, the specter of record population growth led many to take note of rising demand for forest-derived resources. Lyons (1993), for example, observed that ''large increases in demand for wood and fiber are coming by 2010.'' A year earlier, Leslie (1992) had suggested that the forest plantation area would ''have to be increased by 30 percent in the immediate future'' in order to meet needs for fuelwood and industrial wood. Given the plantation area in existence at the time (approximately 100 million ha), Leslie's suggestion translated to a global need for new plantations covering an additional 30 million ha. These estimates were followed by a stunning conclusion reached by the World Energy Council (WEC) (1995), which indicated that between 700 million and 1,350 million ha of land will be needed for biomass energy production by 2050. Heering (1997) put the need for plantation establishment at 27 million ha annually; this rate of establishment, if assumed to continue for 50 years, corresponds to the 1,350 million ha estimate of the WEC. These figures imply a need for as much as a seven- to thirteen-fold increase in global forest plantation area, excluding what might be needed to provide increased volumes of wood for industrial uses. If these estimates did not in themselves provide a strong case for substantial forest plantation establishment, projected impacts of the current movement toward certification of managed forests would seem to suggest a mandate for increased plantation investment. For instance, one of several studies of the impact of certification (Lundstrom et al. 1997) suggests a decrease in long-term timber supply of 12–15 percent if Forest Stewardship Council management guidelines are applied to managed Swedish forests. Together, these kinds of estimates have served to greatly intensify interest in forest plantations.

Forest plantations are typically highly productive as compared to natural forests. Evans (1992) reported that plantations often produce 10 m^3 of wood/ha annually, that wood yields of 20–25 m^3/ha/yr are not uncommon, and that annual yields as high as 45 to 60 m^3 have been attained with some hardwood species. Sedjo (1999), using figures adapted from Clapp (1993), cites annual plantation yields averaging 10–40 m^3/ha, with some values as high as 70 m^3 ha. High plantation productivity has been well documented by many others (Hakkila 1994; Pandey 1995; Sedjo 1999; Steen 1997; Tiarks et al. 1998). In contrast to plantations, natural tropical moist forest commonly yields 1 to 2 m^3/ha annually, which can be increased to perhaps 6 m^3/ha with management (Wyatt-Smith 1987); similar yields are recorded for natural forests in temperate regions (Sedjo 1999). Yields of up to 15 m^3/ha are reportedly attained in some types of managed dipterocarp forests (Wyatt-Smith 1987).

A number of authors have pointed out that higher productivity of plantations means that plantations serve to take pressure off natural forests by reducing the need for harvesting within them (Mather 1990; MERT 1992; Pandey 1995; Sedjo and Botkin 1997; Sedjo 1999; Whitmore 1999). This contention is controversial, however, and will be examined more closely in a later section of this paper.

Restoration of degraded land

Vast areas of land that have been degraded by unsustainable agriculture, short-fallow-period shifting cultivation, logging, heavy industry, war, and other activities are potentially available for plantation establishment. Wadsworth (1997) explained that not all degraded land is realistically available for plantation establishment. He pointed out that ''logging in the tropics is often followed by deforestation and agriculture that degrade the soil, precluding subsequent continuous cultivation or pasturing. Agriculture persists on the better sites, leaving the poorer ones to return to forests. Of these, the best may be suitable for plantations.'' Grainger (1988) estimated that there were 2,077 million ha of degraded land in the tropics alone, and that there was potential for afforestation (or reforestation) of 758 million ha, not including low productivity range and pastureland.

Land degradation as an impetus for forest plantation development is not unique to the tropics. Unsustainable agricultural practices in parts of the southern United States in the early 1900s, for example, led to establishment of large areas of tree plantations in the 1930s (Schultz 1999).

Today, it is widely accepted that forest plantations have great potential for restoring degraded sites in the tropics (Evans 1999; Parrotta 1992; Sawyer 1993). Evans (1999) observes that such plantings can be ''astonishingly successful.'' Brown et al. (1997) note that the profit potential of forest plantations provides opportunities and incentives for implementing intensive management techniques as well as initiation of site rehabilitation activities. Evans (1999) points out that forest plantations not only have future potential, but that tree planting to achieve soil erosion control, whether on steep hillsides or as part of shelterbelts to reduce wind erosion, is already widely practiced. The fact that site rehabilitation through forest plantation establishment also serves to sequester large volumes of carbon (see the following section) provides yet another incentive for a plantation-focused rehabilitation strategy (Evans 1999).

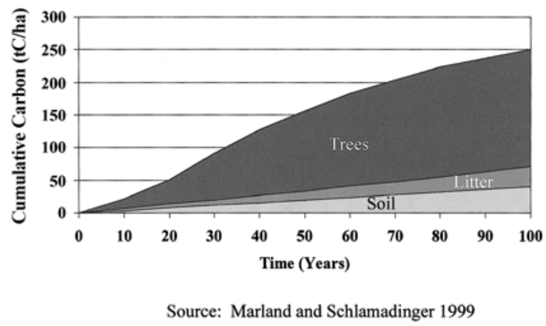

FIG. 1. Cumulative changes in carbon stocks in soil, forest litter, and standing trees after afforestation. Source: Marland and Schlamadinger 1999.

A source of minimal impact renewable materials

The carbon sequestration issue.—It has long been recognized that liberation of carbon dioxide and other gaseous emissions, as a result of combustion of fossil fuels and other human activities, has the potential to warm the earth's atmosphere. This potential was formally recognized in 1997 in Kyoto, Japan, at the United Nations Framework Convention on Climate Change. Also given formal recognition in Kyoto was the capacity of forests to capture carbon from the atmosphere and to store or sequester it for extended periods.

The fact that forests can capture carbon from the earth's atmosphere has led to a number of initiatives to preserve existing forests and to create new forest plantations for the purpose of carbon storage (DiNicola et al. 1997; Wright et al. 2000). There are many examples of forest plantations having been created for this purpose.

It is widely acknowledged that stored carbon stocks increase rapidly when a forest is established on land that was previously not forested (Harmon et al. 1990; Marland and Schlamadinger 1999). As dry wood is 49 percent by weight carbon, one-half kg of carbon is contained within each 1 kg of wood. Moreover, for each kg of carbon captured within wood, 3.7 kg of CO_2 are removed from the atmosphere. Thus, substantial carbon storage accompanies the growth of trees and the accumulation of woody debris on the forest floor (Fig. 1). Carbon accumulation appears to be more rapid when a portion of the wood harvested is used in long-lived products.

Scientific evidence also indicates that a net loss of carbon over the short term may accompany plantation establishment when mature forest is cleared beforehand. In this case, stored carbon is liberated as standing trees are removed, and as decay processes in the soil and litter layer accelerate (Harmon et al. 1990; Marland and Schlamadinger 1999). A net short-term loss appears likely even when a portion of the harvested biomass is incorporated into long-lived products. Over the longer term, assuming efficient conversion of a portion of woody materials into long-lasting products, net storage gains occur after thirty to forty years, even when the planted forests are periodically harvested. Although it is often assumed that trees grown to offset CO_2 emissions need then to be preserved in order to keep the CO_2 from returning to the atmosphere (Marland 1993), recent research shows that carbon storage can be significantly enhanced by periodic harvest of trees and their use in long-lived products. Marland and Schlamadinger (1999) list four ways in which forest growth, harvest, and subsequent use of harvested biomass can impact carbon storage:

1) Growing trees can capture carbon dioxide from the atmosphere and store carbon as woody biomass.
2) Carbon can be stored for long periods of

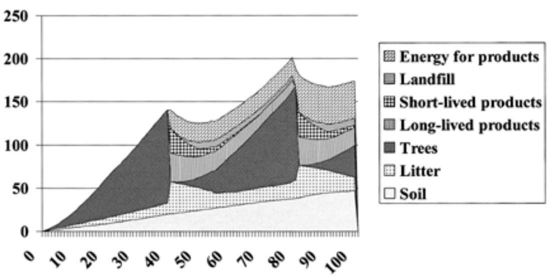

FIG. 2. Cumulative changes in carbon stocks with afforestation and subsequent harvest after 40 year rotation. Source: Marland and Schlamadinger 1999.

time in long-lasting wood products, and in wood-derived products buried in landfills.

3) Liberation of carbon contained within fossil fuels can be prevented by generating energy from biofuels.
4) Because the production and use of wood products are highly energy efficient compared to alternative products, such as those made of steel, concrete, or plastic, wood use avoids liberation of carbon that would result from increased energy consumption associated with alternative materials. These points are illustrated in Fig. 2, which depicts a forest plantation managed on a forty-year rotation with conversion of the wood that is produced to a variety of products.

Though not well understood, this latter point is extremely important, not only in terms of carbon liberation avoided, but from an overall environmental perspective as well. This topic is examined in more detail in the following section.

Minimal impacts in comparison to alternatives.—Environmental life cycle analysis (LCA) involves systematic examination of all environmental impacts associated with a given product. A thorough analysis considers impacts resulting from extraction, transportation, primary processing, conversion to semi-finished and finished products, installation, maintenance, and disposal or reuse. A key part of a life cycle analysis—the life cycle inventory (LCI)—examines all *measurable* raw material inputs, products and by-products, emissions, effluents, and wastes at all stages of extraction, production, use, and disposal.

Extensive LCA/LCI analyses have been completed since the mid 1970s, especially in western Europe, Canada, and Oceana. A few of these studies have examined wood and common substitute products; the results dramatically indicate the advantages of wood as an industrial material.

Although a number of studies could be cited, findings from three recent analyses will be used to illustrate the environmental benefits of producing and using wood as a construction material, rather than several common substitute materials.

The first North American study to focus on the life cycle impact of wood products production and use was done under the auspices of the U.S. National Academy of Sciences, by the Committee on Renewable Resources for Industrial Materials (CORRIM) (Boyd et al. 1976). This effort focused on materials used in the construction of residential buildings and involved system boundaries that encompassed raw materials extraction through building construction. A full range of structural and nonstructural materials were analyzed in this study, including a variety of wood products, steel, aluminum, and concrete, and brick.

Meil (1994) compared the manufacturing emissions and effluents associated with constructing a wood-framed, non-load-bearing interior wall vs. a steel-framed, non-load-bearing wall of the same dimensions. All effluents and emissions associated with all steps in the process were tracked, from forest harvest or mineral extraction, through to construction of the wall. The results demonstrate that selection of building materials can have very substantial environmental implications. Construction of the steel-framed wall was found to require 3.2 times more energy than construction of the wood-framed wall. Even larger differences were found in associated emissions and effluents (Table 1).

Another study by the Athena Sustainable Materials Institute (Canadian Wood Council 1997) examined energy consumption and CO_2

TABLE 1. *Comparative effluents and emissions associated with constructing 90 m^2 wall sections using wood vs. steel framing.*

Type of emission/effluent	Wood wall	Steel wall
CO_2 (g)	313,333	971,000
CO (g)	2,533	11,950
SO_2 (g)	370	3,694
NO_x (g)	1,011	1,575
Particulates (g)	187	591
Suspended solids (g)	12,180	495,640
Nonferrous metals (mg)	62	2,532
Cyanide (mg)	99	4,051
Phenols (mg)	17,715	725,994
Ammonia and Ammonium (mg)	1,310	53,665
Halogenated organics (mg)	507	20,758
Oil and grease (mg)	1,421	58,222
Sulfides (mg)	13	507
Iron (mg)	507	20,758

TABLE 2. *Total energy use and carbon dioxide emissions associated with constructing a large commercial office building of different materials.*

Construction	Total energy use[1]	Above grade energy use[1]	CO_2 Emissions[2]
Wood	3.80	2.15	73
Steel	7.35	5.20	105
Concrete	5.50	3.70	132

[1] GJ × 10^3.
[2] Kg × 10^3.

emissions in constructing a large office building. Three designs were evaluated: 1) a wood building (wood structural beams, wood cladding, wood-framed interior walls) on a concrete foundation; 2) a steel building (steel structural beams, steel cladding, steel-framed interior walls) on a concrete foundation; and 3) a concrete building (reinforced concrete beams, concrete panel exterior, concrete block interior walls on a concrete foundation. Differences in total energy use and carbon dioxide liberation associated with creating each building are shown in Table 2. Although much of the carbon dioxide liberated is traceable to energy consumption, note that the relationship between energy used and carbon dioxide emitted is not direct. Production of concrete, for example, results in liberation of large quantities of CO_2 from two distinctly different sources (Wilson 1993). Approximately ¾ ton of CO_2 results from burning of fossil fuels used to heat a large rotary kiln to temperatures as high as 2,700°F. High-temperature heating of limestone and small quantities of other materials in the rotary kiln is a key step in the production process. Another ½ ton is liberated in converting or calcining of calcium carbonate into lime.

A subsequent study by Pierquet et al. (1998) showed that because of thermal bridging issues, the differences as shown above become even greater when exterior walls are constructed so as to achieve equal thermal insulation or "R" values. Moreover, because of differences in thermal bridging performance of wood, steel, and concrete walls at corners and around doors and windows, even when basic insulation properties of wall sections are equal, both steel-framed and autoclaved cellular concrete walls require more heating energy over the life of a structure than do wood-framed walls.

The environmental advantages favoring the use of wood in construction, as well as for other purposes, are many and substantial. In addition to the environmental advantages, wood is the only widely available industrial raw material that is renewable.

The inescapable conclusion to which LCI/LCA studies such as those referenced above lead is that assuming contemporary levels of efficiency in processing, and technically attainable durability in use, wood should be used to the greatest extent possible consistent with assurance of sustainability. As noted by Marland and Schlamadinger (1999), the greater the manufacturing efficiency and useful product life, the stronger the case for wood becomes. Thus, among the advantages to forest plantations that are managed to provide wood for long-lived products is vastly lower environmental impact per unit of industrial raw material produced.

A final point with respect to life cycle comparisons of various raw materials has to do with various options for producing papermaking materials. Paper production worldwide has soared in recent years, with production outstripping both population and GDP growth rates. This has served to stimulate interest in a variety of alternative papermaking materials, from agricultural crop residues, to agricultural crops planted specifically for the purpose of producing papermaking fiber. While the use of crop residues (in excess of those needed in sustainable farming) as papermaking raw material has long been practiced in many parts of the world and makes a great deal of sense, the specific planting of agricultural crops for this purpose is highly questionable from an environmental point of view. A recent analysis of the environmental impacts associated with papermaking fiber production using annual crops of kenaf vs. fiber production in intensively managed tree plantations again suggested very significant advantages of wood fiber production (Bowyer 1997); differences in landscape impacts were particularly notable.

Restoration of biodiversity

Large-scale plantations are frequently criticized because of their lack of biodiversity. Yet if a plantation is established on an impoverished site, the new vegetation and associated return of wildlife can increase biodiversity (Parrotta 1995). Further discussion of the impact of forest plantation establishment on biodiversity, positive and negative, can be found under the heading ''Environmental Issues Associated with Forest Plantations.''

DO PLANTATIONS TAKE PRESSURE OFF NATURAL FORESTS?

There is disagreement about whether plantations take pressure off natural forests. Sargent (1992) was among the first to question this notion, stating that only under very specific circumstances have plantations contributed to the protection of natural forests. She contends, in fact, that because of a higher perceived and realizable value of plantations as compared to natural forests, plantation growth has actually contributed to the loss of natural forests. Mathur (1993) also suggested that plantations might do little to help protect natural forests, pointing out that production of wood is only one of many functions of natural forests.

Perhaps the most pointed criticism of the natural-forest-saving role of plantations comes from Sargent who notes that production of large volumes of plantation wood will tend to drive down the price of wood in general, thereby stimulating demand for wood from plantations and natural forests alike. Ironically, Sargent's questioning of the environmental role of plantations is given credence by Lovejoy's observation regarding the potential impacts of a boycott of tropical timber (Lovejoy 1990). Lovejoy documented the findings of a workshop that included an assessment of the impact of a loss of timber demand on the value of natural forest. It was concluded that such a development would reduce the value of forests, making more likely a conversion to pasture or cropland. Following the same reasoning, should high wood production in forest plantations, in fact, result in reduced timber value, then the effect on forests could well be similar to that of a boycott.

The possibility for adverse impacts arising from timber demand shifts has led some to suggest that regulations and formal agreements may be needed to protect natural forests in conjunction with plantation establishment. Some, in fact, are now calling for the set-aside of vast areas of forestland in natural or non-managed reserves, with wood production shifted entirely to privately owned natural or modified forests or to intensively managed plantations. That is precisely the strategy that was pursued in both New Zealand and Australia as part of efforts to significantly increase the area of forest plantations.

Regarding the possibility of protection of natural forests as part of a plantation strategy, some authors have questioned whether seeking to abandon timber production in natural forests is a wise idea. More than 40 years ago Dawkins (1958), for example, wrote ''Even where plantations are justified, it does not necessarily follow that all remaining naturally regenerated forests are best left unproductive. If they are, they may become vulnerable to destruction . . .'' More recently, Sedjo and Botkin (1997), for example, gained a great deal of attention from the observation that we [society] could produce all the wood we want on very little land. Less noticed was their caution that it is not necessarily a good idea to prevent any harvesting in native forests. Whitmore (1999) echoed this theme, stating that although plantations can diminish pressure on native forests, the native forests should, nonetheless, continue to be managed extensively. The reasoning behind these admonitions is similar to that of Lovejoy: if the value of forests is diminished, the value of the land occupied by forests is diminished as well, making conversion to agriculture or other uses more likely.

Thus, the debate about whether forest plantations can take pressure off natural forests appears to have come full circle. An emerging view is that yes or no, it would be a mistake to leave vast areas of natural forests in a nonmanaged state.

ENVIRONMENTAL ISSUES ASSOCIATED WITH FOREST PLANTATIONS

Despite widely recognized benefits of forest plantations, there are also widely shared concerns about the possibility of development of massive tree plantations in the tropical regions (Sawyer 1993). Sawyer sums up these concerns with the observation ''Admittedly some plantations provide good soil coverage, prevent erosion, and help regulate the water cycle. But others, due to inappropriate practices when planting and harvesting, or during the construction of forest roads, have triggered serious erosion processes.'' Moreover, according to Sawyer, local water cycles have been disrupted as a result of periodic clearcutting, and in some cases, by increased rates of water uptake due to the physiology of the species chosen or the density of planting. She notes also that pests, diseases, and associated large fires have frequently been associated with large plantations. Acknowledging that careful species selection and application of best silvicultural practices can significantly reduce risks of pests and disease, she contends that, for a number of reasons, best management practices are rarely pursued.

A number of authors take issue with views such as those expressed by Sawyer. Michon, Mary, and Bompard (1986), for example, refer to ''well publicized ecological problems'' with plantations, but go on to note that ''most plantation areas have few problems.'' McNabb, Borges, and Welker (1994) report similarly, in this case specifically regarding the Jari project in Brazil. In their words, ''Jari has been much maligned. In fact, it has brought income to many while safeguarding large areas of native Amazon forest.''

Thus, there is by no means unanimity in the view that plantations, whether large or small, generally lead to environmental problems. Nonetheless, several of the most commonly mentioned problems are briefly examined in this section.

Negative impacts on soil moisture and water yield

Concerns about the impact of plantations on soil moisture and water yield are mostly related to apparent high transpiration rates and impacts on soil moisture depletion, increased moisture interception and evaporation at the canopy level, and reduced stream flow. Many references can be found in the literature to situations in which plantations have been established on pastureland, or on plots adjacent to land used for agriculture. Observations such as the following, from Calder et al. (1992) indicate great impact of plantations on site hydrology: ''When eucalyptus is planted in areas where the roots have access to groundwater, as for example when planted next to irrigation canals, there is no doubt that growth rates are higher by a factor of at least five, and that water consumption is likely to be roughly commensurate.''

Similar trends, although smaller in magnitude, have been reported in New Zealand, mostly in conjunction with establishment of pine plantations. Fahey and Rowe (1992) and

Fahey (1994), for instance, report annual water yield reductions of 25–50 percent after conversion of pasture to plantation forests, particularly on sites where rainfall is limited. Several studies suggest that the reason for this is not a differential rate in transpiration, but instead due largely to interception and reevaporation at the crown. Interception has been found to amount to as much as 30 percent of the rainfall, over a fairly wide range of rainfall amounts (Fahey and Rowe 1992; Pearce and Rowe 1979; Fahey and Watson 1991). Schultz (1999) also reports reduced water yields from pine plantations based on work with loblolly pine in the U.S., but does not distinguish whether this is due to interception losses or high transpiration rates. It should be noted that not all studies show that plantations reduce streamflow. Whitmore (1999) cites several studies that found either no change or higher stream flow associated with plantations as compared to other types of vegetative cover.

Bruijnzeel (1997) acknowledges significant changes in site hydrology following plantation establishment, reporting that there is evidence in tropical regions that the planting of fast-growing trees on grassland will diminish streamflow after canopy closure, particularly during the dry season. He contends, however, that the largest changes in water yield and sedimentation usually occur after natural forest has been converted to plantation. Effects on streamflow rates and sediment loads are said to stabilize within two years of establishment, and at levels slightly above the preconversion levels.

The greatest number of concerns about the effect of plantations on soil moisture and water yield appear to be directed toward the eucalypts. The literature is replete with articles about the hydrological impacts of these species. Davidson (1987), after extensive studies of eucalypts, wrote ''Water use by eucalyptus plantations has been a controversial subject, especially in India. Available scientific evidence indicates eucalypts have no more effect on the water table than several other species of commonly planted trees, and on the basis of unit weight of dry biomass produced, eucalypts are relatively efficient in their use of water and they maintain biomass production under conditions of soil moisture stress.'' Perhaps the most authoritative look at this topic is that by Calder (1992) whose observations parallel those of Davidson. Calder reports that the main impact on site hydrology as a result of plantation establishment on grass or agricultural lands is from increased evaporation, which is likely to result in reduced aquifer recharge and reduced runoff. He also reports that although interception losses from eucalyptus and other tree species are likely to be greater than from shorter vegetation, such losses are likely to be less than those of other tree species of similar height and planting density. Calder further notes that transpiration rates of eucalyptus species are likely to be similar to those of other tree species, except in situations where species of eucalyptus that do not exhibit stomatal regulation are growing in areas where atmospheric demand is high and soil water is freely available. Under these circumstances, according to Calder, eucalyptus may well transpire at very high rates dictated solely by atmospheric demand.

In summary, it does appear that plantation establishment can have a substantial impact on site hydrology, sometimes positive, sometimes negative. At least some of the negative impacts can be avoided by proper matching of species to site.

Erosion and soil degradation resulting from plantation establishment

As noted by Whitmore (1999), the prospect of lowered yields as a result of site deterioration under intensive management of short-rotation tree crops has been a concern of foresters for decades. Recent literature suggests that this is still a major concern. Lai (1997), for example, expresses concerns about the effects of plantation establishment, pointing out that deforestation and change in land use associated with initiating plantation forests can lead to soil compaction, erosion, and depletion of soil organic matter, and thus degradation of physical and nutritional properties of soil. Evans (1992) observes that plantations tend to be kept in an early successional stage, with maximum removal of biomass from the site at harvest. He also reports that plantations are less efficient at trapping released nutrients, due in part to the existence of fewer roots near the surface. The result, he notes, may be significant nutrient loss from sites where trees are harvested. Binkley and Giardina (1997) strongly link a continued supply of soil nutrients to long-term sustainability of high productivity in tropical plantations. They then note that rapid growth of tropical plantations leads to high rates of nutrient accumulation in biomass, and that harvesting at short rotation intervals removes large quantities of nutrients which may, over time, lead to depletion of soil fertility.

This is also a concern of O'Connell and Sankaran (1997), who report that plantation species have been found in some cases to reduce the stores and flux rates of available plant nutrients in soil. They note that on high quality sites there may be little deterioration in soil properties as a result of several rotations of tree crops, whereas on poor sites, common in the tropics, reductions in soil nutrient status and stand productivity are likely to occur unless nutrient supplies are enriched with fertilizers, or through use of nitrogen-fixing species in mixed-stand environments. The length of harvest rotations can apparently accentuate nutrient loss problems. An example of this is provided by Montagnini and Sancho (1994), who found that, because of a higher proportion of nutrient-rich bark in smaller trees as well as other factors, short-rotation harvesting may remove more nutrients than longer-term rotations, both in terms of kg lost/ha/yr and kg lost per kg of wood harvested. These authors did not examine the possibility of on-site chipping of tops with subsequent dispersal.

Regarding these issues, many researchers have indicated that many problems that are encountered in forest plantation management are the result of improper management. For instance, Boardman (1979) studied widespread decline in second-rotation patula pine plantations that had occurred in the 1960s in southern Australia. He found that in subsequent crops the problem was largely overcome by careful treatment of the site at harvesting, increasing the level of silvicultural inputs, and controlling grass competition that had been absent when first rotation crops were planted.

Will (1984), discussing the subject of monocultures in both temperate and tropical regions, indicated that where soil deterioration problems have occurred, poor forest management has usually been to blame. Lai (1997) said much the same thing, explaining that plantation forestry can lead to soil degradation as a result of soil or tree mismanagement, but that judicious soil and vegetation management can improve soil properties, minimize soil erosion risks, and enhance soil quality and productivity. He reports that growing leguminous crops in association with trees is a useful strategy for improving soil properties and controlling erosion. Evans (1999) has written extensively on the soil degradation question. He notes that in almost every case, tree planting in the tropics represents a more intensive land use than that practiced previously, and that high rates of growth and short rotations suggest the possibility that sites will be overstressed, resulting in diminishing fertility and poorer yields. Pointing out that although relatively few studies have been conducted to evaluate the sustainability of intensive plantation practices, Evans concludes that the evidence that has been gathered seems to indicate that productivity loss may not be as serious a problem as many have feared. A number of examples of high productivity over many cutting cycles are provided in Evans' earlier work (Evans 1986, 1988). Reaching much the same conclusions as Boardman, Will, and Lai, Evans (1999) suggests that instances of yield decline in the tropics and subtropics often reflect weed mismanagement or mismatching of species to site, rather than inherent shortcomings of plantation forestry practices.

Related to concerns about short crop rotations and harvesting practices that remove large amounts of nutrients from the site are questions about the abundance and nature of leaf litter under some plantation species. Many of these concerns are summarized by O'Connell and Sankaran (1997) with the following observation: ''In natural and plantation forests, biogeochemical nutrient cycling is dominated by litter production and decomposition. Species of eucalypts and pines, which make up about one quarter of the total area of tropical plantations, generally have higher nutrient use efficiencies (carbon gain per unit of nutrient taken up), and produce litter that is poorer in nutrients than most native tropical trees and other common plantation species. Litter in plantations of *Eucalyptus* and *Pinus*, and species within other genera such as *Casuarina*, usually decays more slowly and accumulates on the forest floor to a greater extent than plant detritus in native tropical forests. The distribution of carbon within ecosystem compartments and its effect on rates of nutrient cycling appears to be a fundamental difference between these species and many native tropical forests. Tree legumes produce litter that is richer in nutrients than *Eucalyptus* and *Pinus* species. However, even in these plantations, some species (e.g., *Acacia auriculiformis*) produce litter that is slow to decay and which accumulates in substantial amounts on the forest floor.''

Sargent (1991) identified a related problem—that of deliberate removal of leaf litter. She documented extensive removal of leaves from the forest floor in eucalyptus pulpwood plantations in Vietnam, pointing out that this had become a very severe problem, both because of susceptibility of the soil surface to washing, and because removal of leaves prevented the development of a humus layer. The importance of maintaining the litter layer or some kind of vegetative cover in order to avoid erosion and to maintain soil moisture is emphasized by Widagada (1981) and Spaargaren and Deckers (1998).

Yet another issue related to soil degradation is soil compaction caused by use of heavy equipment during harvesting. As noted by Tiarks et al. (1998), impacts can range from severe to negligible, depending upon the application or non-application of proper harvesting and management techniques.

Risks of pests and disease

As noted by Sawyer (1993), exotic species have been regarded as both more resistant and more susceptible to pests and diseases.

One of the best discussions of the risks of pests and disease in natural versus plantation forests is found in a recent FAO Forestry Paper (Swedish Agency for Research Cooperation with Developing Countries 1992). On the one hand, it is noted that there are many documented instances of insects and disease causing extensive damage in natural forests, as well as an increasing number of examples of plantations that have been grown over many cutting cycles with few problems. The more than 100-year history of exotic rubber plantations in Malaysia is cited as one example of successful plantation operation over the long term. On the other hand, a strong case is presented to support the contention that plantations, and particularly single species plantations, are at much greater risk to catastrophic insect and disease losses than are natural forests. However, whether exotics are at greater risk than native species to insects and disease is inconclusive. Some researchers have noted that exotics face lower risks than native species, since introduction of a species into a region that is outside of its natural range separates that species from its natural pests and can thus improve health and performance, at least in the short term (Zobel et al. 1987). Clouding this positive result is the fact that there are at least several instances in which introduction of exotic tree species has been accompanied by introduction of pests that have subsequently done serious damage to native species adjoining the new plantation areas (Ciesla 1992). There are also documented instances in South Africa and New Zealand in which introduced pines have, over time, extended their range into surrounding natural forests, suppressing indigenous forest species (Zobel et al. 1987).

Strong criticism of even-aged, single species plantation forestry comes from Schultz (1999), who reports ''Damage from pests and environmental stresses have become increasingly severe in [U.S.] southern pine forests over the past 50 years. This is principally the result of human changes in ecosystems from mixed species to rapidly growing even-aged stands of a single species such as loblolly pine. Research has shown that such development has altered many natural balances that previously kept pathogenic organisms in check in ecosystems.'' Similar views have been expressed by Perry and Maghembe (1989) and Widagda (1981).

There appears to be increasing recognition in the literature that the genetic base of a forest plantation is more important than the number of species involved. Zobel and Talbert (1984) raised this issue, commenting that a monoculture established from rooted cuttings or clonal material would be at considerable risk over any extended time frame. In contrast, a plantation composed of genetically diverse planting stock does not present great risk, even if composed of a single species.

Gibson and Jones (1977) also discussed risk, pointing out that relatively short rotations coupled with intensive management allow plantation managers to react quickly to pest and disease problems, something that is often difficult in a natural forest environment. Brown et al. (1997) also discussed the availability of a considerable number of management options when dealing with intensively managed plantations. They noted that not only does this give flexibility in addressing problems, but also that every crop cycle offers the opportunity for planting superior genetic stock, designed to grow better quality faster.

As with other environmental concerns, many view pest and disease problems as due to factors other than use of exotic species or the planting of monocultures. Burdon (1982) listed four such factors: 1) inappropriate site choice, leading to stress-induced changes in the trees that increases their vulnerability to pests and diseases; 2) use of a poorly adapted seed source; 3) poor silvicultural practices, such as careless pruning and thinning, which can leave scarred live tissue open to infection; and 4) inadequate attention to nutrient and water requirements.

Impacts on biodiversity

Hakkila (1994) describes forest plantations of the southern hemisphere and tropics as, in general, monocultures of introduced species that are of uniform size and spaced geometrically. Thus, he concludes, they are incapable of supporting biodiversity characteristics of native forests. Widagda (1981) also refers to complex versus simple structure within natural forests as a central reason for reduced biodiversity within plantations. He explains that tropical forests represent a heterogeneous resource that provides animals and other organisms with many choices of food and numerous habitats, while tree plantations are a relatively homogenous resource that provides relatively few choices of food and habitats. Sawyer (1993) cites the typical high stocking density of plantations and lack of structural diversity as reasons for relatively low structural diversity within them. She cites an impressive array of comparative studies of diversity within plantations and natural forests to support her contention. Lee (1992), points out that not only are forest plantations incapable of supporting a wide array of biodiversity, but management so as to maximize timber yields typically involves systematic reduction of species diversity through elimination of pests, predators, and competitors.

Few authors dispute that forest plantations support reduced levels of biodiversity than natural forest stands, but an increasing number challenge the contention that plantations necessarily have vastly lower biodiversity than surrounding native forests. Maclaren (1996), for instance, cites a large number of studies that have been conducted in New Zealand that indicate a higher than expected incidence of biodiversity in planted radiata pine forests. Among the studies referenced is one indicating a greater level of plant and animal diversity in ‘‘mature’’ radiata pine plantation—652 pairs of native plant and animal species per 100 ha—than native forests in the same area (Brockie 1992). A similar report resulted from work in Sabah (Duff et al. 1986), which found greater levels of biodiversity within forest plantations than in surrounding areas. Norton (1989), after a series of biodiversity studies in New Zealand, disputed the oft-expressed contention that exotic forests are ‘‘biological deserts.’’ Evans (1992) acknowledges that there is little diversity within individual plantation stands, but points out that production plantations usually consist of several age classes, such that the ‘‘forest’’ as a whole tends to contain different habitat types, such as open ground, areas of young trees, closed thickets, and mature open stands. He explains that an additional source of habitat diversity within plantations is attributable to unplanted areas, including roads and tracks, gullies, rocky areas, and firebreaks that normally account for about one-fifth of the total plantation area.

Another part of the biodiversity debate involves the role that plantations play in restoring biodiversity to an impoverished landscape. Evans (1992) provided several examples of this, noting that planting of caribbean pine on poor savannas in Venezuela has led to a substantial increase in the deer population and the return of the jaguar, that planted cypress forests in Kenya and Tanzania are the home of thriving populations of the Sykes monkey, a species once driven to near extinction, and that the leopard is again found on the Nyika and Vipya plateaus of Malawi as a result of afforestation in these regions. Another study in the Canterbury plains area of New Zealand found the presence of many plant species that had been mostly absent prior to afforestation (Norton 1989).

There is little doubt that plantation forests offer less plant and animal diversity than native forests within the same region. Differences are accentuated when crop rotations are short, and much reduced under management aimed at increasing structural complexity of forest plantations. Thus, it does appear that the way in which plantations are managed has a rather direct influence on the diversity of plant and animal life found within a plantation. The Swedish Agency for Research Cooperation with Developing Countries (1992) lists a number of studies that have focused on design of plantation forests so as to maximize species conservation.

Discussion and summary

Were the human population small, and demands upon the world’s resources negligible to modest, there likely would be few concerns about natural forests, and no forest plantations or even discussion of them. However, the population is anything but small, and population growth is dizzying. Moreover, consumption of natural resources is growing even more rapidly than population, and pressures on all of the world’s natural systems, including forest ecosystems, are growing daily. Given this situation, concern about growing demands on the world’s natural forests is certainly understandable. Understandable as well are concerns about development of vast plantations of often non-native tree species. Yet, at a time when it is increasingly obvious that bold initiatives are needed in order to balance the reality of human wants and needs with the necessity of protecting the environment, it is difficult to understand how one can realistically oppose *both* the exploitation of natural forests and development of forest plantations.

Despite environmental concerns and problems associated with the establishment and sustainable management of some forest plantations, the benefits that accrue from plantations of rapidly growing trees are so significant that further development of forest plantations is virtually assured. Benefits include high commodity production on relatively small land areas, vastly reduced overall environmental impact associated with wood production and use in comparison to available alternatives, and potential for concomitant restoration of degraded land areas and associated biodiversity.

Not every aspect of rapidly growing plantations is beneficial. The implications of increased wood production in rapidly grown plantations on wood quality are significant, and generally negative. Chief among concerns about plantation-grown wood is the likelihood of increased juvenile wood production, and all associated problems. Such concerns are unlikely to slow the trend toward forest plantations, but may serve to accelerate the growth of the composite wood products industry.

To recognize the tremendous advantages of forest plantations or the inevitability of further development does not mean that environmental concerns linked to plantation development should be dismissed. Rather, it is to the advantage of everyone that forest plantations operate sustainably in every sense of the word, and that they provide the greatest possible array of benefits. In view of the size and recent growth of the forest plantation enterprise globally, and the nature of problems that have been encountered in conjunction with development and maintenance of some plantations, it is imperative that steps be taken to address known problem areas and concerns.

Recent findings suggest that many problems associated with plantation establishment and sustainability are traceable to poor planning and/or inadequate management. Research also indicates that questions about a number of issues do not yet have definitive answers. It is clear that great care will have to be taken in plantation management to ensure sustainable high-yield harvest over successive rotations. Given the scale of the emerging plantation enterprise, an aggressive and ongoing program of research should be given high priority.

REFERENCES

BINKLEY, D., AND C. GIARDINA. 1997. Nitrogen fixation in tropical forest plantations. Pages 297–337 *in* E. Nambiar, and A. Brown, eds. Management of soil nutrients and water in tropical plantation forests. Australian Centre for International Agricultural Research, ACIAR Monograph Series No. 43.

BOARDMAN, R. 1979. Maintenance of productivity in successive rotations of radiata pine in South Australia. Pages 543–554 *in* E. Ford, D. Malcolm, and J. Atterson, eds. The ecology of even-aged forest plantations. Institute of Terrestrial Ecology, Cambridge, UK.

BOWYER, J. 1997. Economic and environmental comparisons of kenaf growth vs. plantation grown softwood and hardwood. Pages 323–346 *in* Proc. Fifth Chemical Congress of North America—Chemistry of kenaf properties and materials, American Chemical Society, November 11–15. Cancun, Mexico.

BOYD, C., P. KOCH, H. MCKEAN, C. MORSCHAUSER, S. PRESTON, AND F. WANGAARD. 1976. Wood for structural and architectural purposes. Wood Fiber 8(1):3–72.

BROCKIE, R. 1992. A living New Zealand forest—A community of plants and animals. David Bateman, Ltd., Auckland, NZ.

BROWN, A., E. NAMBIAR, AND C. COSSALTER. 1997. Plantations for the tropics—Their role, extent, and nature. Pages 1–23 *in* E. Nambiar and A. Brown, eds. 1997. Management of soil nutrients and water in tropical plantation forests. Australian Centre for International Agricultural Research, ACIAR Monograph Series No. 43.

BRUIJNZEEL, L. 1997. Hydrology of forest plantations in the tropics. Pages 125–167 *in* E. Nambiar and A. Brown, eds. 1997. Management of soil nutrients and water in tropical plantation forests. Australian Centre for International Agricultural Research, ACIAR Monograph Series No. 43.

BURDON, R. 1982. Monocultures—How vulnerable? What's new in forest research? New Zealand Forest Research Institute, Report No. 115, 4 pp. Rotorua, NZ.

CALDER, L. 1992. Water use of eucalypts—A review. Pages 167–179 *in* I. Calder, R. Hall, and P. Allard, eds. Growth and water use of forest plantations. John Wiley & Sons, New York, NY.

———, M. SWAMINATH, G. KARIYAPPA, N. SRINIVASALU, K. SRINIVASA MURTHY, AND J. MUMTAZ. 1992. Measurements of transpiration from eucalyptus plantations, India, using deuterium tracing. Pages 196–215 *in* I. Calder, R. Hall, and P. Allard, eds. Growth and water use of forest plantations. John Wiley & Sons, New York, NY.

CANADIAN WOOD COUNCIL. 1997. Comparing the environmental effects of buildings. Case Study Report No. 4. 11 pp.

CHAMPION, H. 1949. Biology and technique of afforestation. Pages 14–20 *in* Proc. World Forestry Congress, Brazilia, Brazil.

CIESLA, W. 1992. Recent introductions of forest insects and their effects: A worldwide overview. Regional Conference on the Management of the Woodwasp Sirex noctillo in South American Pine Plantations. Nov. 23–27. Florianopolis, Brazil.

CLAPP, R. 1993. The forests at the end of the world: The transition from old-growth to plantation forestry in Chile. Ph.D. Dissertation, Department of Geography, University of California, Berkeley, CA.

DAVIDSON, J. 1987. Bioenergy tree plantations in the tropics: Ecological implications and impacts. Gland, Switzerland: IUCN. 47 pp.

DAWKINS, H. 1958. Silvicultural research plan, first revision, period 1959 to 1963 inclusive. Forest Department, Entebbe, Uganda. 24 pp.

DINICOLA, A., G. GRAY, AND D. JONES. 1997. Opportunities for forestry investment in the Asia Pacific region through carbon offset initiatives. Regional Wood Energy Development Program Field Document 53. United Nations Food and Agricultural Organization. Bangkok, Thailand.

DUFF, A., R. HALL, AND C. MARSH. 1986. A survey of wildlife in and around a commercial tree plantation in Sabah. Malaysian Forester 47(3/4):197–213.

EVANS, J. 1986. Productivity of second and third rotations of pine in the Usutu forest, Swaziland. Commonw. For. Rev. 65(3):205–214.

———. 1988. The Usutu forest: Twenty years later. Unasylva 40(159):19–29.

———. 1992. Plantation forestry in the tropics: Tree planting for industrial, social, environmental, and agroforestry purposes. Oxford University Press. 403 pp. New York: NY.

———. 1999. Planted forests of the wet and dry tropics: their variety, nature, and significance. New Forests 17: 25–36.

FAHEY, B. 1994. The effect of plantation forestry on water yield in New Zealand. New Zealand Forestry 39(3):18–23.

———, AND L. ROWE. 1992. Land-use impacts. Pages 265–284 *in* M. Mosley, ed. Waters of New Zealand. New Zealand Hydrological Society.

———, AND A. WATSON. 1991. Hydrological impacts of converting tussock grassland to pine plantation. J. Hydrology (NZ)30:1–15.

GIBSON, I., AND T. JONES. 1977. Monoculture in the origin of major forest pests and diseases. *In* J. Cherrett and G. Sagar, eds. Origins of pest, parasite, disease, and weed problems. Blackwell Scientific Publications London: UK. 413 pp.

GRAINGER, A. 1988. Estimating areas of degraded tropical lands requiring replenishment of forest cover. Int. Tree Crops J. 5(1/2):31–62.

HAKKILA, P. 1994. Pine plantations of the southern hemisphere and tropics as a source of timber. Finnish Forest Research Institute, Research Paper 532. 63 pp.

HARMON, M., W. FERRELL, AND J. FRANKLIN. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247:699–701.

HEERING, M. 1997. Quo vadimus? Pages 21–32 *in* O. Bouman and D. Brand, eds. Sustainable forests: Global challenges and local solutions. Haworth Press, New York, NY.

LAI, R. 1997. Soils of the tropics and their management for plantation forestry. Pages 97–123 *in* E. Nambiar and A. Brown, eds. 1997. Management of soil nutrients and water in tropical plantation forests. Australian Centre for International Agricultural Research, ACIAR Monograph Series No. 43.

LEE, S. 1992. Biodiversity. Tree plantation review: Study No. 6. Shell International Petroleum Company/WWF, UK.

LESLIE, A. 1992. How much wood do we need? Pages 76–91 *in* C. Sargent and S. Bass, eds. Plantation politics—Forest plantations in development. Earthscan Publications, Ltd., London: UK.

———. 1999. For whom the bell tolls. Tropical Forest Update 9(4).

LOVEJOY, T. 1990. Consensus statement on commercial forestry sustained yield management and tropical forests. Smithsonian Institution (January). 10 pp.

LUNDSTROM, A., P. NILSSON, AND G. STAHL. 1997. The consequences of certification on possible supply of industrial wood and fuelwood. A Pilot Study. Working Paper No. 23. Department of Forest Resource Management and Geomatics, Swedish University of Agricultural Studies, Umea, Sweden. (Swedish).

LYONS, M. 1993. Facing up to the Asia Pacific resource crunch. Asia Pacific Forest Industries, (May):36–39.

MACLAREN, J. 1996. Environmental effects of planted forests in New Zealand: The implications of continued afforestation of pasture. New Zealand Forest Research Institute, Bulletin No. 198. 180 pp.

MARLAND, G. 1993. Strategies for using trees to minimize net emissions of CO_2 to the atmosphere. Record of testimony before The U.S. House of Representatives, Subcommittee on Energy and Power, Congressional Record, Serial No. 103-92. July 29.

———, AND B. SCHLAMADINGER. 1999. The Kyoto Protocol could make a difference for the optimal forest-based CO_2 mitigation strategy: Some results from GORCAM. Environ. Sci. Policy 2:111–124.

MARSH, E. 1962. The introduction of fast growing exotic tree species for meeting the timber requirements of developing countries. *In* Papers, UNSAT Conference: E/CONF.39/C/13. Geneva, Switzerland.

MATHER, A. 1990. Global forest resources. Timber Press, Portland, OR. 341 pp.

———. 1993. Review. Pages 207–219 *in* Afforestation policies, planning, and progress. A. Mathur, ed. Bellhaven Press, United Kingdom.

MCNABB, K., J. BORGES, AND J. WELKER. 1994. Jari at 25—An investment in the Amazon. J. Forestry 92(2): 21–26.

MEIL, J. 1994. Environmental measures as substitution criteria for wood and non-wood building products. Pages 53–60 *in* Proc., The globalization of wood: Supply, processes, products, and markets. Forest Products Society, Madison, WI.

MICHON, G., F. MARY, AND J. BOMPARD. 1986. Multistoried agroforestry garden system in Sumatra, Indonesia. Agroforestry Systems 4:315–338.

MINISTRY OF EXTERNAL RELATIONS AND TRADE. (MERT) 1992. United Nations Conference on Environment and Development. New Zealand, MERT, Wellington.

MONTAGNINI, F., AND F. SANCHO. 1994. Nutrient budgets of young plantations with native trees: Strategies for sustained management. Pages 213–233 *in* W. Bentley and M. Gover, eds. Forest resources and wood-based biomass energy as rural development assets. Winrock International, and Oxford & IBH Publishing, New Delhi, India.

NORTON, D. 1989. Indigenous plants in the exotic plantation forests of the Canterbury Plains. J. Canterbury Bot. Soc. 23:21–27.

O'CONNELL, A., AND K. SANKARAN. 1997. Organic matter accretion, decomposition, and mineralization. Pages 443–480 *in* E. Nambiar and A. Brown, eds. 1997. Management of soil nutrients and water in tropical plantation forests. Australian Centre for International Agricultural Research, ACIAR Monograph Series No. 43.

PANDEY, D. 1995. Forest resources assessment 1990—Tropical forest plantation resources. FAO, Rome: Forestry Paper 128.

PARROTTA, J. 1992. The role of plantation forests in rehabilitating degraded tropical ecosystems. Agriculture, Ecosystems, and Environment 41:115–133.

———. 1995. Influence of overstory composition on understory colonization by native species in plantations on degraded tropical site. J. Vegetation Sci. 6: 627–636.

PEARCE, A., AND L. ROWE. 1979. Forest management effects on interception, evaporation, and water yield. J. Hydrology (NZ) 18:73–87.

PERRY, D., AND J. MAGHEMBE. 1989. Ecosystem concepts and current trends in forest management: time for reappraisal. Forest Ecology and Management 26.

PIERQUET, P., J. BOWYER, AND P. HUELMAN. 1998. Thermal performance and embodied energy of cold climate wall systems. Forest Prod. J. 48(6):53–60.

SARGENT, C. 1991. Vietnam Forestry Sector Review: Land Use Issues. MOF/UNDP/FAO. VIE/88/037. IIED. London, UK.

———. 1992. Natural forest or plantation? Pages 16–40 *in* C. Sargent and S. Bass, eds. Plantation politics: Forest plantations in development. Earthscan Publishers, London, UK.

SAWYER, J. 1993. Plantations in the tropics: environmental concerns. IUCN/UNEP/WWF, Cambridge, UK.

SCHULTZ, R. 1999. Loblolly—The pine for the twenty-first century. New Forests 17:71–88.

SEDJO, R. 1999. The potential of high-yield plantation forestry for meeting timber needs. New Forests 17:339–359.

———, AND D. BOTKIN. 1997. Using forest plantations to spare national forests. Environment 39(10):14–20, 30.

SPAARGAREN, O., AND J. DECKERS. 1998. The world reference base for soil resources—An introduction with special reference to the soils of tropical forest ecosystems. Pages 21–28 *in* A. Schulte and D. Ruhiyat, eds. Soils of tropical forest ecosystems—Characteristics, ecology, and management. Springer-Verlag, Berlin, Germany.

STEEN, H., ED. 1997. Plantation forestry in the Amazon: The Jari experience. Forest History Society, Durham, NC.

SUTTON, W. 1993. The world's need for wood. Pages 21–28 *in* Proc., The globalization of wood: Supply, processes, products, and markets. Forest Products Society, Madison, WI.

———. 1999. Does the world need planted forests? Proc., Intersessional Expert Meeting on the Role of Planted Forests, April 6–9, Santiago, Chile.

SWEDISH AGENCY FOR RESEARCH COOPERATION WITH DEVELOPING COUNTRIES. 1992. Mixed and pure forest plantations in the tropics. A paper based on the work of T.J. Wormald. FAO, Rome: Forestry Paper 103.

TIARKS, A., E. NAMBIAR, AND D. COSSALTER. 1998. Site management and productivity in tropical forest plantations. CIFOR Occasional Paper No. 16.

WADSWORTH, F. 1997. Forest production for tropical America. USDA, Forest Service, Agricultural Handbook 710. 563 pp.

WEC/IIASA. 1995. Global energy perspectives to 2050 and beyond. World Energy Council, London, UK.

WHITEMAN, A. 2000. Personal correspondence from FAO, Rome, to Dr. Con Schallau, Moscow, Idaho. (February 3).

WHITMORE, J. 1999. The social and environmental importance of forest plantations with emphasis on Latin America. J. Tropical Forest Sci. 11(1):255–269.

WIDAGDA, L. 1981. Biophysical and environmental constraints of tree plantations in Hawaii. Environment and Policy Institute, East-West Center, 37 pp. Honolulu, Hawaii.

WILL, G. 1984. Monocultures and site productivity. *In* Proc. Productivity of Fast Growing Plantations, IUFRO, Pretoria and Pietermaritzburg, South Africa.

WILSON, A. 1993. Cement and concrete: Environmental considerations. Environmental Building News 2(2):1;7–12.

WRIGHT, J., A. DINICOLA, AND E. GAITAN. 2000. Latin American forest plantations—Opportunities for carbon sequestration, economic development, and financial returns. J. Forestry 98(9):20–23.

WYATT-SMITH, J. 1987. The management of moist forest for the sustained production of timber: Some issues. IUCN/IIED Tropical Forest Policy Paper No. 4.

ZOBEL, B., AND J. TALBERT. 1984. Applied forest tree improvement. John Wiley & Sons, New York, NY.

———, G. VANLOYK, AND P. STAJL. 1987. Growing exotic forests. John Wiley & Sons, Somerset, NY. 500 pp.