and 2.1 million hectares per year, respectively. Although agricultural lands are increasing at 3.3, 0.3, and 0.9 million hectares per year, degraded lands are increasing at rates of 1.7, 2.6, and 1.3 million hectares per year.
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Forests as Human-Dominated Ecosystems

Ian R. Noble and Rodolfo Dirzo

Forests are human-dominated ecosystems. Many of the seemingly lightly managed or unmanaged forests are actually in use for agroforestry or for hunting and gathering. Agroforestry does reduce biodiversity, but it can also act as an effective buffer to forest clearance and conversion to other land uses, which present the greatest threat to forested ecosystems. In forests used for logging, whole-landscape management is crucial. Here, emphasis is placed on areas of intensive use interspersed with areas for conservation and catchment purposes. Management strategies for sustainable forestry are being developed, but there is a need for further interaction among foresters, ecologists, community representatives, social scientists, and economists.

Most forests of the world fall between the extremes of intensively harvested plantations and managed conservation forests. Of the ~3.54 billion ha of forested lands (about a third of Earth's land surface) (Fig. 1), about 150 million ha are plantations and another 500 million ha are classified as actively managed for goods and services (*1*, *2*). However, this is a considerable underestimate of the area of forest affected (and often dominated) by human activity as it excludes large areas affected by indigenous gardening, hunting and gathering (*3*), and indirect management such as changed fire regimes.

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Human dominance of forested ecosystems continues to increase. Earth's forested estate has shrunk by about a third (2 billion ha) since the rise of agriculture-based civilizations and continues to be eroded at dramatic rates. Harvesting for wood and fuel is currently about 5 billion m^3 annually and is increasing by about 1.5% (75 million m^3) per year (*1*). In addition, some 10 million ha of new land, cleared largely from forests, is needed each year to support the increase in world population at current levels of nutritional and agricultural yields (*4*). Estimates suggest that forest clearing averaged over 13 million ha per year from 1980 to 1995, which was only partly compensated for by about 1.3 million ha per year of new plantations (*2*).

Forests are major stores of biodiversity and maintain ecosystem services critical to the biosphere as a whole. It is estimated that about 170,000 plant species, or two-thirds of all plant species of Earth, occur in tropical forests (*5*). Even in a supposedly well-collected region of Iquitos, Peru, nearly 70% of the extracted timber comes from a tree that was first described in 1976 (*6*). Forests constitute a major store of carbon [330 gigatons (1 Gt = 10^9 metric tons) in the vegetation and 660 Gt in the forest soils], and the management of forests is a major contributor to greenhouse gas budgets. Forests of mid- and high latitudes are estimated to be net sinks of carbon (0.7 ± 0.2 Gt/year), mostly because of uptake by rapidly growing young forests, whereas tropical forests are probably a large net source (1.6 ± 0.4 Gt/year), mostly because of clearing and conversion to other land uses (*7*).

Clearing of Forests

Most clearing arises from pressures that are external to the forested ecosystem. Throughout the world, there has been a history of undervaluing the forest resource; for example, royalties, purchase costs, or "stumpage" payments have often been set too low to recover the costs of management, let alone the costs of externalities. Low prices encourage land managers to liquidate the existing natural capital of the forest, replacing it with an agricultural system that yields quicker returns. This is exacerbated in societies where immediate needs predominate, which leads to a very high discount rate on future income. These same pressures have led forestry industries to "mine" the existing resource and make insufficient efforts to develop intensively managed regrowth forests, plantations, and protective management. The situation may be made worse by inappropriate interventions, such as trade bans to discourage "unsustainable harvesting," which often serve to reduce the value of the forest resource to the producing country and hasten forest exploitation. A simulation of the impacts of such a ban on Indonesia showed that internal consumption of sawlogs and plywood would increase significantly and that the rate of deforestation would be little affected (*8*).

Therefore, there is a tension between management of forests to protect ecosystem services and genetic resources and management for commercial production or conversion of lands for food production. This tension will increase in the future because of the size of the forest-related carbon pools and fluxes and their importance in mitigating the release of greenhouse gases. The management of the world's forest estate remains a major policy issue for many governments, as reflected in recent international assessments (*9*), reviews and inquiries into national and regional forest management (*10*), and major international efforts to improve forest management practices, including the Global Environment Facility, Tropical Forest Action Plans, and Debts for Nature swaps (*1*).

Forest Management

There is a wide range of forest management practices, with differing goals in relation to production and conservation, which are appropriate to different environmental, cultural, and economic circumstances (Fig. 2). Most fall into one of two categories. The first category includes the variants of traditional agroforestry and shifting agriculture that affect forests throughout the tropics and that are an important feature of the lifestyles of millions of people. The second category is the intensive logging of native forests followed by essentially natural regeneration that is common in temperate regions and in tropical forests. They represent two very different intensities of management. In traditional agroforestry, landholders regularly work in their plots with minimal input of externally sourced energy and fertilizer. In intensive logging, management intervention is less regular and heavily dependent on external inputs. Both are directed toward maintainence of a forested estate, although this estate may be significantly different from the previous forest. Both are important in the future of global forestry, global biodiversity, and global change. The sustainability of both systems depends on the effective management of whole landscapes.

Traditional agroecosystems. Traditional agroecosystems, which include "forest gardens" or "home gardens," combine trees with an understory of annual or perennial crops and sometimes livestock. This provision of food, fiber, fodder, medicine, and building materials lies at the heart of most traditional forest management systems. Villagers live adjacent to their gardens and maintain them through many generations. In present-day Maya towns in the Yucatan peninsula (Mexico), this type of forest garden covers about 10% of the region's forested area. Similar integrated traditional forest management systems are well documented in other tropical regions such as southeast Asia and Brazilian Amazonia (*11*).

Traditional shifting agriculture. Also known as slash-and-burn or swidden agriculture, this system is found in all tropical forest regions. Small patches of land (~0.5 to 2 ha) are cleared by a family or small group using a combination of slashing the understory, felling selected larger trees, and burning. Gardening or agriculture (or both) are practiced on the site for a few years until soil fertility declines. The patch is then abandoned and left to regenerate naturally as a secondary forest over many decades before the site is revisited and the cycle continues. These practices have occurred in many tropical forests for millennia without obvious signs of degradation, although they are believed to be the source of much of the secondary tropical forest (*12*). The system is not viable if increases in population and demands for alternative land uses lead to cycles that are too short to allow for full recovery of fertility. The breakdown of traditional ownership systems contributes to the monopolization by permanent agriculture of the land near villages, forcing swidden agriculture further into the forest.

Jungle rubber systems are an enhancement of traditional slash-and-burn practices in which rubber trees (*Hevea brasiliensis*), fruit, and occasionally timber species are planted during the garden phase. Natural regeneration occurs, leading to an "enriched" secondary forest. The fruit can be gathered and the rubber tapped for several decades. This system extends the productivity of a site from 2 to 5 years to 25 years or more and provides cash income (*13*). Comparable systems are common in the Neotropics, with other native cash crop trees such as *Castilla elastica* (rubber), *Manilkara sapota* (chewing gum), or *Chamaedorea spp.* (ornamental plants or leaves). These systems offer an opportunity to mix cash cropping with traditional lifestyles and may form a transition stage in social development; furthermore, they maintain relatively high-diversity forests in the face of the encroaching monoculture of plantations, oil palms, or other crops. However, the economic feasibility of such systems has been questioned (*14*).

Intensive logging. Most of the world's forests used for commercial timber production are logged selectively or are clear-felled (cutting all trees from a site) and allowed to regenerate by more or less natural means. There is a continuum of management approaches, ranging from no preparation of the site for regeneration after logging, through raking and burning of slash, to more intensive preparation of the soil surface for seed from either natural or artificial sources. Contentious issues include the intensity of the selection of trees for logging (from selective logging to clear-felling), the size of the areas to be logged (coupes), and their distribution in the landscape, decisions that are influenced by the economics of harvesting and the nature of the regeneration.

The nature and extent of clear-felling are bones of contention in many regions. Proponents point out that it is operationally

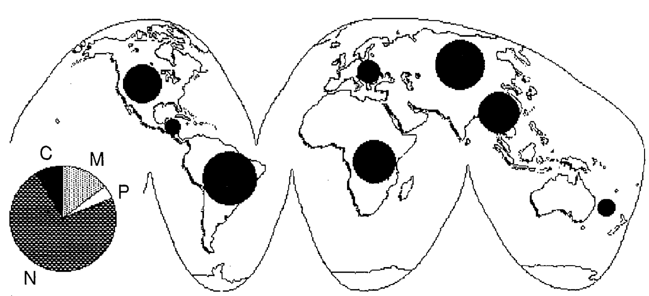

Fig. 1. The area of the world's forests in the Americas, Africa, Europe, the former Soviet Union, Asia, and Oceania. The area of the circles is proportional to the area of forests. The pie diagram shows the distribution of management intensities: C, conservation management (International Union for the Conservation of Nature classes I to III); M, intensive management for production; P, plantation; and N, natural forests, most of which are subject to indirect management through changed fire regimes and hunting and gathering. Sources are (*1–3*).

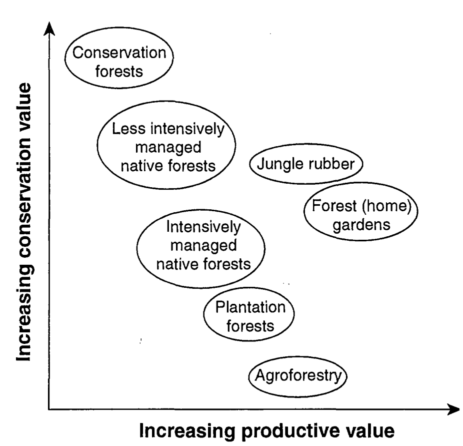

Fig. 2. A classification of forest management systems based on their conservation (biodiversity) value and productive value. Based on (*10*) and (*23*).

and economically efficient, especially where smaller logs have alternative markets (such as wood chips). Logging of larger coupes is also more efficient because, among other advantages, it requires less roading to access a single large site than to access several smaller ones. In areas where burning of the residual material is important in stimulating regeneration, for example, the eucalypt forests in Australia, it is easier in large coupes to set and manage the intense fires. Opponents note that the large areas of exposed soil that result from clear-felling pose the risk of serious environmental damage and loss of biodiveristy during the harvest and early reestablishment phases. The threat posed increases with increasing coupe size. It is also aesthetically displeasing. In southeast Australia, the debate has been behind a series of management changes that have reduced coupe sizes from over 500 ha early in this century, to only a few hectares in the 1970s, to the 15-ha "checkerboard system" that is currently practiced (*15*). And in the United States, it is the policy of the U. S. Department of Agriculture (USDA) Forest Service to phase out clear-felling as a standard practice on national forests, retaining it only as an option for exceptional circumstances (*4*).

Quest for Sustainable Forestry

For many decades, commercial forest management was dominated by the concept of sustainable yield. It arose from scientific management principles developed in Europe, especially Germany, in the 18th century and applied to wood production from intensively managed forests. However, the sustainable yield concept has many shortcomings and is not equivalent to sustainability (*10, 16*). The model on which many management systems were based, that of the regularly planted and harvested "normal forest," is inadequate in systems with a high component of mixed aged and natural regeneration. Also, multiple products are derived from almost all forests—timber, fuel wood, water, fruits, medicinals, and other products such as rattan—and demand changes in unpredictable ways.

Thus, forest management agencies have shifted their "management focus from sustaining yields of competing resource outputs to sustaining ecosystems" (*17*). Although agencies differ in their precise definition of "sustaining ecosystems," the goal implies that efforts should be assessed against the basic principles of sustainable development. In particular, they should be assessed against the two major ecological outcomes essential for sustainability, the maintenance of biodiversity and the maintenance of ecosystem services, which must, in turn, be achieved under socially and economically viable circumstances.

An important step in the transition to sustainable forest use is a full valuation of forest products, including nontimber products such as fruits (*18*) and water catchment and intangible values (*10*). These valuations often show nontimber values to be substantially higher than timber. Economic techniques have been applied for total forest valuation. For example, a study of Mexico suggests a lower bound value of the country's forests of about $4 billion, arising largely from nonconsumptive use, future potential use of genetic resources, existence values, and the functional values of hydrological and carbon cycling (*19*). Recently, Costanza *et al.* estimated that forests of the world provide $4.7 trillion per year of services, or roughly $1000 per hectare per year (*20*). But valuations mean little unless they are accepted by policy formulators and by the users of the forests who make the day-to-day decisions.

Maintenance of ecosystem functioning. Within forests that are treated as a renewable resource, the question remains as to whether the management practices are sustainable in the long term. There are many facets to sustaining ecosystem functioning (*9*), but attention to the wise management of the soil is fundamental (*21*).

Forest gardens are usually sited on the most fertile soils available, and management practices developed over centuries appear to avoid any significant nutrition leakages (*11*). However, as land use intensifies, increased cash cropping occurs and along with it localized problems of soil fertility and pests.

In logged forests, a major question is whether there is a loss of nutrients under the rotation used. Although considerable uncertainties remain, the overall conclusion appears to be that unsustainable losses of soil and nutrients do occur in mismanaged forests, whereas in well-managed, naturally regenerating systems, the nutrient losses can be replaced during the regrowth period, provided that care is taken with the logging process itself (*22, 23*). It is essential that nutrient losses and soil compaction during logging are reduced to a minimum by careful design of road systems and management of equipment movement, with the soils and drainage patterns of the coupe and surrounding landscape taken into account. Nutrient losses are exacerbated if fire is used as part of the site rehabilitation after logging. Problems can also arise if short rotations are used; in some cases, calculations show that net losses of nutrients occur, although these losses are usually of a magnitude that can be replaced by occasional additions of fertilizer. If multiple-use management planning is based on whole landscapes and codes of practice are adhered to, then direct threats to ecosystem functioning can be minimized (*10*).

Maintenance of biodiversity. Although intensive use of a particular patch of forest is likely to threaten some plant and animal species populations, steps can be taken in the management of the forest as a whole to ensure that extinctions are rare. This type of use contrasts with agricultural systems, where there is a major loss of biodiversity and a consequential change in ecosystem processes.

Forest gardens usually are not seen as a major respository of natural biodiversity. Nevertheless, a high diversity of species and cultivars can be maintained through deliberate plantings in combination with native plant and animal species. Studies of several agroforestry systems in Sumatra and west Kalimantan, Indonesia, including jungle rubber (*13*), showed that diversity of both plants and birds was substantially lower in agroforestry areas than in the primary forest. The forest structure was more uniform and diversity decreased as the intensity of planting increased, but some sites have 50 to 80% of the diversity of comparable natural forests. If agroforest systems can help restrict the conversion of forests to grassland or other monospecific crops, they can be used in conjunction with appropriate conservation areas to buffer biodiversity loss.

Numerous studies of biodiversity after logging have shown that there is usually an immediate decline in biodiversity followed by a recovery, although not necessarily of the same species (*24*). However, there is a wide range of outcomes. In an exhaustive study of Australian forestry, the Resources Assessment Commission (RAC) Forest and Timber Inquiry (*10*) concluded that there were no extinctions of animal or plant species that were directly attributable to forestry (logging) practices. In contrast, in southern India, a comparison of plant species diversity in forests with different intensities of management showed that diversity was increasingly reduced with the intensity of management and that the most intensive management brought about the local extinction of some species (*25*).

Multiple use. "Multiple use" is a policy that is frequently adopted formally by forest managers. For example, the USDA Forest Service mission statement says, "As set forth in law, the mission is to achieve quality land management under the sustainable multiple-use management concept to meet the diverse needs of people." Multiple use can be practiced either simultaneously or sequentially in a given area.

One model adopted in many parts of the world has been to set aside areas that are particularly sensitive to damage (for example, streamsides), that are of particular aesthetic value, or that are valuable in conserving biodiversity and to disperse logging operations widely across the rest of the forest estate. This approach has been referred to as the "checkerboard model". Whether this is always appropriate has been challenged by some researchers. For example, one of us (I.R.N.) (*26*) examined the question "Should we harvest forests so as to extract our needs from the smallest possible area, or should we harvest less intensively over a larger area?" With the use of a model based on simple relations between disturbance and biodiversity loss, it was concluded that it is best to restrict harvesting to the smallest possible area. Thus the landscape would be developed with some units managed intensively to yield high production and others managed specifically for conservation and ecosystem-maintenance purposes. Franklin and Forman (*27*) looked in more detail at the pattern of cutting, asking "Should we cut small patches and disperse them as widely as possible? Should we start at one side and clear-cut progressively to the other? Or should we use some other cutting strategy?" They concluded that forest managers should reduce their emphasis on dispersing the cuts and instead use clustered cuts spreading from a few nuclei. They also recommend that some large reserved patches be maintained. Many of their conclusions are reflected in forest planning in the northwest of the United States (*28*) and have been incorporated into the design of harvesting strategies (*16, 29*).

A variant of the above approach is the strip-cutting technique, applied successfully in the Palcazú Valley, Peruvian Amazon (*30*). In this system, harvesting is done in long narrow strips of the natural forest in which all trees are cut, mimicking to some extent the canopy openings created by tree falls. The strips are interspaced in the forest, and the harvest is done in a sequence that permits adequate regeneration of rare shade-intolerant species. Concurrent socioeconomic analysis shows that this is a sound management scheme, the potential of which can be enhanced with additional silviculture practices.

Both of these studies are based on very simple models, but their results appear to be robust in more elaborate and explicit formulations and possibly in other harvested ecosystems (*26*). They point to the need to treat forest management as a challenge in landscape design (*27, 31*).

The Way Ahead

There is strong evidence that past and current forest management techniques are not optimal for achieving sustainability. Many fail to achieve ecological and social sustainability and thus eventually fail to achieve economic sustainability. The end result is often clearing and conversion of the land to nonforest uses. Natural forests, particularly well-preserved tropical forests, are increasingly viewed as a global environmental good. Thus, the issues of cost and compensation must be addressed. The world community should be prepared to pay or compensate the dwellers of tropical forest areas so that they are not forced to inefficiently use or destroy the remaining forested lands.

The system of multiple landholders, each with a small multipurpose, multispecies plot is one type of sustainability in a managed forest. But it is being threatened by a shift toward more cash crops. This illustrates a paradox of landscape management (*31*). Individuals affect local environments relatively lightly, for example, at the forest garden or jungle rubber level, and it is feasible to achieve a management system that is ecologically sound, economically viable, socially responsible, and politically acceptable. These systems can persist provided that they are free of, or buffered from, external influences, but they are very sensitive to disruption by external inputs or demands. Population growth, which is often a result of external influences, and the concomitant desire for cash crops take the decision-making out of the hands of these people.

The more extensive operations based on logging native forests provide examples of grossly unsustainable management, but there are signs of movement toward greater sustainability. There needs to be a move toward whole-landscape management with greater emphasis on areas of intensive use interspersed with areas managed primarily for conservation, recreation, and water catchment purposes. Some rules are being developed, but there is a great need for further interactions between ecologists, foresters, social scientists, and economists.

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