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An Analysis of Global Timber Markets

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Abstract

This paper presents a model of global timber markets that captures the evolution of a broad array of forest resources and timber market margins over time. These margins include the inaccessible northern and tropical margins, plantation establishment, and timberland management. A baseline case is presented and discussed. Five alternative scenarios are then presented. These scenarios allow us to consider several important questions about timber market behavior and the future supply of industrial fiber: (1) What happens along the northern and the tropical inaccessible margins? (2) What role do timber plantations play? and (3) How do shifts in management intensity interact with market forces? The baseline case suggests that both prices and harvests rise over the next 150 years, with most of the increased harvest coming from existing and newly established plantations. Future gains in harvests result mainly from intensification of management, through additional plantation establishment and higher levels of management on selected forests rather than higher harvests in currently inaccessible forests. Prices and harvests are most sensitive to alternative demand and plantation establishment scenarios, and less sensitive to costs of accessing extensive forests.

Keywords: global timber markets, forest plantations, model, forecast

JEL Classification Numbers: Q10, Q21, Q23, Q24

Table of Contents

List of Tables and Figures

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INTRODUCTION

The forests of the globe are incredibly diverse. Not only do ecosystem types vary from boreal forests of northern latitudes to tropical rain forests along the equator, but access and management vary from region to region as well. Large tracts of land near the northern polar regions and the equator have scarcely or never been explored by humans, while many of our temperate forests have been cut-over numerous times. Forests supply a wide range of ecological services as well, including industrial timber and biodiversity, to an expanding global population and economy. While much of the global forested ecosystem has been transformed from "old growth" to second growth, the forces of human activity will continue to change over time. Understanding how timber resources will evolve over time relies on modeling industrial log market activity.

When considering forest resources and markets, several important and interesting questions arise. For example, how important are currently inaccessible forests to global timber markets, and how sensitive are they to shifts in market forces, such as price? Second, if subtropical plantations have become a more important part of the global timber market (FAO, 1993; and Sedjo, 1995), can we expect them to continue playing a bigger role and will they reduce pressure on our inaccessible forest resources? Finally, what role does timberland management play in the future of global markets?

Answering these important questions requires a systematic approach that considers not only regional harvest quantities, but more importantly, marginal adjustments along a continuum

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of timber types and management systems around the globe. We focus on several marginal adjustments in this paper. The first two margins relate to our use of inaccessible northern and tropical forests (the extensive margin), and establishment of fast growing plantations in the subtropical "emerging" region. The economic forces driving both of these markets are global in nature, and both relate to prices, productivity, and the availability of land.

In addition to establishing plantations, we often have found ways to substitute technical knowledge for a declining land base in forestry by increasing timber yields. If the expectation of future prices is higher than today, the incentives exist to expend more on regenerating timberlands than allowing for natural regrowth alone. Simple measures such as this, although costly, can dramatically increase the future yield by enhancing stocking conditions and altering the mix of species to favor the fastest growing, most productive types. In general, we have concentrated efforts such as this on only our most promising lands, the ones which will provide economic return to landowners willing to provide the initial investment. Capturing the adjustment in timberland management is critical for understanding where future supplies of timber will be located.

This paper presents a system-wide, long term model of global timber markets, following the optimal control approaches of Sedjo and Lyon (1990, 1996) and Sohngen (1996). The model shifts harvests, access, plantation establishment, and timberland management optimally through time. We then present a baseline case that serves as a benchmark. Using several alternative scenarios, we then address several important questions raised in this introduction.

GLOBAL FOREST RESOURCES

Forest resources stretch from the boreal softwoods and hardwoods in Canada, Alaska, and the Former Soviet Union, to tropical rainforests in South America and Indonesia. Both the structure and the function of forests varies dramatically between forested ecosystem types, commonly known as biomes, and it is related to such factors as available sunlight, length of growing season, precipitation, and a host of other factors (Holdridge, 1947). Boreal forests, while extensive in area in high latitude regions, grow fairly slowly. Temperate conifer forests, including the temperate rainforests of the Pacific Northwestern United States, and the coasts of Chile and Norway, are mainly softwoods that grow relatively rapidly due to high rainfall and moderate coastal temperatures. Farther inland in North America, Europe, and China exist the temperate deciduous forests, composed of temperate and northern hardwoods--oaks, hickories, maples, and beeches--and warmer temperate broadleaf forests, including the productive southern pine region of the U.S. Closer to the equator are the subtropical and tropical forests, ranging from open savannas where rainfall is limited, to dense tropical rainforests where rainfall is most abundant.

Table 1: Predicted net primary productivity (NPP) and harvests of industrial roundwood in global aggregated biome types (NPP from Haxeltine and Prentice, 1996, and harvests from FAO, 1992).

	NPP	Harvest	Harvest
Ecosystem Type	$g/m^2/yr$	$g/m^2/yr$	prop.
1) Boreal Forest	224.2	14.1	0.06
2) Temperate Conifer	459.3	72.1	0.16
3) Temperate Deciduous	367.2	64.9	0.18
4) Temp. Evergreen Forest	590.3	99.1	0.17
5) Subtropical and Tropical	892.7	15.1	0.02

In general, net primary productivity (NPP) increases closer to the equator (Table 1), although NPP is moderated by rainfall patterns. NPP is a measure of the potential annual growth in ecosystems, as it is the net amount of carbon fixed and sequestered by plants in a given time period. Harvest patterns generally follow trends in NPP, with the exception of harvests in the subtropical and tropical regions. One reason that harvests are not greater in the subtropical and tropical regions relates to the large area of inaccessible lands remaining there to this day (see, for example, Skole and Tucker, 1993, who studied the tropical Amazon region in Brazil). In addition, in many tropical rainforests, relatively few species are utilized currently for industrial products.

Spatially, trends in forest utilization tend to follow NPP, with the exception of the subtropics and tropical forests. But a unique temporal dimension to utilization of forest resources exists as well. Without human intervention, forested ecosystems are a mixture of living, growing, and dying systems. Humans, however, introduce additional complexity to the dynamics of ecosystem structure and function by utilizing forests for their own needs and providing management inputs to increase future supply. When considering the sustainability of forest resources, we must consider not only natural adjustments, but also how human behavior influences stand structure through management.

An interesting case in point considers how forest stocks have evolved over the past 20 to 50 years. For example, while up to 90% of deforestation in the tropical rainforests by 1988 resulted from changes after 1970, it is difficult to link population and economic growth directly to tropical deforestation (Skole et al., 1994). As deforestation has occurred throughout tropical regions, the opposite trends have been noted in temperate zones (Sedjo, 1992, Kauppi et al. 1992, Kuusela, 1994). In North America and Europe, for example, where the economy and timber harvests have grown for the last 50 years, forest growing stocks have been increasing as well. Although the area of forests in Europe has remained constant, the volume of growing stock there has increased 43% since 1950 (Kuusela, 1994), and total harvest has increased 25%. The U.S. case is slightly different. There, timberland area has declined 4% since 1952, but the volume of growing stock has increased almost 28% (Powell et al., 1993). It is not entirely clear what has caused these changes, although they probably result from a mixture of changes in the species distribution, age class distribution, and management intensity.

Shifts in management intensity are another important dimension of forest resources and forest utilization. Over the past 20 years, a fairly large shift in management has occurred as a large area of plantations has been established in both subtropical and tropical regions of the globe, including Central and South America, Africa, Australia, New Zealand, Iberia, Asia-Pacific, India, and China (Table 2). These plantations have become increasingly important suppliers of global wood fiber. Sedjo (1995), for example, estimates that 9.8% of global industrial wood production is derived from these plantations, and that industrial timber production in regions with large areas of plantations has increased faster than the global average over the past 15 years.

Table 2: Estimates of the total area of plantations in subtropical and tropical regions.

Region	Annual Plantation Establishment 1980-1990	Total Plantation Area 1990
	1000 hectares	1000 hectares
Central and South America[1]	322	7,765
Africa[1]	158	4,416
Australia and New Zealand[2]	50	2,044
Iberia[3]	NA	6,450
Asia-Pacific[1]	471	9,404
India[1]	1,009	13,230
China[1]	1,140	31,831
Total	3,140	75,140

[1] FAO (1993); [2] Pandey (1992); [3] Bazett (1993)

This broad overview of forest resources around the globe emphasizes the questions raised in the introduction. The two areas with the lowest utilization rate of available NPP are also the two regions with vast inaccessible land remaining. How we utilize these resources over the next decade and century relates both to timber markets and to environmental considerations. Plantations are also a fairly large question mark. Existing plantations have garnered a large amount of attention recently, but whether or not we continue to establish them at the same rate depends both on the availability of new land and broader economic forces. Timberland management may play a part in increased forest inventories in temperate zones, but can these increases offset interest in liquidating stocks in the inaccessible region? This paper attempts to synthesize available information on forest resources and management behavior in a global model of timber markets, and then utilize that model to answer these provocative questions.

MANAGING DIVERSE FORESTS IN A GLOBAL MARKETPLACE

To account for the broad diversity in timber types, management, and harvesting patterns assembled across the globe, we disaggregate global forest resources into 46 total classes, differentiated by ecosystem type and management. Ecosystem classes encompass structurally similar forested aggregates in particular climatic regions. Yield functions will represent the underlying distribution of species in a particular ecosystem type. The yield of merchantable timber in each age and type class is given by $V_{l,a}$, where l represents the ecosystem and management class, and a represents the age class. $V_{l,a}$ is estimated from empirical literature or adapted from Sedjo and Lyon (1990).

Management classes differentiate ecosystem classes by behaviors that guide harvest and regeneration activity. Ecosystem types are therefore disaggregated into one or more management classes. Each management class has a distinct yield function, which is altered by regeneration and management intensity. General descriptions of the five management classes are given in Table 3.

Table 3: Description of five management classes contained within the timber market model.

Management Classes	Description
Regular (i)	Accessible lands with well developed roads and forest products industry nearby.
Plantation (e)	Accessible lands established as timber plantations. These lands are generally more productive than their regular counterparts.
Tropical Inaccessible (m)	Inaccessible lands along the equator; occurring in South America, Africa, and Southeast Asia.
Northern Inaccessible (n)	Inaccessible lands in northern extremes of the globe; generally Boreal or other northern forest types; occurring in North America, Europe, and the Former Soviet Union
Low Access (s)	Harvested circumpolar inaccessible lands; these lands have recently been accessed, but road structures are not yet well developed; they are far from established forest products industry.

The annual benefit from harvesting forests is measured by Marshallian consumer's surplus in the market for logs delivered to mills, $W(Q_t)$. This simply is the area underneath a global demand function

$$W(Q_t) = \int_0^{Q_t} D(n)dn\,, \tag{1}$$

where

$$Q_t = \sum_l \sum_a H_{l,a,t} V_{l,a,t}\,, \tag{2}$$

and $H_{l,a,t}$ is the harvest of timber from ecosystem and management class l and age class a in time period t.

Alternative timber harvest, regeneration and management behavior for each ecosystem and management class is captured by this model. We begin with harvest behavior on regular, plantation, and low access lands ($l \in i,e,s$). These lands are assumed to be managed like Faustmann forests, in that harvests occur in the oldest age classes first, and continue until the marginal benefits of waiting an additional moment just equal the marginal costs (Lyon and Sedjo, 1983 and Brazee and Mendelsohn, 1990). Marginal costs for these management classes are constant with respect to the harvest volume (q_l), although they vary from ecosystem type to ecosystem type, depending on region specific characteristics, such as road maintenance.

Harvest behavior in the inaccessible regions is modeled differently. From a timber market perspective, the northern inaccessible area contains substantial inventory that could be liquidated if prices are high enough. Current prices, however, are not high enough to motivate large scale forestry development into many of these regions. This results from two factors. First, the costs of building new road infrastructure are high, and second, managers are less able to discriminate among age classes when they build roads. Essentially, harvesters get what they can at the forest edge, but these stands contain a variety of age classes.

To timber markets, these northern inaccessible lands are a backstop region that can provide additional timber if prices increase. If prices are constant, however, the remaining northern inaccessible forests will remain inaccessible. The costs of accessing new timberland involve both building roads and harvesting. In this model, we assume total costs are an increasing (quadratic) function of the cumulative timber harvests in the northern inaccessible region to date, $f_{n,cum}(H_{n,cum})$, where "*cum*" indicates cumulative harvests from the initial to the current time period. If prices are increasing faster than marginal harvesting and accessing costs, then we will continue to expand the edge of this extensive margin. If, however, prices are constant, marginal harvesting costs will rise above the price, and cut off additional access.

Because managers cannot discriminate between different age classes when they build new roads at the extensive margin, the model maintains a single, average age class of northern inaccessible timber. An average yield function represents current estimates of stocks per hectare in those regions. Once lands have been accessed, they are moved into a new, corresponding low access management class. Age class distinctions are maintained in these low access management classes, and the lands are managed as other accessed Faustmann forests with constant marginal harvesting costs per cubic meter harvested. Marginal harvesting costs, however, are typically much higher than other regular access management classes.

Much of the tropical rainforest area in South America and Africa, like northern boreal forests, remains inaccessible to this day (Skole and Tucker, 1993). Two economic reasons may motivate this. First, the volume of merchantable timber per hectare is typically low, even though biomass is very high, because these species have been utilized less intensively than their temperate counterparts in international markets. Second, the costs of accessing new lands for timber purposes is high because it involves building road infrastructure and shipping products long distances.

Fairly substantial areas of rainforests, however, are accessed and cleared every year, either for conversion to agriculture, building roads, or other purposes (FAO, 1993 and Skole et al., 1994). Two types of timber harvests in the tropical inaccessible region may occur with land clearing. First, land nearest newly built roads will be logged with selection cuts, and second, land will be cleared for other purposes such as agriculture and provide some wood for industrial markets. The production of industrial timber for land harvested in either case is low relative to plantations or temperate forests. Over time, it is likely that some agricultural land will convert back to forests, and logged lands will regenerate, allowing for the possibility of another cycle of harvesting on lands that have already been accessed.

Economically optimal harvesting will occur at the tropical inaccessible margin as long as the net value of timber (global price minus marginal accessing, harvesting, and transporting costs) is greater than zero. Total access, harvest, and transport costs are assumed to be an increasing (quadratic) function of the area of land harvested in a given period, $g_m(H_m)$. Utilizing this cost function suggests that in any period, the easiest access land (the lowest marginal cost land) will be harvested first. Continually more costly land will be harvested up to the point where the marginal costs per hectare outweigh the marginal benefits (price).

If prices are rising, higher cost land can be accessed, so that harvesting activity will move further into inaccessible reaches. If prices are constant, however, harvesting activity will still occur, but it will not extend further into the margin. Instead, the model will harvest closer land which has converted back to forests from agriculture, or which has regenerated from previous logging. Age class distributions are maintained, so that harvests in these "second growth" stands can only occur after sufficient time for re-stocking (this is generally greater than 50 years).

The tropical rainforests of the Asia-Pacific region are modeled differently. The model of forest management in these dipterocarp forests is adapted from Sedjo and Lyon (1990), where the forests are managed with sustainable periodic harvests occurring approximately every 50 years. This region is a dominant supplier of industrial tropical hardwood logs, and land yields a higher level of merchantable timber for each hectare harvested than either South America or Africa (FAO, 1993). Harvesting costs are constant marginal costs per unit volume harvested.

Within the economic model, harvesting costs must be subtracted from consumer surplus. For the various ecosystem and management classes described above, harvesting costs are given as:

$$C(\cdot) = \sum_{l \in i,e,s} c_l q_l + f_{n,cum}(H_{n,cum}) + g_m(H_m) \,. \tag{3}$$

Managers must also decide how much to invest in regenerating and managing timber stands once they have been harvested. This decision depends on comparing current marginal costs of additional management intensity with the expected, discounted marginal benefits. Due to long rotations inherent in forestry, this entails long term decision making. Management intensity is modeled similarly in all ecosystem and management types, but parameter values will vary depending on local factors. The methodology utilized here is adopted from Sedjo and Lyon (1990).

The idea is that managers can purchase additional units of timberland management, $w_{l,t}$, at constant prices (marginal cost), $p_{l,w}$. The returns to additional units of management are assumed to be increasing at a decreasing rate (they are concave). Thus, the following two conditions are assumed to hold, $\frac{dV_{l,k,t+k}}{dw_{l,t}} \geq 0$, and $\frac{d^2V_{l,k,t+k}}{dw_{l,t}^2} \leq 0$, where k is the number of years after regeneration that the stock is harvested. Management costs are given as

$$R(\cdot) = \sum_{l} p_{l,w} w_{l,t} \left(G_{l,t} + \beta_{l \in e,t} \right), \tag{4}$$

where $G_{l,t}$ is the area of land regenerated in type l in time t and $\beta_{l \in e,t}$ is the area of new land established in plantations in time t. Hectares harvested in management classes i, e, m, and s are regenerated automatically within their original timber type. The choice of regeneration and management intensity, $w_{l,t}$ is chosen optimally, depending on the relationship of current marginal costs to future marginal benefits.

Management intensity also involves the decision to establish new plantations. While other models have assumed that a fixed quantity enters at a given time (Sedjo and Lyon, 1990), the choice of plantation area in this model is endogenous. If the costs of establishing new plantations are known, then the decision becomes one of comparing the discounted future marginal benefits and the current marginal costs. A cost function for the new plantations is

$$\Psi(\cdot) = \sum_{e} f_e(\mathrm{b}_{e,cum}) \,. \tag{5}$$

The costs of new plantations include both the costs of purchasing new land and the costs of actually establishing new stands. Total establishment costs of new land, $f_e(X_{e,cum})$, are an increasing (quadratic) function of the cumulative area of land planted up to time *t*. Thus, as more and more land is purchased for timber plantations, competition for land will become more keen, driving up market prices for land. Marginal costs, therefore, increase over time, representing the increasing opportunity costs associated with purchasing valuable land resources away from other uses. If prices continue to rise, additional land will continue to enter plantations. If prices are constant or declining, the value of additional land in plantations will drop below the market price, and land will no longer enter plantations. Furthermore, if prices are declining, land does not necessarily leave plantations, but management intensity on that land declines, potentially to natural levels.

Given these alternative land management considerations, net surplus from industrial wood timber harvests in any year is defined as:

$$S_t(\cdot) = W_t(Q_t) - C_t(\cdot) - R_t(\cdot) - \Psi_t(\cdot) \,. \tag{6}$$

Over all periods, the market will evolve according to

$$\underset{H_{l,a,t},w_{l,t},V_{e,t}}{Max} \sum_{1}^{T} \mathrm{r}^{t} S_t(\cdot) \,, \tag{7}$$

which is the discounted net present value of net surplus in global timber markets. Over time, hectares age and the stock of management intensity adjusts. These changes must be monitored with mathematical accounting identities. The aging forest and regeneration of timberland is monitored by

$$X_{l,a+1.t+1} = X_{l,a,t} - H_{l,a,t} \qquad \forall\ l,a,t \tag{8}$$

$$X_{l,1,t+1} = G_{l,t} + \mathrm{b}_{l\in e,t}\ , \qquad \forall\ l,t \tag{9}$$

where the first constraint represents the movement of land from one age class in one period to the next oldest age class in the next period, less the area of land that is harvested, and the second constraint represents movement of land back to the youngest age class after harvest. Note that age classes will not be maintained for the circumpolar inaccessible land class, and that land harvested out of this management class is moved to a corresponding low access class. The stock of management intensity evolves according to:

$$Z_{l,a+1.t+1} = Z_{l,a,t} \qquad \forall\ l,a,t \tag{10}$$

$$Z_{l,1,t+1} = w_{l,t}\ . \qquad \forall\ l,t \tag{11}$$

The model chooses $w_{l,t}$ in any period for any timber type. This quantity of management intensity is associated with a particular set of hectares and follows those hectares through time until harvest.

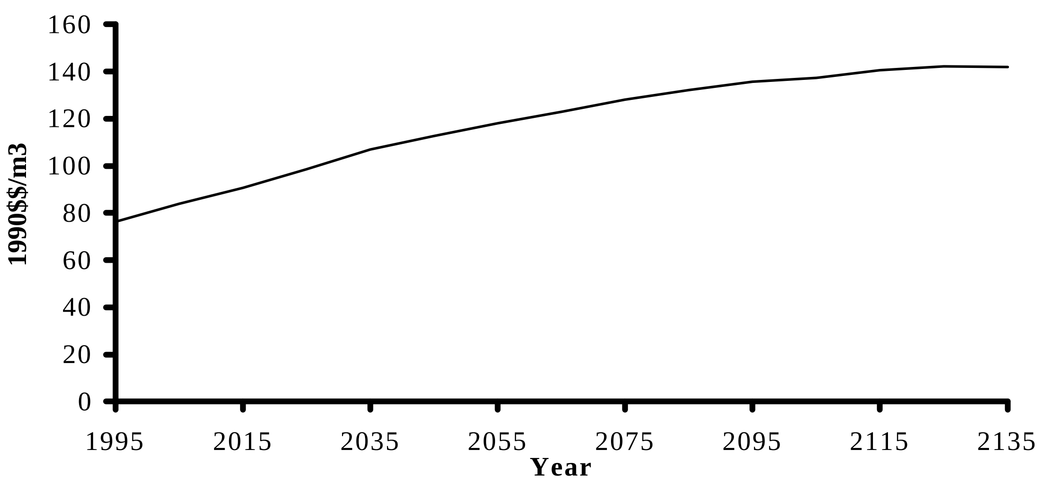
Over time the market will evolve so as to maximize the net present value of net surplus (equation 7), subject to the stock constraints (equations 8-11). In addition, initial stocking conditions (age classes and management intensities) must be provided, as well as a set of parameters for the equations. The model described by equations (7) - (11) is a general mathematical programming model with a non-linear objective function (due to discounting) and linear constraints. Non-negativity constraints are imposed on all choice and stock variables. The model chooses $H_{l,a,t}$, $w_{l,t}$, and $b_{e,t}$ for all land classes in any time period. The model is solved using the GAMS programming language and the MINOS solver.

Terminal conditions are imposed upon this system. The terminal conditions are defined by the steady state that would evolve in this market when demand is held at a constant level. Since demand for forest products is not expected to stabilize until many years into the future (≥150 years), these terminal conditions will have little impact on the net present value of the objective function. The exact specification of terminal conditions will depend on the projected level of demand in the terminal time T.

A BASELINE CASE

As demand shifts, forests age, and prices change, markets will shift harvests, plantation establishment, and management intensity from region to region. The model laid out in the previous section provides a framework for assessing the potential adjustments in different margins over time. In this section, we investigate how markets are likely to evolve in a baseline case.

Figure 1: Global baseline timber prices.



Timber demand in the baseline case is assumed initially to grow at 1.0% each year, declining to 0.0% annually by 2140. Under this scenario, prices rise from \$72 per m^3 initially to \$135 per m^3 (Figure 1). Prices rise fairly rapidly in early periods because demand growth is strongest. Global market clearing prices, such as these, result from the law of one price which holds over the long run. Regional prices are found by subtracting harvesting and transportation costs.

Global harvests increase from 1.8 billion m^3 to 2.5 billion m^3 in 2140. While total harvests rise smoothly, significant variation exists from region to region (Figure 2). Much of this variation arises from shifts in the age class distribution as land is harvested. North America remains the dominant producer, although harvests shift through time. Long term harvests in Europe remain stable but they decline in the Former Soviet Union. Harvests in the Former Soviet Union decline because they have many mature and over-mature stands with low stocking densities in their remaining accessible forests (Backman and Waggener, 1991). Because timber growth rates are slow, and access is limited in many areas where large stocks continue to exist, harvests enter a long period of decline. Chinese harvests increase, but these increases result mainly from plantation establishment in the subtropical south.

Harvests in the northern inaccessible region in the baseline case decline over time because the net marginal value of harvesting additional inaccessible land declines (Figure 3). The decision to harvest these forests is given by the following first order condition:

$$P_{n,t}V_{n,t} - C'(\cdot)_{n,t} - p_{n,w}w_{n,t} + \rho\lambda_{s,1,t+1} \geq \rho\lambda_{n,t+1}, \tag{12}$$

where $(P_{n,t}V_{n,t} - C'(\cdot)_{n,t})$ is the net marginal value of harvesting one additional hectare of inaccessible land (note that C' is the marginal cost of harvesting an additional hectare), $(p_{n,w}w_{n,t})$ is the marginal cost of regenerating that harvested hectare as low accessible land, ρ is the discount factor, $\rho\lambda_{s,t+1}$ is the net marginal benefit of converting one more hectare of inaccessible land today to one year old low accessible land tomorrow, and $\rho\lambda_{n,t+1}$ is the net marginal benefit of retaining that additional hectare of inaccessible land for harvest in the future. $\lambda_{s,t}$ is the present value of future harvests from one year old stands today in low accessible land. $\rho\lambda_{n,t+1}$ may be thought of as the option value of maintaining inaccessible land for future timber

Figure 2: Global baseline timber harvests.

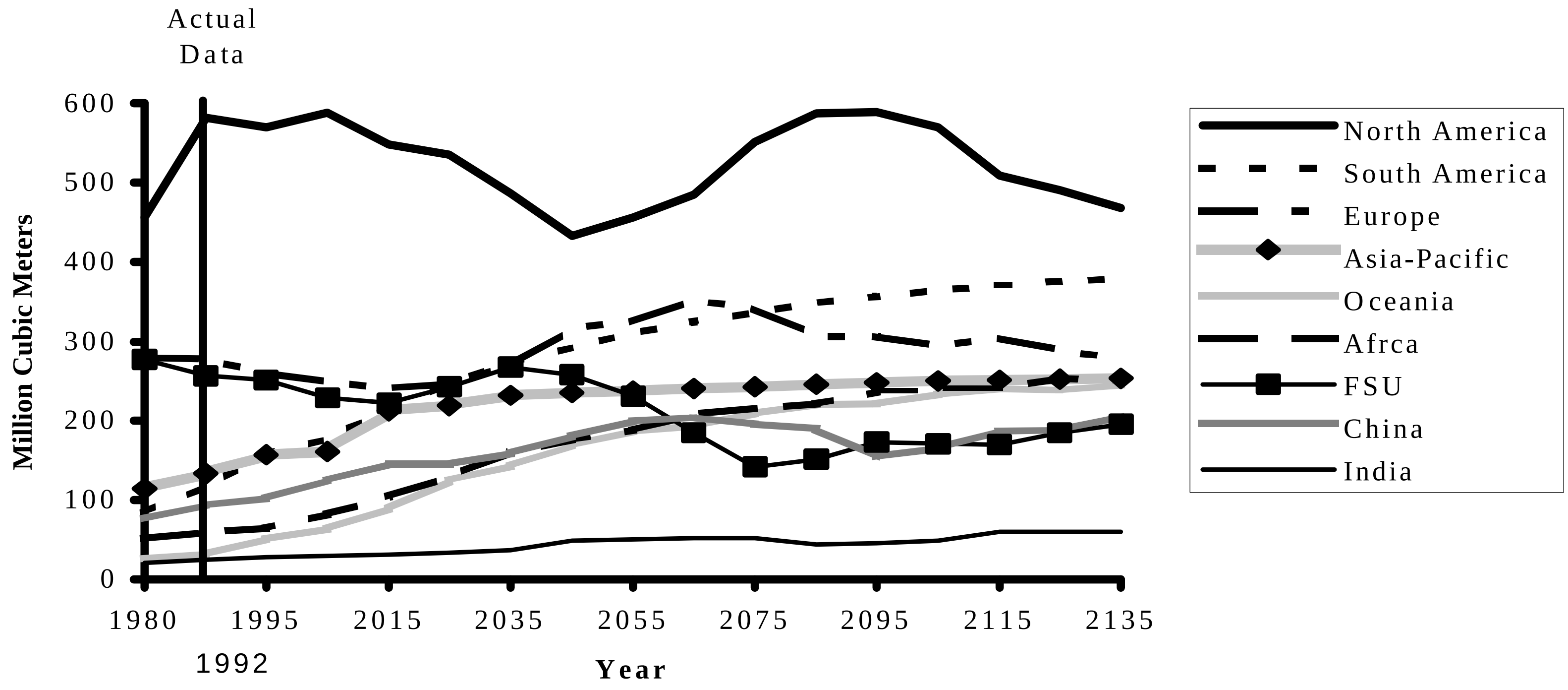
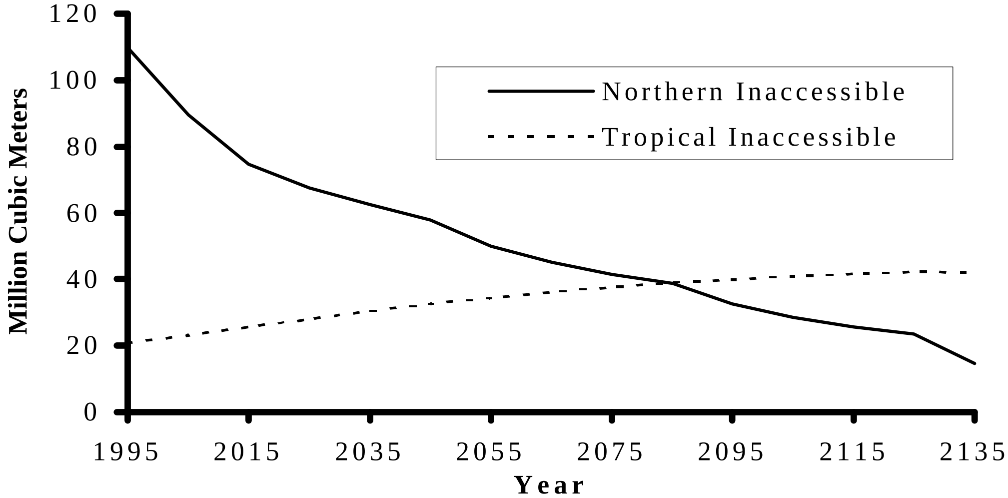


Figure 3: Harvests in northern and tropical inaccessible regions.



consumption. In the baseline case, this option value will be very low because the net value of land in the inaccessible region is driven to 0 over the model run.

These results suggest that other sources of timber supply are better investments than building roads to forests that sustain only a low level of continued production. Initially, the net value of inaccessible stocks is high enough to justify road building activities and harvests. These harvests, however, amount to only 7% of total global timber harvests initially, and this proportion declines over time. In individual regions, China draws the greatest proportion from currently inaccessible regions (26%) and Europe draws the least (<3%).

In the tropical inaccessible region, hectares will be logged only as long as net marginal benefits outweigh the marginal opportunity costs. The net marginal benefits are the net marginal value of harvesting and selling additional hectares, ($P_{m,t}V_{m,a,t}$ - $C'(\cdot)_{m,t}$), plus the net value of returning a harvested hectare to age class one tomorrow, $\rho\lambda_{m,t+1}$. The marginal opportunity costs are the discounted value of pushing this decision one period into the future, $\rho\lambda_{m,a+1,t+1}$. This decision is given by:

$$P_{m,t}V_{m,a,t} - C'(\cdot)_{m,t} + \rho\lambda_{m,t+1} > \rho\lambda_{m,a+1,t+1} \qquad (13)$$

Harvests in the tropical inaccessible region (Figure 3) are only a small portion of total global harvests. Over time, they increase in total volume, and as a proportion of the total timber harvest throughout the time period of analysis, although they remain less than 2% of the global harvest. Only a small portion of the available stock on these lands is utilized currently for industrial purposes, and additional species may become more valuable to global timber markets in the future.

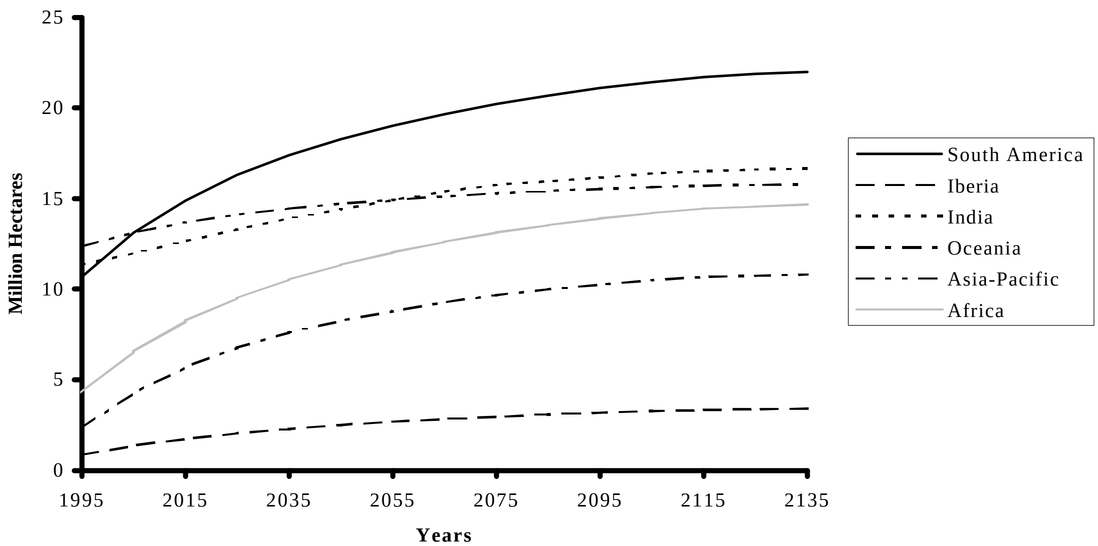
Most of the growth in global timber harvests occurs in the emerging subtropical plantation region. The decision to establish new plantations involves comparing the net marginal benefits of future timber harvests with the current marginal costs of purchasing, clearing, and planting new land:

$$\rho^{k} P_{e,t+k} V_{e} = \Psi' + p_{w,e} w_{e,t} \tag{14}$$

Ψ' is the marginal cost of purchasing high quality plantation land, which rises as more and more land is added to plantations, and it becomes more difficult to compete with other valuable uses of land. $P_{e,t+k}$ is the net price of harvesting tropical timber k periods into the future, where k is the length of one rotation. Rotations of plantation species vary depending on the particular type of plantation established. Many areas have experimented both with pine and eucalyptus species, which are often non-indigenous, as well as long and short rotation local species.

Of these regions, the area and harvest of subtropical South American plantations, which include non-indigenous pines and eucalyptus, as well as indigenous auracaria, expand the most (Figure 4). The most productive South American plantations are being established in subtropical areas of Central America, Southern Brazil, Argentina, and Chile. The rate of plantation establishment declines over time, as land scarcity increases (i.e. opportunity costs of purchasing new land increase), and prices stabilize. Plantations involve a wide variety of indigenous and non-indigenous species, including pines and eucalyptus as the two dominant types established.

Figure 4: Projected area of plantations in the emerging region.



The shift in production from the temperate zone to the subtropical emerging plantation region in the baseline case results from the higher returns available from establishing and managing subtropical plantations, but it is driven also by the limited ability of the temperate zone to increase production in the future. While regions such as North America, Europe, and China, maintain or increase production, long term declines in production occur in the Former Soviet Union.

Increasing the area of subtropical plantations, however, is just one dimension of the continued trend towards more highly productive, managed forests worldwide. Like the decision to establish new plantations, the decision to increase or decrease management intensity involves the long term trade-off between the costs and benefits of the management. The management intensity decision made by managers is given by

$$\rho^{k} P_{l,t+k}\left(\frac{dV_{l,k,t+k}}{dw_{l,t}}\right) = p_{w,l} \tag{15}$$

where $P_{l,t+k}$ is the net price of timber in type *l*, $dV_{l,k,t+k}/dw_{l,t}$ is the marginal change in yield at $t+k$ resulting from an additional unit of regeneration and management intensity applied today, and $p_{w,l}$ is the marginal cost of an additional unit of regeneration and management intensity today.

While units of additional management intensity can be purchased at the same global price in all regions, they will benefit species differently, depending on the shape of the yield function in the particular ecosystem and management type. Thus, changes in management intensity will vary by ecosystem and management type, as shown in for aggregate regions in Table 4. With global prices increasing, management intensity increases across the board, but the largest increases are found in the subtropical, emerging plantation region. Temperate zone forests experience the smallest increases, although North American forests experience the greatest management increases, mainly in southern and Pacific Northwestern softwoods.

Table 4: Average mean annual increment in the nine global regions in the initial and final steady states for the baseline case. The subtropical emerging regions include only timber plantations.

	Temperate Forests				Subtropical Emerging Plantations				
	North America	Europe	F.S.U.	China	South America	India	Oceania	Asia - Pacific	Africa
Mean Annual Increment (m^3/ha/year)									
Initial	2.22	2.13	0.73	2.03	15.04	2.92	17.40	11.43	13.65
Final	2.44	2.28	0.78	2.10	16.70	3.19	20.11	13.09	15.39
% change	10 %	7 %	6 %	4 %	11 %	9 %	16%	14 %	13 %

THREE IMPORTANT QUESTIONS

In this section, we utilize several alternative scenarios of behavior to consider the three important questions raised above: (1) how sensitive is the inaccessible margin to timber market activity; (2) how important are plantations in the long term supply and demand balance; and (3) what role do shifts in management intensity play in long term market behavior? Five alternative scenarios are used to capture a range of possible differences in future market behavior. These scenarios are described in Table 5, and we present summary price and harvest information for these scenarios in Figures 5 and 6.

Table 5: Alternative scenarios used for comparative analysis.

Scenario	Characteristics
High Demand	Demand grows at 1.5% per year initially, declining to 0.0% per year growth by the year 2140.
Low Demand	Demand grows at 0.5% per year initially, declining to 0.0% per year growth by the year 2140.
High Plantation	New, equally productive land is readily available. New land prices are one-half of the baseline case.
Low Plantation	New, equally productive land is difficult to find. This scenario can also represent a case where developing countries are politically instable, and land tenure is not well defined. New land prices, are double the baseline case.
High Inaccessible.	Costs of accessing the inaccessible regions are one-half of the baseline case.

Figure 5: Comparison of price paths for the baseline case and the five alternative scenarios.

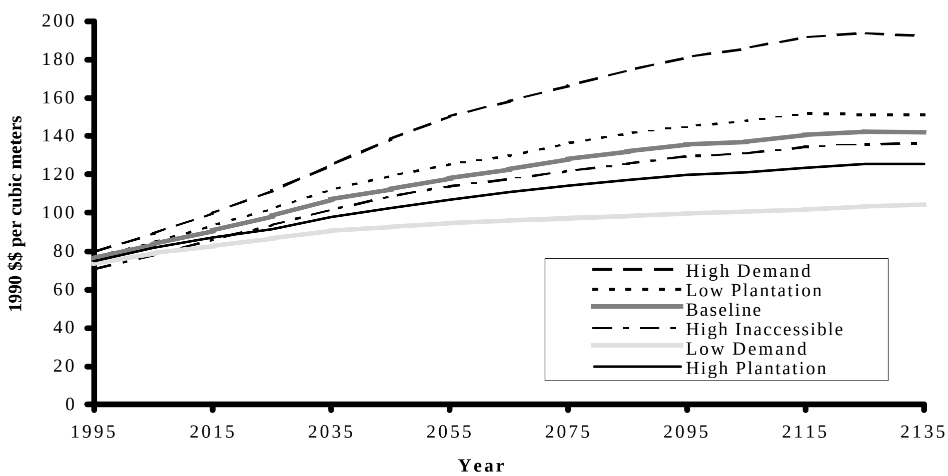
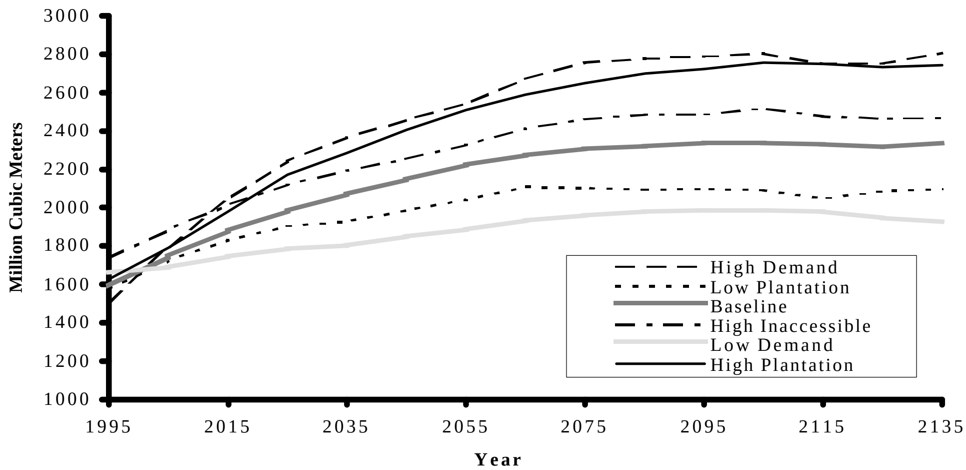


Figure 6: Global total timber harvest pathways under the baseline case and the five alternative scenarios.



Figures 5 and 6 suggest that prices and harvests are most sensitive to adjustments in the rate of growth of demand. The high and low plantation scenarios have a substantial impact on harvests from plantations, but they have a smaller impact on global total harvest levels. This results from market linkages: If plantation establishment is high, long term prices are lower, and other regions of the globe respond with lower harvests and management intensity. Unlike plantations, greater access to currently inaccessible regions has a comparatively small impact on global markets because these regions contain fairly low quality timber.

Adjustments at the Inaccessible Margin

The inaccessible northern and tropical forests remain a major question mark in the future of timber market activity. While economists cannot definitively predict future market behavior, what is perhaps a more important role for economists is to present market linkages, and to show how far-removed forests in the boreal and tropical regions are affected by market activities across the globe. In this section we consider how harvests in these two extensive margins will adjust given the five alternative scenarios.

One measure of the environmental impacts of logging in northern inaccessible forests is the cumulative area of land harvested over time. Table 6 presents this figure for all of the northern inaccessible ecosystem classes under the baseline case and the five scenarios. In all cases, impacts are relatively small, but they both vary significantly from region to region, and the aggregate numbers are weighted heavily by Siberia.

Table 6: Current area of remaining northern inaccessible forests, disaggregated to specific ecosystem types and regions, and aggregate area accessed during model run for the baseline and the five alternative scenarios.

	North America			Nordic	FSU	China		Total
	PNW	Central	Boreal		Siberia	Northern	Southern	
	Million Hectares							
Initial Area	8.9	22.5	125.2	19.6	321.5	14.4	16.4	528.5
Scenario	Area Accessed (1990 - 2140), Million Hectares							
Baseline	**5.2**	**21.3**	**20.9**	**5.0**	**14.6**	**7.7**	**5.8**	**80.5**
Low plantation	5.6	22.5	22.6	5.3	15.8	8.3	6.3	86.5
High plantation	4.5	18.1	17.9	4.2	12.3	6.6	4.9	68.5
Low demand	3.5	14.1	14.0	3.4	9.4	5.1	3.7	53.1
High demand	7.4	22.5	30.1	7.0	21.4	11.2	8.6	108.1
High Inaccessible	8.9	22.5	44.5	10.0	32.4	14.4	13.0	145.7

In North America, for example, harvests are concentrated in the Central (the Acadia region of Canada) and PNW (Pacific Northwestern U.S. and Canada) types. China also accesses a fairly substantial proportion of its inaccessible stocks. These stocks are located in both the northern and southern regions of the country. The Siberian boreal forests of the Former Soviet Union remain relatively intact in all scenarios, mainly because yield of merchantable timber from these lands is so low, and the costs of access are high.

Access in the northern inaccessible regions varies substantially with price. In general, where price levels are highest, as in the low plantation and high demand scenarios, access is the greatest, and where price levels are the lowest, access is the least. The high inaccessible scenario assumes that the costs of accessing these lands are low. While the area of land accessed is fairly sensitive to costs, greater access in these regions does not play a particularly large role in the global market place: Access increases almost 81% over the baseline case, but long term price levels decline by only 4%, and long term harvests increase by only 6% because these lands remain less productive than other forests around the globe.

In considering the tropical inaccessible forests of South America and Africa, the model captures timber harvests from two types of land, that which is accessed strictly for timber, and that which is accessed for conversion to agriculture or other development. Given these results, we can estimate the area of tropical forests necessary to sustain timber harvests at final steady state levels indefinitely. This area represents the amount of land that could be maintained in a productive timber reserve, utilizing low intensity, sustainable timber harvesting practices. While there is little current evidence that sustainable forest management systems are being adopted widely in tropical rainforests, several encouraging studies suggest that it is possible to manage natural forests on a sustainable basis (Hartshorn, 1990 and De Graaf and Poels, 1990).

Table 7 presents the current area of tropical rainforests in South America and Africa, and estimates of the land necessary for a sustainable supply of timber products, as predicted by the model. In general, when prices are highest, more land will be utilized, and when prices are lowest, less land will be utilized. The high inaccessible scenario, however, predicts lower prices and more access because it is cheaper in that scenario to access these lands. The total conversion for sustainable forestry ranges from 6 to 18% of the total area of tropical rainforests remaining today.

Table 7: Total area of tropical inaccessible land remaining in South America and Africa, and area necessary for sustainable timber harvests for the baseline case and the five scenarios.

	Baseline	Low Plantation	High Plantation	Low Demand	High Demand	High Access
	Million Hectares					
Inaccess. Land (circa. 1990)	826.29	826.29	826.29	826.29	826.29	826.29
Sustainable Harvest Area	73.47	80.10	64.34	51.73	103.02	149.30
	Percent of Current Inaccessible Harvested					
Annual Sustainable Harvest Area	0.18%	0.19%	0.16%	0.13%	0.25%	0.36%
Total Sustainable Harvest Area	8.89%	9.69%	7.79%	6.26%	12.47%	18.07%
Average Logging Intensity	2.75 m^3 per Hectare					

An interesting measure of the relationship of northern and tropical inaccessible types to global markets can be found by considering how price changes affect harvests from these regions, or the price elasticity. We estimate this "price elasticity of access" as:

$$\eta_{qP} = \sum_t \left[\frac{d(\sum_n q_{n,t})}{d(P_t^{Global})} \frac{P_t^{Global}}{\sum_n q_{n,t}} \right]. \tag{16}$$

$\eta_{q,P}$ is much higher in the northern inaccessible regions, ranging from 1.84 to 2.34 depending on the particular scenario chosen, than in the tropical inaccessible regions, where it is approximately 1.17. Thus, a 1% increase in prices leads to approximately a 2% increase in harvest from the northern inaccessible regions, and a 1.2% increase in harvests from the tropical inaccessible regions. Although the total volume of timber harvested is low in both northern and tropical regions, small price changes can have a substantial impact on harvest from those regions.

An important implication of these results is that harvests in inaccessible regions are related to global markets through prices. While higher global price levels increase the incentives to liquidate some of these marginal stocks, lower global price levels provide the opposite incentives. Focusing efforts on establishing plantations, for example, reduces long term price levels by 12%, and it reduces access in northern forests by 15% and tropical forests by 11%.

The Importance of Plantations in the Long Term Balance of Supply and Demand

The baseline case presented above suggests that plantations play a crucial role in the long term development of timber markets because they account for most of the growth in timber harvests over the next century and a half. Continued investments from the private sector in plantation establishment, as suggested by this model, rely heavily on political stability in many of these subtropical emerging regions. The low plantation case actually serves two purposes in our analysis here. It allows us to explore the possibility that new, productive land is more costly to find than in the baseline, or it represents the possibility that establishing productive plantations requires significant investments in maintaining land tenure rights.

While the level of plantation establishment and management clearly is important to the overall balance of supply and demand, it is potentially more important to assess the relationship between plantation establishment and other aspects of forest management across the globe. If the area of plantations increases as predicted in the baseline case, prices, harvests, and the level of management intensity in other regions must shift through time as well. The area of new, emerging region plantations established will have a differential effect on particular ecosystem and management classes, depending on relative productivity, and the costs of additional management.

Figures 7 and 8 present the ratio of harvests for the low plantation and the high plantation scenarios respectively in four aggregated regions of the globe. If it is more difficult and costly to establish plantations than predicted in the baseline, the clearly emerging region plantation harvests will be lower than the baseline, but other regions adjust to this as well. Harvests in all other regions increase, with the most substantial impacts occurring in the northern inaccessible region. While harvests in other regions will make up for some of the lost harvest in plantations, it is not enough to compensate, and prices increase to levels greater than the baseline case. The opposite holds if it is easier and less costly to establish these plantations (Figure 8).

Figure 7: Regional adjustments in harvests in the low plantation establishment scenario.

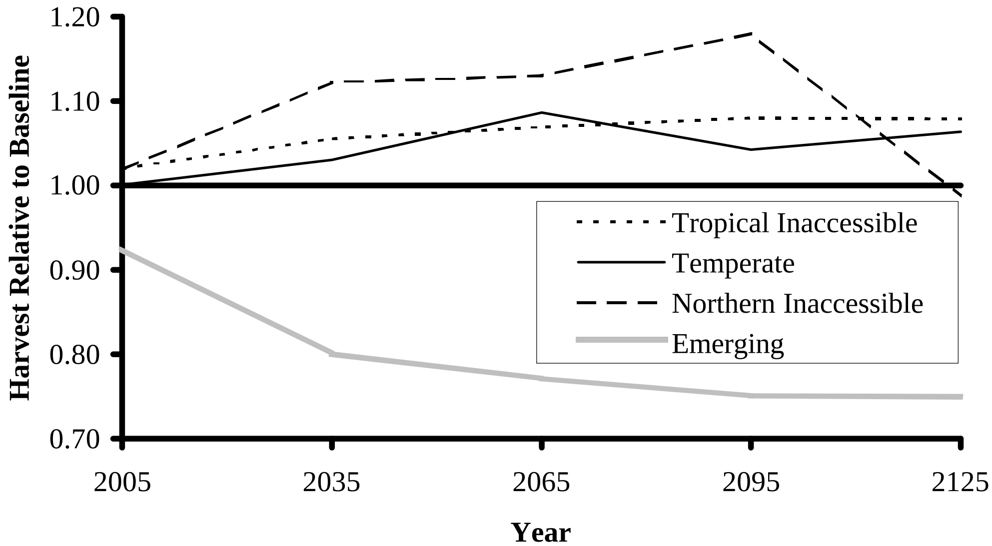
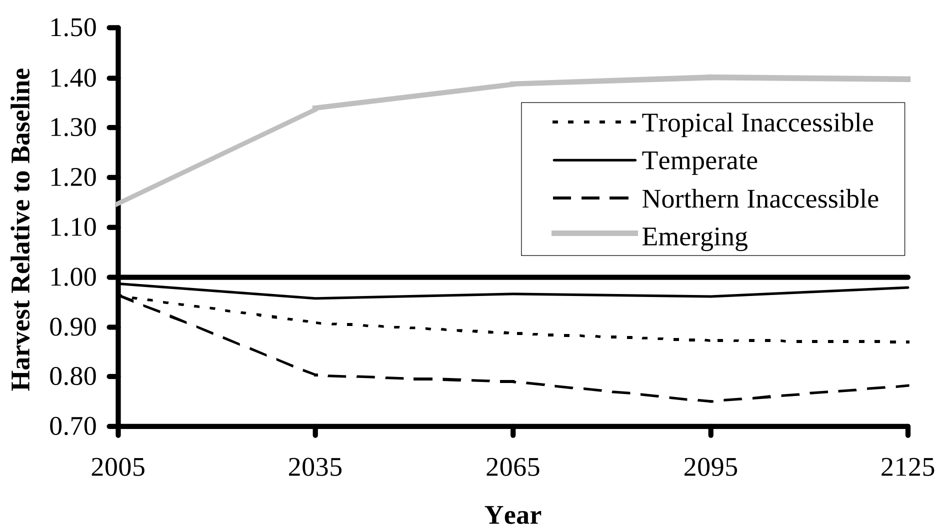


Figure 8: Regional harvest adjustments in the high plantation establishment scenario.



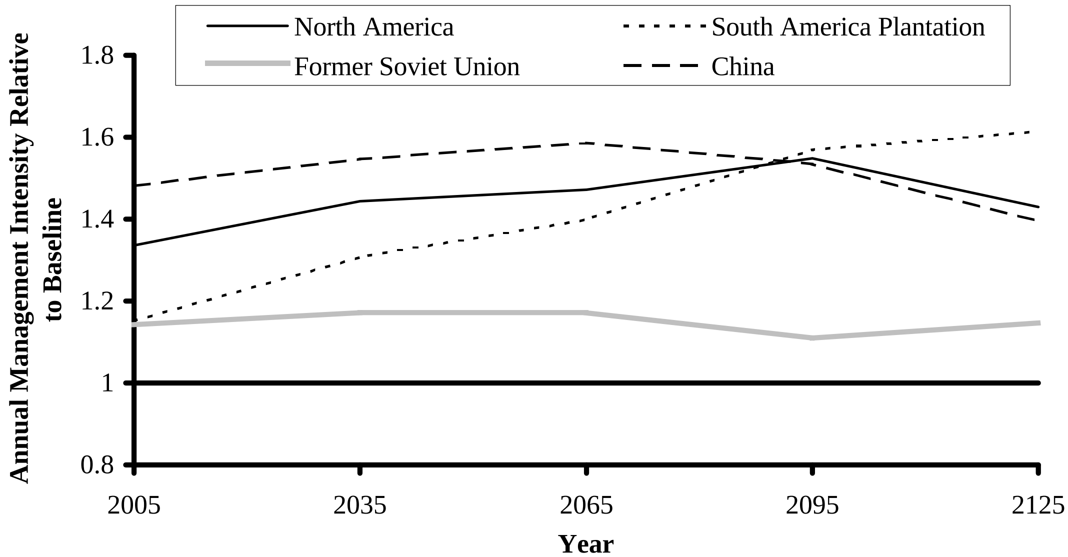
While the level of plantation establishment has substantial impacts on other regions, it is important to recognize that the incentives to establish plantations are guided not only by costs of establishing them, but also by perceived future market price levels. For example, in the high demand scenario, long term prices increase by 35%, and the long term area of plantations increases by 27% over the baseline case. This leads to increases in plantation harvests of 30% over the baseline. Temperate forests adjust as well to the higher prices, but harvests increase there only 10% over the baseline. The emerging plantations are more responsive to perceived future price adjustments. Because land is generally available for these plantations and because relatively small management inputs can lead to substantial future gains, subtropical plantations are a better investment than are temperate forests.

Shifts in Management Intensity

Global forces will lead to adjustments in management intensity from region to region as well. Increases in management intensity in this model imply that humans regenerate more land in order to increase stocking conditions rather than allowing natural stocking conditions to occur. As shown in Table 4 for the baseline case, management intensity increases in most forests, but the greatest increases occur in the subtropical plantation regions. This results from the higher marginal returns per unit of input that is available in subtropical plantation areas.

Management in the different regions displays a different level of responsiveness to alternative scenarios. In general, the temperate forests are the most responsive, particularly those of North America and China (Figure 9). China is fairly responsive because it has such a low level of management today, and its southern area can be very productive if managed properly. The expectation of higher future prices leads to a fairly substantial increase in expenditures today over current costs. The Former Soviet Union, on the other hand, is the least responsive region to higher prices because it exists in such a northerly area, with species that require long time periods to grow.

Figure 9: Ratio of annual management intensity in high demand scenario relative to the baseline case in four particular regions of the globe.



Because management involves long term decisions that compare the marginal costs today with the discounted marginal benefits tomorrow, plantation regions need not respond immediately to long term higher prices. The plantation regions tend to have short rotations and the stock can be turned over many times. These regions, therefore, can adjust slowly over time to rising prices, as shown in Figure 9.

DISCUSSION AND CONCLUSION

This paper illustrates how a diverse set of global forest resources are linked through timber markets. Timber harvests, movement of the inaccessible margin, plantation establishment, and management intensity are inter-related. They must be considered in the context of the global market place. There are several interesting results arise from the baseline scenario. First, prices rise in the future, although the rate of increase amounts to only 0.42% per year over the 150 year time horizon of this model. Second, harvests in temperate forests remain fairly stable, with some regions increasing and some decreasing, while harvests from subtropical plantation regions continue to increase. The largest share of growth in global production results from increasing harvests in subtropical plantations.

Third, harvests in both northern and tropical inaccessible regions amount to less than 10% of total industrial harvests initially. Northern inaccessible harvests decline over time, while tropical inaccessible harvests increase slightly. Fourth, management intensity increases across the globe, with the most substantial increases occurring in subtropical emerging plantations. Other regions with faster growing plantations, such as the southern U.S. and China also experience large increases in timberland management.

One implication of these results is that future growth in timber harvests is likely to be met by intensification of timberland management either through establishing additional plantations or managing existing southern temperate forests more thoroughly. While harvests do occur at the extensive margins, the high cost of investment (i.e. road building, transportation and harvesting) and the limited returns hold harvests at low levels in those areas throughout the model run. These results suggest that current investments in those regions which result from subsidies are inefficient from a global industrial wood market perspective. The limited impact of the high inaccessible scenario suggests that subsidies which increase harvests in these regions have little impact on global markets.

Five alternative baseline scenarios were utilized to discuss the sensitivity of this model around three important trends: (1) harvests at the northern and tropical inaccessible margin; (2) the establishment of subtropical plantations; (3) shifts in management intensity over time. Global prices and harvests are most sensitive to changes in the rate of growth of demand, and they are least sensitive to changes in costs of accessing the inaccessible margin.

Harvests in the inaccessible northern and tropical margins respond directly to higher and lower price levels. When prices grow rapidly, more of the extensive margin is harvested, and vice-versa when prices grow more slowly. Low price growth is simulated either by high plantation establishment, such as would occur if governments in the emerging region were particularly stable, land tenure rights were easy to establish, and finding new, highly productive land was fairly cheap, or low demand growth, such as would occur if substitute products like recycled material were readily available at slightly higher prices.

While plantations are projected to provide a substantial portion of the growth in timber harvests in the coming decades, they are not an unlimited resource. The model assumes that the costs of establishing plantations rise as it becomes more and more difficult to find productive land for plantations, and as they increasingly compete with other uses of land, such as agriculture. When demand grows rapidly, plantations are not established on a sufficient land base to limit increased utilization of the inaccessible margin and higher prices.

Plantation establishment is but one piece of the picture in managing global forests for consumption of timber products. The other piece relates to management of existing temperate forests, as well as existing subtropical plantation forests. Over time, management intensity will increase in response to expected higher future prices, with the largest gains in management intensity occurring in the subtropical plantation regions. Management in some temperate forests, particularly those in the southern parts of North America and China, is very responsive to changes in the path and level of future prices, because the forests respond favorably to additional management inputs. In northern areas such as the Former Soviet Union, forests are less responsive to management inputs.

This paper analyzes timber markets by modeling multiple ecosystem and management classes in the context of a global marketplace. Harvests and management in the vast, diverse, forests of the globe clearly are related across space and time through timber markets, and in particular, through prices. Concerns about encroachment on the remaining areas of undisturbed forests cannot be divorced from harvests in the temperate zone, plantation establishment, and shifts in management intensity. While the future of industrial wood markets is unknown, sensitivity analysis allows us to understand how markets will shift in response to alternative scenarios.

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