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Economic Parameters of Deforestation

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How do economic parameters such as the price of timber and the size of the decisionmaker's discount rate influence land use patterns (particularly deforestation rates) over time?

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Summary findings

Recent debate about how timber prices affect deforestation has focused mainly on how log export bans (imposed in many developing countries to protect domestic timber processing) affect deforestation.

One side argues that the lower domestic timber prices that result from banning log exports increase deforestation by making forestry less profitable than competing land uses, such as agriculture. The other argues that lower timber prices reduce profits from logging, so they slow down deforestation caused by logging.

Von Amsberg argues that the conflicting views result from simplistic analysis that ignores differences between types of forest. The two positions are reconciled by distinguishing between unmanaged forests (for example, biologically mature, previously unlogged primary forests) and managed forests (such as forest plantations cultivated for periodic harvest). This distinction allows the derivation of unambiguous comparative static results and is useful because many nontimber benefits from forests (such as biodiversity conservation) are associated mainly with unmanaged forests.

The distinction between managed and unmanaged forests leads to both unconventional and conventional results:

- All things being equal, a lower timber price results in larger areas of unmanaged forests and smaller areas of managed forests. That is, measures that reduce the producer price for timber (for example, import restrictions in timber-consuming countries and export restrictions in timber-producing countries) are suitable as a second-best policy to reduce the pressure on unmanaged forest frontiers. Most logging in tropical forests occurs in unmanaged forests, so the claim that trade restrictions (such as log export bans) increase deforestation is inconsistent with profit-maximizing land use.
- A fee on land used for logging is preferable to a tax on timber output, which is far more common but encourages logging waste.
- Technological interventions that increase the intensity of forestry or alternative land uses are an ambiguous instrument for the conservation of unmanaged forests.
- If demand elasticity for outputs is high, an intervention that increases the intensity of agriculture, logging, or other land uses increases incentives for conversion of unmanaged forests. The building of roads is particularly harmful to the conservation of unmanaged forests, as it increases incentives for logging and subsequent alternative land uses.
- Proper pricing of forest lands would increase land prices and lead to market-driven intensification accompanied by forest protection. Such pricing policies would be preferable to a technological intervention that increases land use intensity with ambiguous outcomes for forest protection.
- If unmanaged forest is converted to agriculture, the effect of lowering the decisionmaker's discount rate depends on the size of timber rents from logging unmanaged forests. If the standing timber has high commercial value, a lower discount rate would slow conversion of unmanaged forests. If the standing timber has no commercial value, logging is an investment for obtaining future benefits of alternative land use. A lower discount rate would stimulate this investment and increase the conversion of unmanaged forests. Also, if unmanaged forests are converted to managed forests, a lower discount rate can increase conversion since profits from managed forestry are higher with a lower discount rate.

This paper — a product of the Environment, Infrastructure, and Agriculture Division, Policy Research Department — is part of a larger effort in the department to analyze the sources and impacts of deforestation. Copies of the paper are available free from the World Bank, 1818 H Street NW, Washington, DC 20433. Please contact Elizabeth Schaper, room N10-037, extension 33457 (59 pages). August 1994.

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Economic Parameters of Deforestation

Summary

This paper addresses the question of how changes in economic parameters, such as the price of timber, influence land use patterns over time, and in particular deforestation rates. The recent debate about the influence of timber prices on deforestation has been lively and has focussed primarily on the deforestation effects of log-export bans, which were imposed by many developing countries in order to protect their domestic timber processing industry. One side in this debate claims that a reduction in domestic timber prices, resulting for example from a log export ban, increases deforestation since it makes forestry less profitable compared to competing land uses such as agriculture. The other side claims that lower timber prices reduce the profits from logging and hence slow down deforestation resulting from logging.

This paper argues that the conflicting views are due to an overly simplistic approach that ignores the differences between types of forests. The two positions are reconciled by explicitly distinguishing between unmanaged forests, such as biologically mature and previously unlogged primary forests, and managed forests, such as forest plantations, which are cultivated for periodic harvest. This distinction allows the derivation of some unambiguous comparative static results and is useful because many non-timber benefits from forests, such as biodiversity conservation, are to a large extent associated with unmanaged forests only.

Drawing the distinction between managed and unmnaaged forests leads to some unconventional results. The analysis shows that a lower timber price, ceteris paribus, leads to a larger area of unmanaged forests but a smaller area of managed forests, and vice versa. This result suggests that measures to reduce the producer price for timber would be suitable as a second best policy to reduce the pressure on unmanaged forest frontiers. Such measures would include import restrictions in the timber consuming countries, as well as export restrictions in the timber producing countries. Since most logging in tropical

countries occurs in unmanaged forests, the claim that trade restrictions, such as log export bans, increase deforestation is inconsistent with profit maximizing land use.

The effects of changes in economic parameters and economic policies on land use patterns over time are analyzed with a theoretical model and a numerical simulation model of land use. The results support the conventional economic view that a fee on the land used for logging is preferable to a tax on the timber output, which is far more common but would encourage logging waste. Technological interventions that increase the intensity of forestry or alternative land uses (introduction of improved technologies, irrigation infrastructure, etc.) are shown to be an ambiguous instrument for the conservation of unmanaged forests. If the demand elasticity for outputs is high, an intervention that increases the intensity of agriculture, logging, or other land uses increases incentives for conversion of unmanaged forests. The building of roads is particularly harmful to the conservation of unmanaged forests since it increases incentives for logging in two ways: it increases the profits not only of subsequent alternative land uses but also of logging itself.

In contrast, proper pricing of forest lands would increase land prices, and lead to market driven intensification that is accompanied by forest protection. Such pricing policies would be preferable to a technological intervention that increases land use intensity with ambiguous outcomes for forest protection. If unmanaged forest is converted to agriculture, the effect of lowering the decision maker's discount rate depends on the size of timber rents from logging unmanaged forests. If the standing timber has high commercial value, a lower discount rate would slow down conversion of unmanaged forests. However, if the standing timber has no commercial value, logging is an investment for obtaining future benefits of alternative land use. A lower discount rate would stimulate this investment and increase the conversion of unmanaged forests. Also if unmanaged forests are converted to managed forests, a lower discount rate can increase conversion since profits from managed forestry are higher with a lower discount rate.

1. Introduction

Large scale deforestation in tropical countries has become an issue of significant international concern (see, for example, FAO, 1993). While the conversion of forest lands to other uses is not necessarily undesirable in every instance, there are strong economic factors favouring inefficiently excessive deforestation. First, property rights to forests in frontier areas are often not established or not enforced. As a result, there is the excessive depletion which is typical for an open access resource. Second, even when property rights are established, forests provide numerous external benefits that do not accrue to the owner, government forester, or other decision maker. These include regional and global climatic stabilization, soil conservation, prevention of floods, preservation of biodiversity, and non-timber products collected or hunted by members of local communities who do not hold full ownership rights over the forest. Concerns about deforestation focus on the loss of these external benefits from natural forests.

In theory, one could devise economic instruments that would overcome the market failures that lead to excessive deforestation. Secure property rights could be established and enforced to eliminate the open access problem. External benefits of forests could be internalized by taxes on deforestation, or subsidies for the maintenance of forests equal in amount to the external benefits. Such first-best economic policies would lead to efficient individual land use decisions through the operation of market forces. In practice, there are many reasons why first-best policies are not applied. The establishment and enforcement of property rights are costly, sometimes more costly than the value to be protected. Efficient logging taxes (as opposed to stumpage fees, which are assessed not on the land deforested but on timber removed) are almost unheard of. Reasons for the absence of efficient policies can be found in national political economy (e.g., better political representation of forest owners as opposed to the beneficiaries of the positive forest externalities) or in the existence of international externalities (carbon sequestration and biodiversity conservation).

In the absence of first-best policies, the welfare loss that arises from market failures in the forest sector is determined by the incentives, prices and policies in the economy at large. For example, a forest area in a remote frontier region will remain forested as long as transportation and access costs are so high that neither the removal of logs nor agricultural activities on the land will generate a profit. However, changes in prices and policies that are unrelated to the forest sector may change this situation. The building of a road or the devaluation of the national currency could reduce transport costs for logs or increase revenues from agricultural crops up to the point where these activities became profitable and deforestation would occur.

As long as governments do not implement first-best policies for forest management and land use, two questions arise. First, which policies will increase the welfare loss arising from excessive deforestation? Second, which second-best policies can be implemented to reduce the welfare loss arising from excessive deforestation? In many cases, the effects of policies on deforestation are not straightforward. As a result, some policies are simultaneously claimed to reduce pressures for deforestation and at the same time accused of increasing deforestation. Agricultural intensification, for example, is often justified as reducing pressures for deforestation since food requirements can be met with smaller cultivated areas. However, others claim that agricultural intensification increases deforestation since it increases profitability, and, hence, leads to agricultural expansion.

Similarly, there are conflicting views on the basic questions of whether an increase in timber prices leads to increasing or decreasing deforestation. One view is that lower timber prices reduce the profits from and the incentives for logging, and hence reduce deforestation. The opposing view is that lower timber prices reduce the profitability of forestry and hence encourage the conversion of forest lands to other uses such as agriculture (see Vincent, 1990). The effect of timber price changes has particular relevance for the controversial debate about the deforestation effect of log-export bans (LEBs), or other trade restrictions which lower domestic timber prices.

Deforestation is a process during which land is converted from forests to other uses. Deforestation depends on a large number of economic parameters such as the expected time path of the timber price, logging and transport costs, government fees, the decision makers' discount rate, and the return to alternative possible land uses. Many World Bank supported policies and projects impact directly and indirectly on deforestation processes. Direct effects come from changes in the forest area through reforestation or dam projects. While the valuation problems may be significant, at least the quantitative impact on forest area can be known in these cases. Indirect effects of policies and projects include change input or output prices for different land uses and are more difficult to assess. Examples of such impacts include the effects of road building, forest fee structure, trade policy, foreign exchange policy, and productivity changes in the forest product sector as well as agriculture.

Considering the growing international concern about deforestation, there is a particularly strong need for analytical work on these indirect effects of policy changes on deforestation. In addressing the issue, this paper builds on a diverse literature of relevance for the analysis of land use dynamics. There is an extensive literature examining the effects of changes in various economic parameters on the optimal management of a forest (see Jackson 1980, Chang 1983, Nautiyal and Williams 1990, and the review in Hyde and Newman 1991). These papers use comparative statics analysis to determine the effect of changes in production costs, discount rate and various taxes on the optimal rotation age and the optimal management intensity for a given forest. In these models, it is assumed that the land will be used for forestry in perpetuity.

Static land-use models analyze the optimal use of land at a given point in time. This work was pioneered by von Thünen (1826) and applied to forestry by Ledyard and Moses (1974). Von Thünen introduces a bid-rent function and suggests that a given piece of land is put to the use in which it will yield the highest returns. He models rural land use in concentric circles around a city in which all goods are marketed. The increasing transportation costs from locations with greater distance from the city will lead to decreasing land value and decreasing intensity of cultivation until the land value decreases to zero and an uncultivated wilderness begins.

The effect of timber price changes on land use has been explored in recent, less formal, work which applies land use models to deforestation problems (Kishor and Constantino 1993; and Hyde, Amacher, and Magrath, 1993). Barbier (1993) uses a formal model of renewable resource dynamics to analyze forest stock changes in response to policy changes. Several authors have analyzed the empirical relationship between economic parameters and deforestation (see Barbier and Burgess, 1993; and Cropper and Griffiths, 1994). None of the previous work, however, has produced unambiguous and fully satisfying results with regard to the directional impact of apparently simple changes, such as a timber price drop, on deforestation.

The objective of this paper is to provide an analytical framework for determining the indirect effects of policy changes on deforestation. The framework allows for the systematic analysis and reconciliation of opposing views. While the paper focusses on analytical tools for evaluating the land-use effects of policy changes, it also provides some results on the effects of specific policy changes, such as the imposition of a log-export ban, on deforestation. Section 2 outlines the approach and the main results of the analysis. Section 3 discusses the policy implications. Chapters 4 and 5 contain the actual models from which the results of the paper are derived.

Two methodological approaches have been employed. Section 4 contains a partial equilibrium model of profit maximizing land use. This model is based on an exogenous timber price path with the assumption of a declining rate of price increase. This assumption is consistent with empirical observation, and with the results from theoretical models of nonrenewable resource extraction (timber from unmanaged forests) with increasing extraction costs and a renewable back-stop technology (timber from managed forests). This model is used to determine the direction of the effects of policy changes when demand is totally elastic, i.e. for timber exports of a small country. The main results of this section are the comparative statics effects of changes in the economic parameters, such as timber price or logging costs, on the profit maximizing time of logging and the optimal effort in logging.

Section 5 contains a simulation model of profit maximizing land use in which the timber price is endogenized. In the market simulations, the price of timber rises at a decreasing rate until a steady state is reached. The simulation of several policy changes provides insights into the effects of policy changes when demand is not fully elastic, i.e. for local fuelwood demand. Combined with site-specific geographic and economic data, the simulation model could be used as a tool for analyzing future deforestation rates and quantitative impacts of a specific policy intervention.

2. Modelling Approach and Summary of Results

This paper analyzes the links between economic parameters and deforestation through theoretical models based on profit maximizing agents. The models are based on the analysis of the incentives for the use of land in a specific land class, which includes all lands with identical site-specific characteristics. While von Thünen's work focusses on the central role of transportation costs, other site-specific determinants of land use include soil quality, climatic conditions, slopes, road access, factor costs, etc.. The models analyze how economic parameters determine the incentives for land use in a given land class. The ultimate interest, of course, is not in the individual land class but in aggregate land use changes. However, aggregate changes are determined from changes in land use within each class. For example, if a policy change leads to deforestation in some land classes and no reverse change in other land classes, it can be concluded that the policy change leads to more aggregate deforestation.

This paper integrates the land use and forestry literature by using formal comparative statics models similar to those in the traditional forestry literature to analyze questions of land use dynamics. It differs from previous work by simultaneously incorporating two critical factors for understanding deforestation processes: the differences between types of forests and the dynamic nature of land use decisions involving forests.

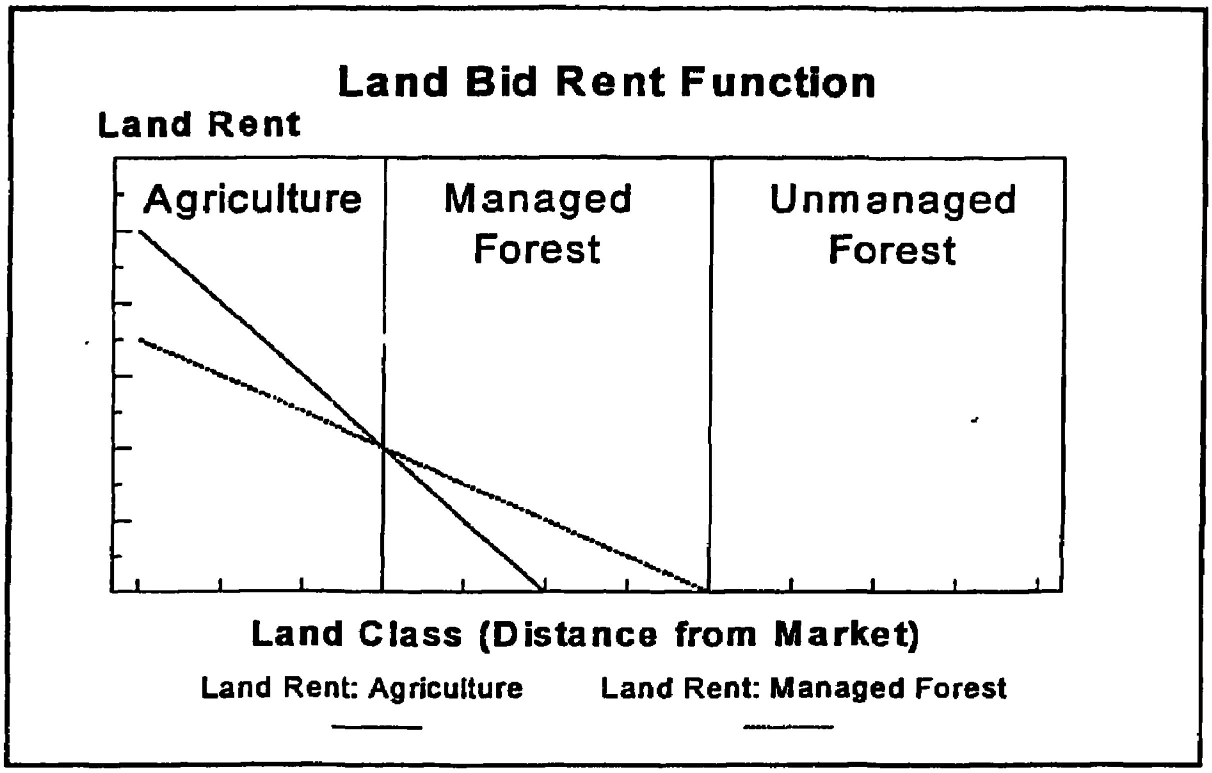

Figure 1

First, the paper clearly distinguishes between managed and unmanaged forests. In unmanaged forests, net timber growth is zero since decaying timber offsets concurrent biological growth. Logging of such a mature forest can be modelled like the mining of a non-renewable resource (see Lyon 1981). Unmanaged forests would include primary forests and second-growth forests that have not been logged for a long time. Managed forests, on the other hand, are logged after a fixed rotation period. Managed forests would include tree plantations and other forests that are maintained with the intention of periodic harvests. Agriculture and managed forests are both seen as land uses competing with unmanaged forests. Following von Thünen's approach, the use of land in one class would be determined by relative profitability. Figure 1 shows a bid-rent function for a situation in which managed forestry would be located between agriculture and the unmanaged wilderness (see Hartwick, 1993, for a similar approach).

In reality, there exist combinations of managed and unmanaged forests, and it may be desirable to consider those in a later extension to this paper. However, the current distinction between these two types of forests proves useful because it leads to some unambiguous analytical results. Moreover, many external benefits, such as the provision of habitat and the protection of biodiversity, are associated with unmanaged forests only. Hence, if policy intervention is justified by the non-timber benefits of a forest, its effects on the extent of unmanaged forests is more important than the effect on aggregate forest cover. To reflect the emphasis on old-growth or unmanaged forests, conversion or logging refers in this paper to the conversion of unmanaged forests to other uses, including managed forests.

The second difference from previous work is that this paper analyzes land use changes in a dynamic context. A static analysis based on a comparison of returns to different land uses at one point in time would be incomplete. Rather, the relevant comparison is between different land use patterns through time. The question is not only whether deforestation would occur on a given piece of land but also when it would occur. It will be shown that, for example, the introduction of forest plantations could increase deforestation in the short run but slow down deforestation in the long run when the plantation output reaches the market. Similarly, an increase in timber prices may have different effects depending on how it changes the future rate of price increases. These important effects are ignored in static models.

In a dynamic context, logging decisions depend on not only current prices but also the expectation about future prices. In this paper, certainty and rational expectations are assumed. Therefore, in the absence of unanticipated shocks, agents determine their profit maximizing behaviour in the first period for all times in the future, based on the expected timber price path. There is no difference between the expected and the realized price path and the expected and realized behaviour. A policy change is an unanticipated shock that changes price expectations, and, therefore, profit maximizing behaviour. The analysis of this paper focusses on the change in behaviour that results from an unanticipated policy change. Note that an anticipated change in policy would not change behaviour.

As a result of geographic conditions, deforestation rates can increase or decrease over time without a change in policy. These changes would be anticipated in line with the expected price and behaviour path of a dynamic land use model. Since deforestation rates can change without policy changes, the relevant question for the analysis of the effect of policy changes, is not whether deforestation rates fall or rise after a change in policy occurs but whether deforestation rates are different from what they would have been if the change in policy had not occurred. Since, for obvious reasons, there is no empirical information available for a comparison of the actual with the counterfactual scenario, this type of analysis is the natural realm of theoretical modelling.

The two economic forces that drive deforestation are the timber value from logging and the returns to alternative land use after logging (farming, cattle ranching or others). In some cases, timber use is not profitable and deforestation can clearly be attributed to agricultural expansion. The forest is then simply burned. In other cases, land is left fallow after logging and deforestation can clearly be attributed to logging. However, logging and future land use are non-exclusive. The decision to convert unmanaged forests is driven by the conversion profit which is the sum of profits from logging and all subsequent land uses. If timber was not used or if land was left idle after logging, logging profits or profits from land use after logging, respectively, would be zero or even negative.

Under secure property rights, the forest owner chooses the optimal time for logging by maximizing the present value of profits from logging and land use after logging. Of course, there may also be lands on which logging is never profitable. Even with secure property rights, non-timber benefits of the forests, such as climatic and soil stabilization, biodiversity conservation, and non-timber forest products, are not internalized. The model with secure property rights is similarly applicable where logging decisions are made by a government that cares about timber benefits but ignores non-timber benefits of the forest. Such government behavior appears reasonable for a variety of reasons: In contrast to non-timber benefits, logging often generates government revenues from stumpage fees. Some non-timber benefits such as climate and soil stabilization will accrue in the future, possibly after the tenure of the current government. A concentrated logging industry can more easily generate lobbying pressure on the government, compared to the less-organized recipients of non-timber benefits. Finally, some non-timber benefits may accrue as international externalities.

In contrast to the secure property rights situation, an alternative scenario with open access to the forest is analyzed. In this scenario, deforestation will occur at the earliest time at which the profits from logging are positive. If it is possible to establish property rights over the land by logging, deforestation will occur as soon as the profits from logging plus the present value of profits from all future land uses are positive.

The models determine the optimal logging time for each land class for different property rights regimes and different economic parameters. Combining the profit maximizing logging time for all classes, a picture of land use over time emerges (see for example Figure 5). In good locations (in the simulation model designated by a low land class index), agriculture is relatively more profitable than forestry. Logging would begin at the most favourable location and, as the timber price rises, proceed to less favourable locations. At a sufficiently high timber price, managed forestry becomes profitable. Once managed forests have sufficiently expanded to meet all timber demand, logging of unmanaged forests ceases, the timber price remains stable, and the steady state equilibrium is reached. Depending on the nature of the extraction costs compared to the cost of managed forestry and the demand for timber, this can occur before or after all unmanaged forests are logged.

The theoretical model in section 4 determines under which conditions a policy shock delays or advances logging in all land classes, so that general statements about the effect of such a shock can be made. The main result is that a drop in the level of the timber price path leads to a delay of logging of unmanaged forests in all land-classes. This result holds for open access with any logging technology as well as for secure property rights with fixed coefficient logging technology. Even with varying logging effort, logging of unmanaged forests is delayed under a technical condition on logging technology that is shown to be reasonable. In all cases, the ultimately preserved quantity of unmanaged forests is the same or larger under a lower timber price. The area of managed forests, on the other hand, is reduced under lower timber prices. Some other comparative statics results for the fixed coefficient model, with an exogenous timber price path under secure property rights, are summarized in Table I. This table shows the comparison of land use at any time after a hypothetical shock between the with- and without-shock scenarios.

Keeping in mind the distinction between unmanaged and managed forests, the intuition of the main result is easily explained. The conflicting views about the effects of timber price changes on deforestation arise from the dual nature of forest land as a storage of timber and as an input to the production of timber. This paper reconciles the two opposing views by analyzing the distinct impacts of timber price changes on different types of forests, which are characterized by different importance of land as storage of timber or as an input to timber production. A higher timber price increases the logging of unmanaged forests which are storage of timber but which are not productive any more, since they are mature. With higher timber prices, the logging of more remote unmanaged forests with higher site specific extraction costs becomes profitable and logging of

Policy Intervention	Area of Unmanaged Forest	Area of Managed Forest	Area of Agriculture
Reduction in Timber Price Level (i.e. from timber unit tax or log-export ban)	+	-	- at the unmanaged forest margin; + at the managed forest margin
Increase in Logging Costs (i.e. from logging tax per area unit)	+	- at the unmanaged forest margin; 0 at the agriculture margin	- at the unmanaged forest margin; 0 at the managed forest margin
Increase in Discount Rate	- if logging unmanaged forest is relatively profitable; + otherwise	? if logging unmanaged forest is relatively profitable; - otherwise	+ if logging unmanaged forest is relatively profitable; ? otherwise
Increase in Agricultural Productivity	-	-	+
Reforestation Subsidy (per area unit)	-	+	-

Table I Changes in Land Use with Exogenous Shocks

unmanaged forests increases. On the other hand, managed forest lands are producers of timber. A higher timber price increases the profitability of timber production and results in more land being devoted to timber production. As a result, higher timber prices lead to a smaller area of unmanaged forest and a larger area of managed forest.

3. Policy Implications

The analysis in sections 4 and 5 provides the methodology for examining the effect of policy choices on land use patterns and deforestation. The paper shows that it is possible to disentangle the complex economic interactions that lead to changes in land use and deforestation. The main instrument for obtaining some clear comparative statics results is the distinction between mining unmanaged forests that are biologically mature and managing production forests for periodic replanting. The results are discussed below in the context of specific policy questions such as timber trade restrictions and agricultural policies.

Log Export Bans and Other Trade Restrictions

Many timber exporting countries have imposed log-export bans (LEBs) or high log export taxes at one stage or another (see Crossley, 1993). LEBs were imposed primarily with the objective of promoting domestic processing and the export of higher valued sawnwood or manufactured goods. Even though LEBs were conceived as instruments of infant industry protection, they have implications for logging rates and a lively debate centers on the environmental effects of LEBs (see Goodland and Daly, 1994). LEBs or other trade restrictions as well as import boycotts reduce external log demand and have the effect of lowering log prices in the exporting country. Following a log-export ban in Costa Rica, for example, domestic log prices have fallen to 20-60 percent of international prices (Kishor and Constantino, 1993, p.12). The view that lower timber prices increase deforstation is reflected in many World Bank documents (see, for example, Brandon and Ramankutty, 1993, p37, and World Bank, 1993).

This paper provides a differentiated answer to the question whether lower timber prices increase deforestation: A lower timber price path reduces logging of unmanaged forests. This result holds under open access as well as under secure property rights with *fixed logging technology. The additional conditions required for the result to hold with variable logging technology are shown to be very likely. Under any circumstances, lower timber prices increase the area of unmanaged forest that will remain after a steady-state is reached in which all timber production has shifted to managed forests. On the other hand, lower timber prices lead to a reduced area of managed forests. The change in total forest area as a result of a timber price drop is undetermined.*

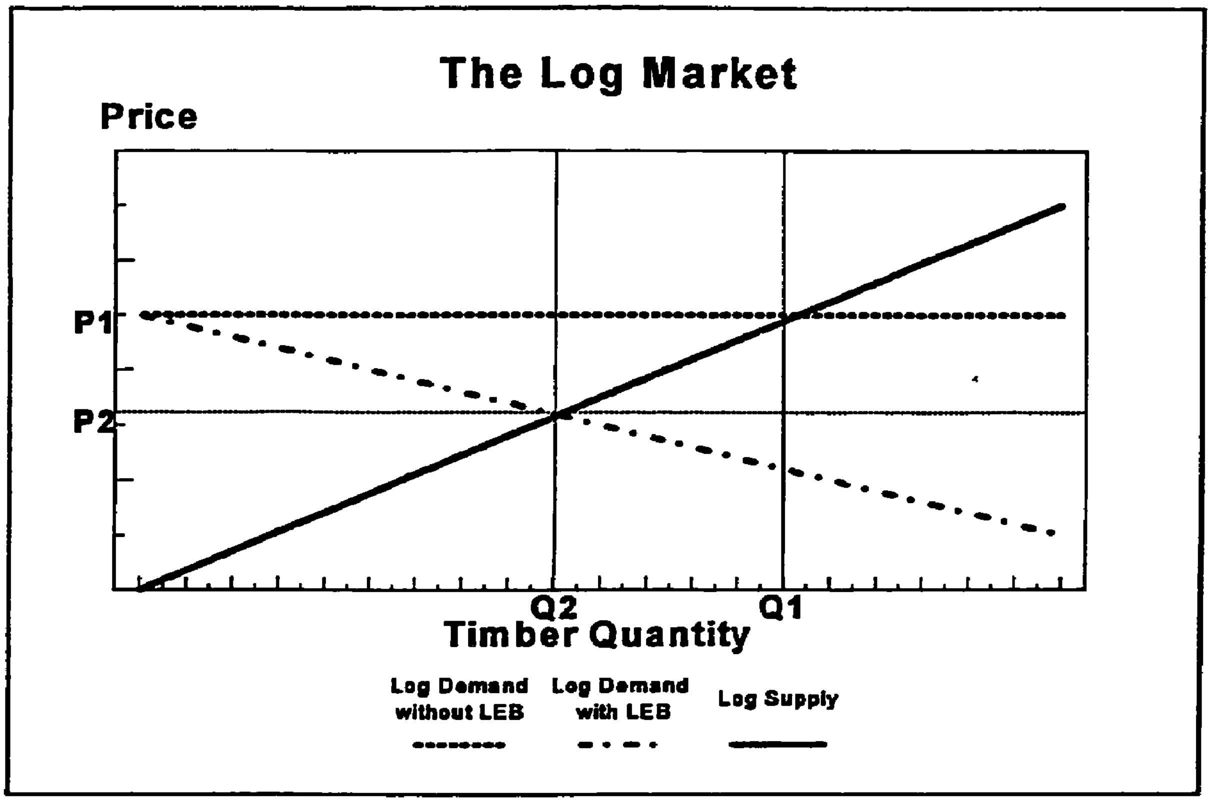

Figure 2

Repetto, 1988, advances a second argument against log-export bans, which is also echoed in many World Bank documents (see Braga, 1992, and references above). The claim is that lower domestic log prices encourage wasteful logging and processing techniques and can, therefore, increase logging. Undoubtedly, lower log prices lead to less efficient logging and processing. The second part of the argument, however, is flawed. This can be shown in Figure 2, which depicts the domestic market for logs. The supply of logs increases in log prices. This increase has at least three sources: an increase in logging intensity on a given plot; an increase in unmanaged forest areas logged; and an increase in the production of logs from managed forests. Moving upward on the supply curve, logging waste is reduced and logged unmanaged forest area is increased.

P_1 is the export parity price of logs (in the absence of trade restrictions). At this price, the quantity of logs extracted is Q_1. If a log export ban is imposed, the demand curve for logs shifts downward if the domestic processing industry is less efficient than international competitors.[1] The fact that processing efficiency declines with log prices (in other words: logs are substituted for other inputs such as labor and capital) is incorporated in the demand curve, which is flatter than it would be without this effect.[2] In any case, the log export ban leads to a shift of the demand curve and along the supply curve. Since the supply curve is positively sloped, logging is reduced whenever a log export ban leads to a lowering of the log price. Thus, while it is true that a log export ban can reduce logging and processing efficiency, this reduced efficiency cannot lead to an increase in the area logged.

This main result has important policy implications, not only for log export bans but also for other policy interventions that reduce the producer price for logs. These policies, including import restrictions by log importing countries or consumer boycotts of tropical timber, will reduce the pressure for logging unmanaged forests and therefore assist the conservation of biodiversity and other external benefits associated with unmanaged forests. On the other hand, the same measures will lead to reduced incentives for managed forestry and a decline in the area devoted to managed forests. Since the aggregate effect

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[1] On the other hand, if domestic prices were above export parity prices, a log export ban would have no effect whatsoever since logs would not be exported in that situation even without the ban.

[2] The slope of the domestic demand curve depends on the structure of the domestic processing industry and is irrelevant for the qualitative argument made here.

on managed and unmanaged forest areas is ambiguous, no statement can be made about the effect on external benefits that are associated with both types of forests, such as carbon sequestration. However, in FAO (1992), it is estimated that 82 percent of the tropical forest area logged between 1981 and 1990 was in previously unlogged (unmanaged) forests. This observation suggests a tentative conclusion that the positive effect of lower timber prices on unmanaged forest conservation will offset the negative effect of reduced managed forests.

The analysis in this paper indicates a positive effect of log-export bans on unmanaged forest conservation. However, this conclusion should not be misread as a recommendation in favor of log export bans. Lower log prices reduce logging and processing efficiency, and encourage logging waste. Log-export bans or other trade restrictions are clearly inferior to the first-best policies for forest protection that are discussed below. Their use as second-best policy instruments can be justified only if first-best instruments are impossible to implement and if the benefits of reduced logging outweigh the efficiency costs imposed on the economy as a result of price distortions. In reality, many log-export bans are in place. The findings of this paper suggest that before these bans are removed, efficient first-best policies for forest protection should be put in place. Adverse effects on the unmanaged forests can be expected otherwise.

Agricultural Intensification, Plantation Forestry and Other Indirect Policies

Agricultural intensification programs as well as forest plantation projects are often justified by the claim that they will reduce the conversion pressures on natural forests. This claim can be analyzed within the conceptual framework suggested by this paper. Agricultural improvements, such as increased yields from improved seed varieties or changed cultural practices, can have different effects depending on the nature of the agricultural improvements and the elasticity of demand for the products. If demand for an agricultural product is very elastic (for example in case of an export crop), and the benefits of intensification apply to all lands, then intensification would increase the returns to agriculture on any given piece of land. Hence, the area of agriculture would expand at the expense of managed and unmanaged forests. In this case, agricultural progress unambiguously increases deforestation. If agricultural intensification does not increase returns to agriculture on currently forested lands (for example because irrigation systems are installed on currently cultivated areas only), there would be no effect on forestry.

Only if the demand for the agricultural product is inelastic (for example for subsistence agriculture), would agricultural improvements lead to a reduction in the area cultivated since the same agricultural output could be produced on a smaller area of land. Then pressures for deforestation would be reduced. The question remains, however, whether increased productivity in subsistence agriculture would not lead to expansion into cash crop agriculture with higher demand elasticity, in which case pressures on forests would increase again. To summarize, the claim that agricultural intensification leads to reduced pressure on forests can be rejected for export agriculture if improvements apply to all lands. In the case of subsistence agriculture, the claim needs to be carefully examined based on local conditions.

The introduction of forest plantations (managed forests) leads to a similar situation. If demand for timber is highly elastic (the case of small timber-exporting countries), the introduction of plantation forests creates additional pressures for conversion of unmanaged forests since it would introduce an additional competing land use. If demand for timber is inelastic (for example where timber supplies fuelwood for the local market), an offsetting effect is introduced by forest plantations. In this case, increased timber supply from plantations reduces the timber price and, thus, reduces the pressure to convert unmanaged forests. As in the case of agriculture, demand for timber in a real-life situation would neither be fully elastic nor fully inelastic. Hence, the resulting net effect from the introduction of plantations is ambiguous and depends on case-specific demand elasticities.

There are other policies that increase producer prices and would, thus, lead to increased productivity of land use in either agriculture or managed forestry. In the case of export goods, the devaluation of the national currency increases the returns from cultivation as well as the returns from logging unmanaged forests. Devaluation would therefore contribute to increased conversion of unmanaged forests. Road building increases the producer prices paid to farmers and forest owners, particularly in more remote and, therefore, often unmanaged forest areas. Road building is, thus, particularly harmful to the conservation of forests, increasing the profitability not only from alternative cultivation but also from logging itself. While increased producer prices reduce logging waste, they also go along with more deforestation of unmanaged forests.

Measures that reduce decision makers' discount rates include the improvement of access to credit and increase in tenure security. Lower discount rates unambiguously increase the area of managed forests. The effect on unmanaged forests at the agricultural margin depends on whether timber rents from unmanaged forests are positive or not. With positive timber rents, a lower discount rate will lead to an increase in unmanaged forests. With negative timber rents, however, logging or land clearing is an investment that is made for obtaining the benefits of alternative land use. A lower discount rate will stimulate this investment and reduce unmanaged forest areas. The latter situation is reported from parts of the Brazilian Amazon (see Schneider 1993). At the frontier between unmanaged and managed forests, a lower discount rate can also lead to increased conversion if the increased returns to plantation forestry outweigh the reduction in opportunity costs of the standing unmanaged forest (this point was made in a static context by Kishor and Constantines, 1993, p 11, and is consistent with the analysis in this paper).

Efficient Forest Protection Policies

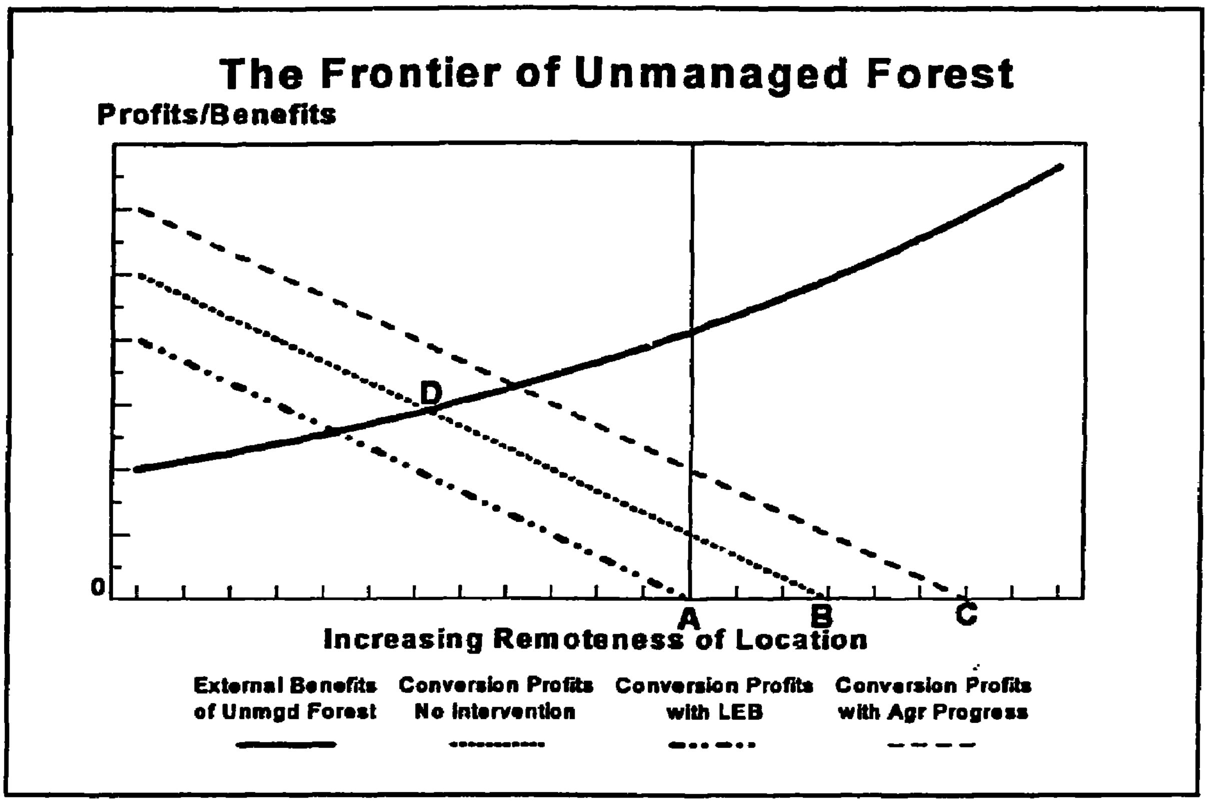


Figure 3

The previous section shows that the increase in the technical efficiency of forestry and alternative land uses is a highly ambiguous tool for the conservation of unmanaged forests. Whenever demand for a product from forests or other land uses is elastic (e.g., for products with a broad market or many substitutes), efficiency-increasing interventions will increase, not decrease, mining of unmanaged forests. The conclusion is clearly that increases in technological efficiency are a questionable tool for protecting forests.

Figure 3 demonstrates the change of land values and location of the unmanaged forest frontier with different policy interventions (see Dixon, 1993, for a similar approach). The following discussion ignores dynamic aspects and second round effects. These would change the size but not the signs of the discussed effects. Without policy intervention, the frontier of unmanaged forests will be at point B where the profits from conversion (logging profits plus present value of profits from subsequent cultivation or managed forestry) become zero. A log export ban or other policies that depress log prices will reduce profits from logging and lead to an inward shift of the frontier to point A (more unmanaged forest remains unlogged). However, reduced timber prices also increase logging waste and reduce processing efficiency. The introduction of improved agricultural or forestry technologies will increase cultivation profits and has the opposite effect of a log export ban: it will move the frontier outward to point C.

Logging is a production process in which timber land and effort are the inputs and timber is the output. The policies discussed above manipulate output demand (timber demand) in order to influence the input demand for forest land. Policies to manipulate output prices are common (the most common form of logging charges is a unit fee on timber and not on forest land) but they distort price incentives and lead to allocational inefficiencies: if timber is taxed instead of forest land, the logging effort per unit of forest would be reduced (logging waste is increased). Based on the external benefits from standing forests, timber land is the underpriced resource that should be taxed. An efficient policy would charge a price for the conversion of forest land equal to the external benefits of unmanaged forests. The frontier would move to point D, where deforestation is reduced without reducing land use efficiency or increasing logging wastes. As a second round effect, efficient pricing of unmanaged forest land would lead to an increase in land values, and thus, to increased land use efficiency.

A first best policy of land conversion taxes equal to external benefits is efficient, and the benefits obviously outweigh the costs of such a policy. The benefits, however, often consist of diffuse, non-monetary (and possibly future), welfare improvements. The costs, on the other hand are usually foregone cash income. Therefore, it is important to consider the opportunity costs of an efficient forest protection policy. Figure 4 can shed some light on these opportunity cost of forest protection.

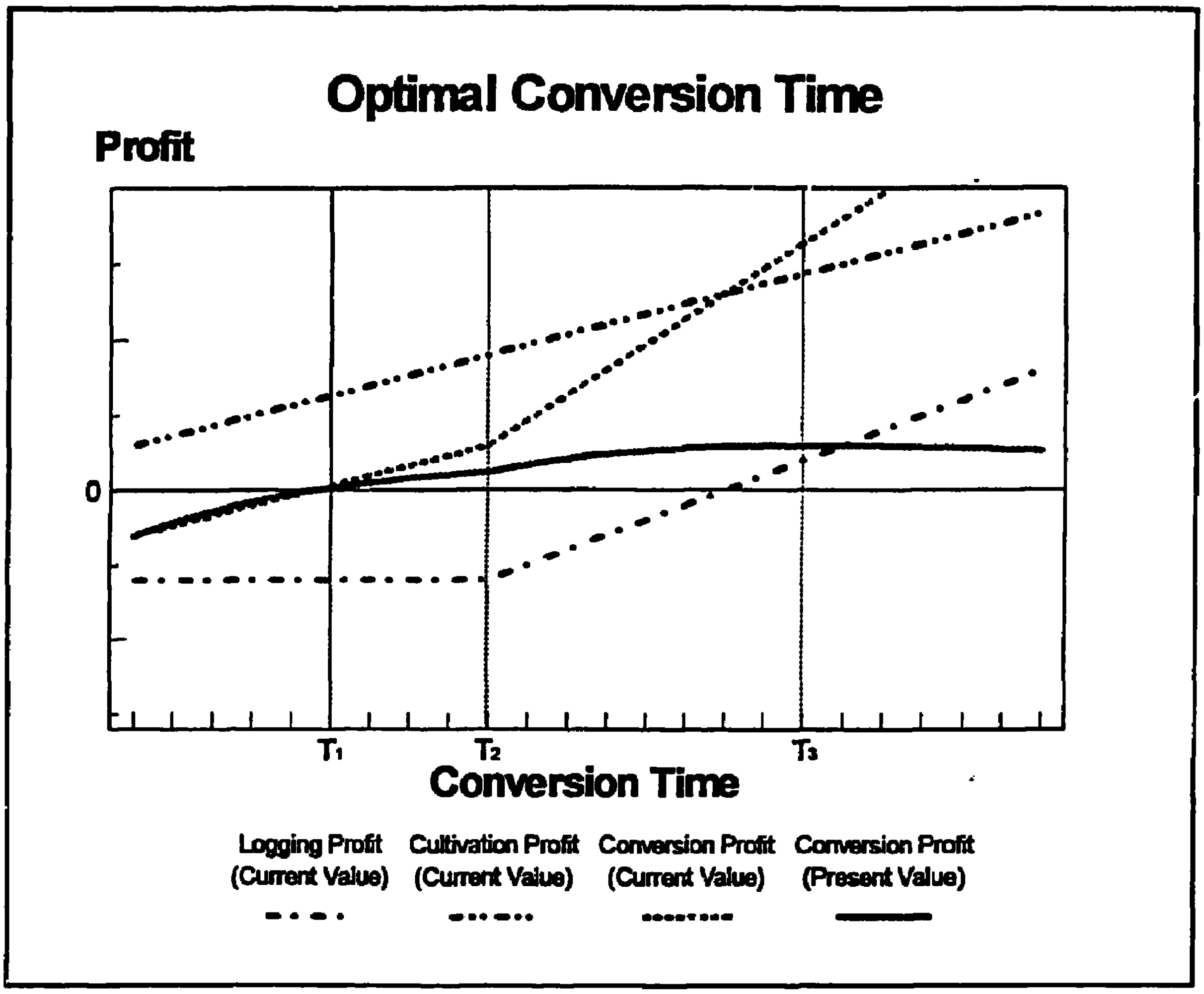


Figure 4

Figure 4 shows the development of profits from logging and profits from subsequent cultivation over time. Both are assumed to increase over time with improved access, economic development and increasing timber prices. Until the time T_2, timber revenues are lower than variable costs (log preparation and transport costs). If the forest is converted before T_2 the timber will not be used but cleared and burned. The (negative) logging profit up to T_2 is simply the land clearing cost. If there is open access to the forest, and land clearing is a mechanism for acquiring property rights, the forest will be converted as soon as the present value of conversion profits (logging profits plus cultivation profits) is greater than zero. T_1 depicts the time at which conversion profits are equal to zero. Figure 4 shows a situation where conversion in the open access case (T_1) will occur before timber use becomes profitable. Hence, all timber will be wasted. In other situations, some timber will be used even in the open access case.

If secure property rights over the forest are established before conversion, conversion will occur not at the time of zero conversion profits but at time, T_3, at which the present value of conversion profits has its maximum. Assuming increasing profits from logging and cultivation, conversion with secure property rights always takes place after conversion under open access. Moreover, the delay of conversion at T_1 does not have an opportunity cost at all, since the profits from conversion at T_1 will be zero. In fact, forest rents are created by delaying logging until T_3 (the point that forest rents are created only by restricting access was made recently by Hyde, Amacher and Magrath, 1993). Hence, a policy to delay logging up until T_3 is not only desirable from an environmental perspective but also creates timber rents. Protection has an opportunity cost only once conversion is delayed beyond T_3. Since timber prices are assumed to rise, this model explains why logging intensity is higher under secure property rights than under open access, and why, in fact, timber is often not used at all under open access.

There are two areas of important additional research that would strengthen the analysis in this paper. First, many of the parameter values that are used in the simulations could be estimated empirically for areas which are ecologically valuable "hot spots". This would allow derivation of quantitative predictions for specific policy interventions. Second, a model of a forest as a stock of homogenous timber is clearly unrealistic. In particular, unmanaged forests consist of a variety of tree species with highly different economic values. Even though some of the qualitative effects of this heterogeneity of timber are captured in the production function for logging, a modelling approach closer to the physical realities of a natural forest would be desirable and requires additional empirical work.

4. A Dynamic Land Use Model with Exogenous Timber Prices

This section contains the formal model of dynamic land use with exogenous timber prices and is divided into three parts. In the first part, secure property rights and constant effort in logging and managing forests is assumed (Leontief technology). Timber land and "effort" are the inputs to production, and timber is the output. Effort is an aggregate of all inputs other than timber land, e.g. labor and capital. The assumption of constant effort allows the derivation of many interesting and unambiguous comparative statics effects. In real forests, however, there is clearly some substitutability between timber land and effort. Different logging intensities can be observed in logging operations throughout the world. Also, there is a wide literature examining the impacts of effort on the regeneration and growth rate of timber. Therefore, the second part of this section relaxes the assumption of fixed effort in logging and managing forest and shows the conditions on the production functions under which the comparative statics results from the constant effort model will continue to hold. The third part of this section analyses a situation with open access to unmanaged forests.

Constant Logging Effort

Consider the owner of a piece of land which is covered with unmanaged forest. The owner maximizes profits by choosing the optimal time for logging the forest and possibly the optimal time for later conversion of the land from managed forest to agriculture or vice versa. There is no return to the owner of an unmanaged forest until it is logged. The following notation will be used (superscripts l, f, and a refer to logging unmanaged forests, managed forests, and agriculture, respectively; superscript c refers to the profit maximizing land use after unmanaged: forest conversion, managed forest, agriculture, or idle):

LPV	the present value of one unit of land under the planned land use time path;
f^l	the marketable timber stock in unmanaged forests;
$p(k,t)$	the price path of timber;
k	an exogenous shock to the timber price path;
t^l	the time of logging unmanaged forest;
t^{l*}	the profit maximizing logging time;
c^l	the logging cost per land area;
$\pi^l(k,t)$	the returns to logging unmanaged forest, $\pi^l(k,t) = f^l p(k,t) - c^l$;
f^f	the harvest rate of marketable timber in the managed forest;
c^f	the cost of managing forests;
u	the fixed time period to maturity of managed forests;
$\pi^f(k,t)$	the instantaneous returns to land in managed forestry, $\pi^f(k,t) = e^{-ru} f^f p(k,t) - c^f$;
$\pi^a(t)$	the instantaneous returns to land under agriculture;
$\pi^c(k,t)$	the instantaneous returns from profit maximizing land use after logging, $\pi^c(t) = \max[0, \pi^f(t), \pi^a(t)]$;
r	the discount rate of the decision maker.

All subscripts denote partial derivatives.

For the timber price path, it is assumed that $p_t > 0$ and $p_{tt} < 0$. The assumption of rising timber prices, and a declining rate of timber price increase is consistent with a situation in which timber from unmanaged forests is depleted with rising extraction costs and a renewable substitute is available in the form of timber from managed forests. These price path assumptions are also supported by the market simulations in section 5 which yield an endogenous price path with the characteristics $p_t > 0$ and $p_{tt} < 0$[3].

---

[3] Strictly speaking, the less restrictive assumptions $p_t > 0$ and $p_{tt}/p_t < r$ are sufficient for obtaining the main results derived in this section. Note that the latter condition is satisfied for any constant rate of price increase less than the discount rate, r.

Consider two exogenous shocks to the timber price path: k' is an increase in the level of the price path (k' does not change the slope of the price path). k" is some other increase in the timber price path, which could also change its slope, for example, a value tax on timber. With these assumptions, the following properties result: $\pi^l_t > 0$, $\pi^l_k > 0$, $\pi^l_c < 0$, $\pi^l_{tt} < 0$, $\pi^l_{tc} = 0$, $\pi^l_{tk'} = 0$, $\pi^f_t > 0$, $\pi^f_k > 0$, $\pi^f_c < 0$ and $\pi^f_r < 0$. Profits from agriculture are assumed to be independent of p, c^l, c^f, and r. Furthermore, profits from agriculture are assumed to be non-declining, $\pi^a_t \geq 0$. For simplicity it is assumed that managed forest produces a constant timber crop with residual instantaneous returns to land of $\pi^f(k,t)$. This model abstracts from the question of optimal effort and optimal rotation periods in the managed forest and focusses squarely on the question of land conversion. Land that is left idle after logging yields zero returns.

The Optimal Logging Time

After unmanaged forest is logged, land use will be determined by maximizing residual returns to land. The optimal time of logging the unmanaged forest is determined by maximizing the present value of returns from logging and subsequent profit-maximizing cultivation where s is the integration variable, running from the time of logging, t^l, to infinity:

$$\max_{t^l} \quad LPV = e^{-rt^l}\pi^l(k,t^l) + \int_{t^l}^{\infty} e^{-rs}\pi^c(k,s)\,ds \tag{1}$$

subject to the condition max LPV > 0. If max LPV ≤ 0, logging would not take place within finite time. The first order condition is:

$$LPV_t = \frac{\partial LPV}{\partial t^l} = e^{-rt^l}\left[\pi^l_t(t^{l*}) - r\pi^l(t^{l*}) - \pi^c(t^{l*})\right] = 0 \tag{2}$$

where subscripts to π and LPV denote partial derivatives. The intuition of this first order condition is that at the optimal time of logging, the rate of appreciation of the timber stock, due to timber price increases, must equal the foregone returns from logging as well as alternative cultivation of the land.

The effect of changes in the parameters on the optimal time of logging, t^{l*}, is determined by solving the total derivatives of (2) with respect to k, c^l, and r for dt^{l*}/dk, dt^{l*}/dc^l, and dt^{l*}/dr, respectively, and simplifying the results with the first order condition:

$$
\begin{aligned}
\frac{dt^{l*}}{dk'} &= -\frac{LPV_{tk'}}{LPV_{tt}} = \frac{r\pi^l_{k'}+\pi^c_{k'}}{\pi^l_{tt}-r\pi^l_t-\pi^c_t} && < 0 \\
\frac{dt^{l*}}{dk''} &= -\frac{LPV_{tk''}}{LPV_{tt}} = \frac{r\pi^l_{k''}+\pi^c_{k''}-\pi^l_{tk''}}{\pi^l_{tt}-r\pi^l_t-\pi^c_t} && < 0 \quad \text{if} \quad r\pi^l_{k''}+\pi^c_{k''}>\pi^l_{tk''} \\
\frac{dt^{l*}}{dc^l} &= -\frac{LPV_{tc}}{LPV_{tt}} = \frac{r\pi^l_c-\pi^l_{tc}}{\pi^l_{tt}-r\pi^l_t-\pi^c_t} && > 0 \\
\frac{dt^{l*}}{dr} &= -\frac{LPV_{tr}}{LPV_{tt}} = \frac{\pi^l+\pi^c_r}{\pi^l_{tt}-r\pi^l_t-\pi^c_t} && < 0 \quad \text{if} \quad \pi^l+\pi^c_r > 0
\end{aligned}
\tag{3}
$$

Hence, on any piece of land an increase in the level of the timber price path advances the profit maximizing logging time. Logging time is also advanced by any other positive price shocks which either decrease the slope of the price path or increase the slope below the value required for (3) to hold. If profits from logging are positive and greater than the reduction in profits from land cultivation with an increase in the discount rate, then an increase in the discount rate advances deforestation.

The Conversion Between Managed Forests and Agriculture

The optimal time of conversion of managed forest to agriculture, or vice versa, is determined by the condition of equal instantaneous profits in both land uses:

$$\pi^{a}(t^{c*}) = \pi^{f}(k,t^{c*}) \tag{4}$$

where t^{c*} is the optimal conversion time. Solving the total derivative of (4) with respect to k, c^f, and r for dt^{c*}/dk, dt^{c*}/dc^f, and dt^{c*}/dr, respectively, gives the comparative statics effects. If profits from managed forests are expected to rise faster than profits from agriculture ($\pi^f_t > \pi^a_t$) then t_c^* marks the time of optimal conversion from agriculture to managed forestry. With the assumptions on profit functions made above:

$$\frac{dt^{c*}}{dk} = \frac{\pi^f_k}{\pi^a_t - \pi^f_t} < 0$$

$$\frac{dt^{c*}}{dc^f} = \frac{\pi^f_c}{\pi^a_t - \pi^f_t} > 0 \tag{5}$$

$$\frac{dt^{c*}}{dr} = \frac{\pi^f_r}{\pi^a_t - \pi^f_t} > 0$$

If, however, $\pi^a_t < \pi^f_t$ (in this case, t_c^* marks the time of optimal conversion from managed forestry to agriculture), then all signs are reversed ($dt^{c*}/dk > 0$, $dt^{c*}/dc^f < 0$, and $dt^{c*}/dr < 0$).

Land Use Changes

Combining these results, a timber price level increase advances logging of unmanaged forest and converison to other uses (including managed forests), advances the conversion of land from agriculture to managed forests and delays the conversion from managed forest to agriculture. Since these results hold for land in any class, an unexpected increase in the timber price path leads to a reduction of the area under unmanaged forests and an increase of the area under managed forest at any time after the shock. Other results include an increase in unmanaged forests with increase in logging costs (or a land-based logging fee), and a reduction in unmanaged forests with an increase in the decision makers' discount rate if logging is profitable. The results of the analysis are summarized in Table I (see page 10).

Variable Logging Effort

The foregoing simple model with constant levels of effort in logging and forest management produces several unambiguous comparative statics results. However, the underlying assumption of constant effort is unrealistic. The following model incorporates effort as an additional decision variable in logging as well as forest management. This model, hence,. addresses the question of substitutability of other input factors such as labor and capital for forest land. Evidence of widely varying levels of logging waste and processing efficiency indicate the importance of this analysis. It will be shown that the effects of some policy interventions hold only under some additional conditions on the forestry production function, f. Hence, this analysis directs attention to further analysis of the empirical parameters that, if estimated, would allow a less ambiguous prediction of the impact of policy interventions.

The modified notation in this model includes:

e^l	the effort in logging unmanaged forest;
e^{l*}	the profit maximizing level of effort in logging unmanaged forests;
w	the factor price of effort;
$f^l(e^l)$	the timber harvest as a function of the logging effort;
$\pi^l(k,t)$	the profit function for logging unmanaged forest, $\pi^l(k,t) = f^l(e^l)p(k,t) - e^l w - c^l$;
e^f	the effort in managed forestry;

e^{f*} the profit maximizing level of effort in managed forests;

$f^f(e^f)$ the timber harvest as a function of the effort in managed forests;

$\pi^f(k,t)$ the profit function for managed forests is $\pi^f(k,t) = e^{-ru}f^f(e^f)p(k,t) - e^f w - c^f$.

Land owners maximize the present value of their land by choice of logging time, and effort in logging as well as forestry:

$$\max_{t^l, e^l, e^f} \quad LPV = e^{-rt^l}\pi^l(k,t^l) + \int_{t^l}^{\infty} e^{-rs}\pi^c(k,s)ds \tag{6}$$

subject to the condition max LPV > 0. If max LPV ≤ 0, logging would not take place within finite time. The profit maximizing logging time, and levels of effort are functions of all parameters, determined by the following first order conditions:

$$\begin{aligned} LPV_t &= \frac{\partial LPV}{\partial t^l} = e^{-rt}\left[\pi_t^l(t^{l*}) - r\pi^l(t^{l*}) - \pi^c(t^{l*})\right] = 0 \\ LPV_{e^l} &= \frac{\partial LPV}{\partial e^l} = e^{-rt}\left[p(t^{l*})\frac{\partial f^l}{\partial e^l} - w\right] = 0 \\ LPV_{e^f} &= \frac{\partial LPV}{\partial e^f} = e^{-r(d+t)}p(t^{l*})\frac{\partial f^f}{\partial e^f} - e^{-rt}w = 0 \end{aligned} \tag{7}$$

The only price change considered is a price level change (k'). Most of the results from the model with constant effort hold in this model as well, i.e. an increase in the discount rate increases logging of unmanaged forests if the latter is sufficiently profitable, and an increase in the costs of either logging or managing forests increases the area of unmanaged forests. The derivation of the comparative statics results is provided in the Appendix and contains the following result for the margin of unmanaged forests and agriculture:

$$\frac{dt^{l*}}{dk}\begin{cases} > 0 & \text{if } -\dfrac{f^l_{ee}f^l}{(f^l_e)^2} < \dfrac{p_t}{rp} \\ < 0 & \text{if } -\dfrac{f^l_{ee}f^l}{(f^l_e)^2} > \dfrac{p_t}{rp} \end{cases} \tag{8}$$

Hence, the result that deforestation proceeds more rapidly with higher timber prices does not hold unambiguously, and an additional condition on the production function is required to hold for this effect. At least theoretically, a rise in the timber price level can lead to a rising appreciation of the timber stock that more than offsets the increase in foregone harvest profits. This can happen if the profit function is highly convex in the timber price and the increase in profits with higher prices is relatively low (i.e., if f_{ee}^l is close to zero, and f^l is small). In this case, logging profits will rise faster over time at a higher price level. As a result, it could become profitable to delay logging.

In order to analyze the robustness of this paper's main result, it is important to gain some appreciation whether the condition for $dt^{l*}/dk < 0$ is likely to be met. If the rate of timber price increase was higher than r, no timber would currently be harvested at all. Hence it is reasonable to assume that:

$$0 < \frac{p_t}{rp} < 1 \tag{9}$$

Hence, with (8) and (9):

$$-\frac{f^l_{ee}f^l}{(f^l_e)^2} > 1 \Rightarrow \frac{dt^{l*}}{dk} < 0 \tag{10}$$

This condition is also sufficient to establish earlier logging with price level increases at the margin of unmanaged and managed forest (see appendix). Now consider a Cobb-Douglas production function:

$$f^l(h,e) \;=\; e^{a}h^{1-a} \quad with\ 0 < a < 1$$

where h is the amount of land used for logging. With h normalized to 1:

$$\begin{gathered}
-\frac{f^l_{ee}\,f^l}{(f^l_e)^2} = \frac{1}{a}-1, \quad hence \\
-\frac{f^l_{ee}\,f^l}{(f^l_e)^2} > \frac{p_t}{pr} \quad iff \quad a < \frac{1}{\frac{p_t}{pr}+1}
\end{gathered} \tag{12}$$

Historical timber price time series indicate real rates of price increase of only one to two percent per annum. Assuming a future price increase of one percent and a discount rate of 5%, the results of the constant-effort model would hold for any a < 0.833. With a Cobb-Douglas production function and competitive markets, a would be the share of timber revenues spent on all logging costs (including labor and capital but excluding timber rents and royalties). From available data, it seems unlikely that a share as large as 83% of log revenues would be spent on logging costs. Similar analysis can be performed for other functional specifications of f. The analysis would suggest that most of the comparative statics results of the constant effort model continue to hold. Clearly, additional empirical analysis of the production function would be helpful to verify this claim.

An additional result can be established for any timber price increase, k", and without any additional condition on the production functions: LPV is increasing in the timber price (since the profit function is increasing in output prices). Therefore, maximized LPV increases with any increase in the timber price path. Thus, if max LPV < 0 (and this piece of land is not logged in finite time), also with any timber price reduction LPV < 0. Hence, with a lower timber price path, there is no unmanaged forest that is ultimately converted that would not also have been converted with higher prices. However, some lands that would ultimately be logged under higher prices may not be logged at all under lower prices. Hence, the unmanaged forest that will ultimately be converted is unambiguously reduced under lower timber prices.

The first order conditions for the transition from managed forestry to agriculture or vice versa are:

$$\begin{aligned} \pi^a(t^{c*}) - \pi^f(k,t^{c*}) &= 0 \\ p(k,t^{c*})\frac{\partial f^l}{\partial e^l} - w &= 0 \end{aligned} \tag{13}$$

The comparative static results are listed in the Appendix.

Combining these results, an increase in the timber price path moves outward the frontier at which unmanaged forests remain unlogged in finite time. An increase in the level of the timber price path also advances the logging time of unmanaged forests and conversion to other uses under condition (8) on all lands that ultimately will be logged. The other results of the model with fixed efforts in logging and forest management hold with some additional restrictions.

Open Access Scenario

If access to the unmanaged forest is open and property rights are acquired by clearing and cultivating land, logging does not take place at the profit maximizing time but as soon as the profits from logging plus the present value of profits from subsequent cultivation are zero. This approach is based on the assumption that all land with positive conversion profits is already logged. The condition that determines logging time is:

$$LPV = \pi^l(k,t^l) + \int_{t^l}^{\infty} e^{-r(s-t^l)} \pi^c(k,s)\,ds = 0 \qquad (14)$$

The conditions for optimal effort in logging and managed forestry are the same as in the previous case with secure property rights:

$$\begin{aligned} LPV_{e^l} &= \frac{\partial LPV}{\partial e^l} = e^{-rt}\left[p(t^{l*})\frac{\partial f^l}{\partial e^l} - w\right] = 0 \\ LPV_{e^f} &= \frac{\partial LPV}{\partial e^f} = e^{-r(d+t)}p(t^{l*})\frac{\partial f^f}{\partial e^f} - e^{-rt}w = 0 \end{aligned} \qquad (15)$$

The comparative statics results can be formally derived, similar to the case of secure property rights. For the open access case the algebra is tedious but the results are rather obvious. Therefore, the formal derivation of the following comparative statics result is not shown here:

$$\frac{dt^{l*}}{dk^{ll}} < 0 \qquad (16)$$

Under open access any type of timber price increase advances the logging time. This becomes obvious by observing that LPV in (14) is increasing in t^l and k ($\pi^l_t > 0$ and $\pi^c_t > 0$ are assumed, $\pi^l_k > 0$, $\pi^c_k \geq 0$ because profit functions are increasing in output price). Therefore, any increase in k has to be offset by a reduction of t^l, or vice versa, in order for (14) to hold.

Appendix to Section 4: Derivation of Comparative Statics Results

In this appendix, a price shock k refers to a change in the level of the timber price path.

The Hessian matrix, H, of the maximization problem (6) is:

$$H = \begin{bmatrix} LPV_{tt} & LPV_{c^l t} & LPV_{c^f t} \\ LPV_{tc^l} & LPV_{c^l c^l} & LPV_{c^f c^l} \\ LPV_{tc^f} & LPV_{c^l c^f} & LPV_{c^f c^f} \end{bmatrix} \tag{17}$$

The matrix of comparative statics effects, B, is:

$$B = \begin{bmatrix} \frac{dt}{dk} & \frac{dt}{dr} & \frac{dt}{dw} & \frac{dt}{dc^l} & \frac{dt}{dc^f} \\ \frac{de^l}{dk} & \frac{de^l}{dr} & \frac{de^l}{dw} & \frac{de^l}{dc^l} & \frac{de^l}{dc^f} \\ \frac{de^f}{dk} & \frac{de^f}{dr} & \frac{de^f}{dw} & \frac{de^f}{dc^l} & \frac{de^f}{dc^f} \end{bmatrix} \tag{18}$$

Let the matrix R be:

$$R = \begin{bmatrix} -LPV_{tk} & -LPV_{tr} & -LPV_{tw} & -LPV_{tc^l} & -LPV_{tc^f} \\ -LPV_{e^l k} & -LPV_{e^l r} & -LPV_{e^l w} & -LPV_{e^l c^l} & -LPV_{e^l c^f} \\ -LPV_{e^f k} & -LPV_{e^f r} & -LPV_{e^f w} & -LPV_{e^f c^l} & -LPV_{e^f c^f} \end{bmatrix} \tag{19}$$

With the implicit function theorem, HB = R. Then, with Cramer's rule:

$$b_{ij} = \frac{|H_{ij}|}{|H|} \tag{20}$$

where b_{ij} is the element i,j of the matrix B, and $|H_{ij}|$ denotes the determinant of the matrix H with column i replaced by column j of matrix R.

Comparative static effects at the margin of unmanaged forest and agriculture

At the margin of unmanaged forests with agriculture, the variables related to managed forestry are irrelevant to the maximization problem. Then, the last rows and last columns of matrices H, B and, R, respectively, can be deleted.

Now H is a symmetric 2 x 2 matrix. The sufficient second order condition is that H is negative definite. This implies $|H| > 0$ (see Chiang 1984, p. 325). Hence, the sign of b_{ij} equals the sign of $|H_{ij}|$. Simplifications with the first order conditions yield:

$$|H_{tk}| = (rf^l f^l_{ee} p p_k + (f^l_e)^2 p_t p_k)/\exp(2rt) \quad \begin{cases} > 0 & \text{if} \quad -\dfrac{f^l_{ee} f^l}{(f^l_e)^2} < \dfrac{p_t}{rp} \\ < 0 & \text{if} \quad -\dfrac{f^l_{ee} f^l}{(f^l_e)^2} > \dfrac{p_t}{rp} \end{cases}$$

$$|H_{tr}| = pf^l_{ee}(f^l p_t - \pi^c)/r\exp(2rt) \quad \begin{cases} > 0 & \text{if} \quad \pi^c > f^l p_t \\ < 0 & \text{if} \quad \pi^c < f^l p_t \end{cases} \qquad (21)$$

$$|H_{tw}| = -(e^l rpf^l_{ee} + f^l_e p_t)/\exp(2rt) \quad \begin{cases} > 0 & \text{if} \quad -\dfrac{f^l_{ee}}{f^l_e} e^l > \dfrac{p_t}{rp} \\ < 0 & \text{if} \quad -\dfrac{f^l_{ee}}{f^l_e} e^l < \dfrac{p_t}{rp} \end{cases}$$

$$|H_{tc^l}| = -rpf^l_{ee}/\exp(2rt) \quad > 0$$

and:

$$\begin{array}{lll}
|H_{el_k}| = (f_e^l \pi_t^c p_k - f^l p_{tt} p_k)/\exp(2rt) & > 0 & \\
|H_{el_r}| = p_t f_e^l (\pi^c - f^l p_t)/r\exp(2rt) & \begin{cases} > 0 & if \quad \pi^c > f^l p_t \\ < 0 & if \quad \pi^c < f^l p_t \end{cases} & (22) \\
|H_{el_w}| = (f^l p_{tt} - \pi_t^c + r p_t (e^l f_e^l - f^l))/\exp(2rt) & < 0 & \\
|H_{el_{c^l}}| = r p_t f_e^l/\exp(2rt) & > 0 &
\end{array}$$

Comparative static effects at the margin of unmanaged and managed forest

Here, H is a symmetric 3 x 3 matrix. The sufficient second order condition is that H is negative definite. This implies $|\mathrm{H}| < 0$ (see Chiang 1984, p. 325). Hence, the sign of b_{ij} is opposite of the sign of $|\mathrm{H}_{ij}|$. Standard simplifications yield the following signs:

$$\begin{array}{ll}
b_{tl_k} & \begin{cases} > 0 & if \quad -\dfrac{f_{ee}^l \left(f^l + \dfrac{f^f}{\exp(rd)r}\right)}{(f_e^l)^2} < \dfrac{p_t}{rp} \\[3ex] < 0 & if \quad -\dfrac{f_{ee}^l \left(f^l + \dfrac{f^f}{\exp(rd)r}\right)}{(f_e^l)^2} > \dfrac{p_t}{rp} \end{cases} \\[6ex]
b_{tl_r} & \begin{cases} > 0 & if \quad (1-rt)\pi^l + tf^l p_t < t\pi^f + \exp(-rd) f^f pd \\ < 0 & if \quad (1-rt)\pi^l + tf^l p_t > t\pi^f + \exp(-rd) f^f pd \end{cases} \\[4ex]
b_{tl_w} & \begin{cases} > 0 & if \quad -\dfrac{f_{ee}^l}{f_e^l}\left(\dfrac{e^f}{r} + e^l\right) > \dfrac{p_t}{rp} \\[3ex] < 0 & if \quad -\dfrac{f_{ee}^l}{f_e^l}\left(\dfrac{e^f}{r} + e^l\right) < \dfrac{p_t}{rp} \end{cases} \\[5ex]
b_{tl_{c^l}} & > 0 \\
b_{tl_{c^f}} & > 0
\end{array} \qquad (23)$$

and:

$$
\begin{array}{ll}
b_{e^l_k}, b_{e^f_k} & \begin{cases} > 0 & \text{if} \quad \pi^f + r\pi^l < f^l\left(p_t - \frac{p_w}{r}\right) \\ < 0 & \text{if} \quad \pi^f + r\pi^l > f^l\left(p_t - \frac{p_w}{r}\right) \end{cases} \\
b_{e^l_r}, b_{e^f_r} & \begin{cases} > 0 & \text{if} \quad (1-rt)\pi^l + tf^l p_t < t\pi^f + \exp(-rd) f^f p d \\ < 0 & \text{if} \quad (1-rt)\pi^l + tf^l p_t > t\pi^f + \exp(-rd) f^f p d \end{cases} \\
b_{e^l_w}, b_{e^f_w} & ? \\
b_{e^l_{c^l}}, b_{e^f_{c^l}} & > 0 \\
b_{e^l_{c^f}}, b_{e^f_{c^f}} & > 0
\end{array}
\qquad (24)
$$

Comparative static effects at the margin of managed forest and agriculture

The comparative statics results are obtained in the standard way from the total differentials of (13). All signs are based on $\pi^a_t < \pi^f_t$ (shift from agriculture to managed forestry). For shifts from managed forestry to agriculture, all signs are reversed:

$$
\begin{array}{ll}
\dfrac{dt^{c*}}{dk} = \dfrac{\exp(-dr) f^f p_k}{\pi^a_t - \pi^f_t} < 0 & \dfrac{de^{f*}}{dk} = \dfrac{f^f_e p_k \pi^a_t}{p f^f_{ee}(\pi^f_t - \pi^a_t)} < 0 \\[2ex]
\dfrac{dt^{c*}}{dr} = \dfrac{\exp(-dr)\, d f^f p}{\pi^f_t - \pi^a_t} > 0 & \dfrac{de^{f*}}{dr} = \dfrac{d f^f_e \pi^a_t}{f^f_{ee}(\pi^a_t - \pi^f_t)} > 0 \\[2ex]
\dfrac{dt^{c*}}{dw} = \dfrac{e^f}{\pi^f_t - \pi^a_t} > 0 & \dfrac{de^{f*}}{dw} = \dfrac{\pi^f_t - \pi^a_t - \exp(-dr) f^f_e e^f p_t}{p f^f_{ee}(\pi^f_t - \pi^a_t)} \quad ? \\[2ex]
\dfrac{dt^{c*}}{dc^f} = \dfrac{1}{\pi^f_t - \pi^a_t} > 0 & \dfrac{de^{f*}}{dc^f} = \dfrac{\exp(dr)(\pi^f_t - \pi^a_t) + f^f p_t}{p f^f_{ee}(\pi^a_t - \pi^f_t)} > 0 \\[2ex]
\dfrac{dt^{c*}}{df^a} = \dfrac{\pi^a_{f^a}}{\pi^f_t - \pi^a_t} > 0 & \dfrac{de^{f*}}{df^a} = \dfrac{p_t f^f_e \pi^a_{f^a}}{p f^f_{ee}(\pi^a_t - \pi^f_t)} > 0
\end{array}
\qquad (25)
$$

5. A Land Use Simulation Model with Endogenous Timber Prices

The following simulation model has the same structure as the theoretical model in section 4. That model was based on an exogenous timber price path and, hence, on the assumption that timber output would not influence timber prices. The objective of the simulation model in this section, on the other hand, is to analyze dynamic land use in a situation in which timber prices respond to supply, as it would be expected, for example, for a local fuelwood market or for a large timber-exporting country. In addition, this section demonstrates that the price path assumption made in section 4 (declining rate of timber price increases) is consistent with the equilibrium price path for timber from mining unmanaged forests with managed forests available as a back-stop. Finally, the simulations illustrate the theoretical results of section 3 and could be used together with the required locational data to estimate deforestation effects in specific real-life policy situations.

The simulation model will endogenize the timber price path. This will make possible the evaluation of policies that have indirect effects on the timber price. For example, a land-based logging fee or the increase in plantation productivity would be likely to have effects on the timber price path that could not be captured by the model in section 4. This model tries to fill the gap between micro-forest models that focus on the optimal rotation period and input mix on a given piece of land and large scale, often global models of the forest sector (see for example Kallio, Dykstra and Binkley 1987) that do not allow the type of regional analysis required for understanding the effects of specific local policy interventions. The model is descriptive rather than prescriptive. Its purpose is to predict the impacts of a project or policy on the forest sector, rather than to determine the optimal level of forest cover or the costs and benefits of changes in the forest cover.

Some of the complexities of forest economics result from the dual nature of a standing forest as final output as well as productive capital. This model maintains the approach of the model in section 4 by distinguishing between unmanaged (or old-growth) forests and managed forests (or forest plantations). Even though this dichotomy is somewhat unrealistic, the distinction not only simplifies the analysis greatly but also clarifies the often opposite impact of a policy on managed versus unmanaged forests. Moreover, the distinction allows more precise analysis of policy impacts on different types of forested land. For example, if conservation of biodiversity is of greatest concern, the analysis would be focussed on logging of old-growth forest. If, on the other hand, global warming is concerned, the analysis would focus on total biomass in old-growth forests as well as plantations.

The Model

The model is based on a simple choice between land uses for agriculture, unmanaged and managed forests. Unmanaged forest is modelled as a mine, e.g. the forest is mature and no more growth in timber is occurring. Managed forests, on the other hand, are modelled as a crop with constant growth and continuous harvest. The model does not consider non-timber products of the forest. This approach is based on the assumption that logging decisions are made independent of non-timber uses of the forest. This in no way suggests that non-timber uses of the forest are less important. However, their importance would have to be reflected in a normative, rather than the present positive model.

The model simulates the market for timber as a single homogenous forest product. There are a finite number of periods $t = 1,...,T$. Supply of timber in any one period is determined by a land use model in which decision makers maximize profits from their piece of land by choice of land use and production inputs. Decision makers are profit maximizing owners of the land with perfect foresight. The timber market is competitive. Hence, land owners treat timber prices as exogenous.

Let Q be the set of all land classes. At any time t, Q is partitioned into five subsets according to the current use of a parcel of land. These subsets are A_t for land under agriculture cultivation, P_t for land under managed forests (plantation), I_p for land left idle, L_t for unmanaged forests that are logged at time t, and F_t for land covered with unmanaged forest. Land classes are denoted by a location index, d, that describes all differences between land classes. d can be a vector; however, in the simple model analyzed here, d is a scalar that can be thought of as distance from a market or transport costs with $d = \{1,2,3,...,D\}$. At time 0, all land is covered by unmanaged forest. After the unmanaged forest is logged in land class d, the owner faces the following profit functions for alternative land uses in each period.

For agricultural activities:

$$\pi_{at}(d) = r_a - c_a(d) \tag{26}$$

where r_a is the exogenous revenue from agricultural products grown on one unit of land and $c_a(d)$ is the cost of agriculture on land in class d with $dc/dd > 0$.

For tree plantations:

$$\pi_{pt}(d) = [p_t - c_p(d)]y_p(e_{pt}) - we_{pt} \tag{27}$$

where $y_p(e_{pt})$ is the annual timber yield as a function of effort e_{pt} ($dy_p/de_p > 0$, $d^2y_p/de_p^2 < 0$), $c_p(d)$ is the per unit cost of transporting timber, and w is the wage rate. The optimal level of effort, e_{pt}^*, is determined by the first order condition:

$$[p_t - c_p(d)]\frac{dy_p(e_{pt}^*)}{de_{pt}} = w \tag{28}$$

Let $\pi_t(d)$ denote the profit from the profit maximizing activity on land of class d:

$$\pi_t(d) = Max[\pi_{at}(d), \pi_{pt}(d), 0] \qquad (29)$$

At the time a unit of logging, the land owner receives the one-time profit:

$$\pi_{lt}(d) = [p_t - c_l(d)]y_l(e_{lt}) - we_{lt} \qquad (30)$$

where $y_l(e_l)$ is the timber yield as a function of effort e_l ($dy/de_l > 0$, $d^2y/de_l^2 < 0$), $c_l(d)$ is the per unit cost of transporting timber, and w is the wage rate. The optimal level of effort, e_l^*, is determined by the first order condition:

$$[p_t - c_l(d)]\frac{dy_l(e_{lt}^*)}{de_{lt}} = w \qquad (31)$$

Now, the owner determines the optimal time of logging, $t_l(d)$, at which the present value of all profits from a piece of land is maximized:

$$t_l(d) = \begin{cases} \underset{t}{argmax} \dfrac{\pi_l}{(1+i)^t} + \displaystyle\sum_{s=t+1}^{T} \dfrac{\pi_s(d)}{(1+i)^s} & if \ \underset{t}{\max} \dfrac{\pi_l}{(1+i)^t} + \displaystyle\sum_{s=t+1}^{T} \dfrac{\pi_s(d)}{(1+i)^s} > 0 \\ \infty & if \ \underset{t}{\max} \dfrac{\pi_l}{(1+i)^t} + \displaystyle\sum_{s=t+1}^{T} \dfrac{\pi_s(d)}{(1+i)^s} \le 0 \end{cases} \qquad (32)$$

where i is the owners discount rate, and $t_l(d) = \infty$ means that the forest in land class d is never logged.

Let d_t denote land of class d at time t. Then profit maximizing land use over time is completely described by the following partition of all land classes at all times t:

$$d_t \in \begin{cases} F_t & \textit{if } t_l(d) > t \\ L_t & \textit{if } t_l(d) = t \\ I_t & \textit{if } t_l(d) < t \wedge \pi_a(d) \leq 0 \wedge \pi_{pt}(d) \leq 0 \\ P_t & \textit{if } t_l(d) < t \wedge \pi_{pt}(d) > 0 \wedge \pi_{pt}(d) \geq \pi_a(d) \\ A_t & \textit{if } t_l(d) < t \wedge \pi_a(d) > 0 \wedge \pi_a(d) > \pi_{pt}(d) \end{cases} . \tag{33}$$

Let q(d) be the quantity of land in each land class, then timber supply, s_t, is given by the sum of production of timber from logging and plantations for each period:

$$s_t = \sum_{d \in L_t} q(d) y_l(e_{lt}^*(d,t)) + \sum_{d \in P_t} q(d) y_p(e_{pt}^*(d,t))$$

The model is closed by assuming a demand function for timber in period t, x. x is a function of timber price, p_t and t,

$$x_t = x_t(p_t) \tag{35}$$

The model is solved by determining the equilibrium price path for timber that leads to market clearing in all periods.

Implementation and Simulation Results

The implementation of the model is based on numerical simulation of the modelled timber market. The market clearing price path is determined by a Mathematica program through an iterative procedure (see the appendix to this section). Once the equilibrium price path is found, land use over time is calculated from the timber supply model.

For the numerical simulations, the following functional forms are used in the model: Demand: $x=k_1p^{-1}$. Logging: $y_l=k_2(1\text{-}\exp[-k_4e_l])$. Plantation: $y_p=k_3\text{Sqrt}(e_p)$. k_1, k_2, k_3, and k_4 are constants. Several simulations were run for hypothetical parameter values and variations from the base case parameters that represent generic unanticipated shocks. The parameter values used in the simulations are listed in the Mathematica program in the appendix. The parameter values were chosen to represent a broad mix of relative profitability of logging unmanaged forests, managed forests and agriculture. Other parameter values were tried and yielded the same qualitative results as presented below. The chosen parameter values, however, yielded continuous land use patterns that make the main results easier to convey graphically. Note that if land classes include not only transportation costs but also other locational parameters, land classes adjacent in the diagrams need not be geographically adjacent.

The equilibrium timber price path and resulting profit maximizing land use in the base case scenario are shown in Figure 5. Note that in this and all other simulations, the resulting equilibrium price path for timber, shows the characteristic of declining rates of increase, as it was assumed for the analysis in section 2 ($p_t > 0$, $p_{tt} < 0$). Intensity of logging and managing forests increases in the current timber price and decreases in site specific production costs. Hence, a scenario with a higher price path implies higher intensity in logging and managing forest at the same location, compared to the base case, and vice versa.

The following paragraphs describe the effect that various modifications in the economic parameters have on the land use patterns compared to the base case introduced above. For simplicity, all simulations are based on a modification of the initial model parameters. Alternatively, an unanticipated shock could be imposed at a later time. The expected qualitative outcome would be the same. The focus of the following discussion is on the differences in land use patterns over time between the base case and the modified scenarios. These differences are the effects that changes in the economic parameters at time zero have on land use, and are, thus, the focus of interest.

The effect of timber price path changes on land use can be analyzed in several ways. The first scenario analyzed imposes a timber tax of 10 monetary units (about 40 percent of the steady state price in the base case). Hence, the model is run to clear the markets with consumer prices set 10 units higher than producer prices. The resulting drop in producer prices is equivalent to the effects of log-export restrictions. This tax leads to a reduction in the producer price compared to the base case that is shown in Figure 6. Consistent with the results of the analysis in section 4, the reduced producer price path leads to a reduction in logging of unmanaged forests and a decrease in the area with managed forests. Hence, the area with unmanaged forests increases, while the area with managed forests decreases. Agriculture contracts at the margin with unmanaged forests and expands at the margin with managed forests.

The effects of a logging fee per area of unmanaged forest is shown in Figure 7. Such a fee could be rationalized as a Pigouvian tax for the external benefits from the standing natural forest. The results of such a fee are a reduction in logging of unmanaged forests. This reduction in logging leads to a reduction in managed forests at the extensive margin. Because of the low intensity of forestry at the extensive margin, the fee leads to a relatively small reduction in timber output after the steady state is reached. Timber prices would be somewhat higher than in the base case, and the margin between agriculture and managed forests would shift in favor of managed forests.

Figure 8 shows the case of transportation costs for timber and agricultural products reduced by 10 percent. With the assumed parameter values, this reduction in transportation cost benefits agriculture more than forestry. Within agriculture or forestry it reduces costs more for land classes with a higher index number (representing further distance). As a result, a reduction in transportation costs leads to increased pressure on the margin and an expansion of agriculture and managed forest at the expense of unmanaged forest. The effect of road building on the timber price path and logging intensity is ambiguous since the reduction in transportation unit costs and the increase in distance due to increased logging operate in opposite directions.

An increase in agricultural productivity is modelled as a one-third increase of the agricultural output quantity that can be sold at a fixed price. This assumes infinite elasticity of the demand for the agricultural product, which could be expected for the exports of a homogenous cash crop from a small country. As shown in Figure 9, the increase in yields would lead to an increase in the agricultural area. The resulting timber price increase would shift the managed forest area into the area of unmanaged forests, which would decline. Of course, these effects depend on the assumed characteristics of the agricultural market. If, in the other extreme, demand for the agricultural product was totally inelastic (i.e. for a subsistence crop), the agriculture area would decline with yield increases, the timber price would fall, and the pressure on unmanaged forests would be reduced.

Figure 10 shows a situation in which no managed forestry exists. This scenario helps understand the effect of forest plantations on unmanaged forests. Without managed forests, timber is a non-renewable resource with increasing extraction costs. As a result, the price path shows an increasing rate of price increase. In the short-run, the introduction of managed forests increases logging of unmanaged forests since managed forests create additional demand for land. The long-run effect, however, is different. Without managed forests, timber prices would rise until all unmanaged forests are (at least asymptotically) depleted. With managed forests, a cap is put on the rise of timber prices at the level at which all demand can be supplied from managed forests. When this price level is reached, it will not be profitable to log remaining unmanaged forests. Hence, the introduction of managed forests increases the area of unmanaged forests that is ultimately preserved.

A scenario of quadrupling the decision maker's discount rate is presented in order to analyze the effects of different tenure regimes on land use patterns. Figure 11 shows the effects of an increased discount rate that could result from a reduced time horizon or increased tenure uncertainty. The variation from the base case is surprisingly small in this scenario. The agriculture area expands into the managed forest area because timber prices are lower and the returns to forestry decline relative to agriculture due to the longer growth period for trees. However, logging of unmanaged forests increases only slightly with a higher discount rate. With the assumed parameter values, timber rents at the margin of unmanaged forests are relatively low, or even negative, since the distance from the center is high. Hence, clearing land is an investment that is less profitable with a higher discount rate. This simulation result indicates that there are some parameter values at which deforestation is driven by the timber price/transport cost interaction and may be relatively unaffected by long-term tenure questions. Under the assumptions made, increasing tenure security alone would not drastically reduce deforestation.

The last scenario compares the base case with an open access scenario. Figure 12 shows this scenario. Logging of unmanaged forests is advanced drastically since it occurs as soon as conversion profits are positive. In the long-run, however, the remaining unmanaged forest is the same with open access and secure property rights since in both cases all lands with positive conversion profits will ultimately be logged. Under open access, the timber price is initially lower (because of excessive supply from still abundant forests), later higher (because excessive logging leads to higher transportation costs) and finally equal to the secure property rights case. Note, that in the open access case it is assumed that property rights are established once the unmanaged forest is logged.

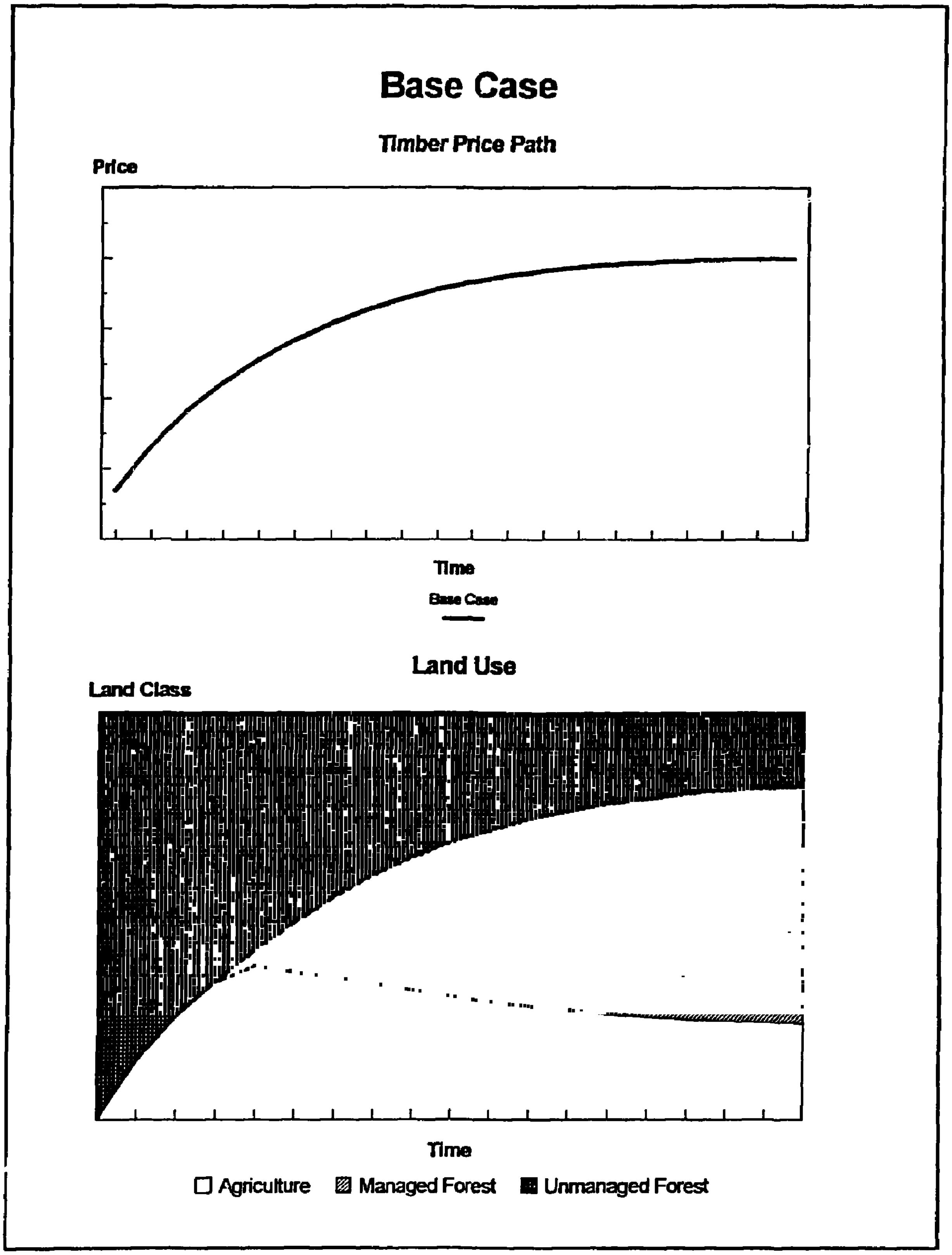
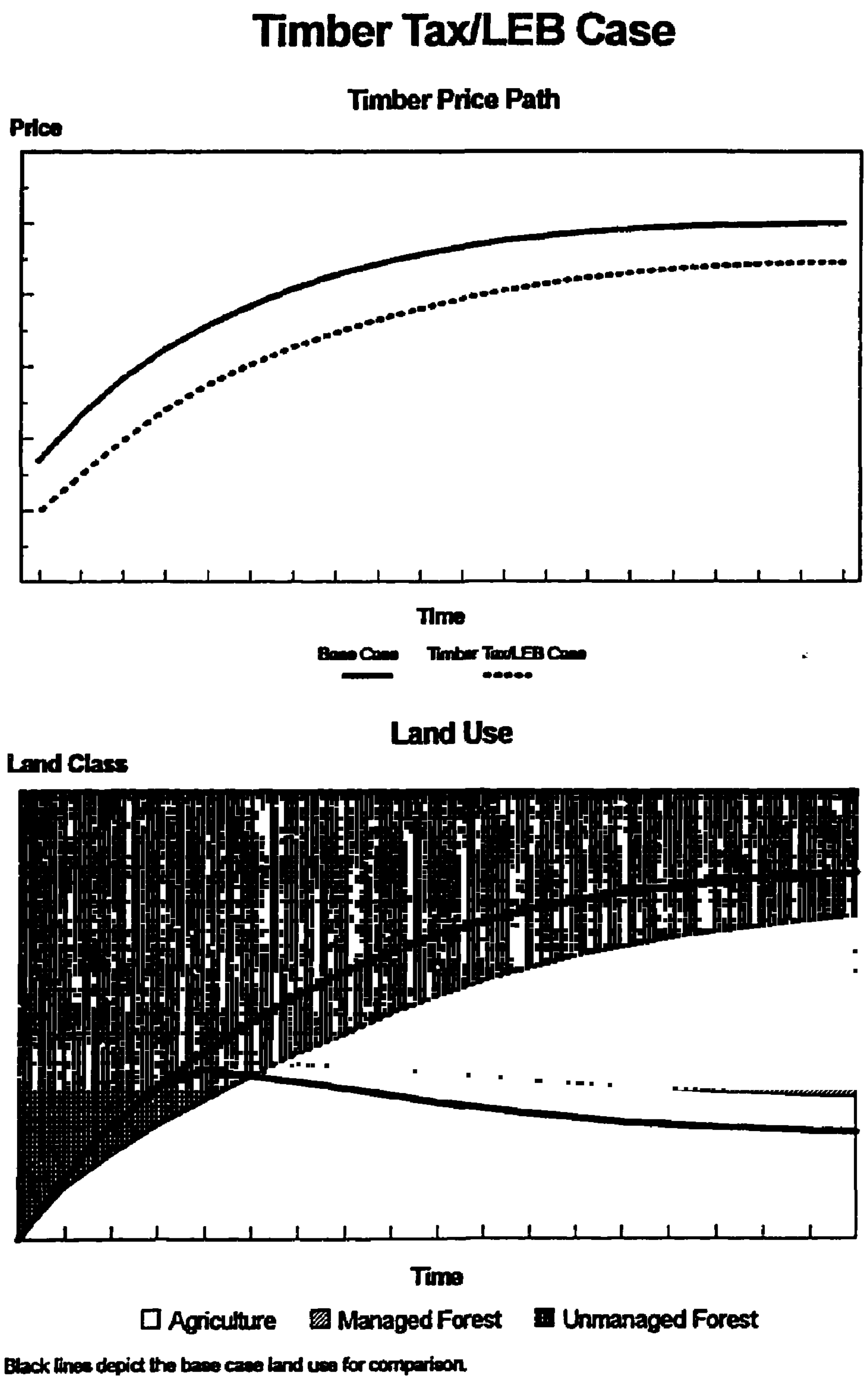

Base Case
Timber Price Path
Price
Time
Base Case
Land Use
Land Class
Time
☐ Agriculture
▨ Managed Forest
■ Unmanaged Forest

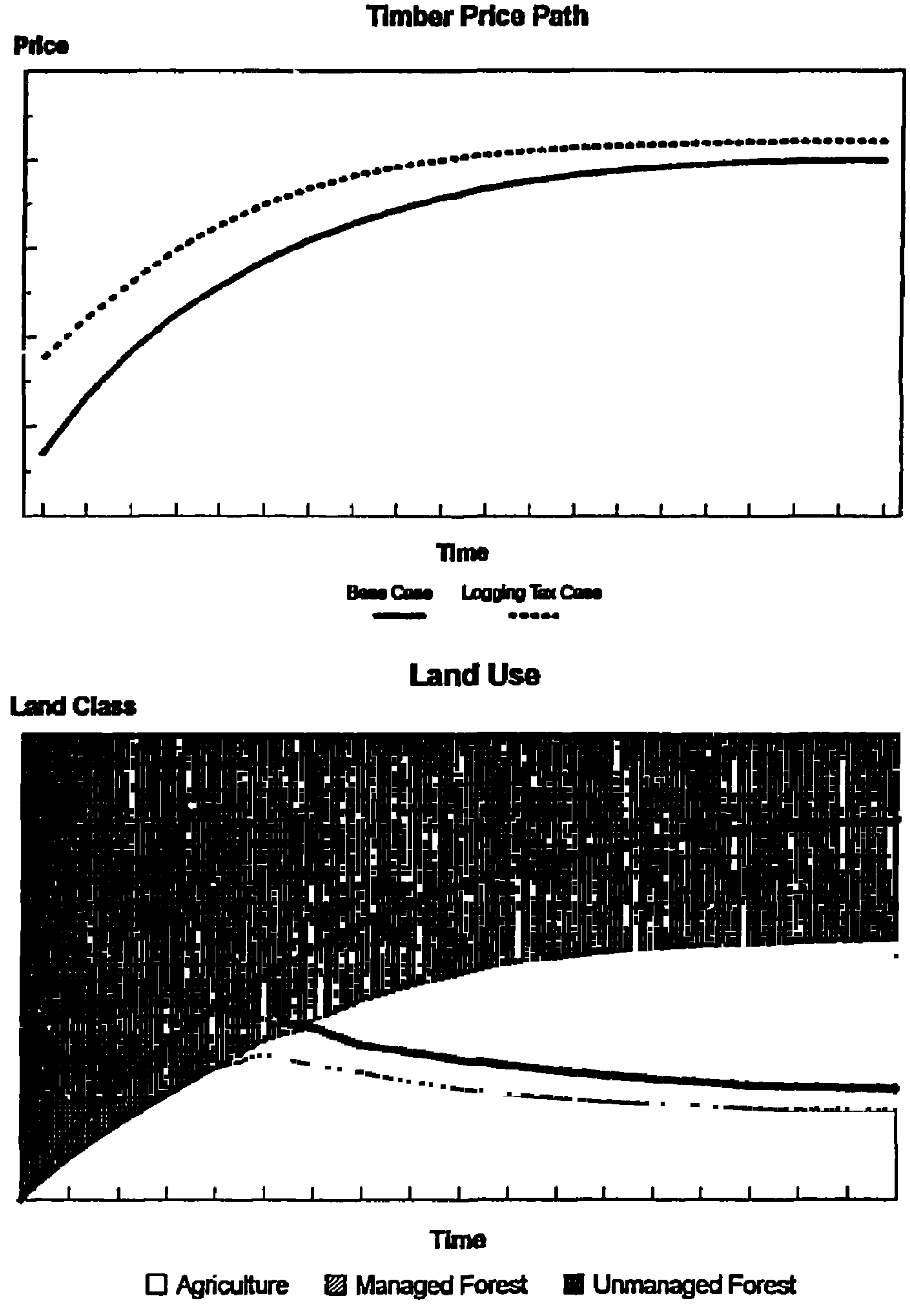
Figure 5



Timber Tax/LEB Case

Black lines depict the base case land use for comparison.

Figure 6



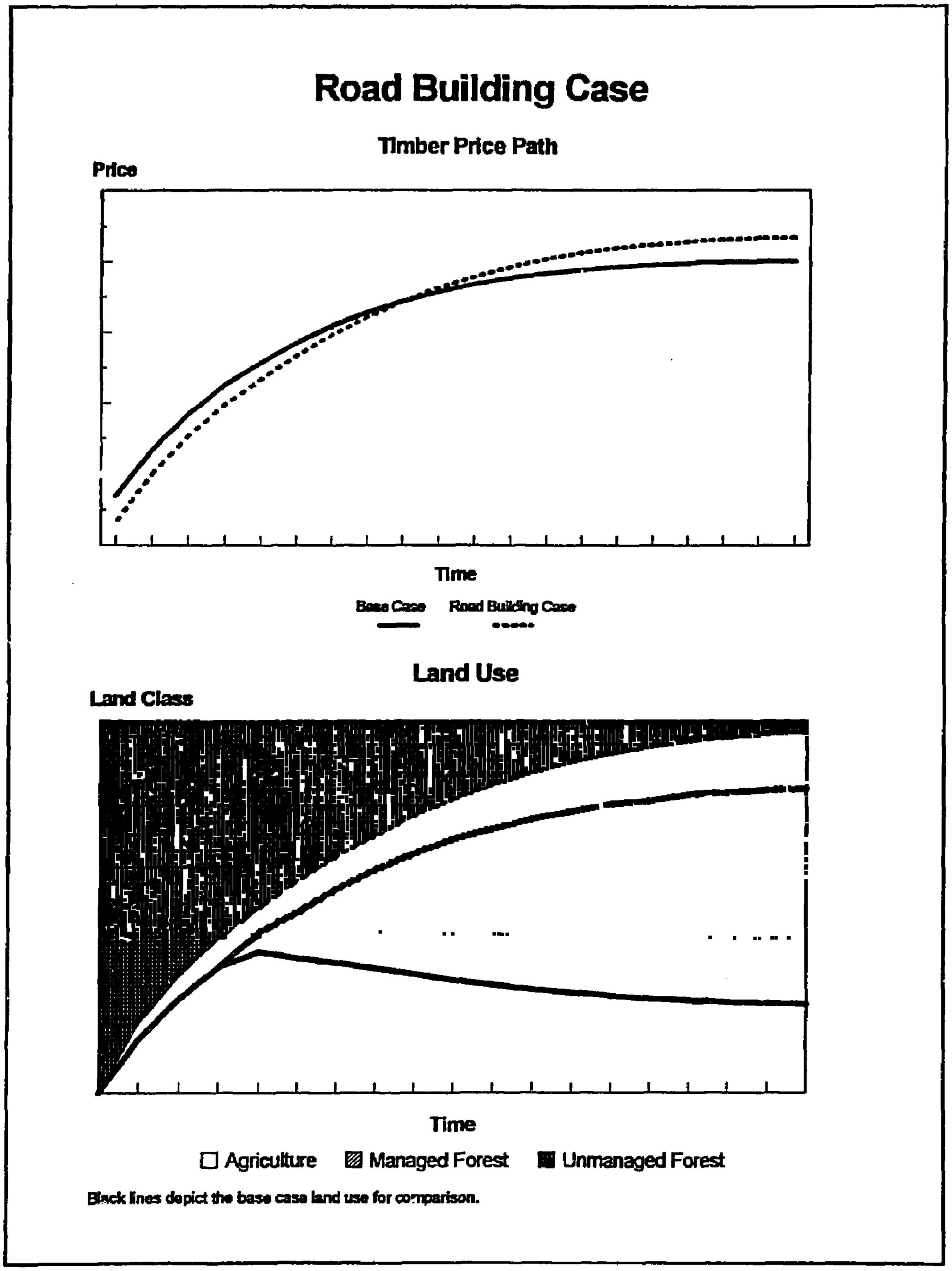
Logging Tax Case

Timber Price Path

Land Use

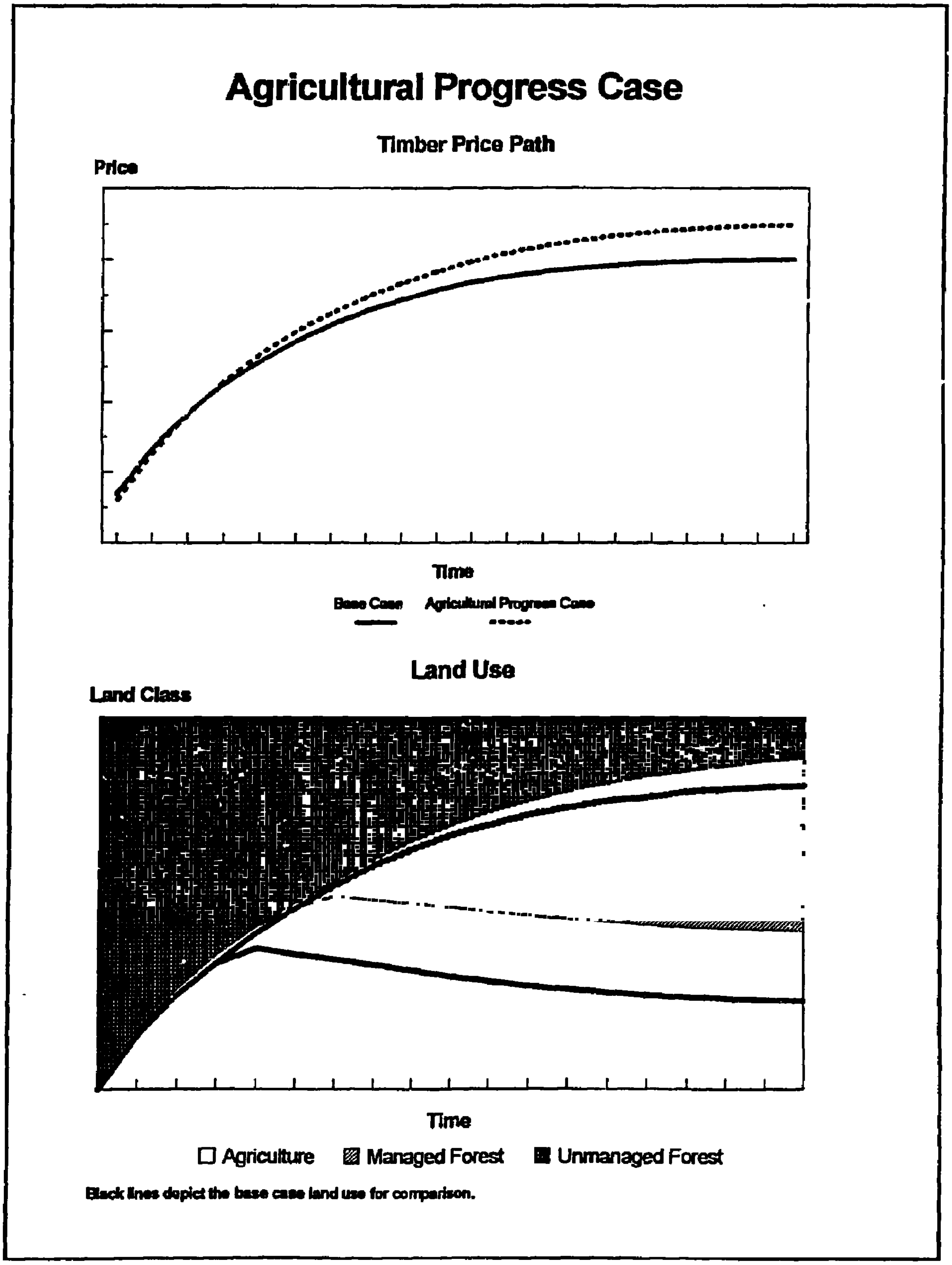
Black lines depict the base case land use for comparison.

Figure 7



Black lines depict the base case land use for comparison.

Figure 8



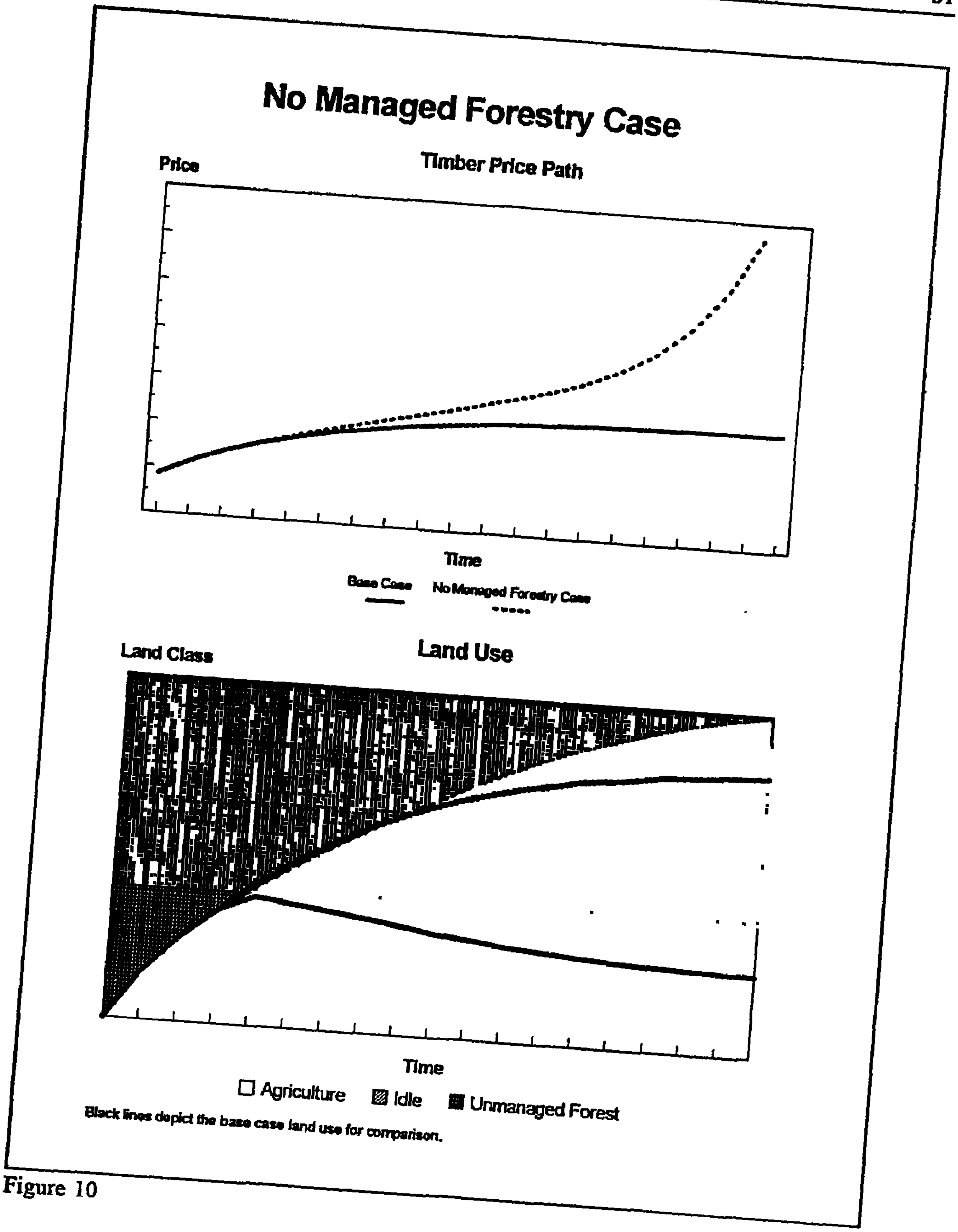
Agricultural Progress Case

Timber Price Path

Land Use

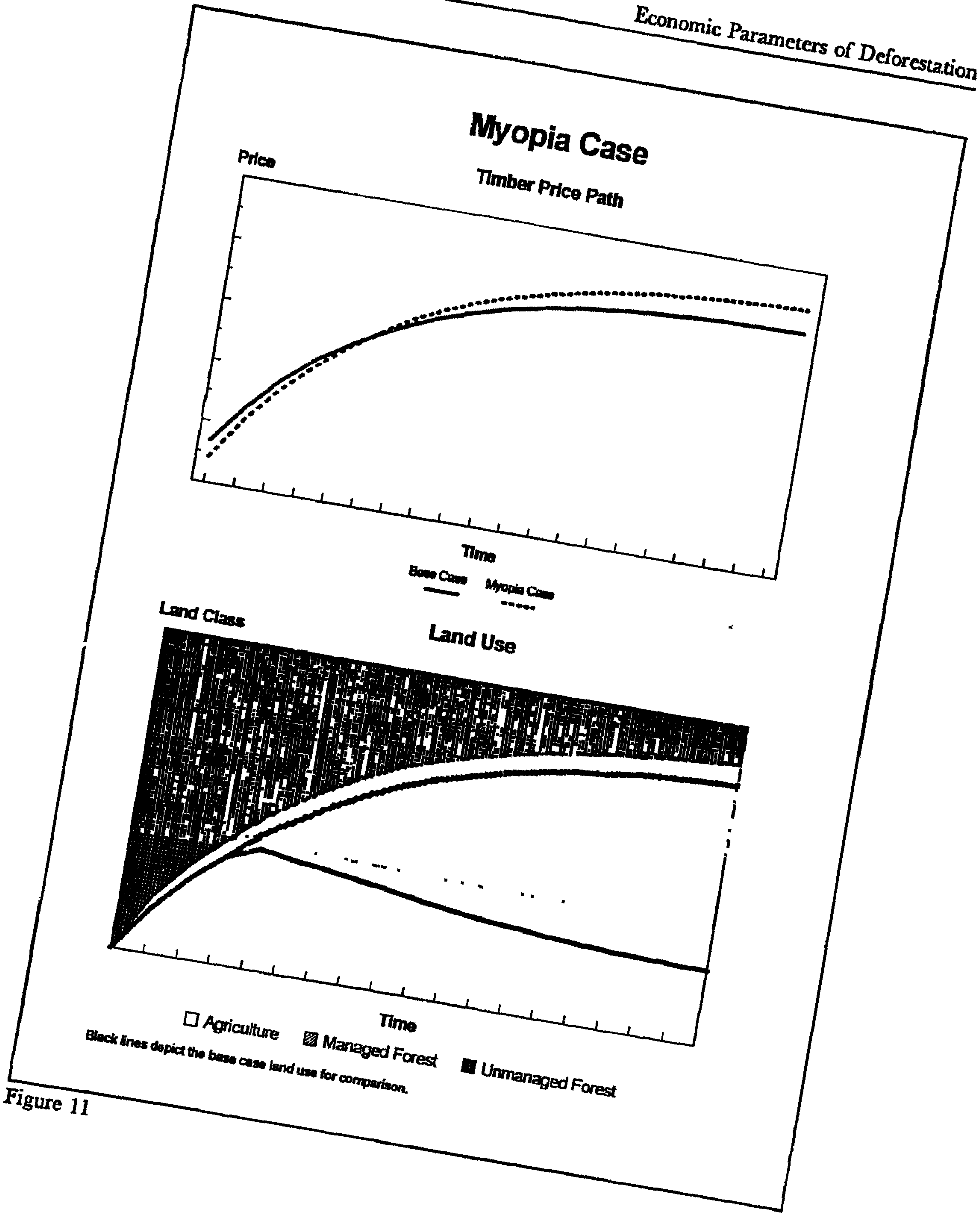
Black lines depict the base case land use for comparison.

Figure 9



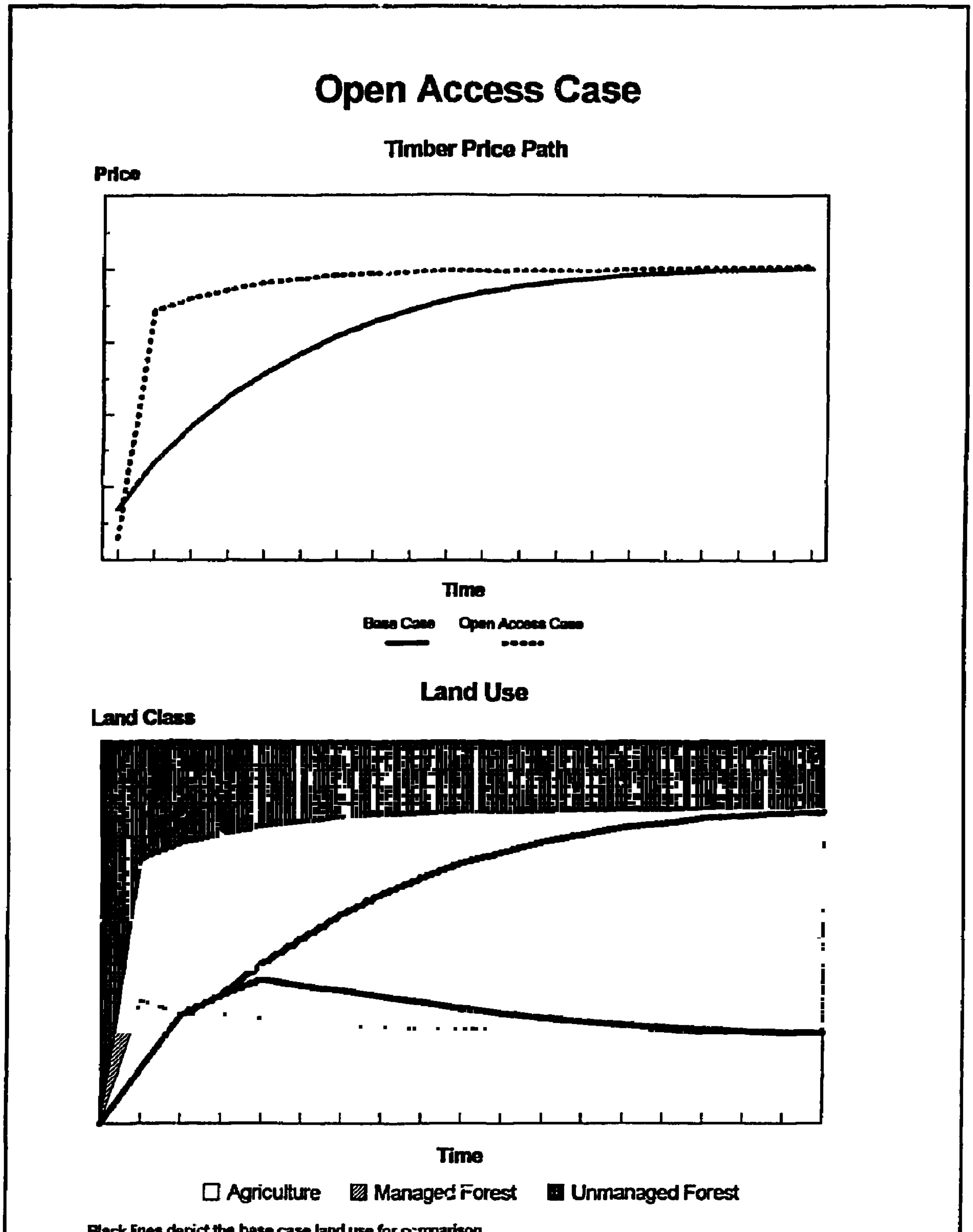
Black lines depict the base case land use for comparison.

Figure 10



Black lines depict the base case land use for comparison.

Figure 11



Black lines depict the base case land use for comparison.

Figure 12

Appendix to Section 5: The Mathematica Program

Base Case

```
<<Graphics`Graphics`
Off[General::spell1]
Off[General::spell]
Off[Power::infy]
Off[Solve::ifun]

(* program control variables *)

dmax=30;                (* highest land index, d *)
dsteps=20;              (* initial number of land index increments *)
tsteps=20;              (* number of time periods *)
thresh = 5;             (* tolerated excessdemand *)
adj = 0.006;            (* initial price adjustment factor *)
iterations = 0;         (* set iteration counter *)
propertyrights = True;
nonpositive[x_] = Min[x,0];

(* economic variables *)

iagx=60;                (* initial agricultural output quantity *)
agx=60;                 (* initial agricultural output quantity *)
agel=1;                 (* price elasticity for agricultural demand *)
arevenue=agx*(iagx/agx)^(1/agel);
                        (* gross revenue from land in agriculture *)
a=5;                    (* cost coefficient for agriculture *)
pproduction=10;         (* plantation productivity factor *)
b=1;                    (* plantation cost factor *)
fstock=28;              (* timber stock in old growth forest *)
logefactor = 50;
                        (* productivity factor of effort in logging *)
c=1.3;                  (* logging cost factor *)
r=.5;                   (* discount rate *)
w = 200;                (* wage rate *)
price = Table[30,{i,tsteps}];
                        (* timber price *)
lltax = 1;              (* logging tax per land unit *)
lttax = 0;              (* logging tax per timber unit *)
pltax = 0;              (* plantation tax per land unit *)
pttax = 0;              (* plantation tax per timber unit *)

demand := Table[1000*(price[[i]])^(-1),{i,tsteps-1}];
                        (* timber demand *)
acost[d_] := a*d;
                        (* per-land transport cost of agriculture *)
pcost[d_] := b*d;
                        (* per-timber transport cost of plantation *)
fcost[d_] := c*d;
                        (* per-timber transport cost of logging *)

plantprod[e_] := Sqrt[e]*pproduction;
                        (* plantation output as function of effort *)
plantprof[d_,p_,e_] := E^(-r)*((p - pcost[d] - pttax) * plantprod[e] - w * e
        - pltax);
                        (* plantation profit *)
temp1 = D[plantprof[d,p,e],e];
                        (* first derivative of profits *)
temp3 = Simplify[e /.First[Solve[temp1==0,e]]];
                        (* profit masximizing effort in plantations *)
temp2 = D[temp1,e] /. e->temp3;
                        (* second derivative of profits *)

logprod[e_,q_] := (1-E^(-q*e)) * fstock;
                        (* logging output as function of effort *)
logprof[d_,p_,e_] := ((p - pcost[d] - lttax) * logprod[e,logefactor] -
        w * e - lltax);
                        (* logging profit *)
temp4 = D[logprof[d,p,e],e];
                        (* first derivative of profits *)
temp6 = Simplify[e /.First[Solve[temp4==0,e]]];
```

```
                        (* profit maximizing effort in logging *)
temp5 = D[temp4,e] /. e->temp6;
                        (* second derivative of profits *)

excessdemand = Table[10000,{i,tsteps-1}];

adjthresh = fstock*dmax/dsteps*1.5;
d = dincr*dmax/dsteps;

While[Max[Abs[N[excessdemand]]]>thresh && iterations < 100,(

(* reducing d spacing if excessdemand below adjthresh *)

If[Max[Abs[N[excessdemand]]]<=adjthresh,

        dsteps=dsteps*2;
        adjthresh = fstock*dmax/dsteps*1.5;
        d = dincr*dmax/dsteps];

(* Calculation of profits and optimal effort for different land uses *)

agriculture = N[Table[arevenue - acost[d],
        {dincr,dsteps},{t,tsteps}]];
                (* d't matrix of profits from agriculture *)

plantation = N[Table[
        ntemp2 = Evaluate[temp2 /. p->price[[t]]];
        effort = Evaluate[temp3 /. p->price[[t]]];
        If[Sign[Re[ntemp2]]===-1 && Im[effort]===0 &&
        Sign[Re[N[effort]]]===1,
                {plantprof[d,price[[t]],effort],
                effort},{-pltax,0}],
        {dincr,dsteps},{t,tsteps}]];
                (* d't'2 matrix of profits and optimal effort in plantation *)

logging = N[Table[
        ntemp5 = Evaluate[temp5 /. p->price[[t]]];
        feffort = Evaluate[temp6 /. p->price[[t]]];
        If[Sign[Re[ntemp5]]===-1 && Im[N[feffort]]===0 &&
        Sign[Re[N[feffort]]]===1,
                {logprof[d,price[[t]],feffort],
                feffort},{-lltax,0}],
        {dincr,dsteps},{t,tsteps}]];
                (* d't'2 matrix of profits and optimal effort in logging *)

(* Present value of annual profits of highest value cultivation *)

pvcprofit = N[Table[Max[0,Part[agriculture,dincr,t],
        Part[plantation,dincr,t,1]]/((1+r)^t),
        {dincr,dsteps},{t,tsteps}]];

(* Highest value cultivation *)

cultivation = N[Table[Which[Part[agriculture,dincr,t]<=0 &&
        Part[plantation,dincr,t,1]<=0,5 (* idle *),
        Part[agriculture,dincr,t]<=Part[plantation,dincr,t,1],1 (* plantation *),
        Part[agriculture,dincr,t]>Part[plantation,dincr,t,1],3 (*agriculture *)],
        {dincr,dsteps},{t,tsteps}]];

(* Present value of logging + cultivating highest value thereafter *)

loggingpv = N[Table[Sum[Part[pvcprofit,dincr,i],{i,t+1,tsteps}]+
        Part[pvcprofit,dincr,tsteps]/r+
        Part[logging,dincr,t,1]/((1+r)^t),
        {dincr,dsteps},{t,tsteps-1}]];

(* d vector of optimal time for logging *)

If[propertyrights,

        logtime = N[Flatten[Table[If[Max[Part[loggingpv,dincr]]>0,
                Last[Position[Part[loggingpv,dincr],
                Max[Part[loggingpv,dincr]]]],
                tsteps+1],{dincr,dsteps}]]],
```

```
        logtime = N[Flatten[Table[If[Max[Part[loggingpv,dincr]]>=0,
                First[Position[Map[nonpositive,Part[loggingpv,dincr],{1}],
                0]],tsteps+1],{dincr,dsteps}]]]

];

(* d*t matrix of optimal land use *)

landuse = N[Table[Which[t<Part[logtime,dincr],4 (* forest *),
        t==Part[logtime,dincr],2 (* logging *),
        t>Part[logtime,dincr],
        Part[cultivation,dincr,t]],
        {dincr,dsteps},{t,tsteps-1}]];

(* t vector of timber supply *)

supply = N[Table[Sum[Which[Part[landuse,dincr,t]==1,
        plantprod[Part[plantation,dincr,t,2]]*dmax/dsteps,
        Part[landuse,dincr,t]==2,
        logprod[Part[logging,dincr,t,2],logefactor]*dmax/dsteps,
        True,0],{dincr,1,dsteps}],
        {t,1,tsteps-1}]];

excessdemandold = excessdemand;
excessdemand = N[demand-supply];
priceold = N[price,5];
iterations = iterations+1;

(* determining response of excessdemand to previous iteration's price
   change, and adjusting price adjustment factor 'adj' *)

If[iterations>1,
        elast = N[Sum[If[Abs[excessdemandold[[t]]]<adjthresh/2,1,
        Abs[(excessdemand[[t]]-excessdemandold[[t]])/
        excessdemandold[[t]]]],{t,tsteps-1}]/(tsteps-1)],
        elast = 1];
Which[elast>1,adj=adj/2,elast<0.5,adj=adj*2];

(* calculating timber price for next iteration *)

price = Join[Table[N[
        If[Abs[excessdemand[[t]]]<adjthresh/2,
        priceold[[t]],priceold[[t]]+adj*excessdemand[[t]]]],
        {t,tsteps-1}],
        {N[If[Abs[excessdemand[[tsteps-1]]]<adjthresh/2,
        priceold[[tsteps-1]],
        priceold[[tsteps-1]]+adj*excessdemand[[tsteps-1]]]]}];

Print[{iterations,dsteps,{adjthresh,Max[Abs[excessdemand]]},elast,adj}];

}]  (* Close WHILE loopp *)

olddsteps = dsteps;
oldlogtime = logtime;
oldlanduse = landuse;

(* Show graph of land use over timber price: olive-forest,
gray-idle, green-plantation, brown-agriculture, black-
logging *)

graphmat = Table[Which[Part[landuse,dincr,t]==1,
        Hue[0.25,1-E^(-1*Part[plantation,dincr,t,2]),1],
        Part[landuse,dincr,t]==2,
        Hue[0,0,E^(-1*Part[logging,dincr,t,2]*logefactor)],
        Part[landuse,dincr,t]==3,Hue[1,1,.5],
        Part[landuse,dincr,t]==4,Hue[.25,1,.5],
        Part[landuse,dincr,t]==5,Hue[.5,.5,.5]],
        {dincr,dsteps},{t,tsteps-1}];

Show[Graphics[RasterArray[graphmat],Axes->True,
        AxesLabel->{"time","d"}]]

(* graph of timber supply *)
```

```
BarChart[supply]
```

```
(* Graph of timber price *)
```

```
ListPlot[price,PlotJoined->True]
```

Modifications from above program for alternative scenarios:

Timber Tax Case

```
demand := Table[1000*(price[[i]]-10)^(-1),{i,tsteps-1}];
```

Logging Fee Case

```
lltax = 250;
```

Road Building Case

```
a=4.5;
b=.9;
c=1.17;
```

Agricultural Progress Case

```
iagx=80;)
agx=80;
```

No Plantation Case

```
pproduction=0.001;
```

Myopia Case

```
r=2;
```

Open Access Case

```
propertyrights = False;
```

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