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Source: *The American Economic Review*, Vol. 88, No. 4 (Sep., 1998), pp. 686-710

Published by: [American Economic Association](#)

Stable URL: <http://www.jstor.org/stable/117001>

Accessed: 04/07/2011 13:41

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# Valuing the Impact of Large-Scale Ecological Change in a Market: The Effect of Climate Change on U.S. Timber

By BRENT SOHNGEN AND ROBERT MENDELSON\*

*This paper establishes a methodology for valuing the impact of large-scale ecological changes in a market. Given the large capital stocks inherent in most ecological systems, the dynamic nature of most ecological change, and the dynamic response of markets, it is critical to build dynamic models to capture the resulting effects. This paper demonstrates how to construct such a model using the impacts of climate change on U.S. timber markets as an example. Across a wide range of scenarios and models, warming is predicted to expand timber supplies and thus benefit U.S. timber markets. (JEL Q10, Q25)*

Many large-scale ecosystem changes result from land management practices or pollution emissions of expanding populations and growing economies. Large-scale ecosystem changes are defined as those occurring over broad areas and potentially long time periods. They may include catastrophic forest fires, shifting from older to younger forests, soil erosion, or altered water quality and aquatic habitat. Combined, these changes are putting increased pressure on the renewable resources needed for market and nonmarket purposes. Society must weigh the costs of preventing or at least mitigating these changes against the damages these changes cause. Unfortunately, many large-scale phenomena, such as those predicted during climate change (Vegetation/Ecosystem Modeling and Analysis Project [VEMAP] Members, 1995), occur over such a large area and an extended period of time, it is difficult to value the stream of impacts.

This paper develops methods for empirically valuing large-scale ecological change in a market for natural resource products. The approach is illustrated with a specific application to measure the impact of climate change on U.S. timber markets. Assessing the impact of climate change on timber markets is interesting for two reasons. First, it entails particularly large-scale ecosystem changes, such as a massive redistribution of the range of existing timber species and substantial changes in annual growth rates (VEMAP Members, 1995). Although these changes may differ from, or may be larger than, those expected from other ecosystem disturbances, the techniques provide important insights into valuing changes regardless of scale. Second, like the valuation of many other ecological changes, it requires dynamic, rather than steady-state, analysis.

Much of the empirical research into valuing ecological change in markets for natural resource products, however, continues to rely on steady-state analysis. Although theoretical dynamic methods are well established (Colin W. Clark, 1990), empirical fishery models, such as those by Jon M. Conrad (1989), James R. Kahn and W. Michael Kemp (1985), and Robert J. Johnston and Jon G. Sutinen (1996), all utilize static approaches. While the forestry literature has addressed dynamic stock adjustments (Kenneth S. Lyon and Roger A. Sedjo, 1983; Richard Brazee and Mendelsohn, 1990), it has not adequately considered how stocks will adjust to dynamic ecosystem changes.

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In the case of climate change, for example, J. Mac Callaway et al. (1994) utilize a dynamic forest market model, but they adopt static climate and ecological models which compare the current climate to a doubled CO<sub>2</sub> equilibrium climate. Others, such as Linda A. Joyce et al. (1995) and John Perez-Garcia et al. (1997) all adopt static economic models that cannot capture intertemporal adaptation.

This paper distinguishes itself from this previous research by focusing specifically on the dynamic adjustment pathway. As shown, this focus turns out to have important consequences for valuing large-scale ecological change. Characterizing this dynamic adjustment pathway rests on three dynamic features. First, the stimulus of change often has an intertemporal path of its own. In our example of climate change, recent predictions suggest that temperature will increase linearly over the next century as greenhouse gases gradually accumulate in the atmosphere (see John T. Houghton et al., 1996).

Second, dynamic ecological change often entails lags and adjustments in the ecological system so that different outcomes occur over time in response to the external stimulus. In the case of climate change, forests may respond at first with widespread dieback as trees fail to adjust to new conditions, followed by a period of adaptation. To capture ecological effects, this study carefully combines climatological, biogeochemical, and biogeographical model results with an economic model to integrate findings from natural science into economic analysis.

Third, the market adjusts and adapts to the external stimulus. To adjust to large-scale change, the market can move harvests over time, plant new trees in anticipation of future needs, and salvage dying forests. The welfare outcome resulting from these complex dynamic adjustments cannot be captured accurately with static models. Given the large capital stocks involved, the dynamic nature of most ecological changes, and the dynamic response of markets, the static comparisons of Callaway et al. (1994), Joyce et al. (1995), and Perez-Garcia et al. (1997) provide poor approximations of the resulting adjustment path.

Section I constructs a dynamic economic model of U.S. timber markets, and describes how the basic model can be adapted to capture

the large-scale effects of climate change. Section II then calibrates the models with market and ecological data, and simulations are developed for multiple climate, ecological, and economic scenarios. Section III presents the results, including a comparison with two static scenarios. These scenarios demonstrate that steady-state comparisons, such as those made in the earlier literature, do not capture the value of ecological impacts in timber markets accurately. In some scenarios northern forests dieback early during climate change, but market adaptation hastens forest adaptation, and it allows the positive long-run benefits of expanding southern forests to occur more quickly.

These results differ dramatically from earlier, regional studies. For example, Joel B. Smith and Dennis Tirpak (1989) predicted that climate change would damage American forests, even though they did not predict market impacts. Their prediction, however, led some economists to conclude that climate change would harm U.S. timber markets (William R. Cline, 1992; Samuel Fankhauser, 1995). More recent economic studies have been more optimistic about timber impacts (see Joyce et al., 1995; Perez-Garcia et al., 1997), but they rely on static economic models that cannot capture stock effects like dieback or shifting ecosystem boundaries.

While impact of climate change on U.S. timber markets is just one of the many sectors likely to be affected by climate change [see James Bruce et al. (1996) for a discussion of nonmarket impacts and Mendelsohn and James Neumann (1998) for a discussion of impacts on other sectors], the importance of capturing dynamic features applies to most service flows from ecosystems, including nonmarket sectors. For example, although it is unclear how public suppliers of forestland will respond to climate change, users of nonmarket services will likely make some attempt to adapt to changing circumstances. To account for the entire set of damages for the globe, one would need to aggregate estimates for different sectors and regions. While timber market damages are likely to represent only a small part of the impacts in developed economies, the dynamic methods described in this paper can be transferred to regions where timber markets are more important to national economies.

## I. A Dynamic Model of Ecological Change

### A. General Case

We begin by developing an ecological-economic model of a renewable resource. Because the dynamic change being measured is complex, a deterministic model is used for tractability. An interesting next step to explore would be to develop a stochastic dynamic programming model of these same decisions.

The resource we consider is composed of stocks of different organisms,  $X_i(t)$ . Each organism grows market products according to  $V_i(a_i(t))$ , where  $a_i(t)$  is the age of the organism of type  $i$  in the system at time  $t$ . Following generic population and organismal biology,  $V_{a_i} > 0$  and  $V_{a_i a_i} < 0$  (for each organism), where the subscripts denote partial derivatives. The output at any moment of this entire system is the sum of the organisms harvested,  $H_i(t)$ , times the output per organism:

$$(1) \quad Q(t) = \sum_i H_i(t) V_i(a_i(t)).$$

Demand for these products is derived from a well-behaved utility function over these and all other goods. An inverse demand function can be expressed as

$$(2) \quad P(t) = D(Q(t), \mathbf{Z}(t)),$$

where  $\mathbf{Z}(t)$  is the vector of all other goods purchased. Demand can shift over time subject to forces in the economy such as overall growth and changes in per capita income. Although there may be several different types of species or organisms, each with a distinctive yield, for simplicity of exposition, we assume that output across organisms is quality adjusted so that total quantity is simply the sum of the products of individual organisms. A more complex demand system model could be constructed to represent quality issues more carefully but would distract from the dynamic focus of this paper.

With equation (2), a Marshallian welfare measure of net consumer and producer surplus can be calculated for each time period as the area under the demand curve minus the costs

of harvesting, regenerating, and holding land in each time period:

$$(3) \quad S(Q(t), \mathbf{Z}(t), \mathbf{G}(t), \mathbf{X}(t)) \\ = \int_0^{Q^*(t)} \{ D(Q(t), \mathbf{Z}(t)) - C(Q(t)) \} dQ(t) \\ - \sum_i \beta_i G_i(t) - \sum_i R_i(t) X_i(t),$$

where  $C(Q(t))$  is the cost of harvesting,  $\beta_i$  is the marginal cost of regenerating an organism,  $G_i(t)$  is the number of organisms regenerated, and  $R_i(t)$  is a rental cost associated with holding an organism in year  $t$ . Although many ecological stocks regenerate naturally, society can enhance regeneration through investments in each period. The total size of the population at time  $t$ ,  $X_i(t)$ , therefore will depend on the initial population size, less what is harvested, plus what is regenerated. Rent,  $R_i(t)$ , captures the opportunity costs associated with the use of underlying resources, such as land. In some circumstances, it may be zero because there is no opportunity cost of the resource. For example, there may be little else one can do with the oceans other than growing fish. However, for most terrestrial resources,  $R_i(t)$  typically is not zero, and it plays a role in harvest and regeneration decisions. Further, total rent,  $\sum_i R_i(t) X_i(t)$ , varies with the size of the stock. Tracking the change in rent is particularly important during ecological change, when the size of  $X_i(t)$  can shift dramatically over time. In the example used in this paper, if land shifts into forestry, society loses the returns from its previous use, which may be grazing or growing crops.

The social planner should maximize the present value of net producer and consumer surplus over time. Letting  $\mathbf{G}(t) = G_i(t) \cdots G_T(t)$  and  $\mathbf{X}(t) = X_i(t) \cdots X_T(t)$ , this is:

$$(4) \quad \text{Max}_{H_i(t), G_i(t)} W = \int_t^\infty e^{-rt} \{ S(Q(t), \mathbf{Z}(t), \\ \mathbf{G}(t), \mathbf{X}(t)) \} dt$$

subject to

$$(5) \quad \dot{X}_i = -H_i(t) + G_i(t) \quad \forall i,$$

$$(6) \quad X_i(0) = X_{i,0} \quad \forall i,$$

$$(7) \quad X_i(t), H_i(t), G_i(t) \geq 0 \quad \forall i,$$

where  $r$  is the discount rate. The decision maker has two control variables, harvest amounts,  $H_i(t)$ , and how much to reinvest in future stock,  $G_i(t)$ . Equation (5) expresses the change in the size of the total population of each type of organism in each period; it is the difference between what is harvested and what is regenerated. Equation (6) is an initial condition for the stock variable, which defines not only the total stock of organisms, but also the age distribution of the initial stock. The age of the stock is distinguished by the yield function for merchantable products that accompanies each organism,  $V_i(a_i(t))$ . The social planner decides how much of the population to harvest,  $H_i(t)$ , and how much to regenerate,  $G_i(t)$ , at time  $t$ .

Using the maximum theorem (Lev S. Pontryagin et al., 1962), equations (4) through (7) can be solved for a set of conditions that must be satisfied in every period for a locally optimal solution of harvests (see Appendix for details):

$$(8) \quad \dot{P}V_i(a_i(t)) + P(t)\dot{V}_i = rP(t)V_i(a_i(t)) + R_i(t). \quad \forall i.$$

$P(t)$  is the price for a unit of organisms, and  $R_i(t)$  is the rental rate of a marginal unit of resource (for example, land) required to support another unit of organisms. Organisms will be harvested along a time path where the marginal benefits of waiting an extra moment to harvest are equated with the marginal costs. The marginal benefits of waiting, the left-hand side of (8), arise from additional growth in the organism,  $\dot{V}_i$ , and changes in price,  $\dot{P}$ . Of course, if prices are declining, the marginal benefits of waiting are reduced. The marginal costs of waiting, the right-hand side of (8), include the opportunity costs of delaying har-

vests and using the resource for one more period. Note, for example, if land remains in forestry,  $R_i(t)$  is the marginal opportunity cost of delaying future rotations.

Investments in future stock,  $G_i(t)$ , require that future marginal benefits just offset the marginal cost. The marginal benefits are simply the present value of future revenue that is expected when the new stock matures and is harvested. The marginal cost is the establishment cost,  $\beta_i$ , plus any resources needed to maintain the stock during its lifetime. The decision must satisfy the following first-order condition:

$$(9) \quad \beta_i + \int_{t_0}^{t_f} [R_i(m_i)e^{-rm_i}] dm_i = P(t_f)V_i(t_f - t_0)e^{-r(t_f - t_0)} \quad \forall i.$$

The impact of ecological change is calculated by comparing the present value of the stream of  $S(\cdot)$  in the baseline case without the change to the same measure with the ecological change scenario. Given some forcing factor which alters species growth rates, mortality, the cost of regeneration, or the underlying opportunity cost of land (by affecting the incomes from alternative uses), the optimal dynamic path for the resource is recalculated. Comparing the present value of net welfare with and without the change provides a careful measure of large-scale ecological change.

The formulation above incorporates changes in other outputs,  $\mathbf{Z}(t)$ , which may accompany the resource in question. In practice, however, the vector  $\mathbf{Z}(t)$  is often independent from the resource in question, so that it can be safely ignored. In cases where that is not appropriate, one needs to explore the use of a general equilibrium model to properly capture interactions across sectors (Joel D. Scheraga et al., 1993).

## B. Modeling U.S. Timber Markets

In this section, we show how the general model can be applied to measure how climate change would affect U.S. timber markets. The principle of optimal forest management (Martin Faustmann, 1968; Paul A. Samuelson,

1976) is to maximize the net present value of future income over an infinite cycle of forest rotations. Faustmann analyzed a steady-state condition with constant prices and rotation lengths over time. In steady state, (8) simplifies to:

$$(10) \quad \bar{P}\dot{V}_i = r\bar{P}V_i(\bar{a}_i) + \bar{R}_i \quad \forall i.$$

Trees should be harvested when the marginal benefit of waiting, the value of annual tree growth, is equated to the marginal cost of waiting, the opportunity cost of the stock and the land. Extending this formula to dynamic prices and rotations (Brazee and Mendelsohn, 1990) leads to (8).

In timber markets, harvesting trees—one product of an ecosystem—involves completely removing individual organisms from the land. Although new trees can be grown to replace the missing individual, they must begin again at age zero. Because annual tree growth declines steadily with age (modeled by a concave yield function), given an age distribution of trees of a particular species type, the optimal tree to harvest is the oldest member (Terry Heaps, 1984). The timber market model assumes that the oldest member is selected first.

The dynamic model of Brazee and Mendelsohn considers only a single species. In practice, however, there are many species from which the forest industry can select. The timber market model in this paper optimizes harvests across multiple species simultaneously. The model assumes that (8) is binding for all species being harvested at any moment,  $t$ .

In addition to harvesting, the model makes regeneration decisions each period. Because all species take several decades to grow to maturity and some take almost a century, this is a long-term decision. Making this decision in a dynamic model with such long foresight is clearly problematic. In the sensitivity analysis, we consequently examine an imperfect foresight scenario. With perfect foresight, the decision maker, at time  $t_0$ , follows (9) in making her regeneration decisions.

With competitive land markets, the annual land rental costs should equal the interest rate times the present value of future net income.

The present value of future net income changes as future prices and rotation ages change. If prices are rising over time, for example, the net present value of the land will increase as well, and  $R_i(t)$  will increase. The stream of rental prices is consequently endogenous and cannot be treated as a constant during the period of transition.

Another problem with a long-term dynamic model is defining terminal conditions. An arbitrary future state could be imposed by fixing future demand levels and stock sizes. The system of equations described by (1), (2), (8), and (9) would eventually resolve to a steady-state Faustmann condition given this future state (Peter Berck, 1981; Heaps, 1984). The limitation of this approach is that the terminal conditions are arbitrary. In order to minimize the impact of choosing the wrong terminal conditions, we choose a terminal state that occurs very far in the future. Because current actions are not sensitive to conditions far into the future, the choice of future condition has little impact on the net present value of welfare. The terminal conditions are discussed more thoroughly at the end of Section II.

### C. Modeling Ecological Change: The Impact of Climate Change on U.S. Forests

The impact of exogenous forces on ecosystems most often depends on the specific example considered. In this paper, we focus on the predicted impacts of climate change on U.S. forests, and consequently timber markets. This allows us to pay careful attention to the specific predictions of scientists. Forest ecologists generally predict that climate change will alter long-run growth rates and species location. However, they disagree about the dynamics of this process. Some argue that climate change will temporarily increase mortality (dieback). Trees will adjust to changing conditions by dying out prematurely and being gradually replaced. Others argue that climate change will affect only the ability of plants to regenerate in certain regions. Because the dynamic path of ecosystems is uncertain, we examine both dieback and regeneration as alternatives.

As carbon dioxide increases and climate changes, the growth rates of existing trees may

gradually change. Over time, this slowly affects the size of the stock. Suppose for example that climate change affects the annual growth of a tree through the function,  $\theta_i(n(t))$ , which relates a climate forcing factor,  $n(t)$ , in time  $t$  to annual growth. The forcing factor relates CO<sub>2</sub> concentrations to climate in time  $t$ . Annual growth becomes:

$$(11) \quad \dot{V}_i(a_i(t), \theta_i(n(t))) \\ = \dot{V}_i(a_i(t))\theta_i(n(t)) \quad \forall i.$$

The size of a tree at time  $t$  is therefore:

$$(12) \quad V_i(a_i(t), \theta_i(n(t))) \\ = \int_0^{a_i(t)} \dot{V}_i(a_i(t))\theta_i(n(t)) dt \quad \forall i.$$

The size depends upon the historic influence of the forcing factor on the growth rate in each past period. The forcing factor has a unique impact on trees of different ages, and the impact is further complicated because  $\theta_i(n(t))$  changes over time. A gradual forcing factor which has been in place for only a short time will tend to have only a minimal initial impact because it takes many years to alter stock size.

The change described in equation (12) will affect (8) and thus alter the harvest rate of each species. Accounting for these effects, equation (8) can be rewritten (see Appendix)

$$(13) \quad \dot{P}V_i(a_i(t), \theta_i(n(t))) \\ + \theta_i(n(t))P(t)\dot{V}_i(a_i(t)) \\ = rP(t)V_i(a_i(t), \theta_i(n(t))) \\ + R_i(t, \theta_i(n(t))) \quad \forall i.$$

In (13), changing growth rates directly affect the marginal benefit of waiting and gradually alter the opportunity cost of waiting as well. Because both marginal benefits and costs of waiting adjust over long periods of time, (13) leads to a complex harvest adjustment relative to the general baseline case.

Increased mortality, dieback, is caused when climate change adjusts the boundaries

of ecosystems, leaving standing trees in the wrong climate (H. H. Shugart et al., 1986; Ronald P. Neilson et al., 1992). Under the dieback hypothesis, existing trees in the wrong climate die. The only option for the timber market is to salvage the dying trees. While ecological change could be expressed in a stochastic model, we adopt a deterministic model for tractability using a certainty equivalence approach. Given annual the mortality rate from dieback,  $\delta_i(n(t))$  due to a forcing factor  $n(t)$ , the expected yield of an organism in year  $t$  for trees alive at the beginning of this year is

$$(14) \quad EV_i(t) = (1 - \delta_i(n(t)))V_i(t) \\ + \delta_i(n(t))\gamma_i V_i(t) \quad \forall i.$$

where  $\gamma_i$  is the fraction of timber that dies back which can be salvaged. This change in marginal conditions affects the optimal harvest decision (see Appendix):

$$(15) \quad \dot{P}V_i(a_i(t)) + P(t)\dot{V}_i \\ = (r + (1 - \gamma_i)\delta_i(n(t))) \\ \times P(t)V_i(a_i(t)) \\ + R_i(t, \delta_i(n(t))) \quad \forall i.$$

$R_i(t, \delta_i(n(t)))$  reflects the fact that the value of land will be altered during climate change. With dieback, the cost of waiting has increased because the delay may entail loss of some stock. This causes the model to harvest stocks which are threatened by dieback earlier. This is an important adaptation because it limits the magnitude of realized dieback by harvesting trees before they die. Dieback also affects the decision to plant. Rewriting equation (9) to account for cumulative mortality (see Appendix), the decision to regenerate becomes

$$(16) \quad \beta_i + \int_{t_0}^{t_f} [e^{-rm_i} R(m_i, \delta(n(m_i))) ] dm_i \\ = P(t_f)V_i(t_f - t_0)e^{-[r + (1 - \gamma_i)\delta_i(n(t_f))](t_f - t_0)} \quad \forall i.$$

Dieback reduces the marginal benefit of replanting species which will be subject to mortality problems today. This encourages forest owners to consider trees which are more suitable for future conditions. By replacing old species with new, more appropriate species, this market adaptation hastens the transition to a new ecosystem and mitigates some of the harmful economic impacts of dieback. However, with long-lived species, this adaptation calls for considerable foresight about the future path of climate change. It is important to consider how much foresight one can expect landowners to possess in this case. We consequently explore two alternatives: perfect foresight where landowners predict the future with accuracy, and imperfect foresight, where they make these adjustments only slowly.

The alternative dynamic pathway for ecological change has climate change affect only regeneration. Existing trees often survive well out of their natural range once they are established. Instead of relying on dieback, ecosystems may change because trees cannot regenerate in areas in which they are poorly suited. Competitive processes favor a new set of species better adjusted to the new ecological conditions. If left to natural forces alone, such an adjustment from the original stock to the new stock may take decades, if not centuries, due to the slow speed of many underlying migratory and competitive processes.

Even under the regeneration hypothesis, adaptation should still occur. Landowners considering new plantations should use (9) to determine which species will maximize present value. By selecting species which will adapt to new future conditions, the market can speed ecological adjustments. The benefits of this rational expectations planting process, however, are felt only in the distant future since it takes many decades for the trees to reach maturity.

Thus, both nature and humans will adapt to changing ecological conditions. With slowly changing growth rates, harvest decisions will be altered subtly at the margin causing harvests to shift over time. With dieback, the economic system moves away from vulnerable situations and causes a fairly rapid adjustment to more stable conditions. By influencing regeneration to favor species of higher value, the

system speeds adjustment towards desirable new conditions.

This complex dynamic adjustment of ecosystems cannot be captured by simple steady-state comparisons. Figure 1 illustrates this point with four plausible cases of ecological change. All four paths have the same initial and final steady-state prices so that a comparison of the before and after steady-state conditions would imply an equal change in welfare. Prices, however, follow a very different path in each case. In case (a), massive dieback, with no salvage and slow regrowth, causes prices to jump quickly to very high levels and to decline only slowly as stocks regrow. In case (b), dieback occurs slowly so prices increase slowly. Case (c) assumes that future growth is slowly reduced. This encourages shorter rotation lengths, causing an initial increase in harvests, followed by ever smaller harvests. Case (d) involves slow dieback with high salvage harvests leading to temporary low prices and long-term high prices. Depending on the timing of high and low prices, these alternative paths would yield entirely different welfare impacts and yet the steady-state comparison would predict they all had the same value.

## II. Empirical Example

Estimating the impact of climate change on timber markets requires linking information from natural science models with an empirical economic model. This set of models is listed in Table 1. We begin with two steady-state predictions of the effect of doubled CO<sub>2</sub> on climate in the United States, given by the models listed in Panel A. The three biogeographical models (Panel B) and three biogeochemical models (Panel C) are then used to predict nine steady-state ecological consequences for each of these climate scenarios (VEMAP Members, 1995). These steady-state results are converted to dynamic responses by first assuming a pathway for climate change, and then using the ecological literature to develop two dynamic ecosystem responses (dieback and regeneration in Panel D) to the path of climate change. This results in a set of 36 ecological responses [(two steady-state climate responses)  $\times$  (nine



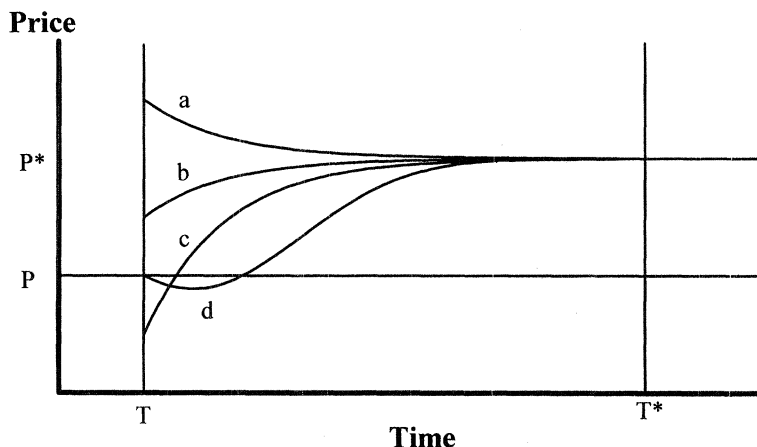


FIGURE 1. POTENTIAL DYNAMIC PATHWAYS OF THE PRICE OF A NATURAL RESOURCE ASSET DURING A TRANSITION IN RESPONSE TO EXOGENOUSLY CHANGING FORCING FACTORS

*Note:* Path (a) assumes a massive dieback followed by gradual regrowth; path (b) assumes slow dieback and gradual regrowth; path (c) assumes gradual species change; and path (d) is a slow dieback with a high conversion of dead stock to markets.

steady-state ecosystem responses)  $\times$  (one dynamic climate scenario)  $\times$  (two dynamic ecosystem change scenarios)], which are introduced into the economic models described in Section I. The causal chain of events is from CO<sub>2</sub> emissions to climate change to ecological change to economic impacts on timber markets. Although there is a small feedback from the storage of carbon in forests and industrial products back to the climate model, we do not model this effect in this paper.<sup>1</sup>

This study focuses on measuring the impact of an effective doubling of atmospheric concentrations of carbon dioxide, allowing us to compare our results with past studies. This scenario requires us to examine a policy which stabilizes concentrations of carbon dioxide at 660 ppmv. General circulation models predict that climates across the world will change in response to such increases. We rely on

the United Kingdom Meteorological Office (UKMO) (C. A. Wilson and J. F. B. Mitchell, 1987) and Oregon State University (OSU) (Michael E. Schlesinger and Z. C. Zhao, 1989) general circulation models to predict how climates will shift in 0.5 by 0.5-degree grid cells in the United States.<sup>2</sup> The climate models make different predictions across the country and across seasons for multiple climatic variables (temperature, precipitation, cloud cover, etc.) for each grid cell. On average, the OSU model predicts changes of +3.0C temperature and +3.0 percent precipitation, while the UKMO model predicts changes of +6.7C temperature and +15 percent precipitation. While these averages suggest that UKMO is more severe, the two

<sup>1</sup> Sohngen et al. (1996) utilize the two sensitivity scenarios in this paper to measure forest carbon flux in the United States, rather than welfare effects. That study suggests that forests may be sources or sinks of atmospheric carbon during climate change, depending on the exact ecological changes predicted.

<sup>2</sup> Sohngen (1996) uses the methods of this paper to explore a wider range of climate scenarios. The qualitative results are robust, although the quantitative results generally change in proportion to the magnitude of the predicted temperature and precipitation change. Some exceptions occur, however, depending on the spatial distribution of the changes predicted by the general circulation models. Differences occur where regional changes in climate have significant impacts on the most valuable species.

TABLE 1—MODELS USED IN THE ANALYSIS

| Models  | Acronym   |
|---|-----------|
| <b>A. General circulation models</b>  |           |
| United Kingdom Meteorological Office (Wilson and Mitchell, 1987)                    | UKMO      |
| Oregon State University (Schlesinger and Zhao, 1989)                                | OSU       |
| <b>B. Biogeographical models</b>  |           |
| Dynamic Global Phytogeography model (F. Ian Woodward et al., 1995)                  | DOLY      |
| BIOME2 (I. Colin Prentice et al., 1992)   | BIOME2    |
| Mapped Atmosphere-Plant Soil System model (Neilson et al., 1992)                    | MAPSS     |
| <b>C. Biogeochemical models</b>   |           |
| Terrestrial Ecosystem Model (Jerry M. Melillo et al., 1993)                         | TEM       |
| BIOME-BioGeochemical Cycles model (Steven W. Running and Joseph C. Coughland, 1988) | BIOME-BGC |
| Century model (William J. Parton et al., 1988)                                      | Century   |
| <b>D. Dynamic climate change scenarios</b>  |           |
| Dieback<br>Regeneration   |           |

scenarios differ in a number of other ways, including the spatial and seasonal distribution of temperature and precipitation change. Note also that the best guess of climate scientists today is that greenhouse gases would cause a warming of only 2C by 2100 (Houghton et al., 1996).

The ecological models in this analysis rely on climate normals—long-term average weather. Although ecosystems are sensitive to changes in interannual variation or weather extremes, there is little agreement in the climate community about how greenhouse gases would change climate variation (Houghton et al., 1996). We consequently do not explore the impact of changes in variation or weather extremes in this analysis.

Following the predictions of climate scientists (Houghton et al., 1996), we assume that temperature and precipitation will change linearly from current levels in 1990 to the doubled CO<sub>2</sub> equilibrium levels by 2060 in each grid cell. In terms of our climate forcing factor, this entails a linear path for  $n(t)$ . Some grid cells will experience increases in temperature or precipitation, while others will experience

decreases. We assume that greenhouse gas policy will stabilize climates at this new equilibrium.<sup>3</sup> Clearly, if no control policy is undertaken, the concentration of greenhouse gases will continue to rise beyond a doubling leading to ever larger climate changes. Because expansion of concentrations well beyond 660 ppm would be the result only of policy decisions made well in the future, we do not examine these potential outcomes in this paper. In principle, however, the model could be extended to explore concentrations well beyond 660 ppm.

An international team of ecologists, known as the Vegetation/Ecosystem Modeling and Analysis Project (VEMAP Members, 1995), evaluated ecological response to the new equi-

<sup>3</sup> More recent evidence from Houghton et al. (1996) suggests that climates and ecosystems will continue to change beyond the year 2100. We explore longer-term climate changes with sensitivity analysis, but we are limited to scenarios where greenhouse gas concentrations are doubled due to the general circulation models utilized for the ecosystem analysis.

librium climates predicted by each general circulation model.<sup>4</sup> This project combined two types of models: biogeochemical and biogeographic (see Table 1). Biogeochemical models compute what would happen to the biological productivity of each ecosystem type. Biogeographic models predict how ecosystem types (biomes) might shift across the landscape. Because biomes have different productivity responses, these two types of models were combined to produce a single prediction of outcomes. The three biogeochemical and three biogeographic models used by VEMAP Members (1995) were used here to reflect the diversity of opinion in the quantitative ecological community. Combining a biogeochemical and a biogeographical model for each ecological prediction yields nine ecological predictions for each climate scenario.<sup>5</sup>

Figures 2–5 present a set of steady-state (2060) biogeographical results for the current and the UKMO climate scenarios. We have aggregated the broad regional ecosystem types of the original ecological models into four timber types: loblolly pine, Douglas fir, white pine, and ponderosa pine.<sup>6</sup> Figure 2 presents the distribution of ecosystems in the United States under the present climate. Figures 3–5 present the new steady-state distributions predicted by each biogeographical model for this

specific doubled CO<sub>2</sub> climate scenario. Although at first glance, these results suggest that loblolly pines will expand northward, the underlying climate model (UKMO) predicts higher temperatures and lower precipitation in the central–southern United States. The effect in Figures 3–5 is a large loss of existing loblolly pine stands.

The geographic changes vary by ecological model but all three biogeographical models predict a shift from northern white pines to southern loblolly pines (see Table 2). Panel A in Table 2 shows the predicted relative size of biomes after climate change compared to their current size for the three biogeographical models. Because loblolly pines are far more productive, the expansion of loblolly pines increases long-term timber supply. The biogeographical models also predict an expansion of the Douglas fir region in all cases except with the Mapped Atmosphere-Plant Soil System (MAPSS) model under the more severe UKMO climate scenario. Panel B presents predictions of the proportion of land currently in forests that shifts out of one biome and into something else during climate change, including other forest types and nonforestland.

The biogeochemistry models, in turn, are used to predict the ecosystem productivity of each biome. For each climate scenario, these models predict either increases or decreases in ecosystem productivity for each biome (Table 3). Because climate change will entail changes in both the distribution of biomes and their productivity, the changes in productivity in Table 3 are based on predicted changes in biome distribution from the three biogeographical models listed at the top of Table 3. The Terrestrial Ecosystem Model (TEM) (Panel A) predicts productivity increases in every forest type, Century (Panel B) predicts both gains and losses, but Biome-BioGeochemical Cycles (BIOME-BGC) (Panel C) under the more severe UKMO scenario predicts large productivity reductions. This range of outcomes in the ecological models is reflected in the final economic results as well.

For each long-term equilibrium scenario, we explore two dynamic ecological pathways: dieback and regeneration. In the dieback scenario, all trees which shift from one biome to

<sup>4</sup> The Vegetation/Ecosystem Modeling and Analysis Project is a multiple-party effort to assess the sensitivity of terrestrial ecosystems and vegetative processes to climatic change (VEMAP Members, 1995). This project was designed for two purposes. The first was to combine a set of different ecological models to get a sense of the range of ecosystem predictions which are possible for a given climate scenario. The second was to provide a rich source of data for economic (and other) analysis such as contained in this paper.

<sup>5</sup> The acronyms used to name the models in the text and tables allow us to differentiate the 36 ecological outcomes predicted by the models used. Both acronyms and references for each model used in this analysis are presented in Table 1. An overview of all six models and their climate predictions can be found in VEMAP Members (1995).

<sup>6</sup> Warm temperate, southern mixed forests are represented by a loblolly pine yield function; maritime temperate coniferous forests are represented by a Douglas fir yield function; cool temperate and boreal forests are represented by a white pine yield function; and continental temperate coniferous forests are represented by a ponderosa pine yield function.

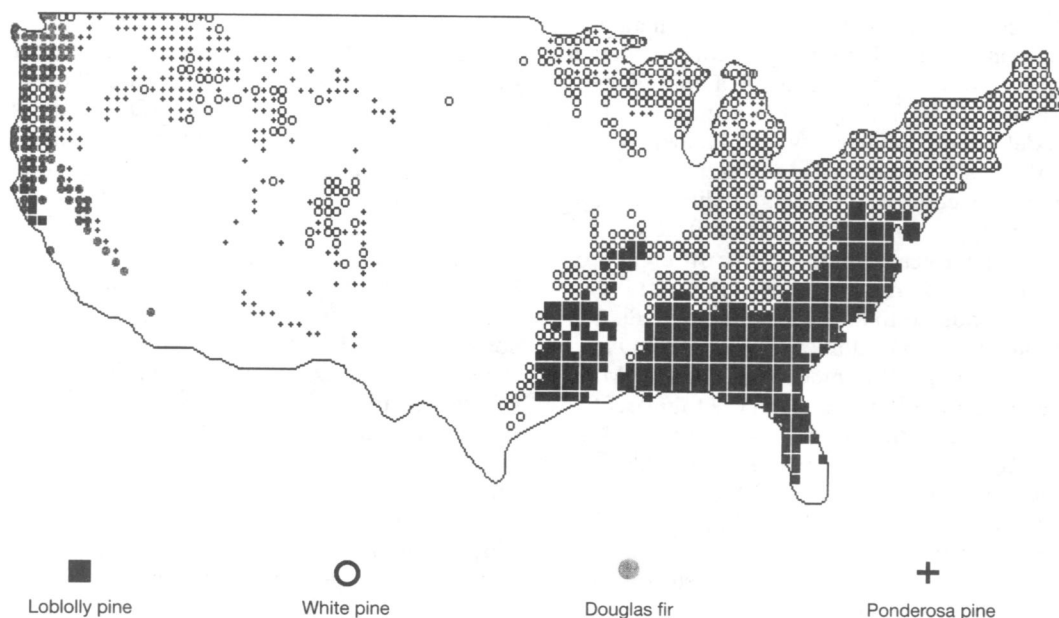


FIGURE 2. CURRENT POTENTIAL GEOGRAPHIC DISTRIBUTION OF ECOSYSTEM TYPES BASED ON AUGUST KUCHLER (1975)

another are assumed to die in the decade that the biome shifts. As can be seen in Table 2, the northern white pine and Rocky Mountain ponderosa pine regions will change a great deal under climate change. These large area changes imply high mortality rates under the dieback scenario while climate is changing.

In the regeneration scenario, biome changes do not kill trees but merely affect the speed of regeneration. Once trees are harvested, either the market will plant new species which are adapted to the new conditions or nature will slowly regenerate these lands. Acres which shift across biomes are assumed to take longer to regenerate naturally.

Each of the 36 dynamic ecosystem adjustment paths are then introduced into the economic model. Yield functions for the timber types associated with each biome type are taken from the forestry literature.<sup>7</sup> Species

growth rates are assumed to change proportionally with ecosystem productivity as in equation (11). The complex spatial configuration of existing stands are aggregated into an aggregate inventory by age for each species type. This inventory is grown over time using the spatial growth patterns dictated by the ecological models.

The economic model chooses harvests and replanting quantities to fit the first-order conditions (8) and (9). In addition, the model equates demand and supply each period. That is, we assume all harvested timber is consumed in the same period. Although it is technically possible to store timber once harvested, it is far more attractive to store timber in the forest where it continues to grow and is subject to a lower risk of degradation. Demand is assumed to have the following form:

$$\begin{aligned}
 (17) \quad Q(t) = & 199 * \left( \frac{Population_t}{Population_{1990}} \right) \\
 & - 46 * \ln(P(t)) \\
 & + 28 * \ln(MGDP(t)).
 \end{aligned}$$

<sup>7</sup> The loblolly pine yield function comes from Francis X. Schumacher and Theodore S. Coile (1960); Douglas fir yield is found in Richard E. McArdle et al. (1949); white pine yield is found in Suren R. Gevorkiantz and Raphael Zon (1930); and ponderosa pine is found in Walter H. Meyer (1938).

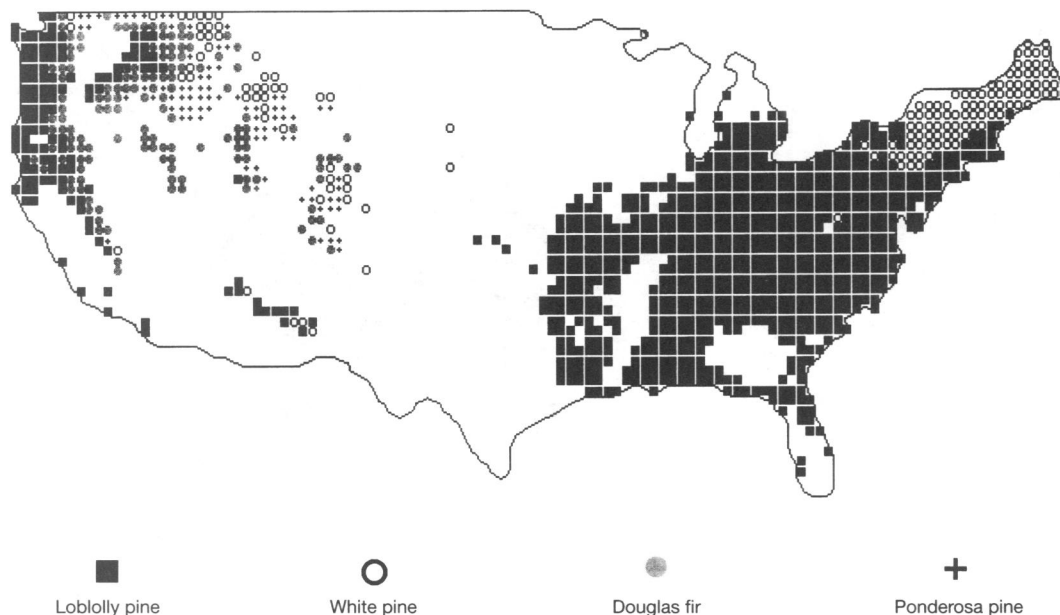


FIGURE 3. BIOME2 BIOGEOGRAPHICAL MODEL (PRENTICE ET AL., 1992) PREDICTION OF POTENTIAL ECOSYSTEM DISTRIBUTION UNDER THE UKMO GENERAL CIRCULATION MODEL DOUBLED CO<sub>2</sub> SCENARIO

Demand shifts outward over time in response to population and manufacturing GDP (MGDP) growth. Manufacturing GDP shifts out exogenously at 1.5 percent annually. Initially population is assumed to grow 1.0 percent per year. The U.S. Bureau of the Census (1993) suggests that fertility rates will decline in the United States in the future, so we assume that population growth declines steadily to 0 percent by 2200. Price and manufacturing GDP elasticity were estimated from historical data for the period 1952 to 1988 (Darius M. Adams et al., 1988). Price elasticity of demand in (17) is  $-1.26$ , and the elasticity of manufacturing GDP per capita is  $0.75$ . Demand is defined in terms of net domestic consumption of timber products (total demand minus net imports). We assume throughout the analysis that net imports do not change. This assumption will be relaxed in future studies which will take into account impacts around the world and trade. The ecological results upon which we rely in this study, however, are only available for the United States. The real interest rate is assumed to be 5 percent. Because the impacts of climate change are in the future, the magnitude of the present value of effects is

sensitive to the choice of interest rates. However, sensitivity analyses on the interest rate indicate that the qualitative results are robust (Sohngen, 1996).

Two management intensity levels are also included in the model. Intensively managed lands, plantations, receive high investment levels from replanting and thinning. Low-management intensity lands are more marginal timber areas which are likely to be regenerated naturally. High-intensity land classes are assumed to be managed to maximize the present value of timber net income. These landowners harvest according to the dynamic harvest and regeneration equations above. Low-intensity landholders, however, do not appear to follow Faustmann criteria, as they are observed to hold many acres of overmature timber. We assume that low-intensity landholders respond to market conditions depending upon prices by harvesting when they observe a period of high prices. The low-intensity lands are assumed to generate an upward-sloping harvest supply function for each timber type.

During climate change, high- and low-intensity lands are assumed to respond differently. After

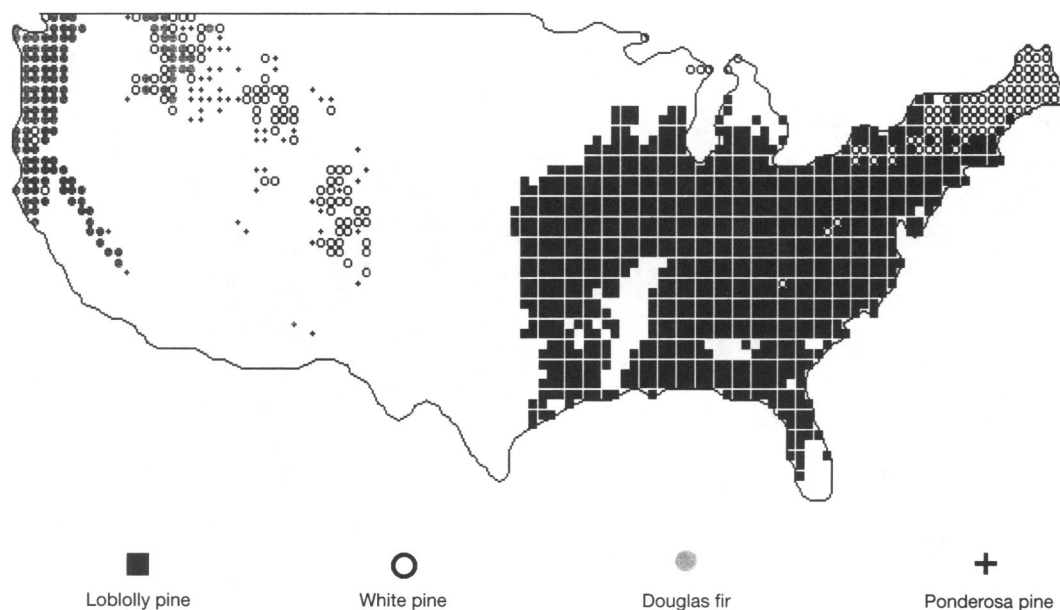


FIGURE 4. DOLY BIOGEOGRAPHICAL MODEL (WOODWARD ET AL., 1995) PREDICTION OF POTENTIAL ECOSYSTEM DISTRIBUTION UNDER THE UKMO GENERAL CIRCULATION MODEL DOUBLED CO<sub>2</sub> SCENARIO

land dies back and converts from one biome to another, for example, high-intensity land will be regenerated quickly with the new species according to equation (9). Low-intensity land, with its reliance on natural regeneration, however, is assumed to regenerate slowly when biomes shift.<sup>8</sup> In addition, we assume that salvage rates,  $\gamma_i$ , are 75 percent on high-intensity land and 50 percent on low-intensity land.

A shooting algorithm is used to solve for equilibrium prices and harvests in each time period. Beginning with an initial stock and price, the algorithm predicts harvest age and regeneration in high-intensity land, harvest quantity from low-intensity land, and price according to the first-order conditions in (8) and (9), upward-sloping supply functions for timber from low-intensity land, and the demand equation in (17). We also allow for shifts between low-intensity and high-

intensity land in response to price. As prices increase (decrease), more (less) bare land will convert to high-intensity management. When scenarios of ecosystem change are considered, equations (13) or (15) replace (8), and equation (16) replaces (9).

These equations define a family of price paths. The optimal path out of these many possibilities is the one that leads from the initial price and harvest to the steady state. The shooting algorithm searches over a set of initial prices for one that moves the system into the new steady state in the future. If the initial price chosen is lower (higher) than the optimal initial price, the price path undershoots (overshoots) the steady state. Most paths can be dismissed quickly because prices shoot off to infinity or to 0. As we get closer to the optimal initial price, it takes more and more periods to determine if we have under- or overshoot the steady state. We determine a price guess as "optimal" if the moment where under- or overshooting the steady state is so far distant that it has no impact on our measure of welfare. In general, model runs of 220 years were sufficient to estimate welfare.

<sup>8</sup> We use three different lags, 10 years in loblolly pines, 20 years in white pines, and 30 years in ponderosa pines and Douglas fir.



FIGURE 5. MAPSS BIOGEOGRAPHICAL MODEL (NEILSON ET AL., 1992) PREDICTION OF POTENTIAL ECOSYSTEM DISTRIBUTION UNDER THE UKMO GENERAL CIRCULATION MODEL DOUBLED CO<sub>2</sub> SCENARIO

### III. Results of Analysis

In order to characterize the welfare impact of the ecological changes, a baseline case without climate change is developed. The baseline case includes growth in manufacturing GDP and population as described above. Timber types are constrained to exist within the area predicted by the baseline ecological model shown in Figure 2. Prices, harvest quantities, rents, and planting are then calculated for each year. Demand grows faster than supply in the baseline scenario, so real prices climb over time even without climate change (Figure 6).

The dynamic ecological changes are then linked to the economic model using the same predictions in manufacturing GDP and population growth, so that yearly changes in timber harvest can be predicted for each of the 36 ecological scenarios. Market prices, quantities, regeneration rates, and rental rates are calculated each year. The results indicate that climate change is expected to expand aggregate timber supply in the long run under all 36 scenarios. Four of these scenarios are illustrated

in Figure 6, which shows that climate change reduces prices below the baseline in all cases. Although some of the scenarios entail productivity reductions on each acre for a given species, the geographic expansion of the highly productive loblolly pines overwhelms productivity reductions. Figure 6 illustrates this for the MAPSS & BIOME-BGC dieback and regeneration scenarios, where timber yields per acre decline (Table 3), but long-term prices are lower than in the baseline.

Comparing the net present value of the future stream of  $S(\cdot)$  for each climate scenario with the baseline reveals a welfare gain under all 36 scenarios (see Table 4). Panel A in Table 4 presents the results for the dieback dynamic ecological change scenario, and Panel B presents results for the regeneration scenario. The present value of benefits range from \$1 to \$33 billion. The average benefits are slightly higher under the milder OSU scenario (\$22 billion) than under the more severe UKMO climate scenario (\$18 billion). Benefits are lower under the UKMO scenario because warmer and drier predictions for a large area of the U.S. South causes the existing

TABLE 2—STEADY-STATE ECOSYSTEM CHANGES FOR THREE BIOGEOGRAPHICAL MODELS USING THE TWO GENERAL CIRCULATION MODEL CLIMATE RESULTS

|                        | DOLY          |             |            |                | BIOME2        |             |            |                | MAPSS         |             |            |                |
|------------------------|---------------|-------------|------------|----------------|---------------|-------------|------------|----------------|---------------|-------------|------------|----------------|
|                        | Loblolly pine | Douglas fir | White pine | Ponderosa pine | Loblolly pine | Douglas fir | White pine | Ponderosa pine | Loblolly pine | Douglas fir | White pine | Ponderosa pine |
| A. Relative size       |               |             |            |                |               |             |            |                |               |             |            |                |
| UKMO                   | 1.98          | 1.48        | 0.22       | 0.37           | 1.81          | 2.47        | 0.10       | 0.43           | 1.54          | 0.55        | 0.26       | 1.13           |
| OSU                    | 1.65          | 1.11        | 0.77       | 0.20           | 1.61          | 1.07        | 0.50       | 0.99           | 1.64          | 0.98        | 0.46       | 1.88           |
| B. Shifting proportion |               |             |            |                |               |             |            |                |               |             |            |                |
| UKMO                   | 0.04          | 0.05        | 0.84       | 0.89           | 0.35          | 0.07        | 0.93       | 0.87           | 0.31          | 0.56        | 0.94       | 0.26           |
| OSU                    | 0.01          | 0.11        | 0.50       | 0.87           | 0.11          | 0.02        | 0.71       | 0.35           | 0.00          | 0.21        | 0.81       | 0.29           |

Notes: "Relative size" is the ratio of the final steady-state forest area divided by the area of the initial steady state. "Shifting Proportion" is the proportion of the initial steady-state forest area that shifts out of the type and into something else, calculated as the area of forestland that converts to something else divided by the initial steady-state area. Changes for the DOLY, BIOME2, and MAPSS models with the UKMO climate scenario correspond to Figures 3–5.

range of loblolly pines to shrink. This suggests that U.S. timber markets will be slightly better off with a mild warming (average of 3C) compared to a more severe warming (average of 6C). However, one must be careful comparing the OSU and UKMO scenarios because they not only vary in severity but also in the spatial and seasonal patterns of climate change.<sup>9</sup>

Another interesting result in Table 4 is that the average welfare value under regeneration (\$21 billion) is only slightly higher than under dieback (\$18 billion). Given that over 80 percent of two regions were vulnerable to dieback, one might have expected far more severe outcomes under the dieback scenario. Three factors can explain why dieback is not more costly. First, the two most vulnerable regions to dieback, the North and the Rocky Mountains, entail low-valued species. Second, har-

vests carefully avoid the worst of dieback by removing trees prior to mortality and through salvage. Third, regeneration allows these vulnerable forests to adapt quickly to climate change by planting more productive suitable species more quickly. For example, under dieback, the low-productivity northern forests are replaced more quickly by loblolly pines than under the regeneration scenario. These factors mitigate the damages caused by the dieback dynamics.

The results from the VEMAP ecological models are noticeably more optimistic than earlier regional models. The major reason for this is that the new models are more comprehensive so that the loss of some forest types due to climate change is balanced by the gain of other forest types. Regional studies that concentrate on how local species would struggle with new climate conditions often fail to anticipate this compensating effect. For example, the U.S. Environmental Protection Agency analysis focused on the decline of northern species through dieback (Smith and Tirpak, 1989). While dying northern forests look horrendous in isolation, the gradual replacement of low-productivity hardwoods by high-productivity loblolly pines is actually beneficial. This biome shift increases overall timber supply and increases net surplus rela-

<sup>9</sup> The timber market consequences of larger CO<sub>2</sub> forcings for the United States is unclear for three reasons. First, the effect of larger future changes on current practices is unclear due to the role of discounting. Second, while the southern range of loblolly pine may decrease, the northern range may continue increasing. Finally, evidence from other regions suggests that subtropical regions are well suited to fast-growing plantations, and the southern United States may readily adapt to using these species during climate change.



TABLE 3—PERCENTAGE CHANGE IN STEADY-STATE ECOSYSTEM PRODUCTIVITY (TIMBER YIELD) PREDICTED BY BIOGEOCHEMICAL MODELS FOR EACH BIOME TYPE

|              | Biogeographical model |             |            |                |               |             |            |                |               |             |            |                |
|--------------|-----------------------|-------------|------------|----------------|---------------|-------------|------------|----------------|---------------|-------------|------------|----------------|
|              | DOLY                  |             |            |                | BIOME2        |             |            |                | MAPSS         |             |            |                |
|              | Loblolly pine         | Douglas fir | White pine | Ponderosa pine | Loblolly pine | Douglas fir | White pine | Ponderosa pine | Loblolly pine | Douglas fir | White pine | Ponderosa pine |
| A. TEM       |                       |             |            |                |               |             |            |                |               |             |            |                |
| UKMO         | 14                    | 34          | 29         | 50             | 16            | 31          | 7          | 26             | 28            | 47          | 14         | 39             |
| OSU          | 32                    | 33          | 19         | 29             | 37            | 43          | 10         | 18             | 40            | 32          | (2)        | 36             |
| B. Century   |                       |             |            |                |               |             |            |                |               |             |            |                |
| UKMO         | (5)                   | (14)        | 7          | 18             | (3)           | (4)         | (4)        | 14             | 7             | (13)        | (6)        | 19             |
| OSU          | (2)                   | (3)         | 11         | 21             | 5             | 9           | 7          | 6              | 10            | 0           | 8          | 0              |
| C. BIOME-BGC |                       |             |            |                |               |             |            |                |               |             |            |                |
| UKMO         | (29)                  | (19)        | (18)       | (11)           | (19)          | (29)        | 3          | (2)            | (16)          | (3)         | (35)       | (11)           |
| OSU          | (9)                   | 7           | 3          | 14             | (2)           | 15          | 16         | 5              | 0             | 2           | 2          | (19)           |

Notes: Changes in ecosystem productivity are conditioned on steady-state results of biogeographical models. Values in parenthesis indicate a percentage reduction in ecosystem productivity.

tive to the baseline case in the long run. Increased production in timber markets due to regrowth of this type begins to occur within 25 years of the onset of climate change. Market adaptation is also an important part of this story since investment can hasten forest adaptation and allow these positive long-run benefits to occur more quickly.

We also explore how robust the model is to alternative assumptions. We present five different scenarios in this sensitivity analysis. First, we consider a more gradual climate change scenario; allowing climates to take 150 years to reach the same equilibrium. This slower scenario is more consistent with recent findings of climate scientists (Houghton et al., 1996) who argue for milder future climate scenarios. Second, we explore what would happen if natural regeneration takes longer to shift from one biome to another. By increasing lags to 30 years in loblolly pines, 50 years in white pines, and 70 years in ponderosa pine and Douglas fir, we assume that unmanaged land remains fallow for this extensive time period once cleared. Third, we allow for higher and lower salvage rates. The high salvage scenario assumes that  $\gamma_i$  is 90 percent on both manage-

ment intensities, and the low salvage scenario assumes that it is 25 percent on both. Fourth, we examine imperfect forester foresight. Instead of assuming that high-intensity managed lands are replanted immediately with the best species for the future, we assume lagged regeneration rates. That is, we assume it takes foresters several years to learn how to plant for changing climatological conditions. Lags were set at 10 years in loblolly pines, 20 years in white pines, and 30 years in ponderosa pine and Douglas fir. Fifth, we consider a high demand and a low demand scenario. In the high demand scenario, demand shifts out at 2.5 percent annually, while in the low demand scenario, it is held at 1990 levels forever.

Four ecological cases are explored for the sensitivity analysis. Two ecosystem model combinations are examined which yield relatively high and low welfare values under the initial assumptions. In addition, both the dieback and the regeneration scenario are presented.<sup>10</sup>

<sup>10</sup> The model combinations chosen for sensitivity analysis are the Dynamic Global Phytogeography model

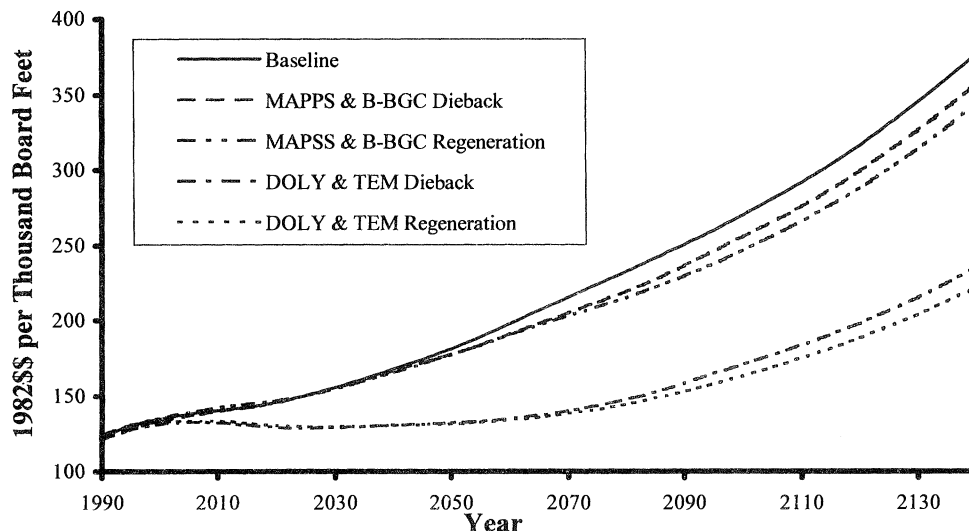


FIGURE 6. PRICE PATHS FOR THE BASELINE CASE AND FOUR ECOLOGICAL OUTCOMES FROM THE CLIMATE CHANGE PREDICTIONS OF THE UKMO GENERAL CIRCULATION MODEL

Table 5 presents the results of the sensitivity analysis. Slowing down climate change reduces the timber benefits. The delay slows the increase in loblolly pine timberland area into the distant future reducing its present value. Slowing natural regeneration on low-intensity lands that shift during climate change has only a small effect on welfare estimates because the lands which are shifting during climate change yield only small amounts of timber. Higher salvage rates substantially increase the welfare value of the dieback scenario and lower rates decrease it. The MAPSS & BIOME-BGC scenario is more sensitive to this assumption because this model predicts more dieback. Imperfect foresight by foresters reduces the expected benefits from climate change (and can even cause a small loss), but the reduction is small. Al-

though assuming perfect foresight to anticipate climate change through planting is certainly a debatable assumption, we have chosen the two most extreme ecological scenarios for sensitivity analysis in order to bound the potential effects of imperfect foresight under alternative ecological scenarios. The welfare estimates are highly sensitive to the assumed baseline growth in the demand for timber. Rapid (slow) demand growth implies higher (lower) baseline prices, which increases (decreases) welfare effects proportionally.

In order to understand the importance of capturing the dynamics of this model, we also present the results of a steady-state comparison. We compare the steady state which would have existed in 2060 under current climate with the equilibrium which would exist in 2060 under the new climate. We use the two scenarios tested in the sensitivity analysis. The predicted change in welfare according to the steady-state comparisons is  $-\$25.1$  billion for the MAPSS & BIOME-BGC combination and  $+\$73.6$  billion in the DOLY & TEM combination. The corresponding estimates in the dynamic model are  $+\$2.63$  and  $+\$31.2$  billion, respectively. The steady-state response dramatically overstates the welfare effect.

(DOLY) (Woodward et al., 1995) and Terrestrial Ecosystem Model (TEM) (Melillo et al., 1993) combination; and the Mapped Atmosphere-Plant Soil System model (MAPSS) (Neilson et al., 1992) and BIOME-BioGeochemical Cycles model (BIOME-BGC) (Running and Coughland, 1988). Results from both models were obtained under the United Kingdom Meteorological Office general circulation model (Wilson and Mitchell, 1987).

TABLE 4—CHANGE IN THE NET PRESENT VALUE OF NET MARKET SURPLUS IN TIMBER MARKETS FOR CLIMATE CHANGE CASES RELATIVE TO THE BASELINE CASE

| Climate scenario | DOLY      |         | BIOME2  |         | MAPSS   |         |
|------------------|-----------|---------|---------|---------|---------|---------|
|                  | Total     | Percent | Total   | Percent | Total   | Percent |
| A. Dieback       |           |         |         |         |         |         |
|                  | TEM       |         |         |         |         |         |
| UKMO             | \$30.05   | 10.62   | \$27.52 | 9.71    | \$19.10 | 6.74    |
| OSU              | 28.94     | 10.21   | 30.16   | 10.64   | 31.77   | 11.21   |
|                  | Century   |         |         |         |         |         |
| UKMO             | 18.87     | 6.65    | 17.89   | 6.31    | 9.46    | 3.34    |
| OSU              | 14.23     | 5.02    | 16.69   | 5.89    | 17.80   | 6.28    |
|                  | BIOME-BGC |         |         |         |         |         |
| UKMO             | 9.35      | 3.30    | 10.31   | 3.64    | 2.63    | 0.93    |
| OSU              | 11.86     | 4.19    | 13.72   | 4.84    | 14.52   | 5.12    |
| B. Regeneration  |           |         |         |         |         |         |
|                  | TEM       |         |         |         |         |         |
| UKMO             | 31.20     | 11.01   | 32.58   | 11.50   | 22.62   | 7.98    |
| OSU              | 31.93     | 11.27   | 33.16   | 11.70   | 35.26   | 12.44   |
|                  | Century   |         |         |         |         |         |
| UKMO             | 20.47     | 7.22    | 22.99   | 8.11    | 11.03   | 3.89    |
| OSU              | 17.11     | 6.04    | 20.34   | 7.18    | 21.92   | 7.74    |
|                  | BIOME-BGC |         |         |         |         |         |
| UKMO             | 10.37     | 3.66    | 14.98   | 5.29    | 3.87    | 1.37    |
| OSU              | 15.06     | 5.31    | 18.01   | 6.36    | 16.72   | 5.90    |

Notes: The change is measured both by the total and the percentage difference. All dollar amounts are in billions of 1982 \$, U.S. currency. Net present value is measured with a discount rate of 5 percent.

Including dynamics moderates the welfare impacts for three reasons. First, the steady-state response does not capture the adjustment and adaptation of markets, especially across time. Second, the steady-state comparison does not capture the gradual changes in ecosystems over time, thereby overstating effects. Third, the steady-state response does not capture the dynamic changes in the economic

baseline, so that the steady-state response assumes 2060 demand conditions immediately.<sup>11</sup>

<sup>11</sup> A similar effect would occur if 1990 economic conditions were used, except that changes would be undervalued because a lower baseline condition is used.

TABLE 5—SENSITIVITY ANALYSIS OF PRESENT VALUE CHANGES TO SEVERAL CLIMATOLOGICAL, ECOLOGICAL, AND ECONOMIC ASSUMPTIONS

|  | Ecological scenario |              |               |              |
|--|---------------------|--------------|---------------|--------------|
|  | DOLY & TEM          |              | MAPSS & B-BGC |              |
|  | Dieback             | Regeneration | Dieback       | Regeneration |
| Initial value of change (billions, 1982\$) | \$30.05             | \$31.20      | \$2.63        | \$3.87       |
| 1. Slow climate adjustment                 | 16.68               | 16.95        | 3.92          | (0.02)       |
| 2. Slow natural regeneration               | 27.79               | 28.99        | 1.73          | 3.00         |
| 3. Salvage                                 |                     |              |               |              |
| High                                       | 35.25               | 31.20        | 8.94          | 3.87         |
| Low  | 27.90               | 31.20        | (2.95)        | 3.87         |
| 4. Imperfect foresight                     | 25.19               | 27.73        | (0.42)        | 1.66         |
| 5. Alternative baselines                   |                     |              |               |              |
| High demand                                | 84.92               | 90.68        | 11.55         | 19.68        |
| Low demand                                 | 15.17               | 15.88        | 1.26          | 2.67         |

Notes: Each of these cases are compared using the UKMO general circulation model climate change scenario.

#### IV. Conclusion

The dynamic ecological-economic model captures the important intertemporal features for measuring changes in market welfare arising from large-scale ecological change. The adjustment pathways for both ecosystems and economic systems are critical for measuring the welfare impacts of ecosystem change. Even when the underlying force for change is gradual and steady, the dynamics of the system play a crucial role in determining both the direction and the magnitude of the outcome. Of course, when considering ecological change, it is important to measure the nonmarket as well as the market impacts. Additional research needs to concentrate on including nonmarket services in the model and so take into account all effects.

In the specific example of the impacts of climate change on timber markets, the large-scale steady-state effects predicted by the ecological models lead to small welfare impacts over time. Although climate change can cause harmful dynamic changes in ecosystems from phenomenon like dieback, dynamic market adjustments

dampen these effects. Further, the ecological models examined in this study actually predicted that the steady states would improve with greenhouse warming. All 36 combinations of ecological-climate models suggested positive results. The magnitude of the effects, however, were reasonably small with an average present value of about \$20 billion. Across the different model combinations, they exhibited a wide range, from \$1 billion to \$33 billion of benefits. Using dynamic models, society can anticipate large-scale ecological changes, measure their consequences, and determine how best to adapt. Armed with this knowledge and a complete accounting of impacts to other market and non-market sectors, society can engage in an informed decision concerning whether it is best to prevent these changes or live with them.

#### APPENDIX

In this Appendix, we show how the first-order conditions presented for the models described in the text are derived from the maximization of market welfare, as described

in equations (1)–(7) in the text. The models described here are a general case with no ecological change, a case where ecological change affects timber yield, and a case where ecological change causes dieback.

### General Case

The original problem was given as equations (1)–(7) in the text. Net surplus is assumed to be continuous in its arguments, and  $S_{H_i} \geq 0$  and  $S_{H_i H_i} \leq 0$ . Utilizing optimal control procedures and relying on the maximum principle (Pontryagin et al., 1962), we can characterize a solution to (1)–(7) in terms of a set of necessary conditions that must hold for each stock of organisms  $i$  considered within the problem. First, let

$$(A1) \quad S(Q(t), \mathbf{Z}(t), \mathbf{G}(t), \mathbf{X}(t)) \\ = \int_0^{Q^*(t)} \{ D(Q(t), \mathbf{Z}(t)) - C(Q(t)) \} dQ(t) \\ - \sum_i \beta_i G_i(t) - \sum_i R_i(t) X_i(t)$$

and express the Hamiltonian as

$$(A2) \quad h = S(Q(t), \mathbf{Z}(t), \mathbf{G}(t), \mathbf{X}(t)) \\ - \sum_i \mu_i(t) [-H_i(t) + G_i(t)].$$

Assuming an interior solution, the following necessary conditions are derived:

$$(A3) \quad S_{H_i}(\cdot) = \mu_i(t) \quad \forall i,$$

$$(A4) \quad S_{G_i}(\cdot) = -\mu_i(t) \quad \forall i,$$

$$(A5) \quad \dot{\mu}_i - r\mu_i(t) = R_i(t) \quad \forall i,$$

$$(A6) \quad \dot{X}_i = -H_i(t) + G_i(t) \quad \forall i.$$

Equations (A3) and (A5) can be combined to obtain (note that in the following,  $\forall i$  has been suppressed in most cases):

$$(A7) \quad \dot{S}_{H_i} = rS_{H_i} + R_i(t).$$

All organisms will be harvested at the point where the marginal gain in net surplus from waiting an additional moment to harvest just equals the marginal cost associated with holding that organism for one more period. Marginal gains in net surplus arise from organismal growth, and possibly, price growth. The sign on  $\dot{S}_{H_i}$  would be uncertain, however, if prices were declining.

Assuming a linear demand function and constant marginal harvesting costs, a quadratic net surplus function can be obtained by taking the integral in (A1) to form:

$$(A8) \quad S(\cdot) = k + A \left[ \sum_i H_i(t) V_i(a_i(t)) \right] \\ - \Delta \left[ \sum_i H_i(t) V_i(a_i(t)) \right]^2 \\ - \sum_i c_i H_i(t) V_i(a_i(t)) \\ - \sum_i \beta_i G_i(t) - \sum_i R_i(t) X_i(t),$$

where  $k$  is a constant of integration. Differentiating (A8) with respect to  $H_i(t)$  results in

$$(A9) \quad S_{H_i(t)} \\ = \left[ A - 2\Delta \left( \sum_i H_i(t) V_i(a_i(t)) \right) \right] \\ \times V_i(a_i(t)) - c_i V_i(a_i(t)).$$

The term  $A - 2\Delta(\sum_i H_i(t) V_i(a_i(t)))$  on the right-hand side of (A9) is the marginal benefit of harvesting one additional unit of organisms. In a competitive market, this is equal to the price, so that:

$$(A10) \quad S_{H_i(t)} = (P^L(t) - c_i) V_i(a_i(t)).$$

In timber markets,  $P^L(t)$  is the price of a log of harvested timber. The value  $P^L - c_i$  is therefore the value of uncut timber logs that are still standing in a forest. Letting

$$(A11) \quad P(t) = P^L(t) - c_i,$$

(A9) can be redefined by finding  $dS_{H_i}/dt$  and substituting. The result is

$$(A12) \quad \dot{P}V_i(a_i(t)) + P(t)\dot{V}_i \\ = rP(t)V_i(a_i(t)) + R_i(t),$$

which is equation (8) in the text.

Differentiating (A8) with respect to  $G_i(t)$  yields

$$(A13) \quad S_{G_i} = -\beta_i.$$

Recognizing that  $\mu_i(t)$  is the marginal net surplus of holding one additional acre of land until the next regeneration decision,

$$(A14) \quad \mu_i(t_0) = P(t_f)V_i(t_f - t_0)e^{-r(t_f - t_0)} \\ - \int_{t_0}^{t_f} \{ R_i(m_i)e^{-rm_i} \} dm_i,$$

then equation (9) in the text can be derived from (A4), (A13), and (A14) as

$$(A15) \quad \beta_i + \int_{t_0}^{t_f} \{ R_i(m_i)e^{-rm_i} \} dm \\ = P(t_f)V_i(t_f - t_0)e^{-r(t_f - t_0)}.$$

#### *Ecological Change: Productivity*

Here, we consider the derivation of equation (13) in the text, where the yield of merchantable products from the ecosystem changes over time. Different species are likely to experience different changes in growth. Recalling that  $\theta_i(n(t))$  relates climate forcing to a change in annual growth, the new yield function is redefined as:

$$(A16) \quad V_i(a_i(t), \theta_i(n(t))) \\ = \int_0^{a_i(t)} \dot{V}_i(a_i(t))\theta_i(n(t)) dt.$$

(A16) can be introduced into the net surplus function, so that (A8) becomes

$$(A17) \quad S(\cdot) = k + A \left[ \sum_i H_i(t) \right. \\ \times \left( \int_0^{a_i(t)} \{ \dot{V}_i(a_i(t)) \theta_i(n(t)) \} dt \right) \\ \left. - \Delta \left[ \sum_i H_i(t) \right. \right. \\ \times \left( \int_0^{a_i(t)} \{ \dot{V}_i(a_i(t)) \theta_i(n(t)) \} dt \right) \\ \left. - \sum_i c_i H_i(t) \right. \\ \times \left( \int_0^{a_i(t)} \{ \dot{V}_i(a_i(t)) \theta_i(n(t)) \} dt \right) \\ \left. - \sum_i \beta_i G_i(t) - \sum_i R_i(t) X_i(t) \right]^2$$

Differentiating net surplus with respect to  $H_i(t)$ , and noting the relationship in (A11), an equation similar to (A10) can be derived:

$$(A18) \quad S_{H_i(t)} = P(t) \left( \int_0^{a_i(t)} \{ \dot{V}_i(a_i(t)) \right. \\ \times \theta_i(n(t)) \} dt \\ \left. = P(t)V_i(a_i(t), \theta_i(n(t))) \right).$$

Finding  $dS_{H_i}/dt$  and substituting that result into (A7), produces equation (13) in the text:

$$(A19) \quad \dot{P}V_i(a_i(t), \theta_i(n(t))) \\ + \theta_i(n(t)) P(t)\dot{V}_i(a_i(t)) \\ = rP(t)V_i(a_i(t), \theta_i(n(t))) \\ + R_i(t, \theta_i(n(t))).$$

Note that  $dV_i(a_i(t), \theta_i(n(t)))/dt = \dot{V}_i(a_i(t))\theta_i(n(t))$ .

Regeneration will also be altered to account for changes in growth rates. Equation (A4) above can be solved to account for the altered yield function. This leads to the following condition:

(A20)

$$\begin{aligned} \beta_i + \int_{t_0}^{t_f} \{ R_i(m_i, \theta_i(n(m_i))) e^{-r m_i} \} dm_i \\ = \left( P(t_f) \int_{t_0}^{t_f} \{ \dot{V}_i(m_i) \theta_i(n(m_i)) \} dm_i \right) \\ \times e^{-r(t_f - t_0)}. \end{aligned}$$

#### Ecological Change: Dieback

This section shows how dieback will affect marginal harvest and regeneration decisions. Although it is possible to model dieback as a stochastic problem, we instead analyze a deterministic analogue to the stochastic problem. This allows a direct comparison to the baseline model, and it provides for a more tractable numerical solution. We begin by describing how an expression for expected yield is obtained.

Letting  $\delta_i(n(t))$  be mortality from exogenous dieback due to forcing factor  $n(t)$  and  $\gamma_i$  be the proportion of timber that can be salvaged if it dies back, the expected yield for a tree alive at the beginning of a year is given by

$$\begin{aligned} (A21) \quad E[V_i(a_i(t))] \\ = (1 - \delta_i(n(t))) V_i(a_i(t)) \\ + \delta_i(n(t)) \gamma_i V_i(a_i(t)). \end{aligned}$$

Over all the time that a tree is subjected to the possibility of dieback, this is

$$\begin{aligned} (A22) \quad E[V_i(a_i(t))] = V_i(a_i(t)) \\ \times \prod_{a_i(0)}^{a_i(t)} (1 - (1 - \gamma_i) \delta_i(n(t))). \end{aligned}$$

In continuous time, this can be expressed as

$$\begin{aligned} (A23) \quad E[V_i(a_i(t))] \\ = V_i(a_i(t)) e^{-(1 - \gamma_i) \delta_i(n(t)) a_i(t)}. \end{aligned}$$

Equation (A23) can be incorporated into (A8) to obtain

$$\begin{aligned} (A24) \quad S(\cdot) = k + A \left[ \sum_i H_i(t) (V_i(a_i(t)) \right. \\ \left. \times e^{-(1 - \gamma_i) \delta_i(n(t)) a_i(t)}) \right] \\ - \Delta \left[ \sum_i H_i(t) (V_i(a_i(t)) \right. \\ \left. \times e^{-(1 - \gamma_i) \delta_i(n(t)) a_i(t)}) \right]^2 \\ - \sum_i c_i H_i(t) (V_i(a_i(t)) \\ \times e^{-(1 - \gamma_i) \delta_i(n(t)) a_i(t)}) \\ - \sum_i \beta_i G_i(t) - \sum_i R_i(t) X_i(t). \end{aligned}$$

Differentiating net surplus with respect to  $H_i(t)$  and  $t$  allows us to obtain the following result:

$$\begin{aligned} (A25) \quad \dot{S}_{H_i} = \frac{d}{dt} [P V_i(a_i(t)) \\ \times e^{-(1 - \gamma_i) \delta_i(n(t)) a_i(t)}] \\ = \{ \dot{P} V_i(a_i(t)) + P \dot{V}_i \\ - (1 - \gamma_i) \delta_i(n(t)) P V_i(a_i(t)) \} \\ \times e^{-(1 - \gamma_i) \delta_i(n(t)) a_i(t)}. \end{aligned}$$

Combining (A25) with (A3) and (A5) produces equation (15) in the text:

$$\begin{aligned} (A26) \quad \dot{P} V_i(a_i(t)) + P(t) \dot{V}_i \\ = (r + (1 - \gamma_i) \delta_i(n(t))) \\ \times P(t) V_i(a_i(t)) \\ + R_i((t), \delta_i(n(t))), \end{aligned}$$

Equation (16) in the text is found by noting that (A14) becomes

$$(A27) \quad \mu_i(t_0) = P(t_f)V(t_f - t_0) \\ \times e^{-[r + (1 - \gamma_i)\delta_i(n(t_f))](t_f - t_0)} \\ - \int_{t_0}^{t_f} \{ R_i(m_i, \delta_i(n(m_i))) \\ \times e^{-[r + (1 - \gamma_i)\delta_i(n(m_i))m_i]} dm_i$$

and combining (A27) with (A13) and (A4).

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