Sustainable Forest Ecosystems and Management: A Review Article

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ABSTRACT. Concerns about the sustainability of forest resources and ecosystems have been expressed almost from the beginning of modern studies of forest management by ecologists, biologists, economists, and other specialists. However, the focus of this concern has gone through several transformations. Environmental scientists have emphasized the maintenance of forest ecosystems in the face of different types of human intervention. Economists and forest managers, on the other hand, have emphasized the capacity of forest systems to provide valued ongoing flows of goods and services for human societies.

This paper takes stock of forest resource and ecosystem sustainability from both ecological and economic perspectives. It seeks to identify how these disciplinary perspectives contribute to a better understanding of sustainability, and where the most significant conceptual and factual gaps are found. Of particular interest are two related themes: how economic efficiency and sustainability may differ in their implications for forest system management, and how criteria for forest system sustainability are related to the scale of management decisions (e.g., individual forest site versus region versus the global biosphere). FOR. SCI. 42(3):366–377.

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I. Introduction

Concerns about the sustainability of forest resources and ecosystems have been expressed almost from the beginning of modern studies of forest management by ecologists, biologists, economists, and other specialists. However, the focus of this concern has gone through several transformations. Environmental scientists have emphasized the maintenance of forest ecosystems in the face of different types of human intervention (ongoing harvesting, land conversion, air and water pollution, climate change). Addressing this concern requires understanding the functions and interactions among components of forest ecosystems on different temporal and spatial scales.

Economists and forest managers, on the other hand, have emphasized the capacity of forest systems to provide valued ongoing flows of goods and services for human societies. Initially, emphasis was on maximizing either the sustained volume or the sustainable value of timber yields (see Hyde 1980 for an extensive treatment of the distinction between "nondeclining even flow" and present value maximization). Subsequent research has taken a broader view, recognizing that forest systems provide a number of valued goods and services, some traded in markets and others outside of markets. These values are generated by a complex set of natural and human production processes.[1]

Within the past few years, particularly in the wake of the "Brundtland Report" (World Commission on Environment and Development 1987), discussion of sustainability has evolved to a broader emphasis on the relationship between economic progress and the natural world. There is concern regarding whether the depletion or degradation of "natural capital," including forest ecosystems, imperils the ability of human society to maintain or improve living standards for current and future generations. This renewed and broadened attention to sustainability brings out explicitly the ethical dimensions of the issue, and it puts particular emphasis on more global resource questions as well as local concerns. In the context of forestry, attention in particular has been on the

[1] Another recurrent theme in forestry management has been the stability of communities dependent on forest extraction. Such concern can be used, for example, to justify intensification and extensification of forest cutting to maintain timber flow.

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United Nations' Tropical Timber Agreement and the Framework Convention on Biodiversity. There are a number of other national efforts (e.g., preservation of old growth in the Pacific Northwest) and multilateral efforts (e.g., an effort by the European Union to develop quantitative indicators of sustainable forest management) as well.

This paper takes stock of forest resource and ecosystem sustainability from both ecological and economic perspectives. It seeks to identify how these disciplinary perspectives contribute to a better understanding of sustainability, and where the most significant conceptual and factual gaps are found. Of particular interest are two related themes: how economic efficiency and sustainability may differ in their implications for forest system management, and how criteria for forest system sustainability are related to the scale of management decisions (e.g., individual forest site versus region versus the global biosphere). In addressing these points we do not attempt to comprehensively survey the relevant literature. Instead we refer selectively to literature that seems useful in developing the arguments, with particular emphasis on recent compendia that contain a wealth of additional references.

The next section of the paper provides a general overview of sustainability. Section III discusses key aspects of forest ecosystems that appear to have relevance for sustainability. Section IV similarly reviews the literature on economic forest management. The fifth and concluding section discusses how forest management might be adapted in light of sustainability concerns and summarizes major conceptual and knowledge gaps warranting further investigation.

II. The Concept of Sustainability

While the concept of sustainability remains somewhat imprecise, there is growing agreement that two basic sets of issues underlie it (see Toman 1994 and references therein). The first set of issues concerns intergenerational fairness and the moral responsibility of the current generation to its descendants, both immediate and in the longer term. How much of an obligation do we assume for safeguarding the potential well-being of our descendants; what are we willing to give up in terms of immediate benefits for ourselves?[2] The second set of issues concerns the role of assets provided by nature, including forest ecosystems, in satisfying both current interests and the obligations we assume to the future. To what extent are these assets crucial in satisfying intergenerational interests; to what extent can other forms of wealth be substituted? While many economists, ecologists, and ethicists would agree that these are salient questions, there is by no means agreement on the answers.

[2] Our focus here is entirely on human interests, though these interests can be defined broadly enough to include concerns about the circumstances of other animals and concerns about ecosystems per se (as "gifts of nature" rather than just stores of materials and waste sinks). An even more "ecocentric" view, one that tries to endow other living things with inherent moral standing, seems philosophically problematic and of limited practical significance in current policy debates.

A. *Intergenerational Responsibility*

Regarding moral responsibility to the future, it seems intuitively obvious that many if not most people feel some stewardship obligation to succeeding generations. There are, however, difficult philosophical as well as empirical questions about how such obligations are specified. Are we responsible to the next generation as a whole, to just our immediate descendants in the next generation, or to "the future human community" in a broader sense, including hypothetical beings whose circumstances and interests we can only dimly perceive?

Recognition of intergenerational stewardship obligations brings to the fore the potential conflict between these obligations on the one hand, and conventional economic theory and practice on the other hand. The conventional economic approach seeks to maximize the present value of a stream of aggregate benefits less costs. This is a specific intergenerational social welfare criterion with specific moral implications regarding the status of different generations. The standard present value criterion does not include connections between the welfare of the current generation and the (potential) welfare of its descendants. The arithmetic of discounting means that any potential damages inflicted upon the next generation by the current generation are of almost no consequence, and we can delete the word "almost" in the previous phrase when referring to subsequent generations.

Economic theory and practice can be extended to incorporate greater intergenerational concern, though the theoretical extensions are only beginning to be considered, and progress in changing applied economic methods is even more rudimentary. The first key step is recognizing that economic efficiency, broadly defined, need not (in fact, does not) require just the conventional maximization of present value. Economic efficiency, in the sense of the Pareto criterion, only requires that welfare in no generation can be increased without a corresponding decrease in the welfare of other generations. There are likely to be infinitely many trajectories of ecosystem management and economic activity satisfying this condition.

The current generation can use a variety of social values to choose among these possibilities given its concerns for future generations' (potential) well-being as well as its own immediate welfare. One common prescription for dealing with intergenerational concerns is to lower discount rates for projects with substantial intergenerational impacts. However, this approach can involve economic distortions (not to mention ecological damages) that can result from lowering discount rates. For example, lower interest rates encourage dam construction that provides flood control but destroys timber and other ecosystem values on the inundated land.

An alternative conception involves concern for the future as a public good with a "shadow price" like any other valued good and service.[3] This shadow price balances the effect of discounting in evaluating impacts on future generations that are relevant to current decision-making. The standard present

[3] Equity issues within generations likewise can be thought of as involving a societal public good, but our focus here is on intergenerational concerns.

value criterion is a special case with a zero shadow price. Still another possible social welfare ordering, if the current generation is strongly concerned with intergenerational justice, is a Rawlsian maximin rule (see Howarth 1992 for a justification of this approach in terms of individual preferences). Society may also seek to balance growth and justice by seeking nondeclining welfare across generations, allowing the future to be better off than the past, or by letting the future to be worse off provided a threshold level of well-being is respected (see Toman et al. 1995 for further discussion).

From an operational perspective, this conception of the issue requires at least some rough efforts to gauge the intensity of intergenerational concerns surrounding particular ecosystem management (and other) activities. This is by no means a simple task, and economists are just beginning to think about the empirical difficulties. Questions arise as to whether all the valuations needed to use this extended efficiency framework can be meaningfully measured. More generally, questions remain about whether welfare-based models are either adequate or appropriate for addressing the issue. For example, if people see the issue as one of basic moral rights, then the economic model may have little explanatory power. These questions will remain points of contention that transcend concern for sustainable forest ecosystem management.

B. Resource Substitutability and a "Special" Status for Ecological Assets

Once one accepts the idea of intergenerational responsibility as important to social decision-making for sustainability, the next question is how such a responsibility can be met. Let us define the term *capital* broadly to include all the resources and capabilities provided to future generations for meeting their material and nonmaterial needs and desires. Capital can come in many forms—the natural endowment, built structures and tools, and human knowledge and technique, to name broad categories. The human species has been engaged for some time in a process of converting "natural capital" into other forms. As a consequence, material (and to a lesser extent, overall) well-being has risen dramatically, albeit unevenly over time and space. The process of capital conversion has grown in speed and intensity as the size of the human population and its material demands have risen.

Can this process continue until some kind of global steady-state ultimately is reached, or will natural limits to human development be encountered as the scale of human impact increases? If there is a significant chance of the latter, then natural capital must be seen as having a special status in the bequest to future generations. If at some point the large-scale substitution of other capital for degraded natural capital is no longer manageable, then natural capital must be singled out for protection. In this case, we cannot just substitute other forms of capital for natural capital, since the scope for doing so is limited by assumption; we face a harder absolute tradeoff between current and future material standards.

The concept of natural limits currently is unfashionable, at least among most economists, in part because of the failure of "doomsday" energy models in the 1970s to be convincing and in part because the concept of physical limits goes against some basic axioms used to construct much of the current body of resource economics. The prevailing view is that some combination of material substitution or technical change (knowledge substitution) *can* alleviate physical limits, so the emphasis needs to be placed instead on the maintenance of economic activities and institutions (well-functioning markets, progressive R&D) to ensure that any constraints *will* be alleviated.

It is important to note that the intuition against which these axioms are validated includes a number of empirical observations where physical scarcity over certain temporal and spatial scales *was* alleviated by economic responses. The GDP of industrialized countries grew substantially from the early 1970s to the late 1980s, even with a halving of energy intensity. Earlier, England adapted to coal use when fuelwood stocks were depleted. Industrial and developing countries have shown a strong capacity to reduce the intensity of water and minerals use when economic incentives have motivated such changes. In North America, concerns about scarcity from the diminution of forests in the United States has been consistently overstated (Clawson 1979). Wood depletion has led to a long-run rising price trend that has encouraged replanting.

Notwithstanding these observations, there is a persistent critique of the standard substitution model from ecologists, other natural/life scientists, and a few economists that cannot be rejected out of hand.[4] At one level these criticisms can be made in general physical terms. The Conservation Law implies that substitution of other inputs for energy (direct or embodied in other inputs) cannot be unlimited, and that waste sinks will face growing congestion problems with increases in human scale. The Entropy Law implies that we will have to become progressively more clever and devoted to the capture of solar flux to offset the increasing disorder of energy and materials in our biosphere. Critics of the conventional economic wisdom assert that the ability of human adaptation to meet these challenges must at least be questioned, given the rapidly growing scale of human activity relative to planetary resources.

Stated in this way, the potential limits seem somewhat abstract and possibly very remote. A more immediately compelling argument is made by ecologists who argue that well-functioning ecosystems are a valuable asset for which large-scale substitution is problematic. Such ecosystems undergird all life processes, including nutrient and waste circulation and maintenance of genetic diversity, as well as provide cultural and spiritual benefits to humankind. Of particular importance, in this view, are relatively unmanaged ecosystems that tend to have greater organizational complexity, genetic diversity, and natural resilience compared to more highly managed systems. Our knowledge of how these systems operate, including various threshold effects or discontinuities, is so limited that our capacity to "run" them at high intensity for significant periods while avoiding or remediating damages is likely to remain limited at least for

[4] For a thorough sampling of this perspective see the papers in Costanza (1991); see also Ruth (1993).

some time The ability to substitute other investments for serious large-scale damage to basic life processes also is likely to remain limited; and without these processes, the notion of compensatory investments for future generations starts to lose its meaning. It follows from this argument that special attention to the protection of "landscape-level" ecosystem integrity is needed to meet obligations we assume to the future (if not also to the present). This concern contrasts sharply with the maintenance of a fixed harvest flow.

We emphasize that the strength of this imperative for ecosystem safeguarding is scale-dependent. Local damages may allow for greater substitution possibilities than large-scale threats to the extent that local damages affect only the components of larger scale systems, whose services can be replaced by intact components elsewhere. Critics of the conventional economic substitution argument can assert with some justification that past substitution pressures did not operate at the same scale as today's current threats (species loss, climate change, forced "over-simplification" of ecosystems from human pressures that reduce productivity and resilience), which are global or involve large regions. On the other hand, the severity of current threats remains controversial, and even rough methodologies for determining what scales are critical with regard to the substitution problem are only in the process of being developed. One example of this is the work by Norton and Ulanowicz (1992), who start with a view of ecological structure involving a nested hierarchy of subsystems.[5] Small-scale subsystems are more adaptable and less critical than the larger scale systems (e.g., fecundity of a particular species at a particular location versus species diversity throughout a region). They propose that any ecological threats of a scale involving systems that can only recover over a generation or longer inherently involve limited substitution possibilities and moral actions. This formulation needs further consideration from the standpoint of human interests and values, but it is one promising beginning.

C. Implications for Sustainable Forest Ecosystems and Management

The key lesson from this discussion for our purposes seems to be the need to carefully identify (1) the different facets of forest ecosystems of relevance to human welfare broadly defined, (2) the spatial scale relevant to management for different aspects of human welfare (e.g., local timber cutting versus ecosystem species diversity), and (3) the capacity for substitution or damage remediation over different temporal scales. Short-term, small-scale impacts pose little threat to the ability to replace assets or compensate future generations for their loss, and a standard bioeconomic efficiency model would seem readily applicable for determining preferred management strategies. Conversely, longer or larger impacts put more of a burden of proof on conventional value-maximizing prescriptions. All three of these points seem to challenge the conventional forest management model, with its emphasis on nondeclining even flow, its limited attention to substitution possibilities or technical change, and its limited attention in some cases to spatial aspects of larger scale ecosystems that affect stand-level productivity.

If all the benefits, costs, and risks of different ecosystem states could be estimated, and if the "shadow price" associated with concern for the future also could be gauged with some confidence, then in principle one could simply use the conventional value-maximizing framework even with threats of long-term and large-scale damages. In practice, however, this probably assumes too much regarding our (probabilistic) information about the natural world, our ability to monetize ethical concerns, and the capacity of social institutions to aggregate dissimilar interests. An alternative approach to address these problems that is often advocated in the sustainability literature involves the invoking of some "precautionary" or "safe minimum" criterion—placing an extra burden of proof on irreversible natural disruption, while also paying some heed to the costs of foregone resource use (see Toman 1993, 1994).[6] We discuss the applicability of such decision strategies to forest system management in the concluding section of the paper.

III. Forest Ecosystems and Ecological Management Principles

Studies of ecosystems incorporate consideration of organisms and the interactions among them, and the complex of physical and geochemical factors that create the whole environment (Tansley 1935). The fields of ecological energetics, bio-geochemistry, and community and population biology were united into the study of the whole system that integrates biological scales and physiochemical perspectives. Energy flow was identified as the key parameter of ecosystems (Haldane 1931), and organisms and biomass were conceived as manifestations of energy. It has since been recognized that the living portion of the world, the biosphere, is a composite of ecosystems (Hutchinson 1970). This composite forms a continuum of ecosystem interactions that can be scaled up or down depending on the spatial focus of observation. For example, ecosystems can transcend scales from tidal pool to a whole continental shelf.

Ecosystems are therefore boundary-less. The wide range of services and benefits that humans derive from forest ecosystems cuts across temporal and spatial scales. Franklin (1993) makes this point forcefully when he argues for the inadequacy of considering only the forest stand for management; interrelationships among stands in the system

[5] This work in turn is a subset of a larger body of ongoing research on how to define and measure ecosystem "health" and "integrity"; see Costanza et al. (1992) for further discussion.

[6] It is important to note that the concern for irreversibility here must ultimately involve changes in the human condition, not just the condition of ecosystems. Fossil energy mining is physically irreversible for all intents and purposes, but a safe minimum standard has not generally been invoked for this activity here because progress in energy demand efficiency, production efficiency, and the development of substitutes so far has forestalled irreversible consequences for human well-being. (Some would view the threat of climate change as a rationale for a safe minimum standard for protection of the biosphere, which in turn would imply curbs on fossil fuel use.)

are important as well It is necessary, as Franklin says, to consider this whole matrix, to be cognizant of the sea that relates the islands as well as the islands themselves. However, management of ecosystems cannot be considered without some sort of boundary. Human actions have to be defined by both spatial and temporal limits. Thus, recognition of these interdependent scales is needed if forest ecosystems are to be managed effectively (see also Dale and Rauscher 1994). As noted by Gordon (1993) and Mladenoff and Pastor (1993), management also must reflect ecosystem process. How ecosystem processes are regulated remains a subject of debate in ecological science. However, one can surmise that both dynamic equilibrium and non-equilibrium forces play roles in determining dependable versus discordant regulation of ecosystem processes at any location (Botkin 1990). Which of the two kinds of forces play a more defining role in ecosystem processes must be considered in the context of the spatial and temporal scale of the location. No one location will develop in the same way as another because each has experienced a unique set of geological, climatic, and biological circumstances that have shaped its own identity. This dynamic, whether or not in equilibrium, may not change in ways that are beneficial to humans. Constraints to obtaining different services from ecosystems reflect the inherent factors that allow ecosystem processes to function.

A. *Ecosystem Processes and Scales*

Three important sets of ecological parameters of ecosystem processes can be identified (Berlyn and Ashton 1994). The first set, energy and its bio-geochemical cycles, can be considered the foundation underlying ecosystem function. Energy flow and bio-geochemical cycles can be characterized for all ecosystems as open. However, it is their relative differences in openness across scale that determines differences in their productivity. Highly productive systems, such as flood plains and tidal marshes, are considered freely open with nearly complete dependence on flux inputs of energy and nutrients from upstream or downstream. Many upland systems situated on infertile soils can be characterized as less open and can be considered more dependent on energy and nutrient capture within the system. Conceptually, freely open systems can be regarded as intensive resource users compared to those that are less open and that have evolved more conservative adaptations in resource use.

The second set of parameters, succession, food chains, and their trophic levels, is the reflection of this foundation in living organisms. For example, differences in system openness and resource use efficiency can be gauged by measures of organismal productivity (i.e., rate of biomass accumulation) and efficiencies in nutrient and water use relative to photosynthate assimilated.

The third set of parameters concerns resiliency. Resiliency is a measure of repetition or redundancy of both biogeochemical and organismic processes (cycles, trophic levels, food chains) and therefore an indicator of ecosystem fragility (Borman and Likens 1979). More resilient ecosystems, by implication, have greater levels of repetition or redundancy of process than more fragile ones.

However, redundancy does not mean the same as complexity. For example, many moist tropical forests might be extraordinarily complex but retain very little redundancy. Hypothetically, this can make them susceptible to sudden changes in environment. The reason is that the complexity of systems has evolved over long periods of time from variation in one dimension. In mixed-dipterocarp forests, most tree species become represented in a stand from an existing seedling bank at the forest groundstory that is released after a disturbance. Complexity therefore exists in the variation (i.e., shade tolerance, drought tolerance) among species undertaking the same adaptation. These species have few or no other modes of regeneration. In contrast, other forests in more variable and undependable climates, and by implication more variable and undependable disturbances regimes, are simple in floristic composition and structure. However, a single species in these environments can have several modes of regeneration (i.e., vegetative coppice, seedling bank, buried seed) that provide greater redundancy in forest regeneration and subsequent successional processes. Paleoecological theory now suggests that ecosystems that evolve in less variable and more dependable climates might have extraordinary "superficial complexity" but less novelty in the range of regenerative mechanisms capable of withstanding change in disturbance and stress regimes (Behrensmeyer et al. 1992) Measurements of these three sets of parameters can highlight ecosystem health and sustainability. Appropriate standards of measure have yet to be determined, but some attempts are being made (Vogt and Gordon 1994).

Though ecological processes are boundary-less, ecosystem management is only feasible when operations can be conceived of at certain relatively discrete scales. A sequence of three increasing scales for accommodating ecosystem processes includes (1) forest stands; (2) watersheds (a landscape scale); and (3) physiographic regions. Different scales are appropriate for different services and benefits derived from forest ecosystems Some direct uses—timber, game, other product harvests—can be managed at the stand level. Other values—water management, recreation, habitat maintenance—shade into the landscape scale as well. Still other values, especially those related to biodiversity and carbon sequestration, are relevant at regional as well as smaller scales.

A key point, as noted above, is the interdependence of ecosystem conditions at different scales. In particular, the conditions that promote benefit flows at the level of a particular stand depend on conditions found on adjacent or related stands and, indeed, on the entire matrix of interrelated conditions that determine ecosystem health at the landscape level This consideration is critical for those plant and animal species dependent on certain kinds of combination and scale in stand heterogeneity (the amount of structural contrast and edge among stands) across the landscape (Hunter 1990) Thus, management at multiple scales is indicated not just to secure the full range of multiple-use values provided by forest ecosystems, but also to secure those stand-level benefits that are the traditional focus of forest management.

With these thoughts in mind, we turn to indicators of ecosystem conditions at different scales. At the scale of the stand, considerations must include the functional integrity of the energy and nutrient cycles, and the type, frequency, and size of disturbances that initiate regeneration and facilitate the dynamic of species succession. Functional attributes might also include avoidance of threshold minimum levels of such substances as soil carbon, surface organic matter, and nitrogen. The variability of climate and geology promotes ecosystems with different limiting factors and, therefore, different cycles, different disturbance regimes, and different indicators of threshold requirements.

Because cycles of energy and nutrients are inseparable from the hydrologic cycle, watersheds are potentially useful scales for managing the arrangement of stands and their states. The shifting steady-state mosaic first defined by Borman and Likens (1979) can be considered at this scale. The appropriate arrangement and management of operations within a watershed can protect the integrity of organismal and bio-geochemical processes at a more aggregate level. However, watersheds come in many sizes ranging from those such as the whole Amazon basin to others that might include only the headwaters of a small stream. In most circumstances small tributary watersheds are the most useful scales to consider for purposes of stand management, while larger scales are more appropriate for landscape-level values. It is also important to recognize that different kinds of watersheds can influence the degree of openness of energy flow and organism movement across watershed boundaries. A kettle hole as a system, with no watershed outlet, is more completely isolated and independent of its surroundings than the regular tidal flushing of an estuary. Understanding the degree of watershed openness and interdependence on surrounding watersheds obviously has critical implications for forest management.

The last scale considers redundancy of spatial and temporal pattern of stands and watersheds across the landscape. Physiographic regions are convenient boundaries of management because of their landscape uniformity in geology and the nature of topography. Together with climatic factors (i.e., temperature and rainfall amount and flux) a variety of bioregional classifications have been developed that characterize broad overall rates of ecosystem processes (e.g., Krajina 1965). The hydrologic cycle can be used to interpret the nature and connectivity of a region's underlying geology and climate and therefore promotes a region's spatial delineation. This is because pattern and density of water flow off the land surface generally indicates differences in resistance of rock to weathering, soil permeability, and erosion and therefore difference in productivity. Important considerations at this scale include the role of buffers, and connectivity of riparia and uplands in order to address ecosystem values that in certain intensively managed circumstances are not the dominant driving values of land use, but that need to be recognized and sustained within the matrix comprised of the physiographic region, watershed, and stand.

B. *Management to Reflect Ecological Conditions*

How has human intervention affected forest ecosystems at different scales? Noss (1993), in a biting critique of conventional single-value timber management practices, asserts that they have had a number of deleterious effects. Stands have become both younger and more simplified than a healthy natural forest would maintain. Stands also have become smaller and more isolated, natural fire cycles have been suppressed, and human incursions have been encouraged by extensive road networks. These forces, he argues, adversely affect necessary cyclic patterns of successions, biodiversity, and water management. Others would find a number of exceptions to these generalizations and would state the point far less forcefully.

A key point in assessing this critique of conventional management is the recognition that the ecological and human consequences of forest system degradation depend on their scale. Degradation at a local scale is more easily accommodated, both ecologically and economically, than damage at the scale of a watershed or physiographic region. It follows that management must be scale- as well as site-specific (Smith 1986). This is a recognition that generally no one management or silvicultural system can work for all sites within the physiographic region-watershed matrix, given the variability of both the ecological constraints and socioeconomic values that exist across a landscape. From an ecological perspective, being site-specific in management is an appropriate accommodation of the differences in rates of ecosystem process that occur across the landscape. For instance, though the process of succession might be the same in one stand as compared to another within a watershed or physiographic region, there may be gradients of resource fertility from the valley up to ridge or from upland down to coastal plain. These gradients are also a reflection of site resilience to degradation.

Effective management requires an understanding of where on this gradient each stand exists. For example, one extreme of this gradient would be a site which is fertile and highly resilient. People have traditionally pushed such sites to conform to values that led to intensive cultivation techniques. History has demonstrated that this can be sustained for long periods of time, as on the Rhine River and Nile Delta, where continuous cultivation has gone on for thousands of years. The other extreme of the resource gradient would be an infertile site with low resiliency. On such sites, effective management should be low-input, with as little tinkering with ecosystem processes as possible.

In many instances history has demonstrated human failure to understand and match site fertility and resilience to appropriate kinds of land use. Examples that might be considered land use failures are the clearing of many upland tropical moist forests for pasture and arable agriculture and their subsequent abandonment. Many natural forestlands are restricted to upland sites that are less fertile, and in many circumstances are therefore more fragile to degradation.

Management for single values, particularly on fragile but ecologically complex sites, cannot help but simplify ecosystems process.[7] Many examples exist of situations where management has led to oversimplification. One example is

[7] This is as true for cropping, animal husbandry, or nonagricultural uses as it is for forestry.

the management of mixed-dipterocarp forests on the Malayan peninsular. Some of these forests have been managed for over 100 years initially for gutta percha, a latex used for electrical wire insulation; then dark meranti, dense timber species used for load-bearing construction; and then for light meranti, light timber species used for plywood. The use of various intensive techniques that maximized one commodity and excluded other species perceived as having no current value promoted the sequential simplification of these structurally complex forests. In the long run, because market values changed more rapidly than the forest could grow, the forest that developed became both "biologically inflexible" and incapable of accommodating continued market changes.

It follows that maintaining the essential ecological integrity of a forest ecosystem at higher scales is important for maintaining value "redundancy" and flexibility to changes in ecological conditions or human demands at systemic or lower scales. Though ecological integrity is a useful concept, translating what it means on the ground is very difficult at present because of an inadequate amount of site-specific data that clearly demonstrate integrity thresholds of ecosystems. An example directly relevant to management might be taken from recent studies in the Pacific northwest that suggest silvicultural techniques need to more closely emulate natural disturbance processes (e.g., accumulation of substantial dead wood) at landscape scales (Franklin 1993, Parker 1993). However, these observations do not dispose of management dilemmas. Human impacts (from harvesting or other activities) could be quite intense at local scales without necessarily compromising larger ecosystem integrity. Unfortunately, the current state of ecological knowledge regarding stand/landscape relationships is too limited to allow us to pinpoint when an accumulation of stand-level degradation compromises higher-level functions.[8] However, efforts to bridge this gap are emerging in the literature (see, e.g., the review in Shugart et al. 1993).

Even if ecological science could better characterize the relationship between stand and landscape dynamics, a management dilemma would remain in that too little is known about the consequences for humans of ecosystem degradation. We can probably venture that very large-scale, irreversible alteration of forest ecosystems is not in our own immediate interest, let alone consistent with satisfying an assumed obligation to future generations. However, this is too crude a filter in itself for determining forest management decisions. The knowledge gap between ecological conditions and human interests also casts a shadow over economic analyses of forest ecosystem management, as discussed below.

IV. Economics of Forest System Management

In this section we briefly review several strands of literature pertaining to the economics of forest system management. The first strand concerns the economics of value-maximizing harvesting of a single forest site. The second strand concerns extended value-maximizing analyses that incorporate the multiple uses of and benefits from a single forest site and related stands in a larger forest system. We also consider models of land use which emphasize the extensive margin for forest management as well as the intensity of management of specific stands. The section concludes with some observations on valuation, uncertainty, and irreversibility.[9]

A. *Value-Maximizing Stand Harvest Models*

Models of forest rotation that maximize the present value of net harvest proceeds are probably the most familiar species of economic tool in the forest management literature, so we review this literature only cursorily here. The basic model posits a stationary environment (no ecological or economic trends) in which a single forest site is cut for timber at regular intervals and then regrows or is regenerated. The value-maximizing harvest interval balances the marginal value of harvest delay—greater maturity and economic value of the stumpage—against the marginal cost of waiting as reflected in a discount factor. The marginal value reflects the fact that delay will increase the size and thus the value of the next harvest but will also decrease the net present value of all future harvests by delaying them (given the regularity of the harvest interval).[10]

From the standpoint of harvest management, *any* choice of harvest interval can generate a sustainable outcome in the sense of a sequence of harvest that can be perpetuated over an indefinite time. Present value maximization selects one of these sustainable patterns. Other choices also are possible. In particular, society could choose to maximize the "sustained yield" (the average yield over time) or the sustained rent; the latter criterion reflects economic choice but eschews discounting. Either of these options will lead to a longer rotation period and a larger average age of the standing stock; from an intergenerational perspective, these rules may endow the future with more forest endowment than present value maximization. In the same vein, it can also be shown that a higher discount rate reduces the rotation period that maximizes present value. Increases in timber value shorten the rotation, while increases in replanting costs increase the period.

Since Faustmann's original presentation of the rotation model in 1849, it has been extended to include a number of

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8 Dale and Rauscher (1994) note that no one class of models, whether concerned with short-term impacts on individual trees or centuries-long changes in the biosphere, is adequate for analyzing the effects of climate change.

9 As one reviewer of the paper has pointed out, our focus here is mostly on the neoclassical mainstream. This is the literature that has figured most prominently in economists' critiques of forestry management methods, and it has in turn been the primary target of ecological economists' critiques. Some limitations on the applicability of this model already have been noted in Section II. A key assumption in policy applications of the neoclassical model is the capacity of government to identify and effectively rectify market failure due to externalities. A less sanguine view of this capacity is expressed by Anderson and Leal (1991). It should also be noted that the frameworks reviewed here all are partial-equilibrium models that do not fully address interactions between forestry management and other social goals, or the endogenous evolution of technology affecting the supply and demand for forest products.

10 In a single-cut model, the "own rate of return" on waiting—the rate at which stumpage value increases with the harvest date—equals the rate of return on other assets. The multiple-cut model has a shorter rotation period than the single-cut model, reflecting the delay effect discussed in the text

considerations such as various assumptions about maintenance and replanting costs, price and cost trends, management through thinning, and uncertainties such as fire risks.[11] Even with these extensions, however, value-maximizing rotation models remain focused on one aspect of forest management—timber harvest—and one societal decision rule—standard present-value maximization. The arguments in Section II imply that this focus is too narrow to adequately address sustainability issues. However, the models represent an advance over volume-maximization models like the Hanzlik model. As Hyde (1980, Chapter 2) points out, these give rise to harvest plans that do not maximize the value obtained from timber management. The even flow model does generally yield longer rotations, which may promote some ecological values. However, it would be preferable to explicitly introduce these values in the management model.

B. Multiple-Use Site Management

One natural extension of the Faustmann model is the consideration of tradeoffs between harvest values and site values generated by standing forests. These values could reflect multiple-use possibilities, as with a forest stand that can be used as a recreational site or source of biodiversity as well as for timber harvest. They could also reflect existence values that are unrelated to direct use possibilities by those valuing the standing forest.

Hartman (1976) analyzes multiple-use management of a single forest stand in which nonharvest values vary with stand age. Many of these values (e.g., preservation of old-growth ecosystems) could be seen as increasing with stand age, but other values (e.g., those related to some recreational activities) may decline with stand age. The basic idea in the Hartman model is that these nontimber values increase over the growth interval of the forest, with the process of accumulating these values beginning again after each cut. A key assumption in this framework is that these values can be regenerated with the forest growth; there are no absolute irreversibilities. However, the regeneration period could be very long (i.e., the amenity flow could be nugatory until the stand becomes very old).

Introducing multiple values in this framework considerably complicates the determination of the present-value-maximizing rotation period. As pointed out by Bowes and Krutilla (1989), in many cases the Hartman rotation will be longer than the Faustmann rotation but shorter than the rotation that would be chosen for amenity value maximization alone. Initial conditions may affect the harvest decision; very old stocks may be preserved in perpetuity, while younger stocks are cut to avoid the wait for future amenity services. Forests that would be economic to cut on the basis of harvest values alone might be preserved indefinitely in the Hartman solution. On the other hand, it is in principle possible that multiple-use considerations would expand the timber harvest if doing so promoted nontimber values (e.g., by expanding wildlife with a broken canopy). Generally, the value-maximizing rotation will depend on the slope and curvature of the function describing the flow of amenity services, as well as on the overall value of nontimber services.

Changes in harvest and nonharvest values and the costs of harvest can have ambiguous effects on the rotation, in contrast to the Faustmann solution. From the standpoint of sustainability, it is perhaps most interesting to note that an increase in the discount rate does not necessarily shorten the rotation period. A rise in the interest rate increases the opportunity cost of delaying harvesting, but it also increases the relative benefit of delaying harvest by increasing the ratio of current amenity values to the present value of cumulative amenity values. Another complication is that amenity values can introduce conconcavities into the maximization problem, giving rise to multiple local extreme points (solutions to the first-order conditions) and discontinuous responses to changes in economic conditions. For example, a small increase in the value of providing wildlife forage may abruptly lower the rotation period in order to open the canopy more frequently (see also Swallow et al. 1990 for further discussion).

C. Multiple Uses, Multiple Stands

The analyses discussed so far are limited to management of a single stand of fixed size. This is a serious drawback since amenity values depend on the whole landscape structure, not just the age of the stand. There are also shortcomings even for a narrower analysis of timber management. In particular, the fixed-stand model indicates that a biological harvest rule yields an older average stand age than an economic harvest rule. However, application of this rule would render some economically marginal forest lands submarginal, thereby changing the area under harvest management. To get around these difficulties, it is necessary to analyze management of multiple stands with attention to extensive as well as intensive margins.

Bowes and Krutilla (1989) discuss an extension of the Hartman framework to multiple interrelated sites. Here the interrelationship arises because the flow of amenity services depends on the age distribution of forest stocks within and across sites. The amenity production function considered by Bowes and Krutilla is not explicitly spatial—amenity values do not depend on where trees of different age classes are located in relation to each other. Thus, for example, in their model the same flow of amenity services could be derived from a hectare of old growth scattered across a larger area and a hectare of concentrated old growth. This is an obvious limitation of the assumed production relationship.

Introducing multiple interrelated sites only complicates the theoretical analysis. One possibility is a steady-state age distribution (the so-called "even flow cycle") with a Hartman solution for the rotation period. However, cyclic patterns also are possible, as are corner solutions for some tracts that involve perpetual clearing or preservation. Models of this type can only be approached through dynamic programming, and analysis of them with this

[11] See the citations in Bowes and Krutilla (1989, chapter 4, footnote 23), Clark (1976, chapter 8), and Wear and Swallow (1993). Clark's analysis is interesting in that it indicates that discounting, by inducing greater take through thinning relative to clearcutting, may smooth the time path of harvest over time. However, his analysis assumes a fixed area under harvest management. When the extensive margin is variable, the effects of discounting are less clear, as discussed below.

approach is hindered by the complicated dynamics of the system (e.g., nonconcavities and the possibility of multiple steady states) and by limited empirical capacity to specify the relevant production relationships.

A somewhat more explicitly spatial framework is found in Swallow and Wear (1993) and Wear and Swallow (1993). These authors focus on a specific stand in space (the "focal stand") which generates a flow amenity value that depends on the ages of adjacent stands.[12] Through conceptual analysis and simulation, they show that bringing in locational interdependence generally leads to a sequence of nonconstant rotations which may change discontinuously with shifts in economic or ecological conditions, as already discussed in connection with the Hartman model. This line of research appears promising, though the solutions are dauntingly complex and practical extensions to multiple-site management are not straightforward.[13]

D. Ricardian Land Use Models and the Extensive Margin

Single or multiple stand dynamic management models emphasize the optimal timing of land use on specified parcels. As just noted, rich models generate very complex time profiles of land use both within and among parcels. An alternative analytical strategy is to focus more on the determinants of long-term land use across different land parcels, following the classical Ricardian model of agriculture and land rent on the "extensive margin." The application of this model to forest management is developed in Hyde (1980, Chapter 4) and more recently in Hyde et al. (1994).[14]

In the Ricardian model, different land sites can be arranged according to their long-term rent potential, given specified economic and technological conditions.[15] Some sites will be so valuable in nontimber uses that they will be converted, e.g., to agriculture or urban land uses. Other sites that will not profitably support intensive agricultural use could support managed plantation forestry.[16] Still other sites will not generate revenue streams sufficient to cover agricultural or forest plantation management costs, but they can support profitable periodic cuts of natural regrowth. Finally, some sites will be too unproductive or too remote to profitably support any harvest activity; these submarginal locations may receive some development for recreational uses or be left undeveloped, according to the Ricardian model, unless economic conditions warrant a reevaluation of the extensive margin.

On sites that will support forest harvest, Faustmann-type economic considerations determine the frequency of cut However, the number of sites subjected to harvest and the total harvest volume will depend on the total demand for forest products and the differential costs of management across sites, not just on the opportunity cost of investment capital and site-specific costs as in the Faustmann stand model. Consideration of both intensive and extensive management margins considerably complicates the assessment of harvest responses to economic influences. In particular, whereas the Faustmann model would indicate a negative steady-state relationship between harvest volume and interest rates on a given site, a rise in interest rates also will have a short-term positive effect on timber supply by inducing a liquidation of standing inventories, and it may have a positive long-term effect if the interest rate increase induces conversion (or reversion) of land from agriculture to forest.

Sedjo and Lyon (1990) have developed the basic framework discussed above into a numerical simulation model of world timber supply. In their model, growth rates on different forest sites depend on stand age and regeneration inputs, as in the Faustmann model. The model also includes depletion of existing old-growth stocks and the determination of the extensive margin for harvests. The Faustmann dynamics and Ricardian margin analyses are integrated using an optimal control framework. The model does not include multiple-use values, however.[17]

In principle, the Ricardian model can be extended to multiple uses (joint products) so that, for example, a site that would be periodically cut after natural regrowth (or subjected to plantation management), when one only considers harvest values, might be preserved if the social rent stream is higher in a preserved state. However, such extensions would introduce many of the complications encountered in the Bowes-Krutilla analysis. A simpler alternative is to consider harvest decisions subject to *a priori* restrictions on the diminution of specified ecological values. For example, harvest decisions can be constrained by requirements for old growth acreage preservation or limits on harvesting patterns (thinning versus clear-cutting). However, the discussion in Section III suggests that without a more explicitly spatial framework, it may be difficult to adequately represent some harvest constraints that bear on ecosystem conditions.

One key insight emerging from the land-use perspective on forest management concerns the effects of property rights and other land-use policies on the location of the extensive margin and, thus, on the degree of forest preservation consistent with different market outcomes. It is now widely recognized that failures to adequately police forest access through either private or communal property rights systems contributes significantly to excessive rates of deforestation. Simi-

[12] As these authors point out, their focus is on a single stand rather than the forest-level analysis of Bowes and Krutilla, but in doing so they can bring locational effects more to the fore.

[13] Hof and Joyce (1992) present a model which incorporates a richer spatial configuration of land allocations within a larger area, but they use single-period nonlinear programming to determine a statically optimal configuration.

[14] It should be pointed out that the multiple-use, multiple-stand analysis in Bowes and Krutilla (1989) includes an assessment of the margin between managed and unmanaged sites. The Ricardian approach discussed here does not capture all the intertemporal subtleties of the Bowes and Krutilla approach, but it does provide a more tractable framework for qualitative analysis. The complexities encountered in the theoretically more general Bowes-Krutilla approach warn us of potential problems in applying simpler methods.

[15] Rent here is used in the economist's sense of surplus revenue over all opportunity costs of production, including long-term returns to capital and entrepreneurship.

[16] The question of whether plantation or agricultural sites are "further out" on the extensive margin depends on their relative costs of management and output values.

[17] Binkley and Van Kooten (1994) survey other large-scale simulation models that can be used to evaluate the effects of climate change.

larly, excessive stimulus to land conversion (e.g., agricultural subsidies) will impinge on both harvest and nonharvest forest values.

Such market failures and policy failures point to significant potential complementarities in the pursuit of market value maximization and ecological preservation. It may well be, for example, that many of the forest lands that are the richest but most fragile sources of nonharvest values—water control, biodiversity, aesthetics, and recreational opportunities—also are marginal harvest resources in the absence of distortions. In this case, correcting the distortions in land use also will promote ecological values. However, the complexity of spatial relationships in ecosystems and the relative lack of understanding of such relationships cautions us that this "win-win" scenario may not prevail in some important instances.

E. Valuation, Uncertainty, and Irreversibility

We have noted that the threat of irreversible and costly degradation is one of the major concerns raised by those who argue for sensitivity to ecosystem conditions in forest management. As noted above, the amenities production function in a multiple-use model can in principle capture the idea that benefits such as those derived from old-growth forests may regenerate very slowly, or essentially not at all, after the forest is cut. This long-term or permanent loss in future benefits becomes part of the opportunity cost of harvest in the dynamic programming solution to the multiple-use problem, and if this opportunity cost is sufficiently large the result will be preservation of the site or sites.[18]

This argument presumes full knowledge of both the irreversible ecological changes and their costs. However, in the face of uncertainty about the fate of ecosystems under different management systems, preservation also allows the manager to maintain greater options in the pattern of future use (see Krutilla and Fisher 1985 and references therein). This option value may be an important argument for preserving a forest site, even if a deterministic analysis suggests that the value-maximizing strategy is more active management.[19] Addressing this issue requires an extension of the multiple-use model to include uncertainties about future ecological conditions and demands for various ecological services.

This approach to uncertainty and irreversibility assumes that the various ecological contingencies and their human consequences at least can be enumerated. In practice, our knowledge appears to be much more limited. The depth of ecological uncertainty already has been noted. On the economic side, we can estimate harvest values fairly accurately, and we have some estimates of recreational values (see, e.g., Krutilla and Fisher 1985, chapter 7, and Englin and Mendelsohn 1991), but we know far less about the value of more "diffuse" ecosystem services. The debate about how to measure biological diversity, let alone value it, is an obvious case in point (see, e.g., Weitzman 1992, Solow et al. 1993, and Simpson et al. 1994); but there are knowledge gaps regarding the value of other services as well. Until these gaps are narrowed, the economic theory of irreversibility will outpace practical ability to address the problem.

V. Summary And Conclusions

Several basic points seem to emerge from the discussion in this paper.

A. Ecological Concepts and Applications

To understand the natural functioning of forest ecosystems and their components, a focus on individual stands alone is inadequate. Both harvest and nonharvest values depend on interdependencies among stands. However, there also are drawbacks to thinking of forest ecosystems just as aggregates of stands. The whole functions differently than the sum of its parts. To be best understood, forest ecosystems need to be seen as a nested set of structures embracing the stand, the watershed, and the physiographic region. Conditions on smaller scale units depend on the states of the system at higher scales as well as determining these states. Because humans have an interest in the functioning of forest ecosystems at all scales (e.g., stand-level timber productivity, watershed-level flood control, regional biodiversity, and global carbon sequestration), effective management must also consider ecosystem conditions at multiple scales.

However, these observations do not settle all questions of forest management. Also needed is a description of relationships between various human interests and ecosystem characteristics. A purely hierarchical or lexicographic management practice would permit smaller scale exploitation of forest ecosystem resources only to the extent that larger scale functions were unimpaired. In effect, the marginal cost of larger scale ecosystem degradation would be treated as infinite. While there may well exist a scale of degradation at which this is roughly the case, in many other situations one can imagine some tradeoffs between small-scale and large-scale values. To account for them wisely requires information on human values from economics and other social sciences.

The scale principles enunciated above do not address how forest ecosystem attributes actually interact at different scales. There are ongoing studies of these relationships, but much remains uncertain. This is a dilemma not only for ecological science but also for the expanded use of ecological information in forest management.

B. Applicability of Economic Models to Sustainable Forest Ecosystem Management

While the concept of sustainability continues to elude precise definition, it can be said that sustainability emphasizes both responsibility to future generations and a concern for limits on substitution possibilities that might limit the satisfaction of this assumed responsibility. Compared to this,

[18] See, e.g., Krutilla and Fisher (1985) and Barrett (1992). Hyde (1980, Chapter 6) presents an interesting example of how these considerations may interact with regulatory policy. For the site in question (the French Pete drainage in Oregon), he concludes that unconstrained value-maximizing mining of old growth is likely to economically dominate recreational values; but given mandated even-flow constraints that limit harvest volume, preservation of the site for recreational values likely dominates multiple-use management.

[19] There is similarly a "quasi-option value" (Fisher and Hanemann 1987) reflecting the value of delaying irreversible actions until more information about their consequences is available.

the scope of the standard present value criterion in economic models of forest management clearly is narrower. The multiple-use models in principle offer an advance over economic harvest optimization models for addressing issues of sustainable forest system management; these in turn offer advantages over volume maximization models commonly used by foresters.[20] The multiple-use models recognize that there is a multiplicity of services provided by forest ecosystems, some of which may argue for preservation of sites. The models offer some capacity to deal with forests at different spatial scales, recognizing that site management cannot be divorced from management at an ecosystem level. In principle at least, questions of irreversibility can be addressed. Again in principle, they also could be extended to encompass broader social criteria that put more weight on intergenerational bequests.

Having said this, it must also be said that serious conceptual and practical problems remain in the application of existing economic management models to sustainability issues. Both types of problems ultimately grow out of difficulties in representing the production function for timber harvest and ecological services. One is left with lingering doubts as to whether the stylized service supply functions represented in economic management models do justice to the way forest ecosystems work at different spatial and temporal scales. This highlights again the disadvantage of limited information about complex ecosystems. But even if these ecological questions could be addressed, the appropriate values of ecological services to guide management, including values related to irreversibility, also remain in doubt.

C. *Precautionary Practices Revisited*

The knowledge and techniques needed to fully address gaps in both ecological and economic analysis will remain elusive for some time to come. In this situation some kind of "safe minimum standard" approach may have appeal as a response to potential losses from development versus preservation. Perceived risks of greater and more irreversible losses from large-scale human impact may reflect informed scientific judgment, risk aversion, or some other motivation. Regardless of the rationale, the perceived asymmetry would call for greater attention to protection of large-scale ecosystem integrity than might be indicated by a simple comparison of expected social benefits and costs (let alone a comparison of only a subset of benefits and costs).

A safe minimum standard approach to forest system management could in practice involve several elements that reflect concern with ecosystem values. Management for timber values would be subject to larger-scale constraints on ecosystem integrity, insofar as these constraints can be identified given current information. In particular, harvest methods could more closely mimic natural processes Further protection for ecosystem functions may require the setting aside of significant contiguous patches in some locations, at least until knowledge of how ecosystem functions respond to human intervention increases.

This approach to forest system management is *not* incompatible with improved economic efficiency in the conventional sense. Indeed, as indicated in Section IVD, removal of market distortions could have significant environmental as well as economic benefits. The safe minimum standard instead can be seen as complementing conventional economic efficiency when large-scale hazards call a broader set of social interests into question. Of course, a precautionary strategy can be overdone. How far it should or can be taken is a social value judgment that can be only partly informed by economic or ecological analysis.

[20] There is evidence that even the simplest financial analysis models are not always applied successfully in forest management (see, e.g., Hyde 1980 and Repetto 1988). This only underscores the gap between academic analysis and public agency practices, as in the controversy over below-cost timber sales. While we believe that there is a definite need for better integration of ecological and economic principles in forest system analysis and management, there are also gains available from more extensive use of the current state of the art in economic management.

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