CHAPTER 10

NONLINEARITIES, BIODIVERSITY CONSERVATION, AND SUSTAINABLE FOREST MANAGEMENT

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Abstract. There are two broad approaches for jointly producing timber and conserving biodiversity in forests: segregated management, in which timber production is emphasized in some parts of the forest and biodiversity conservation in others, and integrated management, in which conservation measures are incorporated into logging regimes. Nonlinearities in forestry production sets affect the relative economic superiority of these two approaches. Such nonlinearities can result from economic, institutional, and ecological factors. They can cause segregated management to be superior to integrated management even in forests comprised of identical stands. The policy relevance of this and other effects of nonlinearities on spatial aspects of forestry management depends, however, on the relative values of biodiversity and timber.

1. INTRODUCTION

"Sustainable forest management" (SFM) as commonly defined requires more than the successful regeneration of timber trees after harvest. One of its most important dimensions is the conservation of biological diversity. All certification systems for SFM contain requirements related to biodiversity. The most prominent international certification organization, the Forest Stewardship Council, has declared ten principles of SFM, and two of them pertain to biodiversity conservation (Forest Stewardship Council, 2002). Principle 6 states that "Forest management shall conserve biological diversity and its associated values … and, by so doing, maintain the ecological functions and the integrity of the forest." Principle 9 states that "Management activities in high conservation value forests shall maintain or enhance the attributes which define such forests." Similarly, the International Tropical Timber Organization (1998) has established seven criteria for SFM, with Criterion 5 focusing on biodiversity.

Kant and Berry (Eds.), Economics, Sustainability, and Natural Resources: Economics of Sustainable Forest Management, 207-222.

Certification systems allow flexibility in the management approaches used to conserve biodiversity in timber production forests. They explicitly recognize that biodiversity can be conserved either by prohibiting logging in some parts of a forest or by modifying harvesting methods in the areas where logging is allowed. That is, possible approaches include both the spatial segregation of biodiversity conservation from timber production and the integration of conservation measures into logging regimes.[1] For example, Indicator 5.7 of the International Tropical Timber Organization (1998) calls for the "Existence and implementation of management guidelines to … keep undisturbed a part of each production forest" (p. 14), while its Criterion 5 states that "Biological diversity can also be conserved in forests managed for other purposes, such as for production, through the application of appropriate management practices" (p. 13). Common examples of the latter practices include reducing the number of trees felled and adopting directional felling methods or cable logging to reduce damage to residual trees and the forest floor.

In this paper we demonstrate that nonlinearities in forestry production sets affect the relative superiority of spatially segregated and spatially integrated approaches for conserving biodiversity in timber production forests. By "forestry production sets" we refer to the technically feasible combinations of biodiversity and timber that can be produced from a forest for a given level of management inputs. By "nonlinearities" we refer to violations of the standard assumptions about production sets, such as that their boundaries are continuous, smooth, and outward bowed (i.e., convex). Our focus is on the implications of nonlinearities for spatial aspects of forest management. In this regard this Chapter complements Chapter 9 in this volume by J. Barkley Rosser, which focuses on dynamic aspects.

A nonlinear relationship between the amount of biodiversity conserved in a forest and the amount of timber harvested can result from a variety of factors. We consider three: economic, institutional, and ecological. We show that some nonlinearities favor segregated approaches while others favor integrated approaches. We also show that nonlinearities can lead to the counterintuitive result that segregated management can be superior to integrated management even in forest estates comprised of identical stands.[2] That is, the justification for segregated management does not hinge on some forest stands being richer in biodiversity than others. As will be discussed, this particular result illustrates the possibility that nonlinearities can generate multiple forest management equilibria.

This paper is intended to be illustrative, not comprehensive. It does not provide a taxonomic survey of forest management nonlinearities, nor does it provide a complete review of the literature on this topic. Instead, it employs a series of three simple models to illustrate the effects of different types of nonlinearities. These models are drawn from our previous work, with some modifications to make the exposition within this paper as consistent as possible. Although the models' formulations differ, they share the feature that their main results can be depicted in a straightforward way using production possibility frontiers.[3] More complex nonlinear models can of course be formulated. Our intention is to strip away the complexity and to expose the intuition as to how nonlinearities affect the choice between segregated and integrated forest management approaches.

We begin with a general theoretical model that demonstrates how a nonlinearity at the level of an individual forest stand can favour segregated management at the level of the forest estate. This model was first presented in a paper by Vincent and Binkley (1993). The particular nonlinearity in this first model is a nonconvexity. We then consider a model that illustrates how a nonconvexity can result from economic and institutional factors. This second model is from a paper by Boscolo and Vincent (2003), who in addition to presenting it in a theoretical context applied it to tropical rainforest data from Malaysia. We summarize their simulation results, which underline the important point that a nonconvex production set does not necessarily imply that segregated management is superior to integrated management. The relative values of biodiversity and timber also matter.

The third and final model considers nonlinearities resulting from two ecological factors: species' populations being clumped instead of randomly distributed across the forest, and species having minimum viable populations within reserves where logging is prohibited. The first factor favours more integrated management, in the sense of having a large number of small reserves spread across the forest (in the extreme, a refugium within each annual cutting block), while the second favours more segregated management, in the sense of having a small number of large reserves (in the extreme, just a single reserve in one location in the forest). This model is from a paper by Potts and Vincent (2004). In contrast to the previous two models, the production set in this model is convex. Like Boscolo and Vincent (2003), Potts and Vincent applied their model to rainforest data from Malaysia. We show a subset of their results, which, similar to the results in Boscolo and Vincent, illustrate the impact of relative economic values on the relative superiority of more integrated and more segregated management approaches.

We conclude the paper by summarizing the findings in the paper and discussing the implications for SFM, especially in the context of tropical rainforests.

2. A GENERAL MODEL OF NONLINEARITIES IN FORESTRY PRODUCTION SETS

Figure 10.1 pertains to a model in which production possibilities at the stand level are affected by management effort.[4] The vertical axis shows the physical output of biodiversity (e.g., the number of species preserved), and the horizontal axis shows the physical output of timber (e.g., cubic meters harvested). The model can be interpreted as being either static or dynamic; in the latter case, the axes are expressed in terms of discounted sums of current and future outputs. The production possibilities frontier shifts from SM^B to IM to SM^T as more management effort is applied to the stand. Intermediate frontiers also exist; we show just these three because they are sufficient to illustrate the difference between segregated and integrated management.

Suppose that the forest contains two stands, which is the minimum number necessary to illustrate this difference. Moreover, suppose that the stands are identical in all respects, with production possibilities as shown in Figure 10.1, and that a given level of management effort is to be allocated between them. If effort is split evenly between the stands, then the production possibilities frontier is identical for each stand and equals IM. If instead effort is split unevenly, then the stand receiving more effort has a frontier of SM^T, while the stand receiving less effort has a frontier of SM^B.

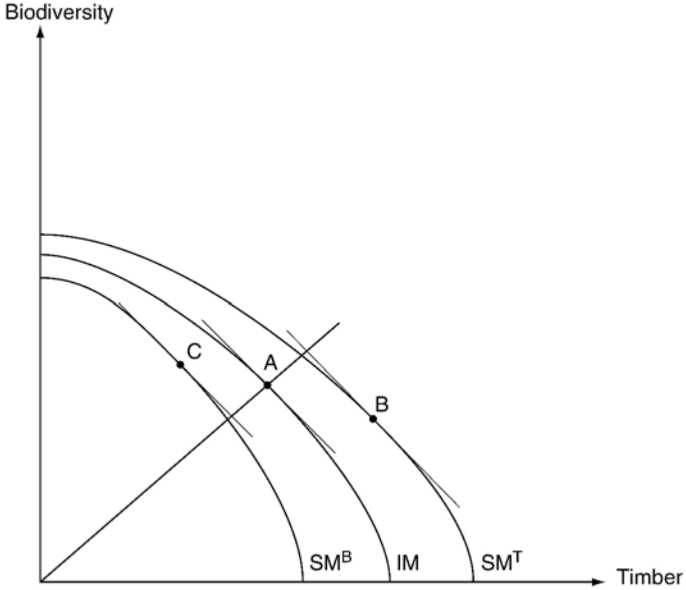


Figure 10.1. *Superiority of Segregated Management in a Two-Stand Model with a Nonconvex Production Set*

Let us make the additional assumption that SM^T and SM^B are equidistant from IM along any ray from the origin, with the distance rising as the biodiversity-timber output ratio falls (i.e., moving clockwise along IM). Equidistance is obviously a special assumption. It is not necessary for the result we are about to prove, but it makes the proof easier. We will discuss the implications of relaxing it.

Suppose that the values of timber and biodiversity are such that the ratio of these values, the relative price line, is tangent to IM at point A. If effort is split evenly between the two stands, then both stands should be managed at this point. This is the integrated management equilibrium (hence the abbreviation IM for the frontier): both stands are managed identically, with each one producing a mix of biodiversity and timber.

This is not the only equilibrium, however. The geometry of the frontiers implies that the price line is tangent to SM^T at a point B that lies to the right of the ray that passes through point A, and is tangent to SM^B at a point C that lies to the left of the ray. These two points represent the segregated management equilibrium (hence the abbreviation SM). The stands are no longer managed in an identical way. Production at point B is relatively more specialized in timber, while production at point C is relatively more specialized in biodiversity. The degree of specialization depicted in Figure 10.1 is not complete, but it would tend more toward complete specialization—only biodiversity conserved in one stand, and only timber produced in the other—if we drew the figure so that the distance of SM^T and SM^B from IM rose more rapidly as one moves clockwise along IM (i.e., if the intercepts of SM^T and SM^B on the timber axis were farther apart).

Which equilibrium is superior? Note that the tangents through points B and C intersect the ray at points beyond where SM^T and SM^B, respectively, intersect it. Given that SM^T and SM^B are equidistant from IM, these divergences imply that the aggregate value of production is greater when one stand is managed at point B and the other is managed at point C than when both are managed at point A. Segregated management is superior to integrated management, even though the two stands are identical.

If there are diminishing returns to management effort, so that the outward shift of SM^T away from IM is less than the inward shift of SM^B, then this result still holds as long as the outward shift of the former is sufficiently large compared to the inward shift of the latter. That is, it holds as long as the returns to management effort across the two products do not diminish too rapidly. This observation points toward the underlying condition that drives the superiority of segregated management in this model: management effort has a nonconvex impact on production (Helfand & Whitney, 1994). The allocation of effort at the integrated-management equilibrium satisfies the first-order conditions for optimality—the price line is tangent to IM at point A—but not the second-order conditions, which pertain to how rapidly the returns to management effort are diminishing at that point. In contrast, the allocation at the segregated-management equilibrium satisfies both sets of conditions. This nonconvexity creates a diseconomy of scope between biodiversity and timber: starting with one stand managed at B and the other at C, shifting effort from the former to the latter to allocate management more evenly leads to an appreciable decrease in the aggregate production of timber without a sufficiently offsetting increase in the aggregate production of biodiversity. Spatially segregating production of the two products mitigates this diseconomy.[5]

We close by noting that the equilibria depicted in Figure 10.1 are interior solutions. Corner solutions are also possible. If the price line is sufficiently flat, then the equilibria are on the biodiversity axis; if it is sufficiently steep, they are on the timber axis. Given that SM^T and SM^B are equidistant from IM along any ray, including the axes, segregated management offers no advantage over integrated management in such cases. It generates the same aggregate value of biodiversity and timber as does integrated management, not a greater value. The superiority of segregated management in the model therefore depends on not only the nonconvexity in the production set but also on the relative values of biodiversity and timber. As we will see, relative economic values also affect the relative superiority of the two management approaches in the models in the next two sections.

3. NONLINEARITIES DUE TO ECONOMIC AND INSTITUTIONAL FACTORS

Perhaps the most surprising feature of the analysis in the previous section is the result that segregated management can be superior to integrated management even when forest stands are identical. How empirically relevant is this result? In a landmark study of the management of U.S. national forests for timber and nontimber values, Bowes and Krutilla (1989, p. 342) reported empirical optimization results in which

> … a higher relative recreational value did not necessarily lead to a longer rotation, even when older stands were generally preferred for their amenity values. Instead, we might see an increasing amount of the area set aside as protected old growth, while a shorter timber rotation cycle was instituted on the remaining sites in the management unit. We found such solutions even when the management area was perfectly homogeneous. Such harvest solutions could not be found if the stands were treated independently.

This is a perfect illustration of the effects of a production nonconvexity as predicted by the model in Figure 10.1. Indeed, in the theory section of their book Bowes and Krutilla (pp. 51-87) attribute such solutions to nonconvexities, although they depict them using isocost curves instead of production possibilities frontiers. They conclude that "It seems likely that specialization of land use, such as we found, is often apt to result in more effective production of such services as wildlife and increased water flow than would be possible from uniform management of a land areas" (pp. 342-343). Subsequent studies by Swallow and Wear (1993) and Swallow, Talukdar, and Wear (1997) offered additional empirical evidence of nonconvexities in forest production sets. In the cases they examined, the nonconvexities resulted from ecological interactions among stands.

Helfand and Whitney (1994) mentioned a common characteristic of production systems that can create a nonconvexity: fixed costs. Boscolo and Vincent (2003) examined the effects of this economic factor—specifically, fixed logging costs—on the joint production of biodiversity and timber.[6] They also examined the effects of institutional factors that can have a similar impact on the production set. Figure 10.2 illustrates how fixed logging costs can make production at the stand level nonconvex. The vertical axis shows the discounted sum of current and future physical outputs of biodiversity,[7] while the horizontal axis shows the net present value of current and future timber harvests (i.e., net income to the forest owner). The production set for the stand consists of two parts. One is the usual set of points bounded by the production possibilities frontier. The other is point A, which is the no-logging point. Fixed logging costs are responsible for the discontinuity between these two parts. They cause the net present value of timber harvests to be negative when harvests are small. These production points lie to the left of the vertical axis between the intercept of the frontier and point A. Although they generate positive outputs of biodiversity, they are dominated by the no-logging point, which generates higher outputs of both biodiversity (A is a larger positive amount) and timber (zero instead of negative). The production set is nonconvex because the tangent from point A to point C lies above points on the frontier between point C and the intercept of the frontier on the biodiversity axis.

Institutional factors can create a similar discontinuity even if fixed costs are negligible. In principle, detailed logging regulations can be designed that minimize the impacts of timber harvesting on biodiversity. For example, specific trees might be selected for felling at specific times, with adjustments made for unique site characteristics and current environmental conditions. Application of such regulations would generate a smooth frontier connecting point A to the point of maximum timber production (i.e., the intercept on the timber axis). But in practice, such regulations are beyond the administrative capacity of many countries, especially developing countries, to monitor and enforce. Such countries instead typically employ much simpler regulations, such as minimum diameter cutting limits and fixed cutting cycles. The result is that for any given timber harvest, the accompanying level of biodiversity conservation is lower than it would have been under the "ideal"—but administratively infeasible—regulations. The frontier thus shifts down, leaving a gap between the no-logging point and points on the frontier that involve some production of timber. The result is again the nonconvex production set depicted in Figure 10.2.

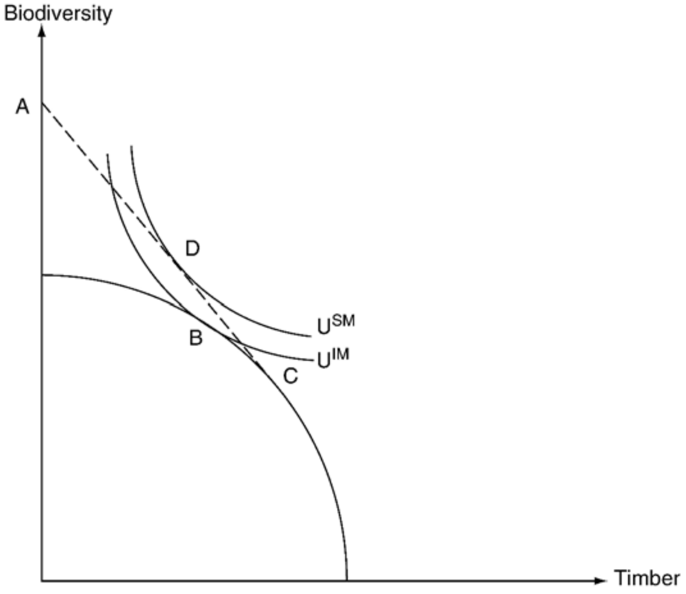


Figure 10.2. *Effect of Nonconvexities due to Fixed Logging Costs and Administrative Constraints in an n-stand Model*

Suppose that the forest contains *n* identical stands, each with the production set shown in Figure 10.2. The aggregate economic welfare generated by the forest is given by U(**B**,**T**), where **B** and **T** are the aggregate outputs of biodiversity and timber across the stands. The price of timber is fixed (e.g., the region or country is a price-taker in timber markets), but the marginal welfare values of biodiversity (U_B) and timber income (U_T) are not. The welfare function is homothetic, so that $U[\mathbf{B},\mathbf{T}] = nU[\mathbf{B}/n,\mathbf{T}/n]$, where $U[\mathbf{B}/n,\mathbf{T}/n]$ is the average welfare value of a stand in the forest. Figure 10.2 shows two indifference curves for the average welfare function. The curve labeled U^{IM} shows the average welfare attained if all stands are managed identically, at point B. This is the integrated-management equilibrium. The segregated-management equilibrium involves managing αn stands at point A, which is completely specialized in the production of biodiversity, and $(1-\alpha)n$ stands at point C, which is more specialized in the production of timber than point B. The average production per stand in this equilibrium is indicated by point D, and average welfare is given by U^{SM}, which is higher than U^{IM}. Since average welfare per stand is higher under segregated management, so is total welfare aggregated across the n stands. As in Figure 10.1, segregated management is superior to integrated management even though all stands are identical.

The nonconvexity in this model is policy-relevant only if point B, the integrated-management equilibrium, lies to the left of point C, as in Figure 10.2. If point B lies to the right, on the convex portion of the production possibilities frontier, then integrated management dominates segregated management. Boscolo and Vincent investigated this issue by constructing a dynamic model of management of a tropical rainforest stand. They drew data from a large-scale, long-term forest inventory plot in Malaysia. They used the model to estimate the production set for the stand. They predicted the outputs of biodiversity and timber that would be generated over a 60-year time period under different harvest regimes (cutting cycles, logging technologies, minimum diameter cutting limits). They measured biodiversity by using an index related to differences in forest structure between the managed stand and an old-growth stand. Structure was defined by the basal area in different species groups and diameter classes.[8] They assumed that a stand with a structure more similar to that of an old-growth stand would be richer in biodiversity.

Figure 10.3 shows the empirical production set for the Malaysian rainforest. Each point in the figure shows the outputs of biodiversity and timber for a given harvest regime. The vertical axis is the present value of the biodiversity index, and the horizontal axis is the net present value of timber harvests. The present values were calculated using a discount rate of 2 percent. The present value of the biodiversity index has a maximum of 7.62 units at the no-logging point,[9] and the net present value of timber harvests has a maximum of $4,744. The figure shows the points where fixed logging costs cause the net present value of timber harvests to be negative. It also shows, as a dotted line, the tangent from the no-logging point to the frontier of the set (i.e., the point corresponding to point C in Figure 10.2). The (inverse) slope of the tangent is US$1,274 per index unit of biodiversity. This is nearly identical to a crude estimate of the current global welfare tradeoff between biodiversity and timber income, US$1,100 per index unit, implied by forest valuation studies reviewed by Lampietti and Dixon (1995).[10] Although the estimates of the slope of the frontier and the welfare tradeoff are obviously approximate, they imply that points B and C nearly coincide for the Malaysian rainforest. Segregated management would appear to offer little advantage compared to integrated management for this particular forest at the current point in time.

On the other hand, a stylized fact in environmental economics is that nonmarket values of the natural environment, such as passive-use values associated with biodiversity, are rising more rapidly than commodity values, such as timber (Krutilla 1967, Fisher, Krutilla, & Cicchetti, 1972). If this is the case, then the biodiversity-timber income indifference curves are becoming flatter over time. The future welfare tradeoff will be higher than the current US$1100 per biodiversity index unit. The integrated-management equilibrium will move to the left of point C, the welfare associated with it will fall below the welfare associated with segregated management, and point D will slide to the left along the tangent as logging is prohibited in more stands.

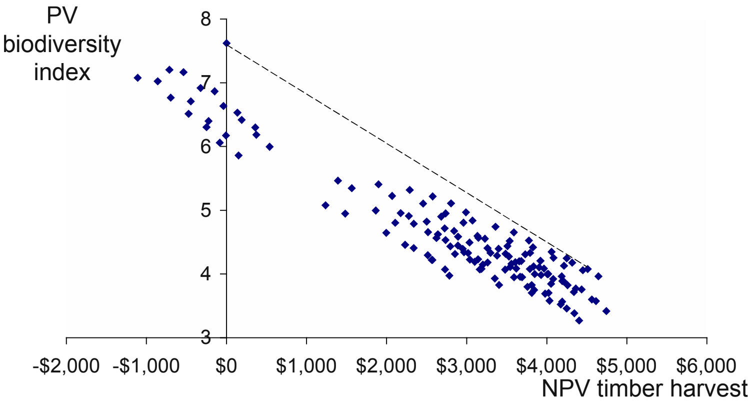


Figure 10.3. *Production Set for a Malaysian Rainforest Stand Harvested under Different Cutting Cycles, Minimum Diameter Cutting Limits, and Logging Technologies (Conventional vs. Reduced Impact)*

Even with these changes, however, the potential gains from segregated management appear to be modest, at least for the forest in Figure 10.3. The nonconvexity is not very large: the intercept of the frontier implied by the points in the figure is only 12 percent below the no-logging point. Moreover, nearly all of this gap is due to administrative constraints on logging regulations as opposed to fixed logging costs. The gap will be negligible in countries with strong institutions, and thus so will be the economic advantages of segregated management.

4. NONLINEARITIES DUE TO ECOLOGICAL FACTORS

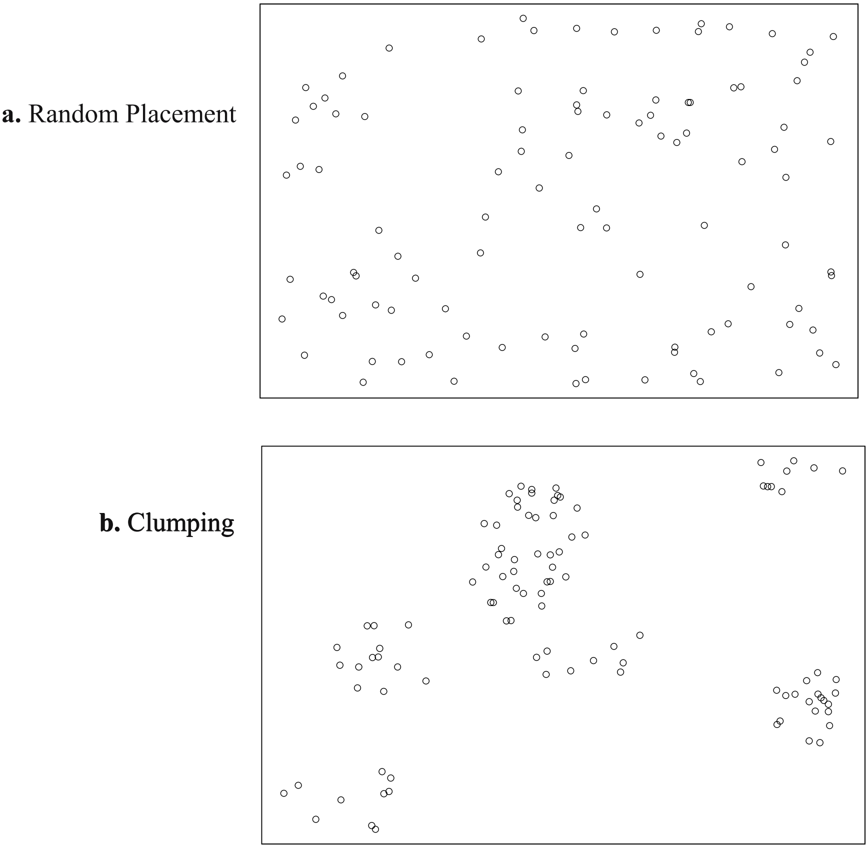
Potts and Vincent (2004) also use simulation to evaluate the relative superiority of segregated and integrated management of tropical rainforests for biodiversity and timber. Their model differs from the one in Boscolo and Vincent (2003) in several ways. The most important is that they highlight nonlinearities that are due to ecological, not economic or institutional, characteristics of the forest. In contrast to the two previous models, these nonlinearities do not make the forest production set non-convex, but they still affect the choice between the two management approaches.

Potts and Vincent consider a narrower management question than Boscolo and Vincent. Within a forest of A hectares, they ask how large an aggregate area, a, should be set off limits from logging, and how many equal-sized reserves, m, this protected area should be divided into. The remaining forest area, $A - a$, has negligible biodiversity value but produces timber. The model is static, but it can be given a quasi-dynamic interpretation if one thinks of the forest as being divided into n equal-sized annual harvest areas, or coupes, with the number n being an exogenous parameter and only $1/n^{\text{th}}$ of $A - a$ harvested each year. In this context, integrated management refers to a solution in which $m = n$: a reserve is associated with each coupe. In contrast, under segregated management $m < n$: biodiversity conservation is spatially concentrated into a smaller number of reserves. The model thus allows a gradation of management regimes, from more integrated (m being closer to n) to more segregated (m being closer to 1), not a binary choice between the two approaches as in the previous two models.

The production set in this model consists of the set of all possible combinations of the number of species preserved and the production of timber. The number of species preserved, S, is a function of both the total protected area and the number of reserves: $S\left[a,m\right]$. This is a more direct measure of biodiversity than in the model in the previous section, which used forest structure as a proxy measure. The amount of timber produced is simply proportional to the area of timber production forest, $A - a$. The economic value of reserves is a function of the number of species preserved, $V\left[S\left[a,m\right]\right]$. Timber production is valued at p_T per hectare. The static welfare function is thus given by $W\left[a,m\right] = V\left[S\left[a,m\right]\right] + p_T\left(A-a\right)$.[11] $S\left[a,m\right]$ is assumed to be concave,[12] and so $W\left[a,m\right]$ is concave too.

Spatial distributions of species' populations and minimum viable populations create nonlinearities that affect the optimal choice of a and m. Let us consider these two nonlinearities in turn. Recent ecological studies have found that the majority of tropical tree species have populations that are spatially aggregated, or clumped, instead of randomly distributed throughout the forest.[13] Figure 10.4 illustrates this difference. Clumping is apparently more pronounced in tropical forests than in temperate and boreal forests (Condit et al., 2002). It arises due to two main reasons, habitat heterogeneity and dispersal limitations. For the latter reason, it can occur even in forests with relatively uniform physical characteristics (topography, soils, etc.).

When they are clumped, individual trees of a given species (conspecific individuals) are not equally likely to occur everywhere in the forest. The probability of occurrence is a nonlinear function of the occurrence of other trees of the same species instead of being a fixed number that does not change across the forest. The result is that the expected number of different species occurring within a reserve of a given size is smaller compared to the case of random placement, while the variance in the number of species across reserves is larger. For a given total protected area, these statistical properties favor a reserve system with a larger number of reserves over a system with a smaller number of reserves. That is, they favor more integrated management. These effects of clumping enter the model through the first-order condition for m, $S_m = 0$.



a. Random Placement

b. Clumping

Figure 10.4. *Random Placement vs. Clumping of Trees of a given Species*

The tendency of clumping to favor a larger number of reserves is weaker when the total protected area is smaller, however, because then each reserve might be too small to contain minimum viable populations of very many species. The minimum viable population is the threshold number of species below which a species will not survive. It makes the relationship between survival of a species and population size nonlinear. For a given number of reserves, it favors a reserve system with a larger area over a system with a smaller area. That is, it favors more segregated management—the opposite of clumping. It has this effect through the first-order condition for a, $S_a = p_T/V'$. Note that this expression includes the marginal values of biodiversity and timber, V' and p_T. The optimal total protected area is larger when biodiversity is more valuable relative to timber. As in the two previous models, relative economic values interact with nonlinearities in the production set to determine the relative superiority of segregated vs. integrated management.

Potts and Vincent construct a simulation model to study the empirical implications of these factors. They analyze a forest of 10,000 hectares, which is the approximate minimum size of a sustained-yield timber concession in Peninsular Malaysia harvested on a 30-year cycle (i.e., $n = 30$). A cycle of this length is typical for tropical rainforests. They use Hubbell's unified neutral model (Hubbell, 2001) to predict the number of tree species and the populations of those species in a forest of this size. They use the negative binomial distribution (He & Gaston, 2000, He & Legendre, 2002, Plotkin & Muller-Landau, 2002) to predict the expected numbers of species and individuals of those species in reserve systems with a ranging up to 25 percent of the forest and m ranging up to 30 reserves. This range of values of a is consistent with the experience of Perak Integrated Timber Complex, the first concession in Peninsular Malaysia to be certified as sustainable by the Forest Stewardship Council, which agreed to reserve 10-20 percent of its concession as a condition of certification.[14] Simulating values of m up to 30 is necessary to determine whether integrated management, $m = n = 30$, is optimal. Although thresholds like minimum viable populations can potentially create nonconvexities, Potts and Vincent find that the empirical production set in their model is convex within the range of values of a and m they considered.

Potts and Vincent consider a set of cases defined by the degree of clumping and the minimum viable population size. Their cases reflect the range of values for these ecological parameters reported in the tropical ecology literature. Figure 10.5 shows results for the case of a scale-independent clumping parameter and a minimum viable population of 100 trees. The horizontal axis shows the proportion of the forest that is logged (i.e., $1 - a/A$), and the vertical axis shows the number of tree species contained in the reserve system (i.e., $S[a,m]$). The top curve in the figure shows the production possibilities frontier: the maximum number of species for a given proportion of timber production forest. The numbers along this curve show the numbers of reserves that yield these maximum values. As expected, the species-maximizing number of reserves increases as the total protected area increases (i.e., as the percentage of timber production forest decreases): the minimum viable population is then less likely to be violated. Yet, the largest number of reserves is only 10, which is far below the perfectly integrated-management solution, 30. The bottom curve shows the number of species protected by 30 reserves.[15] Although the number of species preserved for this reserve number becomes greater as total protected area rises, it remains far below the numbers on the frontier.

In sum, the third model includes two ecological nonlinearities, the clumping of conspecific trees and minimum viable populations. The former favors spatial dispersion of biodiversity reserves, which makes management more uniform (integrated) across the forest, while the latter favors a spatially more concentrated reserve system, which makes management more specialized (segregated). The net result for the case shown in Figure 10.5 is that more segregated management is superior. This is especially true when less of the forest is protected, which occurs when the relative value of biodiversity is lower. Other cases that Potts and Vincent examine indicate, not surprisingly, that segregated management is even more superior when species' population distributions are more random and when minimum viable populations are larger.

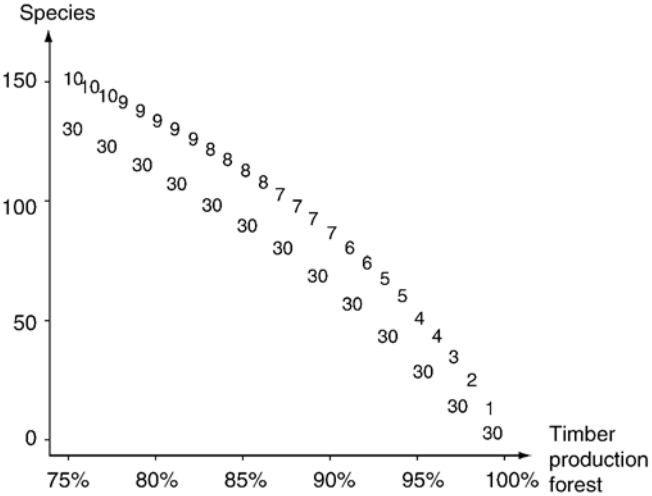


Figure 10.5. *Production Set for a Malaysian Rainforest when the Clumping Parameter is Fixed and the Minimum Viable Population is 100 Trees*

5. CONCLUDING REMARKS

We have reviewed three models that illustrate the effects of economic, institutional, and ecological nonlinearities on the relative superiority of integrated and segregated approaches to forest management. We have demonstrated that nonlinearities at smaller spatial scales—for example, nonconvexities in stand-level production sets and clumping of the populations of individual trees—can have important management implications at larger scales. The general tendency appears to be for nonlinearities to favour segregated forest management—emphasizing timber production in some areas and biodiversity conservation in others, even if the stands are identical—although the strength of this tendency depends on forest characteristics and the relative values of biodiversity and timber. The economic and institutional nonlinearities in the empirical example shown in Figure 10.3 are relatively small, and hence so are the potential gains from segregated management in that example. A higher relative value of biodiversity strengthens the tendency toward segregation when nonlinearities result from fixed logging costs or administrative constraints on logging regulations, as in Figure 10.2, but weakens it when nonlinearities result from clumped population distributions, as in Figure 10.5.

A tendency toward segregated management does not necessarily mean complete specialization. In the segregated management equilibrium represented by points B and C in Figure 10.1, there is some output of both timber and biodiversity at both points; it is the proportions of the outputs that differ between the points. Although the segregated management equilibrium in Figure 10.2 includes a proportion α of the stands being managed at the no-logging point A, it also includes $1-\alpha$ of them being managed at point C, where there is some output of both timber and biodiversity. Finally, although in Figure 10.3 we have assumed that biodiversity conservation is negligible in harvested forests, even under this assumption the figure still shows that there is a gradation of approaches depending on how much of the forest is put off limits to logging, with management being more segregated (just a single reserve) when little of the forest is protected and more integrated (multiple reserves, albeit not one in each annual coupe) when more of it is protected. The flexibility that SFM certification systems allow in the choice of segregated and integrated management approaches is therefore appropriate.

Biodiversity is defined explicitly only in the second and third models, and in both cases the definitions are based on numbers of tree species. Despite this focus on just one component of floral diversity, the results from these models have bearing on the conservation of other taxonomic groups found in forests, including animals. Many animals, especially invertebrates, are associated with particular tree species through pollination or herbivory. If as in the third model trees are clumped, then such animals are likely to be, too. In fact, a frequently cited study by Taylor, Woiwod, and Perry (1978) of nearly 90 animal species found that only one had populations that were randomly distributed at all densities. Of course, differences between plants and animals in terms of mobility and minimum viable populations imply that a reserve system that is designed to be optimal for floral conservation is unlikely to be optimal as well for faunal conservation, but in both cases the nonlinearities that underlie Figure 10.5 should have similar qualitative impacts on the relative advantages of more segregated and more integrated approaches.

We close by drawing attention to two nonlinearities that are especially relevant to SFM in tropical forests but have opposite impacts on the relative advantages of the two management approaches. Both were mentioned earlier. Administrative constraints necessitate the use of simpler forest management regulations, which as we have seen tend to favor segregated management. On the other hand, the clumping of tree populations tends to favor integrated management. Given that the topic of this volume is the economics of SFM, it is perhaps useful to close with these reminders that SFM must take into account institutional and ecological factors in addition to purely economic ones.

NOTES

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[1] Other terms that are often used to distinguish between segregated and integrated forest management include specialized vs. uniform management and dominant-use vs. multiple-use management.

[2] We define a stand as a spatially distinct management unit containing a relatively homogeneous forest type.

[3] Other applications of production possibilities frontiers to the analysis of the joint production of biodiversity and timber include Rohweder, McKetta, and Riggs (2000) and Lichtenstein and Montgomery (2003).

[4] For example, the budget that is available to spend on silvicultural operations.

[5] For a discussion of diseconomies of scope between environmental quality and industrial output in the context of industrial pollution, see Baumol and Oates (1988, ch. 8).

[6] They also considered carbon sequestration.

[7] It might seem odd to discount a physical quantity like biodiversity, but in fact economists discount physical quantities all the time. For example, in calculating the net present value of a future timber harvest, economists implicitly discount the quantity of timber harvested, since the value of the harvest, which is what is directly discounted, is the product of the quantity of timber harvested and the price of timber. Biodiversity in Figure 2 and other figures in this chapter must be discounted so that the relative values of biodiversity and timber, which appear in the indifference curves and price lines, are defined consistently.

[8] The index was a “proximity to climax index” that took the structre of a virgin (unlogged) stand as the reference point. It was calculated as 1 minus the root mean squared error between the actual structure of the stand and the structure before logging (i.e., the structure of the virgin stand). The index has a value of 1 for a given period if the forest has the same structure and composition as the virgin forest and 0 if it is bare land.

[9] The biodiversity index is calculated at 5-year intervals. With a 60-year time horizon, the undiscounted value would thus be 13.

[10] See Boscolo and Vincent (2003) for a description of how this tradeoff value was calculated. Essentially, the present value of benefits associated with biodiversity in developing country forests, reported in Lampietti and Dixon (1995), was divided by Boscolo and Vincent’s estimate of the present value of the physical biodiversity index for a virgin stand in Malaysia.

[11] With n fixed, the first-order conditions for the quasi-dynamic model discussed in the previous paragraph are equivalent to those for this static model as long as p_T is scaled to be consistent with the area harvested in a given period.

[12] Potts and Vincent demonstrate that this function is concave in their simulation model.

[13] See, for example, He, Legendre, and LaFrankie (1997).

[14] Moreover, capping a at 0.25 in the simulation model is desirable from a statistical standpoint because the negative binomial model provides inaccurate predictions when total protected area accounts for a large portion of the forest.

[15] The integrated-management solution in this model is not an equilibrium. It satisfies the first-order condition for a but not the first-order for m, as evidenced by the fact that the curve for $m = 30$ lies within the production possibilities frontier.

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