CARBON STORAGE, INCOME, AND HABITAT DIVERSITY IN MANAGED TROPICAL FORESTS

Marco Boscolo and Joseph Buongiorno[1]

ABSTRACT.—A recurrent theme in the tropical forestry literature is the need to manage tropical forests for multiple-uses. To improve our ability to quantify the economic trade offs between income from timber production and other environmental services, we developed an optimization model for the management of a lowland dipterocarp forest stand in Peninsular Malaysia. Forest productivity and environmental performance were quantified by a growth model calibrated using a dataset from the Pasoh forest. This study presents some results of optimal cutting policies for a forest stand in a steady state. Economic (NPV) and ecological criteria were considered such as habitat diversity and carbon storage. To maintain minimum levels of carbon storage or habitat diversity caused significant reductions in NPV. Trade offs are accomplished by lengthening the felling cycle and by modifying the cutting regime.

INTRODUCTION

Managers and policy makers are increasingly recognizing that tropical forests provide various commodities and environmental services of global value. For example, tropical forests play an important role as carbon sinks and harbor an extreme diversity of life, both of perceived interest to the global community (de Montalembert 1991). Such recognition has fueled a search for ways to manage tropical forests sustainably and for multiple uses (e.g., Peters et al. 1989; Panayotou and Ashton 1992).

However, while the need to account for sustainability and multiple values in forestry decisions is widely recognized, its implications for forest management are not clear. What are the characteristics of sustainable forest use? How should current management schemes be modified to consider non-timber values? Answering these questions is important, for example, in the design of policy instruments that can achieve given levels of environmental protection and in the evaluation of their feasibility and cost-effectiveness.

To address these issues we developed an economic model to quantify the effect of non-timber goods (carbon storage and habitat diversity) on the optimal cutting policy in the management of a lowland tropical rain forest in peninsular Malaysia. Our objective was to extend and complement previous models by explicitly recognizing the effect of logging damage and by considering both carbon storage and biodiversity. Logging damage was modeled explicitly because, in dipterocarp forests, it strongly affects the structure of the unharvested portion of the forest stand (cf. Appanah and Weinland 1990) and is, therefore, an important determinant of forest productivity. Carbon storage and biodiversity were considered simultaneously to highlight the differences, and similarities, of their effects on tropical forest management.

The purpose of this paper is to briefly summarize the features of this model and to present some results obtained by optimization analyses. Analyses were carried out with reference to steady state scenarios. This approach was chosen to obtain results that are independent from initial conditions, while embodying the principle of

[1] Marco Boscolo, Center for Tropical Forest Science, Smithsonian Tropical Research Institute and Harvard Institute for International Development, Harvard University. Joseph Buongiorno, Department of Forestry, University of Wisconsin-Madison.

sustainability. In fact, in a steady state, the forest stand yields the same flow of benefits at each cycle, in perpetuity. It also provides valuable information for policy making which often compares the desirability of "equilibrium" or "sustained yield" states.

THE MODEL

The model adopted for this study is an extension of the transition matrix model developed originally by Buongiorno and Michie (1980). Boscolo et al. (1997) modified it to allow for multiple-species (similarly to Buongiorno et al. 1995, and Ingram and Buongiorno 1996). In this model, transition probabilities (growth and mortality parameters) depend on species group and tree size. Ingrowth depends on species composition and stand density. The model was calibrated with data from a 50-hectare, demographic plot located in peninsular Malaysia and predicts the evolution of a forest stand with trees grouped in 3 species cohorts (dipterocarps, commercial non-dipterocarps, and non-commercial) and seven size classes. Model parameterization and calibration are described in Boscolo et al. (1997). The effect of harvesting on stand structure and composition included consideration of logging damage, which we assumed as proportional to the timber volume extracted. The effect of logging on the residual stand was based on data obtained from the literature (e.g., Appanah and Weinland 1990, Pinard et al. 1995).

MANAGEMENT CRITERIA

The desirability of alternative steady states was judged by two ecological criteria (mean carbon storage and deviation from the climax state) and by an economic criterion (Net Present Value).

The first ecological criterion considered was the amount of carbon stored in the living tree biomass. At any given point in time, the carbon storage depends on the forest state, which itself depends on the growing stock before logging, the intensity of the last cut, and the time interval since that cut. In a steady-state regime, the amount of carbon in the stand, before harvest, is the same at the beginning and at the end of the cutting cycle. The carbon stored increases steadily as the stand grows between harvests. To account for this variation, the *mean carbon storage* (MCS) was chosen as a measure of the sink capacity of a representative stand in steady-state[2]. Mean carbon storage over a cutting cycle is:

$$[1] \qquad \text{MCS} = \sum_{l=t}^{t+p} K_l \;/\; (p+1),$$

where K_l is the carbon stock at the end of year l. One ecological goal would be to keep MCS as high as possible.

A second ecological criterion (DEV) measured the distance between a given stand and its climax state, and was defined as:

$$[2] \qquad \text{DEV} = \max\,(\text{DEV}_{ij}),$$

with $\text{DEV}_{ij} = (B^*_{i,j} - B_{i,j}) / B^*_{i,j}$, where $B^*_{i,j}$ is the basal area of trees of species i and size j in the climax forest, while $B_{i,j}$ is the basal area in the managed stand after the cut. Thus, according to this criterion, the structure and

[2] As noted elsewhere (see, for example, Stavins 1996, and Boscolo et al. 1997) there exist other carbon accounting procedures. Summarizing carbon flows in an index such as MCS treats equally carbon flows in the near and distant future.

composition of the climax forest is set as the most desirable state. Moreover, of alternative sustainable stand states, the one closest to the climax state is deemed preferable.

For management purposes, one ecological goal would be to keep DEV, the maximum deviation (among all species and size classes) from the climax distribution, as small as possible. The effect of this mini-max criterion is to give special attention to the tree category that is least represented and that, in a managed stand, will deviate the most from that observed in natural climax stands. It is the analog to the maxi-min diversity criterion of Buongiorno et al. (1995), and both are consistent with the concept of a "safe minimum standard of conservation" (Ciriacy-Wantrup 1968).

The Net Present Value (NPV) was considered as the economic criterion, given by the present value of future timber revenues, net of all costs (including the cost of the investment in the growing stock). Thus, in a steady state, the economic harvest and the growing stock should be chosen so that the maximum NPV is attained. To discount future revenues the interest rate was set to 6 percent per year, the return (net of inflation) of alternative investment opportunities in Malaysia (Ingram and Buongiorno 1996).

A COMPARISON OF ALTERNATIVE STEADY STATES

Optimization of either ecological criterion (i.e., max MCS or min DEV) led to a solution almost identical to the climax state. In this solution, the stand would store 214 tons/ha with a basal area of 25 m^2/ha. Therefore, in absence of other constraints, maximization of either ecological criterion was attained by complete preservation at a cost, in terms of NPV, of $4240/ha.

Maximization of the economic criterion led to a solution where all commercially valuable trees (dipterocarps and commercial dipterocarps with dbh ≥ 30 cm) would be cut every 20 years. This solution attained a NPV of $702/ha while MCS dropped to 168 tons/ha. At the same time, the maximum deviation from the climax state rose to 100 percent (at least one tree category is completely felled).

To assess the effects of ecological considerations on the optimal economic cutting policy, a minimum carbon storage and a maximum deviation constraint were imposed. Through parametric variations of the minimum acceptable level of carbon storage (or maximum tolerable level of deviation in the case of the tree distribution criterion), we derived alternative steady states and measured their economic and ecological performance.

Table 1.—Steady state that maximized soil rent while keeping mean carbon storage at 200 tons/ha

	dipterocarps		comm. non-dipterocarps		non-commercial	
diameter class	number of trees/ha	cut	number of trees/ha	cut	number of trees/ha	cut
cm						
10-20	30.1	0.0	74.4	0.0	275.2	0.0
20-30	11.5	0.0	21.6	0.0	65.2	0.0
30-40	5.3	4.7	10.9	0.0	20.3	0.0
40-50	3.5	3.5	5.7	0.0	7.5	0.0
50-60	2.4	2.4	3.8	0.0	3.0	0.0
60-70	1.2	0.0	2.1	0.0	1.0	0.0
70+	1.8	0.0	1.9	0.0	1.0	0.0

Felling cycle:	55 years
Total number of trees (before cut):	549 trees/ha
Total number of trees (after cut):	497 trees/ha
Basal area (before cut):	23.7 m2/ha
Basal area (after cut):	21.4 m2/ha
Residual stand damaged:	7.7 %
Extracted volume:	0.24 m^3/ha/yr
Harvest revenues (net):	$413/ha
Present value of harvests:	$17/ha
Value of residual stock:	$1785/ha
Net Present Value:	-$1767/ha
Mean Carbon Storage:	200 tons/ha
Maximum deviation of all tree categories:	100%

Storing more carbon required decreasing the harvest while increasing the felling cycle. For example, to attain a MCS of 200 tons/ha, the annual harvest would have to be lowered from 0.85 m^3/ha (obtained through unconstrained NPV maximization) to 0.24 m^3/ha and the felling cycle increased from 20 to 55 years. At the same time, the NPV would fall to -$1767/ha (Table 1).

Similar results were obtained when NPV maximization was constrained by a minimum deviation of the tree distribution from the climax state. To keep basal area in any species-size class within at least 50 percent of that in a virgin stand would require an annual harvest of 0.42 m^3/ha and a felling cycle of 30 years. The NPV would fall to -$1730/ha (Table 2).

Table 2.—Steady state that maximizes soil rent while deviating by less than 50 percent from the tree distribution in the climax state

	dipterocarps		comm. non-dipterocarps		non-commercial	
diameter class	number of trees/ha	cut	number of trees/ha	cut	number of trees/ha	cut
cm						
10-20	35.0	0.0	68.1	0.0	276.8	0.0
20-30	13.2	0.0	19.3	0.0	64.5	0.0
30-40	5.8	3.1	8.4	3.9	20.1	0.0
40-50	3.6	1.6	3.4	1.1	7.5	0.0
50-60	2.5	0.7	1.8	0.2	3.0	0.0
60-70	1.5	0.2	0.9	0.0	1.0	0.0
70+	3.0	0.1	0.8	0.0	1.0	0.0

Felling cycle:	30 years
Total number of trees (before cut):	541 trees/ha
Total number of trees (after cut):	490 trees/ha
Basal area (before cut):	22.3 m2/ha
Basal area (after cut):	20.2 m2/ha
Residual stand damaged:	7.5%
Extracted volume:	0.42 m^3/ha/yr
Harvest revenues (net):	$228/ha
Present value of harvests:	$48/ha
Value of residual stock:	$1778/ha
Net Present Value:	-$1730/ha
Mean Carbon Storage:	191 tons/ha
Maximum deviation of all tree categories:	50%

As it can be seen by comparing Tables 1 and 2, the two ecological criteria led to different cutting regimes. To attain a MCS of 200 tons/ha, only dipterocarp trees with dbh ≤ 60 cm would have to be cut (Table 1). Some tree categories would have to be harvested completely. Therefore, according to our tree distribution criterion, we would still record a 100 percent maximum deviation from the climax state. On the other hand, to maintain a tree distribution at least 50 percent of that in a primary stand would require a light tree selection in all commercial classes. This solution would improve the tree distribution criterion together with MCS, which would increase from 168 to 191 tons/ha.

DISCUSSION AND PRELIMINARY CONCLUSIONS

Using a model calibrated with data from a 50-hectare demographic plot in peninsular Malaysia, we explored the features of steady states characterized by different combinations of management criteria. Applications were presented with respect to economic (NPV) and ecological criteria: mean carbon storage and deviation from the climax state.

To improve either ecological criterion caused a significant reduction in terms of NPV. This trade-off would be accomplished by a progressive lengthening of the felling cycle and by modifications of the cutting regime. The main difference between the carbon storage and tree distribution constraints is in the resulting optimal harvests. A MCS between 168 and 195 tons/ha, for example, would require all dipterocarp trees with dbh > 30 cm to be cut. Thus, this criterion implied the total elimination of at least one tree category. Instead, a tree distribution closer to the climax state would be obtained with a light tree selection in all commercial classes which would also attain some increase of MCS. This result suggests that the goal to maintain some diversity will also generate some co-benefit in terms of increased carbon storage while the opposite will not necessarily be true.

The analyses also suggest that the high timber value of Malaysian lowland dipterocarp forests translates into a high cost of maintaining carbon storage and habitat diversity. In other words, the modification of cutting policies such as felling cycles or cutting prescriptions is an expensive strategy to protect the above non-timber values. These results are consistent with the findings of Boscolo et al. (1997), who used the growth model to simulate future harvest revenues and variations in the carbon stock when logging a virgin forest stand. Their results are summarized in Figure 1, where each point corresponds to a particular combination of felling cycles, diameter cutting limit, and logging technology. In particular, the diagram displays the combinations of the control variables that were Pareto efficient (i.e., where one output, carbon or harvest revenues, could not be improved without diminishing the other).

It should be noted that their economic and carbon storage indicators differed from the ones used for the steady state analyses. With respect to carbon, for example, carbon flows were used instead of mean storage[3]. Furthermore, variations of carbon storage overtime were discounted as if carbon had a market price. These differences impair a direct comparison of results between the simulation and the optimization analyses. Notwithstanding these differences, Figure 1 indicates that significant carbon savings can be attained at a relatively low cost in terms of present value of harvest revenues. Thus, the shift from conventional to reduced-impact logging methods could be a more cost-effective way to achieve carbon savings than imposing restrictions on cutting practices.

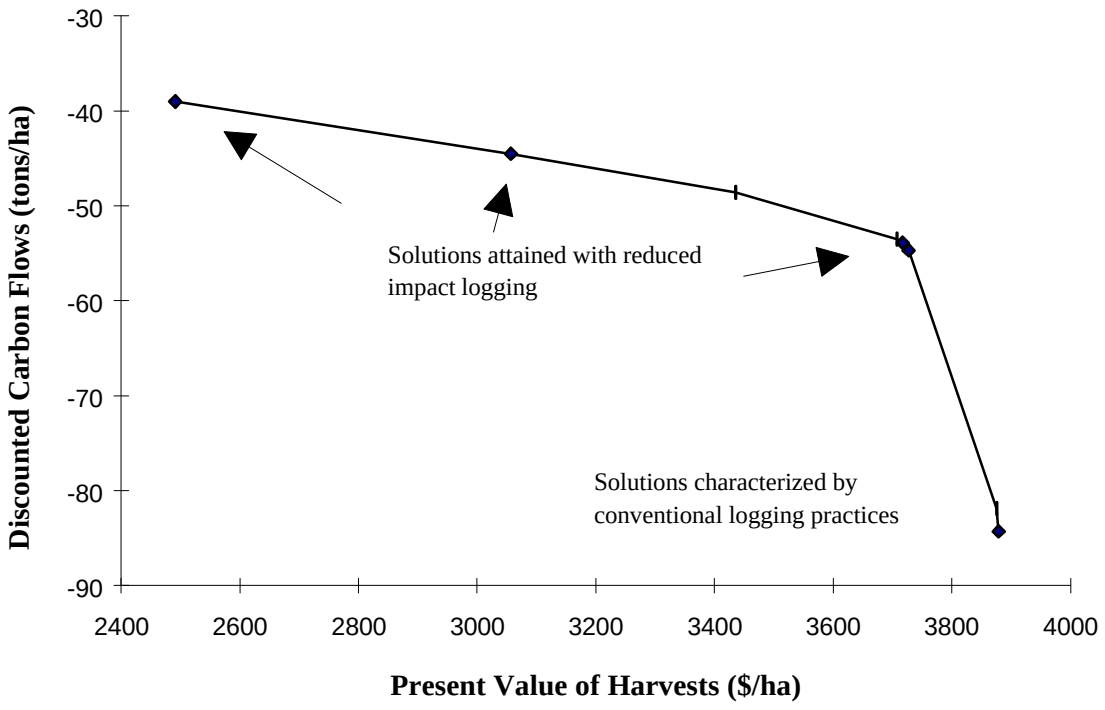

Figure 1.—Trade-Off Curve between Present Value of Harvests and Discounted Carbon Flows (Source: adapted from Boscolo, Buongiorno and Panayotou 1997)

This appears to be true, at least, when logging a virgin stand, since more trees of large dimensions are extracted and, therefore, more damage is caused to the residual stand. In a managed forest, on the other hand, fewer and smaller trees are extracted[4] and a lower level of damage is caused (Tables 1 and 2). Additional research is needed to assess the ecological and economic benefits and costs of modifying logging technology in logged-over stands.

Finally, quantification of the economic trade offs between economic and ecological criteria in tropical forestry remains an important area of research as is the study of which policy instruments will yield environmental protection at the least cost. These are some of the themes on which our current research is focused.

[3] In our steady state analysis, it did not make much sense to compute carbon flows since a fixed initial reference point did not exist. In fact, in our steady state analysis, the stand initial conditions were generated as part of the optimal solution. Thus, we replaced carbon flows by mean storage, perhaps a simpler and more intuitive concept as well.

[4] Unless, of course, different species are harvested or felling limits are modified at each cut.

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