PN-ACA-788

SIMULATING OPTIONS FOR CARBON SEQUESTRATION THROUGH IMPROVED MANAGEMENT OF A LOWLAND TROPICAL RAINFOREST

Marco Boscolo, Joseph Buongiorno, and Theodore Panayotou

Environment Discussion Paper No. 17
January 1997

CTFS/HIID SOCIOECONOMIC RESEARCH PROJECT
A collaborative effort between HIID and the Center for Tropical Forest Science, Smithsonian Tropical Research Institute
&
EPA FORESTRY PROJECT
EPA/HIID Cooperative Agreement on International Forestry Issues

Marco Boscolo is a research associate at the Harvard Institute for International Development and Center for Tropical Forest Science, Smithsonian Tropical Research Institute. Joseph Buongiorno is a faculty member in the Department of Forestry, University of Wisconsin-Madison. Theodore Panayotou is a Fellow of the Harvard Institute for International Development and Director of the International Environment Program.

Acknowledgments: We are grateful to S. Appanah, Peter Ashton, Awang Noor Abd. Ghani, Rick Condit, Elizabeth Losos, Robert Stavins, and Jeffrey Vincent for valuable suggestions and comments on earlier drafts. We thank the Forest Research Institute of Malaysia (FRIM) and N. Manokaran, J. LaFrankie, K.M. Kochummen, E.S.Quah, J.E. Klahn, P.S. Ashton and S.P. Hubbell in particular for the biological data. The 50 hectare forest plot at the Pasoh Forest Reserve is an ongoing project of the Malaysian Government initiated by the Forest Research Institute of Malaysia and under the leadership of N. Manokaran, Peter S. Ashton and Stephen P. Hubbell. This work was prepared with partial support from the Smithsonian Tropical Research Institute's Center for Tropical Forest Science through a grant from the Southern Company, from the Environmental Protection Agency through the cooperative agreement with HIID on "Economic Analysis of International Forestry Issues" and from the Harvard Institute for International Development.

The views expressed are solely those of the author(s) and do not necessarily represent the views of the U.S. Agency for International Development, the host government, or the Harvard Institute for International Development. The boundaries, colors, and other information shown on any map in this volume do not imply any judgment on the legal status of any territory or the endorsement or acceptance of such boundaries.

This paper is for discussion purposes and HIID welcomes comments, which will be relayed to the authors. This document should not be quoted without the permission of HIID or the author(s).

For additional information please contact: International Environment Program, Harvard Institute for International Development, One Eliot Street, Cambridge, MA 02138.

Tel: (617) 495-5176. Fax: (617) 496-8040.

B

SUMMARY

This study estimated the trade-offs between financial returns from timber production and carbon sequestration in the management of a tropical lowland rainforest in Peninsular Malaysia. Trade-offs between the two management criteria and cost-effectiveness of carbon sequestration were evaluated for alternative felling cycles, diameter cutting limits and adoption of reduced impact logging methods. Simulations were driven by a growth model calibrated with data from a 50 hectare demographic plot in Peninsular Malaysia. This plot defined the initial state for all simulations.

From a financial point of view, under any scenario, felling all valuable trees proved superior to a selective cut with a diameter limit. Lengthening to 50-60 years the current customary felling cycles of 30 years was desirable since it did not affect financial returns, while it increased carbon storage in the stand. The additional amounts of carbon sequestered per hectare by lengthening the felling cycle are, however, small.

Net carbon sequestration could also be increased by reducing logging damage. The cost-effectiveness of this approach depended primarily on the incremental cost to achieve such damage reduction. If logging damage were reduced from 40% to 15% at an additional cost of about $150/hectare, carbon savings would cost $3 to $5 per ton of carbon.

However, findings suggest that there is no financial incentive in current management practices to reduce logging damage. In the absence of regulations and/or other forms of economic incentives harvesting practices will continue to reduce net carbon sequestration.

1. INTRODUCTION

The growing evidence that increased levels of carbon dioxide in the atmosphere are related to global warming (IPCC 1990, Houghton et al. 1996, Santer et al. 1996) and the risks of welfare losses associated with an increase in global temperatures have prompted several countries to consider options for offsetting current carbon dioxide emissions (UNCED 1992). One of such options takes the form of a tradable permits program where units of carbon sequestered from the atmosphere in one location could be marketed to offset emissions in other locations. Forestry activities are among the initiatives that promise cost-effective CO_2 abatement, especially where rapid rates of tree growth are combined with high environmental benefits.

Forests influence carbon concentration in the atmosphere by assimilating CO_2 through biomass build-up and by releasing it through biomass decay. In climax forests, where growth, mortality, accumulation and respiration are in a long-term balance, harvesting causes biomass, and consequently carbon, to be lost (or sunk into lasting end-uses such as lumber built into houses). Carbon storage is then gradually recovered as the forest grows in the following years (Bormann and Likens 1979).

Several forestry practices can increase carbon sequestration. They include afforestation, reforestation, preservation of forestland from conversion, adoption of various agro-forestry practices, lengthening the felling cycle, increasing diameter cutting limits to enhance carbon storage, and adoption of low impact harvesting methods. In tropical countries research has been done to assess the potential of carbon sequestration through reforestation, protection of forest from land-use conversions, and agro-forestry activities (cf. Faeth, Cort and Livernash 1994, Trexler and Hagen 1995). Possibilities to achieve cost-effective carbon sequestration by modifying current management systems of natural tropical forests have, however, been addressed only to a limited extent (Putz and Pinard 1993), partly because of insufficient knowledge regarding the growth dynamics of tropical forest stands.

Modifying the management of natural tropical forests can improve residual conditions favoring both future productivity and levels of carbon storage while maintaining high economic returns. Incentives to manage tropical and temperate forests for both timber and carbon may soon appear in several countries (see, e.g., the US Climate Change Action Plan). As a result, the activity of carbon sequestration might be rewarded in monetary terms. This prospect provides an opportunity for economic gains to both managers of forest resources and parties interested in acquiring carbon credits. To measure the potential for such gains it is important to assess how the forest resource can be managed for multiple-use (timber and carbon storage) and to identify where the cheapest carbon can be "bought".

The objective of this paper is to develop a matrix growth model that simulates the growth dynamics of a lowland dipterocarp forest in Peninsular Malaysia and to identify which combinations of timber harvest and carbon storage are technically feasible. Moreover, since the value of timber can easily be assessed, knowledge of the production possibility frontier between timber and carbon allows estimation of the opportunity cost of carbon sequestration in monetary terms.

The literature presents several methods to estimate the costs of carbon sequestration through forestry activities. They include: (a) simple average-cost estimations (e.g., Sedjo and Solomon, 1989; Dudek and LeBlanc, 1990); (b) "least-cost" approaches, where the marginal cost of carbon sequestration is derived by adopting increasing land rental rates or purchase costs (Moulton and Richards, 1990) or by estimating the cost to remove land from agricultural production (Parks and Hardie, 1995); (c) mathematical programming techniques (e.g., Adams et al., 1993, Hoen and Solberg, 1994); and (d) econometric studies (e.g., Stavins, 1995)[1]. The approach we adopt can be considered a "least-cost" study, in the sense that the cost of carbon sequestration is evaluated for alternative management schemes which are then ranked in order of cost-effectiveness.

Our study differs, however, from existing ones at least in two important respects. First, while existing studies on the costs of carbon sequestration through forest activities have primarily focused on the implications of modifying forested areas through afforestation, reforestation or retarded deforestation, in this study we address the potential for carbon sequestration by modifying management schemes on an existing forest stand. Second, our analysis looks at an uneven-aged tropical forest stand where carbon sequestration can be achieved by modifying the felling cycle, the diameter limit, and logging technology. Other analyses that have looked at the implications of considering carbon values for forest management have generally focused on rotation age issues, with almost exclusive reference to even-aged stands (see, e.g., Binkley and van Kooten, 1994; Plantinga and Birdsey, 1994; Englin and Callaway, 1995). Management options such as continued growth, fertilization, thinning, planting, and clearfelling with and without green tree retention have been considered by Hoen and Solberg (1994) for an even-aged forested area in Norway.

In this paper the following questions are addressed:

1. When carbon sequestration and/or other environmental benefits are ignored, which type of management regime is best in the pursuit of financial interests?
2. If an interest exists in saving carbon through forest management, how can it be achieved at the least cost? How does the cost-effectiveness of alternative management decisions (felling cycle, diameter cutting limit, logging technology) compare to each other?
3. What is the supply schedule of carbon savings from a tropical forest stand?

2. A MODEL FOR THE MANAGEMENT OF A LOWLAND TROPICAL RAINFOREST

Addressing these questions requires knowledge of the forest growth dynamics that determine resource carbon storage and timber yield capabilities. To mimic such forest dynamics we have developed a model based on transition matrices, of the kind originally developed by Usher (1966) and further refined by Buongiorno and Michie (1980) through incorporation of an ingrowth function dependent on stand density.

[1] This review is by no means comprehensive and is meant only to provide a framework to assess how our work fits into existing methodologies. A more comprehensive review can be found in Richards and Stokes (1995).

In this model, the stand state is represented by the vector $\mathbf{y}_t = [y_{i,j,t}]$ where $y_{i,j,t}$ is the number of trees per hectare of species i ($i = 1,m$),, diameter class j ($j = 1,n$) , at time t. The harvest at time t is given by the vector $\mathbf{h}_t = [h_{i,j,t}]$. The growth model consists of a system of equations where the stand state at time $t+1$ is predicted from the stand conditions at time t, after harvest:

$$
\begin{aligned}
y_{i,1,t+1} &= (y_{i,1,t} - h_{i,1,t})\ a_{i,1} + I_i \\
y_{i,2,t+1} &= (y_{i,1,t} - h_{i,1,t})\ b_{i,2} + (y_{i,2,t} - h_{i,2,t})\ a_{i,2} \\
y_{i,3,t+1} &= (y_{i,2,t} - h_{i,2,t})\ b_{i,3} + (y_{i,3,t} - h_{i,3,t})\ a_{i,3} \\
&\cdots\cdots\cdots \\
y_{i,n,t} &= (y_{i,n-1,t} - h_{i,n-1,t})\ b_{i,n} + y_{i,n,t}\ a_{i,n}
\end{aligned}
\tag{1}
$$

where $a_{i,j}$ is the probability that a live tree at time t will be still alive at time $t+1$ and in the same diameter class, $b_{i,j}$ is the probability that a live tree at time t and in class $j-1$ will be in class j at time $t+1$.

In matrix form the model is formulated as (Buongiorno and Michie 1980):

$$\mathbf{y}_{t+1} = \mathbf{G}(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{c} \tag{2}$$

where:

$$\mathbf{G} = \begin{bmatrix} \mathbf{G}_1 & & & \\ & \mathbf{G}_2 & & \\ & & \cdots & \\ & & & \mathbf{G}_m \end{bmatrix} \qquad \mathbf{c} = \begin{bmatrix} \mathbf{c}_1 \\ \mathbf{c}_2 \\ \cdots \\ \mathbf{c}_m \end{bmatrix}$$

and where

$$\mathbf{G}_i = \begin{bmatrix} a_1 & & & \\ b_2 & a_2 & & \\ & \cdots & \cdots & \\ & & b_n & a_n \end{bmatrix} \qquad \mathbf{c}_i = \begin{bmatrix} I_i \\ 0 \\ \cdots \\ 0 \end{bmatrix}$$

The model assumes that transition probabilities (and the underlying growth and mortality rates) are independent of stand state while ingrowth (the number of trees that enter the smallest diameter class between t and t+1) is expected to be dependent on stand density and composition. This is a modification of the ingrowth model proposed by Buongiorno et al. (1995). Ingrowth of

a species is a positive linear function of the number of trees of that species and as a negative function of total stand basal area. At any time t the ingrowth function is:

$$I_{i,t} = \alpha_i + \beta_i \sum_{i=1}^{m} \sum_{j=1}^{n} B_j (y_{i,j,t} - h_{i,j,t}) + \gamma_i \sum_{j=1}^{n} (y_{i,j,t} - h_{i,j,t}) \quad (3)$$

where B_j is the basal area of a tree belonging to diameter class j.

The model parameters were estimated with data from a large (50 hectare) demographic plot located in the Pasoh forest, Negeri Sembilan, Peninsular Malaysia. The plot, established by the Forest Research Institute of Malaysia in 1985 (Manokaran et al. 1990) was then censused in 1987 and 1990. During the censuses all free-standing, woody stems with a diameter at breast height (dbh) ≥ 1 cm were identified, tagged, mapped, and their diameter recorded. Previous analyses of census data can be found in Kuchummen et al. (1990), Manokaran and LaFrankie (1990), Manokaran et al. (1992), and Appanah and Weinland (1993).

For the present study only trees with dbh ≥ 10 cm were considered. Biomass of these trees accounts for most of the standing biomass and, consequently, carbon storage. The trees of the 50 ha plot have been divided into seven, 10 cm, diameter classes and 3 species groups: commercial dipterocarps (D), commercial non-dipterocarps (O), and non commercial trees (N). The distinction between commercial dipterocarps and non-dipterocarps was made for two reasons: (1) previous studies (e.g., Wan Razali, 1988; Appanah and Weinland, 1991) have shown that dipterocarp species generally exhibit a higher growth rate; and (2) current management requires different diameter cutting limits, generally higher for dipterocarps. Table 1 shows that dipterocarps occupied one third of the basal area on the 50 ha. plot in the Pasoh forest in 1987.

2.1. *Development of a steady-state constrained matrix growth model*

Michie and Buongiorno (1984) review 4 methods to estimate transition probabilities from inventory data. The simplest approach is to compute the a_i and b_i probabilities as the proportions of trees that, during a time interval, stay in the same class or move on to the next one (method I). This is the method that has been most extensively applied (cf., e.g., Mendoza and Setyarso 1986, Osho 1991). However, when applied to the Pasoh dataset, it led to a model that – though accurate for short term predictions – gave unacceptable steady-states (e.g. with a negative number of trees in some classes). Such a model could not be used to analyze sustainable management regimes over long time periods. Similar problems in the development of a matrix model for a lowland tropical forest in Malaysia have been reported by Ingram and Buongiorno (1996). They dealt with this problem by computing the parameters a_i and b_i with equation (1) by assuming that they knew the steady state (the climax forest) and the mortality rates. A similar approach was applied by Houde and Ledoux (1995) on natural forest stands in Guyana. We also derived the matrix parameters from the steady state (including knowledge of ingrowth) by assuming that the upgrowth parameters, b_i, measured from the two censuses were representative of their true value while the mortality rates were not. The basis for this assumption is that: (i)

diameter growth (directly related to the b_i probabilities) can be estimated with more accuracy than tree mortality; (ii) growth rates were consistent with other growth and yield studies in Peninsular Malaysia; and (iii) anecdotal evidence suggests that windstorms are not uncommon in the area. Since no windstorm occurred between the two censuses, we hypothesized that mortality between 1987 and 1990 was unusually low and could not be used for long-term predictions. Indeed, to predict the long term effects of forest management, natural disturbances need to be accounted for, either as random events with a certain probability distribution or as (constant) expectations of long term mortality rates.

Here, expected mortality rates were derived from the steady-state, or climax, forest (cf. Bormann and Likens 1979). The concept of steady state has often been used in the past to verify long-term model reliability. It can also be used to infer the long-term mortality rates. Since the 50 hectare plot is located in a pristine forest, characteristics like basal area, diameter distribution and composition by broad species groups are believed to represent the result of a long evolutionary process. Therefore, the average plot condition per ha was chosen as an approximation of the forest's steady state, i.e. its ecological climax.

Assuming that the parameters $b_{i,j}$ are independent of stand state (more on this below) and that they are measured accurately by the censuses allows the derivation of the parameters $a_{i,j}$ (and thus of mortality) from the diameter distribution ($y_{i,j}^s$) and ingrowth in steady state (I_i^s). From equation (1):

$$a_{i,1} = -(I_i^s - y_{i,1}^s)/y_{i,1}^s$$

$$a_{i,2} = (y_{i,2}^s - y_{i,1}^s\, b_{i,2})/\, y_{i,2}^s \qquad (4)$$

.....

$$a_{i,n} = (y_{i,n}^s - y_{i,n-1}^s\, b_{i,n})/\, y_{i,n}^s$$

which implies a mortality $m_{i,j} = 1 - a_{i,j} - b_{i,j+1}$. Table 2 shows all the transition probabilities for the matrix model. The mortality rates obtained in this way are higher than those observed between the censuses, as expected.

While the transition probabilities are independent of stand state in this approach, the ingrowth is not. To estimate the effects of stand density and composition on ingrowth (equation (3)) the 50 ha plot was divided into 50 subplots of 1 hectare each. The results of the estimation of the ingrowth equation (3) from the subplot data are in table 3. All coefficients had the expected sign: ingrowth of each species group was influenced negatively by the stand basal area and positively by the number of trees of that group. The coefficients of determinations varied between 9% and 32%, so that most of ingrowth variability was not explained by the model. This suggests that little might be lost by modeling ingrowth as a constant (Buongiorno et al. 1995), at least for the O and N species. Much of the variation in ingrowth is probably random and hard to predict (Vanclay 1992). Still, the effect of the independent variables on ingrowth was statistically

significant at the 5% level in all three equations, suggesting a systematic effect of stand state on ingrowth.

The procedure to derive the $a_{i,j}$ coefficients relies on the assumption (shared by all fixed-coefficients matrix models) that mortality and growth rates are independent of stand density. This assumption was tested on the fifty, 1 hectare, subplots. For each subplot we measured basal area, growth, and mortality rates for the three species groups (D, O, and N). Mortality rates were then computed for two size classes (1-30 cm, and above 30 cm) while growth rates were averaged in 4 size classes (10-20, 20-30, 30-40 and 40+). There was no statistically significant (α=0.05) relationship between mortality and stand basal area. There was a significant effect of density on growth rates only for a few sizes and species and the effect was, generally, quite small.

Other studies of tree growth in tropical forests of South East Asia also suggest that this assumption is plausible. Though Hutchinson (1979, cited by Panayotou and Ashton 1992) reported very significant responses of diameter growth to thinning in Sarawak, Malaysia, other studies report that the effect of stand density on diameter growth may be smaller. Wan Razali (1988) found a statistically significant effect of stand basal area on diameter growth in Peninsular Malaysia, but this effect was very small (halving basal area - from 25 to 12.5 m^2/ha - would increase annual diameter growth by a fraction of a millimeter). Primack et al. (1987) comparing logged and unlogged forests in Sarawak could not detect a significant difference in growth rates.

Perhaps the most complete study of tree growth in Peninsular Malaysia was done by Liu and Ashton (1996). They developed a new index of inter-tree competition (neighborhood pressure, *np*) and measured its effect (along with other dimensional, topographical and ecological variables) on tree growth in an unlogged primary forest. Their models explain much more diameter growth variation than previous studies. Yet, they found that among over 500 species, less than half showed a statistically significant effect of *np* on diameter growth and, in these cases, this effect was small. For the species affected by competition, a 1% variation in *np* corresponded a -0.06% variation in diameter growth. Thus, a 50% reduction in *np* would increase diameter growth by only 3%. A 30 cm dbh tree growing at 6 mm/yr. (or 2%/year) would, after a reduction of 50% of *np*, grow at a rate of 2.06% (= 2% + 3% of 2%). In 20 years this difference amounts to about 0.5 cm, i.e. by ignoring the effect of competition on diameter growth one would predict a tree size of 44.6 cm instead of 45.1 cm. Therefore, the simplifying assumption of transition probabilities independent of stand state should not affect the overall validity of the model predictions in this case.

3. SIMULATING THE OUTCOME OF ALTERNATIVE MANAGEMENT DECISIONS

With the model developed in the preceding section we have simulated the impact of alternative management regimes on financial returns and carbon savings at the stand level. For a given forest tract, forty management scenarios were simulated, each one with a different combination of the decision variables: felling cycle, diameter cutting limit, and effort to reduce logging

damage[2]. Each simulation gave estimates of harvested and residual number of trees, basal area, volume and biomass for each species group. From these data, carbon storage and revenue estimates were derived.

3.1. *Decision variables*

Formerly, the lowland tropical rainforests of Peninsular Malaysia were harvested according to the Malaysian Uniform System (MUS, Wyatt-Smith 1963). Under this system all valuable trees are felled, and the residual stand above a certain minimum diameter is poison-girdled. The stand is then left to grow for 60 to 70 years. The MUS was later substituted by the Selective Management System (SMS) in which diameter cutting limits are higher than under the MUS, ranging from 45 to 65 cm, no poison-girdling takes place, and felling cycles are shortened to approximately 30 years (Thang 1987). The simulation scenarios cover the whole range of possible felling cycles and diameter limits:

- *Felling cycles.* The simulations assumed cuttings every 30, 40, 50, 60, or 70 years.
- *Diameter cutting limits.* Under the MUS all commercial trees above 45 cm are cut (Thang 1987). Diameter limits are higher when selective systems are adopted and generally different for dipterocarps and non-dipterocarps. However, for simplicity, and to reduce the number of simulations, the same diameter limit was however applied to all commercial trees: 30, 40, 50 or 60 cm.
- *Logging damage.* The SMS in Malaysia assumes that harvesting damages about 30% of the residual trees, but these figures may be too conservative (cf. Wyatt-Smith 1988; Appanah and Weinland 1991). Logging damage could be decreased by: cutting woody climbers before harvesting, mapping the area to be logged, careful planning and building of roads and skid trails, directional felling, and minimal use of bulldozers (Panayotou et al. 1994). Putz and Pinard (1993), referring to a reduced-impact logging project in Sabah, Malaysia, estimated that reduced-impact logging could increase costs by about $135/ha, and reduce damage from 40% to 15% (Pinard et al. 1995). There is, however, little evidence to support this cost figure which we rounded to $150/hectare.

3.2. *Management criteria*

The performance of each management scenario was judged from two main criteria: financial returns and carbon sequestration.

Financial returns. Financial returns were measured by the Net Present Value (NPV) of timber extractions over a long time period:

[2] As such, the scenarios considered are not endogenous to economic conditions, i.e., each scenario is not necessarily the most efficient one for a given set of prices for timber and input factors. The selection of the efficient scenarios is done subsequently (and "exogenously"), by ranking them in order of cost-effectiveness.

$$NPV = \sum_{t=0}^{T} (TR_t - TC_t)/(1+r)^t \qquad (5)$$

where TR_t is the total revenue from timber sale in year t, TC_t is the total cost and r is the yearly interest rate. The real interest rate was set at 6%[3]. The time horizon (T) was 200 years. By that time, and in fact much earlier, a stand cut according to a particular regime has reached a dynamic steady-state: the growth just replaces harvest, and the cut is sustainable, forever. In addition, increasing the time horizon beyond 200 years changes the NPV very little. Therefore, the NPV is near that obtained by following a given scenario over an infinite length of time. The commercial volume harvested was estimated with the following volume equations (FFD 1987):

$$V = 0.3211 - 0.002175\,D + 0.0003521\,D^2 \quad (\text{for } 10 \le D < 30 \text{ cm})$$

$$V = 0.1991 + 0.006148\,D + 0.0004081\,D^2 \quad (\text{for } 30 \le D < 60 \text{ cm})$$

$$V = 0.8602 - 0.03872\,D + 0.0013164\,D^2 \quad (\text{for } D \ge 60 \text{ cm})$$

where V is in m^3 and D is the diameter at breast height, in cm. The same equations are used for the three species groups. Stumpage values were derived by subtracting harvesting costs from log prices (ITTO and FRIM 1994). To compute net revenues, volume-based charges (estimated at 10% of the log price) and area-based charges ("premiums", estimated at $350/ha, partly based on Awang Noor [1994] and ITTO and FRIM [1994]) have also been deducted. Tree volume and value are in Table 4. Trees of zero value were not cut in the simulations.

Carbon sequestration. The analysis takes into account variations in carbon stored in living trees (carbon accumulated in above and below ground biomass) and does not consider carbon stored in soil or end-uses. Following Hoen and Solberg (1994), carbon sequestration was measured as "net carbon accumulation", i.e. the difference between carbon stored and withdrawn over time, per unit of land. When the storage of carbon in lasting end-uses such as buildings, furniture etc. is ignored, harvesting results in a negative net accumulation (loss). In the following years the stand grows, accumulates biomass and stores carbon (see Fig. 1).

To account for the carbon flows at different points in time at least three different approaches are used in the literature. Richards and Stokes (1995) classify them as flow summation, mean carbon storage, and discounting (or levelization). Flow summation measures the total tons of carbon sequestered, regardless of when sequestration occurs. The results are comparable only for scenarios of the same length of time, and they are indifferent to the schedule of carbon sequestration (cf. Faeth, Cort and Livernash 1994). The mean carbon storage is the average amount of carbon stored per year over the period analyzed. Mean carbon storage reflects the time needed to store carbon and converges to a limit as the planning horizon increases. However – like flow summation – mean carbon storage assumes indifference between carbon sequestration (or storage) in the near or distant future. Discounting, used here, discounts the amounts of CO_2

[3] The average lending rate in Malaysia from 1976 to 1990 was 5.7% per year, net of inflation (Ingram and Buongiorno, 1996).

sequestered from the atmosphere in each period as if it were money. Net Present Carbon Accumulation (NPCA) was computed as:

$$NPCA = \sum_{t=0}^{T} (C_{t+1} - C_t)/(1+r)^t \qquad (6)$$

where C_t, the amount of carbon stored in a forest stand at time *t* (in ton/ha), is:

$$C_t = TAGB_t \times f_1 \times f_2 \qquad (7)$$

and where TAGB is the Total Above Ground Biomass (in ton/ha), f_1 is a correction factor that accounts for root biomass (estimated at 10% of TAGB, Whitmore 1984), and f_2 is the ratio of carbon to organic biomass (0.5, Kira 1978).

As suggested by Brown et al. (1989), TAGB was estimated at double the commercial biomass which, in turn, was computed as the sum of the products of commercial volume and average wood density (Desch 1941, 1954) for each species group. The current average biomass in the Pasoh plot was 388 tons/ha[4], corresponding to a total tree biomass (above and below ground) of 428 tons/ha and a carbon storage of 214 tons/ha (see table 5). Like costs and timber revenues, carbon flows occurring at different points in time were discounted at 6% per year. Indeed, if a market for carbon storage existed, the value of one ton of carbon stored would be computed and discounted exactly like timber revenues.

4. RESULTS

The simulations of management alternatives were done over 200 years. The initial state was the average state per hectare in the Pasoh plot. Since the plot is near a climax state, the simulations show the effect of different managements on a virgin lowland tropical forest stand.

4.1. *Best management to maximize financial returns: baseline solution*

The results of the simulations are in Table 6 for conventional logging methods and Table 7 for reduced-impact methods. The solution that yielded the highest NPV/ha (baseline solution) consisted of cutting every 40 years all commercial trees with diameter greater than 30 cm by conventional logging methods. This scenario gave a NPV of $3880/hectare and is essentially the management that was practiced in the lowlands of Peninsular Malaysia until the mid seventies[5]. Our simulation differs, however, from the MUS since no poison-girdling or harvesting of non-

[4] Kira (1978) reports another set of allometric relationships obtained from some destructive sampling carried out in the Pasoh forest during 1971 and 1973. By using Kira's relationships we obtained a value for TAGB of 388 tons/ha, identical to the estimate derived following Brown's approach.

[5] As noted above, this management system (the Malaysian Uniform System or MUS) was later substituted by the Selective Management System (SMS) as the core of forestry activities moved from the lowlands to hill areas.

commercial trees has been simulated. The simulation detail showed that most of the NPV was obtained from the first cut that extracted about 90 m^3/ha. The following cuts yielded much less in volume[6], and even less in monetary terms because of discounting. Therefore, whether the second cut was in 30 or 70 years, the NPV/ha did not change much. This means that, from a financial point of view, the length of the felling cycle matters little as long as all valuable trees are felled in the first cut. Instead, the choice of a diameter limit is critical. NPV/ha was reduced by more than $1000 by increasing the diameter limit from 30 to 60 cm (Table 6).

Comparing Tables 6 and 7 shows that under no combination of felling cycle and diameter cutting limit was the reduction of logging damage financially attractive. While the volume obtained from future cuts was higher, discounted future revenues did not compensate for the additional cost.

4.2. *The cost of storing carbon in the forest*

The solution that maximized the NPV/ha led to a net present carbon accumulation of -84 tons/ha (it is therefore a loss). This is the discounted sum of carbon removals (from logging) and carbon accumulations (through biomass build-up) over 200 years. When carbon savings is an objective of management, Tables 6 and 7 suggest that carbon losses can be reduced by lengthening the felling cycle, increasing the diameter cutting limit, or reducing logging damage.

Each of these adjustments (or a combination of them) represents a divergence from the baseline. Since the baseline was defined as the solution that maximizes financial returns, any divergence from that solution involves a cost in terms of reduced NPV/ha. By comparing the amounts of carbon saved with the corresponding costs in NPV terms it is possible to investigate which alternatives achieve carbon savings at the least cost.

Starting from the solution with a felling cycle of 40 years and a diameter cutting limit of 30 cm, the most cost-effective strategy to store carbon in trees is to lengthen the felling cycle. Postponing the second cut from 40 to 50 years increases NPCA by 2.5 tons of carbon/hectare at a NPV cost of $3/ha. This translates into a cost of carbon sequestration of only $1.2/ton. At a rate of 2.5 tons of carbon per hectare, however, large forest areas are required to store significant amounts of carbon. Lengthening the cutting cycle had, however, practically no effect on the NPV with a discount rate of 10%.

The second cost-effective strategy to save carbon is to reduce logging damage. The effectiveness of this alternative depends on the cost of implementing reduced-impact logging instead of conventional logging methods. For a felling cycle of 50 years and a diameter limit of 30 cm,

[6] Some stands that have been treated in the past according to the MUS exhibit now good stocking levels of commercial species (Ashton, pers. comm., 1996). This fact apparently contradicts our simulation results. As noted above, however, our simulations did not replicate exactly the MUS, i.e., did not eliminate non-commercial species by either harvesting or poison-girdling. If simulations had considered the harvesting (or poison-girdling) of non-commercial species the proportion of commercial trees at the second and subsequent harvests would have been significantly higher than predicted.

reduced-impact logging increased NPCA by 27 tons/ha with a sacrifice in NPV of $149/ha. Thus, carbon removals can be reduced at a cost of $5.5/ton. The same results were obtained with a discount rate of 10%.

Carbon savings can also be achieved by increasing the diameter cutting limit. With a felling cycle of 40 years, increasing the diameter limit from 30 to 60 cm increased NPCA by 10 tons/ha. However, this is obtained at a NPV cost of over $1200/ha which translates in a cost of carbon sequestration of over $120/ton.

To summarize the opportunity cost of carbon sequestration through natural forest management we mapped the production possibility frontier between NPV and NPCA (Figure 2). It consists of the combinations of felling cycle, diameter cutting limit and reduced logging damage that were Pareto efficient, i.e., where one output (NPV or NPCA) could not be improved without diminishing the other. Assuming that all feasible combinations of carbon and income are contained in a convex set, the frontier was drawn by connecting the extreme points. Figure 2 shows that significant carbon savings could be attained at low cost by reducing logging damage. The other alternatives (lengthening of the felling cycle and/or increasing the diameter cutting limit) gave little carbon sequestration per ha or were expensive.

The opportunity cost of increasing carbon storage per hectare of lowland tropical rainforest in Malaysia is shown in Figure 3. The origin is the baseline (NPV maximizing) alternative. The figure shows that the cost per hectare increases steeply beyond 30 ton/ha of NPCA.

Following Putz and Pinard (1993) we assumed so far that reduced-impact logging could be achieved at a direct cost of $150/ha. However, this figure is very uncertain. Because reduced-impact logging could achieve carbon savings efficiently, we investigated the sensitivity of the marginal cost of carbon saving (in terms of NPV/ha foregone) to alternative direct costs of implementing reduced-impact logging methods. The marginal cost ($/ton) is the reduction in NPV due to increasing NPCA by one ton/ha.

Table 8 shows the marginal cost of storing carbon in the forest for different costs of reducing the logging impact: $75, $150, $300, or $600/ha. As reduced-impact logging was made more expensive it became more cost-effective to lengthen the felling cycle to 60 or even 70 years before switching from conventional to reduced-impact logging. If reduced-impact logging involves additional expenditures of $75/ha, carbon savings of ca. 30 tons could be achieved at a marginal cost of $2.4/ton. At an implementation cost of $150/ha, it becomes $5.5/ton, $11.2/ton at $300/ha and $23.2/ton at $600/ha. In Figure 4 these results are compared with the marginal cost of carbon savings from using conventional logging.

5. DISCUSSION AND CONCLUSION

In this study we addressed the potential for and cost-effectiveness of carbon sequestration through improved management of lowland tropical forests by performing a stand level analysis for a rainforest in Peninsular Malaysia. Though not much forest area in Peninsular Malaysia is

left in the lowlands, similar forest types are still abundant in the islands of Sumatra and Borneo (P. Ashton, personal communication, 1996) that are currently being harvested with conventional logging systems. The study suggests that, if logging damage could be reduced from 40 to 15% at a cost of $150/ha, carbon storage in natural tropical forests could be increased at a cost of only $5/ton, in terms of NPV of income. This is significantly lower than comparable cost estimates of carbon sequestration achieved through tree plantation (cf. Richards and Stokes 1995 for a review of studies both in the USA and in developing countries) and compares favorably with carbon taxes currently adopted in Denmark, Finland, the Netherlands, Norway, and Sweden (which range from $16/ton to $172/ton, Muller 1996) or with a recent carbon sale by Costa Rica to Norway at an average price of $10/ton (R. Castro Salazar, personal communication, 1996). The average cost of carbon sequestration through adoption of reduced-impact logging was even lower with higher diameter limits. For a diameter cutting limit of 60 cm, reduced-impact logging would increase carbon storage at a cost of $3.3/ton. This estimate is remarkably close to the figure proposed by Putz and Pinard (1993).

Our analysis has derived the cost of carbon sequestration in natural forests through management, per unit of land. Further research should have a broader scale, with the goal to derive the *global* supply function for carbon sequestration. To this end several considerations are in order. First, the results presented in this paper are based on a model calibrated with data from a lowland tropical forest in Malaysia. This type of forest is different from hill dipterocarp forests and from lowland forests of other tropical regions. Differences in location, site quality, stand composition, structure, growth, and value of products are likely to affect the cost-effectiveness of carbon sequestration. The sensitivity of the cost of carbon sequestration to these variations could be addressed through comparative studies.

Second, our analysis has considered the trade-offs between financial returns (NPV/ha) and carbon sequestration. However, trade-offs exist also between timber and other forest products and services (watershed protection, biodiversity, recreational opportunities etc.). For example, current research in Peninsular Malaysia by Mohd Shahwahid and colleagues, points out the high cost of dredging induced by logging practices in the catchment area of the Ulu Langat Forest Reserve, in the state of Selangor. There, the hill forest helps prevent sedimentation of mini-dams and regulate water flow. Preliminary results suggest that high dredging costs are caused by logging with conventional methods. Reduced-impact logging may reduce dredging costs by about 30%. These examples confirm that environmental impacts must be accounted for and, as we expect them to benefit from more careful harvesting practices, their inclusion will make the cost-effectiveness of carbon sequestration even better.

REFERENCES

Adams R.M., D.M. Adams, J.M. Callaway, C. Chang, B.A. McCarl (1993). *Sequestering Carbon on Agricultural Land: Social Cost and Impacts on Timber Markets*, Contemporary Policy Issues (11):76-87.

Appanah S. and G. Weinland (1991). *Will the Management Systems for Hill Dipterocarp Forests Stand Up?* Journal of Tropical Forest Science **3**(2):140-158.

Appanah S. and G. Weinland (1993). *A preliminary analysis of the 50-hectare Pasoh demography plot: I*, Dipterocarpaceae. FRIM, Research Pamphlet No. 112.

Awang Noor Abd. Ghani (1994). *Economics of Revenue Systems in Malysian Timber Concessions,* Ph.D. dissertation. Michigan State University.

Binkley C.S. and G.C. van Kooten (1994). *Integrating Climate Change and Forests: Economic and Ecological Assessments*, Climatic Change **28**:91-110.

Bormann F.H. and G.E. Likens (1979). *Patter and Process in a Forested Ecosystem,* Springer-Verlag.

Brown S., A.J.R. Gillespie and A.E. Lugo (1989). *Biomass Estimation Methods for Tropical Forests with Applications to Forest Inventory Data*, Forest Science **35**(4):881-902.

Buongiorno J. and B. Michie (1980). *A matrix model of uneven-aged forest management*, Forest Science **26**(4):609-625.

Buongiorno J., J.L. Peyron, F. Houllier and M. Bruciamacchie (1995). *Growth and Management of Mixed-Species, Uneven-Aged Forests in the French Jura: Implications for Economic Returns and Tree Diversity*, Forest Science **41**(3):397-429.

Desch H.E. (1941). *Dipterocarp Timbers of the Malay Peninsula,* Malaysian Forest Records n. 14 and 15 (vol I).

Desch H.E. (1954). *Manual of Malayan Timbers*, Malaysian Forest Records n. 15 (vol. II).

Dudek D.J. and A. LeBlanc (1990). *Offsetting New CO_2 emissions: A Rational First Greenhouse Policy Step,* Contemporary Policy Issues (8):29-42.

Englin J. and J.M. Callaway (1995), *Environmental Impacts of Sequestering Carbon Through Forestation,* Climatic Change **31**:67-78.

Faeth P., C. Cort and R. Livernash (1994). *Evaluating the Carbon Sequestration Benefits of Forestry Projects in Developing Countries*, WRI.

FFD (Federal Forest Department) (1987). *National Forest Inventory II, Peninsular Malaysia 1981-82*, Forest Management Unit. Kuala Lumpur.

Hoen H.F. and B. Solberg (1994). *Potential and Economic Efficiency of Carbon Sequestration in Forest Biomass Through Silvicultural Management*, Forest Science **40**(3):429-451.

Houde L., and H. Ledoux (1995). *Modelization in natural forests: stand stability*, Bois et Forêts des Tropiques, **245**:28-31.

Houghton J.T. et al. (1996). *Climate Change 1995: The Science of Climate Change,* Cambridge University Press.

Hutchinson I.D. (1979). *Liberation thinning: A tool in the management of mixed dipterocarp forest in Sarawak.* UNDP/FAO/MAL/76/008. Sarawak Forestry Department. Kuching, Sarawak, Malaysia.

Ingram D. and J. Buongiorno (1995). *Income and diversity trade-offs from management of mixed lowland dipterocarps in Malaysia,* Journal of Tropical Forest Science (forthcoming).

IPCC (Intergovernmental Panel on Climate Change) (1990). *Policy Makers Summary of the Scientific Assessment of Climate Change.*

ITTO (International Tropical Timber Organization) and FRIM (Forest Research Institute of Malaysia) (1994). *Economic Case for Natural Forest Management.*

Kira T. (1978). *Community architecture and organic matter dynamics in tropical lowland rain forests of South East Asia with special reference to Pasoh Forest, West Malaysia,* Pp. 561-590 in P.B. Tomlinson and M.H. Zimmerman (Eds): Tropical Trees as Living Systems. Cambridge University Press.

Kochummen K.M., J.V. LaFrankie and N. Manokaran (1990). *Floristic composition of Pasoh Forest Reserve, a lowland rain forest in Peninsular Malaysia,* Journal of Tropical Forest Science. **3**(1):1-13.

Liu J. and P.S. Ashton. (1996). *Modeling Biodiversity and Timber Dynamics in Landscape Mosaics,* Harvard Institute for International Development, Harvard University, Cambridge, MA. Unpubl. manuscript.

Manokaran N. J.V. LaFrankie, K.M. Kochummen, E.S. Quah, J.E. Klahn, P.S. Ashton and S.P. Hubbell (1990). *Methodology for the Fifty Hectare Research Plot at Pasoh Forest Reserve,* Research Pamphlet no. 104. FRIM.

Manokaran N. and J.V. LaFrankie (1990). *Stand Structure of Pasoh Forest Reserve, a lowland rain forest in Peninsular Malaysia,* Journal of Tropical Forest Science **3**(1):14-24.

Manokaran N. J.V. LaFrankie, K.M. Kochummen, E.S. Quah, J.E. Klahn, P.S. Ashton and S.P. Hubbell, (1992). *Stand Table and Distribution of Species in the 50-ha Research Plot at Pasoh Forest Reserve,* FRIM.

Mendoza G.A. and A. Setyarso (1986). *A transition matrix forest growth model for evaluating alternative harvesting schemes in Indonesia,* Forest Ecology and Management. **15**:219-228.

Michie B.R. and J. Buongiorno (1984). *Estimation of a matrix model of forest growth from re-measured permanent plots*, Forest Ecology and Management **8**:127-135.

Moulton R.J. and K.R. Richards (1990). *Costs of Sequestering Carbon Through Tree Planting and Forest Management in the United States,* USDA Forest Service GTR WO-58.

Muller F. (1996). *Mitigating climate change: the case for energy taxes,* Environment **38**(2).

Osho J.S.A. (1991). *Matrix model for tree population projection in a tropical rain forest of south-western Nigeria,* Ecological Modelling. **59**:247-255.

Panayotou T. and P. Ashton (1992). *Not By Timber Alone. Economics and Ecology for Sustaining Tropical Forests*, Island Press. Washington D.C.

Parks P.J. and I.W. Hardie (1995). *Least-Cost Forest Carbon Reserves: Cost-Effective Subsidies to Convert Marginal Agricultural Land to Forests,* Land Economics **71**(1):122-136.

Primack R.B., E.O.K. Chai, S.S. Tan and H.S. Lee (1987). *The Silviculture of Dipterocarp Trees in Sarawak, Malaysia. II. Improvement Felling in Primary Forest Stands,* The Malaysian Forester **50**(1):43-61.

Panayotou T., A. Rosenfeld and L. Kouju (1994). *To Offset or Not to Offset: US Power Utility Offsets CO_2 Emissions by Financing Reduced Impact Logging in Malaysia*, A Case Study for the 1994 HIID Asia Environmental Economics Policy Seminar, Harvard Institute for International Development, Cambridge, MA.

Pinard M.A., F.E. Putz, J. Tay and T.E. Sullivan (1995). *Creating Timber Harvest Guidelines for a Reduced-Impact Logging Project in Malaysia*, Journal of Forestry **93**(10):41-45.

Plantinga A.J. and R.A. Birdsey (1994). *Optimal Forest Stand Management When Benefits Are Derived from Carbon*, Natural Resource Modeling **8**(4):373-387.

Putz F.E. and M.A. Pinard (1993). *Reduced Impact Logging as a Carbon-Offset Method,* Conservation Biology. **7**:4.

Richards K.R. and C. Stokes (1995). *National, Regional and Global Carbon Sequestration Cost Studies: A Review and Critique,* Pacific Northwest Laboratories. June.

Santer B.D., K.E. Taylor, T.M.L. Wigley, T.C. Johns, P.D. Jones, D.J. Karoly, J.F.B. Mitchell, A.H. Oort, J.E. Penner, V. Ramaswamy, M.D. Schwarzkopf, R.J. Stouffer, and S. Tett (1996). *A search for human influence on the thermal structure of the atmosphere,* Nature. **382**:39-46.

Sedjo R.A. and A.M. Solomon (1989). *Climate and Forests,* in: N.J. Rosenberg, W.E. Easterling III, P.R. Crosson, and J. Darmstadtler (eds.). Greenhouse Warming: Abatement and Adaptation. Resources for the Future. Washington, D.C.

Stavins R.N. (1995). *The Costs of Carbon Sequestration: A Revealed-Preference Approach,* The RAND Journal of Economics (in press).

Thang H.C. (1987). *Forest Management Systems for Tropical High Forests, with Special Reference to Peninsular Malaysia,* Forest Ecology and Management **21**:3-20.

Trexler M.C. and C. Haugen (1995). *Keeping It Green: Tropical Forestry Opportunities for Mitigating Climate Change*, World Resources Institute. Washington D.C.

UNCED (United Nations Conference on the Environment and Development) (1992). *Framework Convention on Climate Change*, UN. Washington D.C.

Usher M.B. (1966). *A matrix approach to the management of renewable resources, with special reference to selection forests,* Journal of Applied Ecology **3**:355-367.

Vanclay J.K. (1992). *Modelling regeneration and recruitment in a tropical rain forest,* Canadian Journal of Forest Research **22**:1235-1248.

Wan Razali Wan Mohd (1988). *Summary of Growth and Yield Studies in Tropical Mixed Forests of Malaysia*, Paper submitted to the FAO as a compilation of training material.

Whitmore T.C. (1984). *Tropical Rainforests of the Far East*, Clarendon Press, Oxford.

Wyatt-Smith J. (1963). *Manual of Malayian Silviculture for Inland Forests*, Malayan Forest Record no. 23. Forestry Department. Peninsular Malaysia.

Wyatt-Smith J. (1988). *Letter to the editor*, Forest Ecology and Management **24**:219-223.

Table 1. Number of trees, species and basal area by group in the 50 ha plot in 1987*

Timber group	number of trees	number of species	basal area (m^2)
Dipterocarps (D)	3174	29	398.8
Commercial non-dipt. (O)	4944	98	275.8
Non-commercial (N)	17772	540	556.9
TOTAL	25890	667	1231.5

* only trees with dbh ≥ 10 cm.

Table 2. Transition probabilities

		Dipterocarps (D)			Commercial non-dipterocarps (O)			Non-commercial (N)		
j	diameter class (cm)	a_j	b_{j+1}	m_j	a_j	b_{j+1}	m_j	a_j	b_{j+1}	m_j
1	10-20	0.945	0.022	0.033	0.961	0.012	0.027	0.955	0.012	0.033
2	20-30	0.943	0.036	0.021	0.959	0.022	0.020	0.950	0.017	0.033
3	30-40	0.923	0.052	0.025	0.957	0.025	0.018	0.946	0.015	0.039
4	40-50	0.928	0.047	0.025	0.952	0.021	0.028	0.960	0.031	0.009
5	50-60	0.948	0.035	0.017	0.969	0.024	0.007	0.921	0.018	0.061
6	60-70	0.952	0.044	0.005	0.957	0.034	0.009	0.945	0.023	0.032
7	70+	0.981	0.000	0.019	0.962	0.000	0.038	0.977	0.000	0.023

Table 3. Ingrowth equations, by timber group

Dipterocarps (D)			
		Independent variable	
Statistics	Constant	basal area (m^2/ha)	D trees/ha
Coefficient	$3.10 = \alpha_1$	$-0.10 = \beta_1$	$0.017 = \gamma_1$
standard error	0.99**	0.04*	0.004**
R^2_{adj}	0.32		
Commercial non-dipterocarps (O)			
		Independent variable	
Statistics	Constant	basal area (m^2/ha)	O trees/ha
Coefficient	$3.84 = \alpha_2$	$-0.13 = \beta_2$	$0.017 = \gamma_3$
standard error	1.02**	0.05*	0.008*
R^2_{adj}	0.09		
Non-commercial (N)			
		Independent variable	
Statistics	Constant	basal area (m^2/ha)	N trees/ha
Coefficient	$13.27 = \alpha_3$	$-0.30 = \beta_3$	$0.017 = \gamma_3$
standard error	4.14**	0.11*	0.009
R^2_{adj}	0.15		

Table 4. Estimates of tree volume and stumpage value ($/tree in 1991)

diameter class (cm)	volume/tree (m^3)	Stumpage value[a] ($/tree)		
		D	O	N
10-20	0.368	0	0	0
20-30	0.487	0	0	0
30-40	0.914	29	13	0
40-50	1.302	59	32	0
50-60	1.772	104	61	0
60-70	3.905	230	135	0
70+	5.361	316	186	0

[a] net of taxes

Table 5. Initial stand state (ha $^{-1}$)

diameter class (cm)	Trees				Basal area (m^2)				Biomass (tons)			
	D	O	N	Total	D	O	N	Total	D	O	N	Total
10-20	30.5	61.5	262.3	354.2	0.5	1.1	4.6	6.3	14.8	29.4	140.0	184.2
20-30	11.6	17.5	61.5	90.7	0.6	0.9	3.0	4.5	7.5	11.1	43.4	62.0
30-40	5.4	8.9	19.8	34.1	0.5	0.9	1.9	3.3	6.6	10.6	26.2	43.3
40-50	3.9	4.6	7.2	15.8	0.6	0.7	1.1	2.5	6.8	7.8	13.6	28.2
50-60	3.6	3.1	2.9	9.5	0.8	0.7	0.7	2.3	8.3	7.1	7.4	22.8
60-70	2.5	1.7	0.9	5.2	0.8	0.6	0.3	1.7	13.1	8.8	5.3	27.3
70+	5.9	1.6	0.9	8.4	2.6	0.7	0.4	3.7	41.7	10.9	7.3	59.9
Total	63.5	98.9	355.4	517.8	6.5	5.5	12.1	24.2	98.8	85.7	243.2	427.8

Table 6. Net Present Value ($/ha) and Net Present Carbon Accumulation (tons/ha) for various cutting cycles and diameter cutting limits. Harvesting with conventional methods

diameter limit (cm)	cutting cycle (yrs) 30	40	50	60	70
			NPV ($/ha)		
30	3866	3879	3875	3866	3857
40	3598	3608	3603	3593	3583
50	3225	3231	3223	3212	3203
60	2681	2674	2659	2646	2636
			NPCA (tons/ha)		
30	-88.6	-84.3	-81.9	-80.5	-79.6
40	-85.1	-80.8	-78.3	-76.9	-76.1
50	-82.4	-77.9	-75.5	-74.1	-73.3
60	-78.7	-74.1	-71.6	-70.2	-69.4

Table 6.a. Net Present Value ($/ha) and Net Present Carbon Accumulation (tons/ha) for various cutting cycles and diameter cutting limits. Harvesting with conventional methods (r=10%)

diameter limit (cm)	cutting cycle (yrs)				
	30	40	50	60	70
			NPV ($/ha)		
30	3839	3840	3836	3833	3831
40	3569	3568	3564	3561	3559
50	3194	3191	3186	3183	3182
60	2637	2629	2623	2620	2618
			NPCA (tonsC/ha)		
30	-90.1	-88.3	-87.5	-87.2	-87.0
40	-86.4	-84.5	-83.8	-83.4	-83.3
50	-83.4	-81.5	-80.7	-80.4	-80.3
60	-79.4	-77.5	-76.7	-76.4	-76.2

Table 7. Net Present Value ($/ha) and Net Present Carbon Accumulation (tons/ha) for various cutting cycles and diameter cutting limits. Harvesting with reduced impact methods

diameter limit (cm)	cutting cycle (yrs)				
	30	40	50	60	70
			NPV ($/ha)		
30	3713	3731	3727	3717	3707
40	3459	3469	3460	3447	3435
50	3095	3098	3084	3069	3057
60	2564	2547	2524	2505	2491
			NPCA (tons/ha)		
30	-58.2	-56.0	-54.7	-53.9	-53.4
40	-53.2	-51.0	-49.7	-49.0	-48.5
50	-49.2	-46.9	-45.6	-44.9	-44.5
60	-43.8	-41.4	-40.1	-39.4	-38.9

Table 7.a. Net Present Value ($/ha) and Net Present Carbon Accumulation (tons/ha) for various cutting cycles and diameter cutting limits. Harvesting with reduced impact methods (r= 10%)

diameter limit (cm)	cutting cycle (yrs) 30	40	50	60	70
			NPV ($/ha)		
30	3689	3690	3687	3683	3682
40	3422	3420	3415	3411	3409
50	3049	3044	3038	3034	3032
60	2495	2483	2475	2470	2468
			NPCA (tonsC/ha)		
30	-60.5	-59.5	-59.1	-58.9	-58.9
40	-55.2	-54.2	-53.8	-53.6	-53.5
50	-50.9	-49.9	-49.5	-49.3	-49.2
60	-45.2	-44.2	-43.8	-43.6	-43.5

Table 8. Marginal cost of storing carbon in forest stands for alternative costs of implementing reduced-impact logging (RIL)

cumulative carbon savings (ton/ha)	marginal cost ($/ton)	solution features		
		dbh lim (cm)	cycle (years)	logging method
		Incremental cost of RIL = $75/ha		
0.0	0.0	30	40	conventional
2.5	1.2	30	50	conventional
28.4	2.4	30	40	RIL
29.7	6.2	30	50	RIL
30.4	15.7	30	60	RIL
30.9	24.0	30	70	RIL
35.8	55.3	40	70	RIL
39.9	92.4	50	70	RIL
45.4	102.7	60	70	RIL
		Incremental cost of RIL = $150/ha		
0.0	0.0	30	40	conventional
2.5	1.2	30	50	conventional
29.7	5.5	30	50	RIL
30.4	14.3	30	60	RIL
30.9	20.0	30	70	RIL
35.8	55.3	40	70	RIL
39.9	92.4	50	70	RIL
45.4	102.9	60	70	RIL
		Incremental cost of RIL = $300/ha		
0.0	0.0	30	40	conventional
2.5	1.2	30	50	conventional
3.9	7.1	30	60	conventional
30.4	11.2	30	60	RIL
30.9	16.0	30	70	RIL
35.8	55.5	40	70	RIL
39.9	92.4	50	70	RIL
45.4	102.7	60	70	RIL
		Incremental cost of RIL = $600/ha		
0.0	0.0	30	40	conventional
2.5	1.2	30	50	conventional
3.9	7.1	30	60	conventional
4.7	11.3	30	70	conventional
30.9	23.2	30	70	RIL
35.8	55.3	40	70	RIL
39.9	92.4	50	70	RIL
45.4	102.7	60	70	RIL

The Environment Discussion Paper Series

EDP #1. Jeffrey Sachs. "Keynote Address -- Economies in Transition: Some Aspects of Environmental Policy."

EDP #2. Darius Teter, Jeffrey Vincent, and Kadar Wiryanto. "Coal Mining in Indonesia: Environmental Impacts, Sustainability, and Economic Development."

EDP #3. Anil Markandya and Abdul Shibli. "Industrial Control Policies in Asia."

EDP #4. Scott Farrow. "The Czech Republic: Potential Cost Savings From Using Economic Instruments."

EDP #5. Eva L. Ensmann, Ljuba Gornaja, and Bruce A. Larson. "The Pollution Policy 'Cocktail' in Estonia: Economic Incentives and Problems for Implementation."

EDP #6. Scott Farrow. "Comparing Economic and Administrative Instruments: The U.S. Experience."

EDP #7. Randall A. Bluffstone and Theodore Panayotou. "Optimal Environmental Liability Policy for Central and Eastern Europe."

EDP #8. Jeff Vincent, Theodore Panayotou, and John Hartwick. "Resource Depletion and Sustainability in Small Open Economies."

EDP #9. Robert N. Stavins and Tomasz Zylicz "Environmental Policy in a Transition Economy: Designing Tradable Permits for Poland."

EDP #10. Theodore Panayotou. "Effective Financing of Environmentally Sustainable Development in Eastern Europe and Central Asia."

EDP #11. Kathleen Segerson. "Environmental Accidents: An Economic Framework for Policy Evaluation."

EDP #12. Rein Ahas and Bruce Larson. "Sustainable Market-Based Forestry and the Financial Benefits of Forest Management in Estonia: a Local Level Case Study."

EDP #13. Robert Deacon. "Economic Aspects of Forest Policy in Lithuania."

EDP #14. Randall Bluffstone. "What Tax is Best? The Economics of Natural Resource Taxation in Lithuania."

EDP #15. Michael Kozeltsev and Anil Markandya. "Pollution Charges in Russia: The Experience of 1990-1995."

EDP #16. Glen D. Anderson and Boguslaw Fiedor. "Environmental Charges in Poland."

EDP #17. Marco Boscolo, Joseph Buongiorno, and Theodore Panayotou. "Simulating Options for Carbon Sequestration Through Improved Management of a Lowland Tropical Forest."

The Environment Reprint Series

ERP #1. David Bloom. "International Public Opinion on the Environment."

ERP #2. Cornel Tarhoaca, Clifford Zinnes. "Revenue Considerations for Establishing an Environmental Fund: The Case of Romania."

ERP #3. Glen Anderson, Tomasz Zylicz. "The Role of Environmental Funds in Environmental Policies of Central and Eastern European Countries."

ERP #4. International Environment Program. "Impediments to Environmental Investments in CEE and the NIS."

ERP #5. Bruce Larson. "Environmental Policy Based on Strict Liability."