Habitat diversity and forest harvesting strategies

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Abstract

This paper studies economically optimal harvesting strategies in a forest landscape comprised by different habitat types. The analysis links a Markovian transition model of forest succession with an optimal control problem of forest management. The Markov model describes forest succession in the landscape based on transition probabilities for the change of the successinal stage of each forest patch in the landscape. The optimal control approach optimises harvest decisions where harvests are modelled as jump controls. They are two decisions to make: the intensity and timing of harvests in the climax patches of the forest. In this paper, we study the economically optimal harvesting rule to evaluate the drivers of the logging activities in this context and the forest habitat diversity associated with applying these optimal management strategies. The numerical results are derived from simulations of the forest dynamics parameterising the model for a tropical rain forest in Malaysia.

Key words: forest habitats, harvest decisions, Markov transition process, succession dynamics, bioeconomic modelling, jump controls.

1. Introduction

The fact that biodiversity conservation has been added to international political agendas and that the emerged consensus in ecology is that biodiversity conservation cannot be based on reserved areas alone, brings new challenges to commercial forestry (e.g. Franklin, 1993, Pimentel et al., 1992), and there is now a growing emphasis on making biodiversity preservation an integral part of management of forest lands European Commission (2003). Management of a multipurpose forest, i.e. promoting economic returns for landowners while maintaining and enhancing levels of biodiversity in forests, is however a complex task. Managing for biodiversity conservation requires an understanding of the effects of forestry practices on the dynamics of the forests at different temporal and spatial scales: short-term and long-term effects at stand and landscape levels. Landscape level management approaches have therefore been advocated attempting to include interactions between forest stands in the assessment of alternative forest management activities (Rose and Chapman, 2003, Swanson and Franklin, 1993, Swanson, 1993, Baskent and Yolasigmaz, 1999). Harvesting is one of the main forest management activity shaping forested ecosystems. Landscape management approaches imply that consideration is given not only to how changes in the age of a particular stand affect biodiversity but also how harvest activities affect the composition of tree species in the area of concern (e.g., Huth et al. 2005). Another concern stated by Hunter (1990) and Oliver (1992) is the importance of focusing on habitats in biodiversity conservation in managed forests. Accepting these concerns, protecting biodiversity requires conservation of a diversity of habitats which in turn renders a landscape perspective essential for the evaluation of biodiversity conservation policies.

To promote biodiversity conservation in forests it is therefore essential to understand how economically motivated forest management practises affect habitat diversity. In the present paper, we develop a model to this address question. Closest to our research is the work of Lin and Buongiorno (1998) which focused on measuring the tradeoffs for different management strategies between timber revenues and forest diversity, defined as the proportional abundance of stands in different states. Previous research, Buongiorno et al. (1994) and Lin et al. (1996) assessed the consequences of different forest practices on tree diversity, measured by species and size (diameter) based on the Shannon index. Liu et al. (1994) simulated animal population dynamics and economic revenues in response to various landscape

structures and timber management scenarios. Huth et al. (2004) study the effects of different logging scenarios, characterised by rotation length, logging method, cutting limit and logging intensity, on the yield and changes in species composition. These effects were assessed using a multicriteria decision analysis.

In this paper, we consider each successional stage in a forest as a habitat for a range of species. In ecological theory the change of species composition with time since last disturbance is termed succession and the different plant species communities associated with different time lags are termed successional stages. In a given ecosystem, each stage typically contains a particular spectrum of plants and provides habitat for a particular spectrum of animal species. In the present paper we explore forest management in a forest landscape with three different successional stages or habitats (gap, intermediate, and climax; for details, see Köhler et al. 2002).

The economically optimal harvesting strategy is determined by a bioeconomic framework modelling harvesting decisions as jump controls (Thavonnen and Salo, 1999; Termansen, in press; Touza et al., 2006). Under this approach the dynamics of the forest landscape is represented in two ways: one is the dynamics that occur continuously through time, and the other is the sudden change in the forest when there is a harvest. In our model there are two main decisions: the optimal moment to harvest (i.e., the optimal rotation length), and the intensity of harvest (i.e., the optimal fraction of climax habitat to be harvested). The optimisation is subject to the economic characteristics of the harvesting activity and the dynamics of the forest system which is modelled as a Markov (succession) process (e.g., Horn 1975; Acevedo et al. 1995; Johst and Huth 2005) with constant transition rates between the three habitat types. Numerical simulations for a tropical forest in Malaysian (Deramakot Forest Reserve) were conducted based on the Markov transition probabilities provided by the well-tested forest simulator Formix3 (Köhler et al. 2002). The Deramakot Forest Reserve is a forest estate with commercial status that covers an area of 55.083 ha of lowland Dipterocarp forest in the east of central Sabah. In this part of Malasya the mixed Dipterocarp forest is the most important source of commercial timber. Simulations reveal that optimal management regimes converge toward a disturbed forest landscape dominated by intermediate habitat. We determine the forest state associated with optimal harvesting and investigate how the optimal harvesting rules and the forest state depend on different ecological and economic parameters.

Our results suggest that a forest landscape dominated by the intermediate successional stage is the optimal outcome under large variations in economic parameters. This suggests that simple price incentives might not be able to generate successful biodiversity conservation outcomes.

This paper has three sections. In the first section, the bioeconomic model for a forest landscape with diverse habitats is presented, and the optimal cutting conditions are derived. In the second section, the optimal solution is simulated for a Malaysian tropical forest. Finally, conclusions are drawn.

2. Economically optimal rotations in a forest landscape comprising three types of habitats

In this model the dynamics of the forest succession follows a Markov transition model where the change in the forest structure between harvests follows a Markov process. $S=\{1,2,3\}$ is the set of the successional stages, representing respectively gap habitat, intermediate habitat and climax habitat. At any time t, each forest patch can be in one of these three succession states. Transitions from one type of habitat to another occur according to certain probabilities p_{ij} which represents the probability of a forest patch changing from a particular state j to another state i. Recall that the main property of the Markov chain is that if a patch is in a state j at a given time moment t, then the probability that it will be in a state i at a subsequent time $t+1$ does not depend on the patch states prior to time t.

Let x_i represent the fraction in the landscape occupied by habitat i where i=1,2,3. Harvest activities reduce the proportion of climax habitat and increase the proportion of gap habitat. These changes in the structure of the forest due to harvest activities are represented by jumps in the state variables. The harvests occur at discrete moments (jump points where the patch state changes discontinuously) within the planning period, $t_k \in [0,T]$, where k=1, ...,K. Let t_k^+ represent the time immediately after the jump and t_k^- the time immediately before the jump.

The owner maximises the net benefits from the forest landscape by choosing the time at which harvest takes place, t_k, and the optimal fraction of climax habitat to be harvested h_k. The net benefits from forest activities result from the economic rewards received from cutting climax habitat patches. We assumed that the costs of harvesting depend on the amount of climax habitat: the higher is the proportion of climax habitats the lower are the harvesting costs. The net timber benefits after harvesting a given proportion of trees in the climax habitat are the returns associated with each harvest operation.

The problem can be expressed as

$$\max_{t_k h_k} \sum_{k=1}^{K} (ph_k - c(x_3, h_k)e^{-rt} \qquad k=1...K \tag{1}$$

$$\dot{x}_1(t) = p_{12}x_2(t) + p_{13}x_3(t) - p_{21}x_1(t) - p_{31}x_1(t) \tag{2}$$

$$\dot{x}_2(t) = p_{21}x_1(t) + p_{23}x_3(t) - p_{12}x_2(t) - p_{32}x_2(t) \tag{3}$$

$$\dot{x}_3(t) = p_{31}x_1(t) + p_{32}x_2(t) - p_{13}x_3(t) - p_{23}x_3(t) \tag{4}$$

$$x_3(t_k^+) - x_3(t_k^-) = -h_k \tag{5}$$

$$x_1(t_k^+) - x_1(t_k^-) = h_k \tag{6}$$

$$x_i(0) = x_i^0 \tag{7}$$

We represent the Markov process as a system of differential equations[1] (2) (3) and (4) to simulate the successions in the forest landscape. They can also be written as

$$\dot{x}_i(t) = \sum_{\substack{j=1 \\ j \neq i}}^{3} p_{ij}x_j(t) - \sum_{\substack{j=1 \\ j \neq i}}^{3} p_{ji}x_i(t)$$

Based on this Markov process the state of the forest is determined by the fractions occupied by the different habitats. Equations (5) and (6) capture the magnitude of harvest. When harvest activities occur, the proportion of climax habitat is suddenly reduced and the proportion of gap habitat is suddenly increased accordingly. Variables $x_3(t_k^+)$, and $x_1(t_k^+)$

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[1] Shugart et al. (1973) wrote the Markov process as a system of differential equations for large regions context.

denote the proportion of climax and gap habitat, respectively, just after harvest activities, while $x_3(t_k^-)$ and $x_1(t_k^-)$ are the proportions of climax and gap habitat, respectively, just before harvest. Equation (7) is the initial stock constraint.

2.1 The Hamiltonian function and necessary conditions

The present-value Hamiltonian and first order necessary conditions for the solution to this problem are (following Seierstad and Sydsaeter, 1987, pp. 194-199);

$$H(x_i(t), \lambda_i(t)) = \sum_{j=1}^{3} \lambda_i \left(\sum_{\substack{j=1 \\ j \neq i}}^{3} p_{ij} x_j(t) - \sum_{\substack{j=1 \\ j \neq i}}^{3} p_{ji} x_i(t) \right) \tag{8}$$

where $\lambda_i(t)$ represents the costate variables associated with the proportion of each habitat in the landscape. More clearly, the present-value Hamiltonian function can also be expressed as,

$$
\begin{aligned}
H(x_i(t), \lambda_i(t)) = {}& \lambda_1(t)(p_{12} x_2(t) + p_{13} x_3(t) - p_{21} x_1(t) - p_{31} x_1(t)) + \\
& \lambda_2(t)(p_{21} x_1(t) + p_{23} x_3(t) - p_{12} x_2(t) - p_{32} x_2(t)) + \\
& \lambda_3(t)(p_{31} x_1(t) + p_{32} x_2(t) - p_{13} x_3(t) - p_{23} x_3(t))
\end{aligned}
\tag{9}
$$

Between harvest instants, the optimal time path of the costate variables must satisfy

$$\dot{\lambda}_i = -\frac{\partial H}{\partial x_i} \qquad \forall t \neq t_k \tag{10}$$

which implies

$$\dot{\lambda}_1 = \lambda_1(t) p_{21} + \lambda_1(t) p_{31} - \lambda_2(t) p_{21} - \lambda_3(t) p_{31} \qquad \forall t \neq t_k \tag{11}$$

$$\dot{\lambda}_2 = \lambda_2(t) p_{12} + \lambda_2(t) p_{32} - \lambda_1(t) p_{12} - \lambda_3(t) p_{32} \qquad \forall t \neq t_k \tag{12}$$

$$\dot{\lambda}_3 = \lambda_3(t) p_{13} + \lambda_3(t) p_{23} - \lambda_1(t) p_{13} - \lambda_2(t) p_{23} \qquad \forall t \neq t_k \tag{13}$$

The evolution of the costate variables can thus be expressed in a matrix form, $\dot{\lambda} = \lambda(t)B$,

where $B = \begin{bmatrix} p_{21} + p_{31} & -p_{21} & -p_{31} \\ -p_{12} & p_{12} + p_{32} & -p_{32} \\ -p_{13} & -p_{23} & p_{13} + p_{23} \end{bmatrix}$ is a matrix independent of t, and

$\lambda(t) = \lambda_1(t), \lambda_2(t), \lambda_3(t))$ is a vector of the costate variables which depend on t. Therefore, the general solution of this system is

$$\lambda(t) = \lambda(t^+) \exp^{Bt} \tag{14}$$

where $\lambda(t^+)$ is the value of the costate variable just after harvest (i.e. the value at the beginning of each rotation), t is the time between rotations (i.e. the time since the last rotation).

At the harvest moments, $t_1 ... t_K$, the following necessary conditions must also hold

$$\lambda_3(t_k^+) - \lambda_3(t_k^-) = -\frac{\partial \Pi(x_3(t_k^-), h_k^*)e^{-rt}}{\partial x_3} \tag{15}$$

$$\left[\frac{\partial \Pi(x_3(t_k^-), h_k^*)e^{-rt}}{\partial h} - \lambda_3(t_k^+) + \lambda_1(t_k^+) \right](h_k^* - h_k) \geq 0 \tag{16}$$

where h_k^* represents the optimal fraction of climax habitat harvested. Moreover, for all t when there is no harvest,

$$\left[\frac{\partial \Pi(x_3(t_k^-), 0)e^{-rt}}{\partial h} - \lambda_3(t) + \lambda_1(t) \right]h_k \leq 0 \tag{17}$$

From (16) by choosing $h_k=0$ we get that $\dfrac{\partial \Pi(x_3(t_k^-), h_k^*)e^{-rt}}{\partial h} + \lambda_1(t_k^+) \geq \lambda_3(t_k^+)$, while assuming

h_k large positive, implies $\dfrac{\partial \Pi(x_3(t_k^-), h_k^*)e^{-rt}}{\partial h} + \lambda_1(t_k^+) \leq \lambda_3(t_k^+)$. Hence, it is clear that these

terms should be equal

$$\frac{\partial \Pi(x_3(t_k^-), h_k^*)e^{-rt}}{\partial h_k} + \lambda_1(t_k^+) = \lambda_3(t_k^+) \qquad\qquad \forall t_1...t_K \qquad\qquad (18)$$

And from (17) we see that

$$\frac{\partial \Pi(x_3(t_k^-),0)e^{-rt}}{\partial h} + \lambda_1(t) \leq \lambda_3(t) \qquad\qquad \forall t \neq t_k \qquad\qquad (19)$$

Finally, at all the harvest instants, $t_1...t_K$, the difference in the value of the Hamiltonian immediately after and before the jump must meet the following condition

$$H(x_i(t_k^+), \lambda_i(t_k^+)) - H(x_i(t_k^-), \lambda_i(t_k^-)) - \frac{\partial \Pi(x_3(t_k^-), h_k)e^{-rt}}{\partial t} = 0 \qquad (20)$$

where the last term yields $\partial \Pi e^{-rt}/\partial t = -r\Pi e^{-rt}$

Note that using Equation (8) the Hamiltonian just before the harvest is calculated as follows,

$$H(x_i(t_k^-), \lambda_i(t_k^-)) = \lambda_1(t_k^-)(p_{12}x_2(t_k^-) + p_{13}x_3(t_k^-) - p_{21}x_1(t_k^-) - p_{31}x_1(t_k^-)) +$$
$$\lambda_2(t_k^-)(p_{21}x_1(t_k^-) + p_{23}x_3(t_k^-) - p_{12}x_2(t_k^-) - p_{32}x_2(t_k^-)) +$$
$$\lambda_3(t_k^-)(p_{31}x_1(t_k^-) + p_{32}x_2(t_k^-) - p_{13}x_3(t_k^-) - p_{23}x_3(t_k^-))$$

$$(21)$$

And the Hamiltonian just after the harvest,

$$H(x_i(t_k^+), \lambda_i(t_k^+)) = \lambda_1(t_k^+)(p_{12}x_2(t_k^+) + p_{13}x_3(t_k^+) - p_{21}x_1(t_k^+) - p_{31}x_1(t_k^+)) +$$
$$\lambda_2(t_k^+)(p_{21}x_1(t_k^+) + p_{23}x_3(t_k^+) - p_{12}x_2(t_k^+) - p_{32}x_2(t_k^+)) +$$
$$\lambda_3(t_k^+)(p_{31}x_1(t_k^+) + p_{32}x_2(t_k^+) - p_{13}x_3(t_k^+) - p_{23}x_3(t_k^+))$$

$$(22)$$

Equations (10)-(13) represent the dynamics of the costate variables between harvest activities. Each of these conditions captures how the rate at which each unit of the different habitats contributes to the forest returns change with time. These conditions reflect the relationship between the habitats in the landscape and the probabilities of the habitats to change state (i.e. the rate at which the fraction of the habitats is changing). This can be more

easily seen in the solution of this system of first-order differential equations (equation 14). It indicates that the path of each habitat's imputed value is related to the other habitats' shadow value just after harvesting, and to the probabilities of moving between habitats (captured in matrix B).

Conditions (15), (18), (19) and (20) characterise the optimal choice of the intensity of harvest, h, and the moments in time $t_1...t_K$ at which harvest operations occur. Condition (15) indicates that the discrete change in the shadow price of climax habitat at harvest moments should equal the derivative of the profit function with respect to the stock, i.e. the forest benefits associated with having one more unit of climax habitat. Harvesting implies less climax patches in the landscape, and given the stock dependency of the harvesting costs, the internal price of climax habitat just before harvest is lower than that just after the harvest. Condition (18) indicates that it is not optimal to carry out harvesting activities while the internal price of climax exceeds the gain from harvesting. After the harvesting activities; harvested climax patches are set to gap habitat, starting thus the succession process. Therefore managers´ marginal gains from harvesting activities are the marketed price and the internal value of gap habitats. Harvest will occur when the internal price of climax habitat equals the marginal net benefits for harvested climax habitat plus the internal price of gap habitat. One should never have a situation in which the gain that could be obtained from harvesting is higher than the internal price of climax, because in this situation one would not be maximising forest benefits. According to condition (19), as long as the imputed value of climax habitat is higher than marginal benefits plus the imputed value of gap habitat, no harvest will take place; and only downward jumps are possible.

Finally, condition (20) determines the rotation length (i.e. the harvest moment) for the climax habitat that optimises the economic benefits. The Hamiltonian before and after the jump, $H(t^-)$ and $H(t^+)$, capture the value of the *growth* of the forest habitats before and after the logging activities, respectively. These two values are different because the forest conditions change as a result of the harvesting activities. The last term, $r\Pi e^{-rt}$, is the forgone interest payments that could be earned if revenue from harvesting were invested at an interest rate r. $H(t^-)$ is the value of the change in the relative frequency of the habitats in the landscape if harvest is delayed. $H(t^+)$ also captures this value if the following rotation is postponed, and

therefore it is a function of the forest conditions if harvest would have taken place. This indicates that the optimal timing of logging activities is a compromise between those returns associated with a potential delay in harvesting because a delay implies "a marginal gain" $H(t^-)$, and also "a marginal loss" ($H(t^+)$ and $r\Pi e^{-rt}$); and only when these terms are equal harvest will take place. In the context of a single stand this cutting condition has been shown to be equal to the classical Faustmann-Hartman Equation (Faustmann 1849; Ohlin 1921; Pressler 1860; Thavonnen and Salo 1999; Touza 2003). In the following sections, we will explore in more detail this cutting condition in a forest landscape through numerical analysis.

2.3 Numerical analysis

The Markov transition model used for the simulation of the forest succession was parameterised for the Deramakot Forest Reserve (Malaysia) based on Köhler et al (2002). In the paper by Köhler et al (2002) the transition probabilities for the Markov process were estimated using a process-and agent-based model, FORMIX3, which calculates tree growth in a forest landscape where neighbouring stands interact through gap processes. The Markovian transition matrix takes the following values:

$$\begin{bmatrix} 0.923 & 0.006 & 0.002 \\ 0.077 & 0.979 & 0.006 \\ 0 & 0.015 & 0.992 \end{bmatrix}$$

According to this matrix, the probability that patches of gap habitat will remain gap habitat is 92.3%; no gap habitat will change directly to climax habitat; and intermediate patches will change to climax with a probability of 1.5%. The dynamics of the different habitats given by this transition model are presented in Figure 1. In the steady-state, the proportion of gap habitat is very small; intermediate habitat occupies about a third of the landscape; and the remaining land is occupied by climax habitat. The above transition parameters were also used for calculating the optimal path of the costate variables (cf. eq. (14)).

The profit function is specified as,

$$\pi(t) = \left[ph_k - Cx^{-\alpha}h_k \right] e^{-rt} \tag{23}$$

where $C > 0$ and $\alpha > 0$. In this function, costs are assumed to be dependent on the stock of the resource. p is the unit timber price. $c(x_3)$ is the unit harvesting cost which declines with the amount of climax habitat; C is the level of costs, and α measures the extent to which the costs decline with the abundance of climax habitat.

Using eq. (23), the imputed values of gap and climax habitat after each harvest, and the potential harvest are calculated using conditions (15) and (18),

$$\lambda_1(t_k^+) = \lambda_3(t_k^+) - (p - Cx_3^{-\alpha})e^{-rt} \tag{24}$$

$$\lambda_3(t_k^+) = \lambda_3(t_k^-) - \alpha Cx_3^{\alpha-1}e^{-rt} \tag{25}$$

These equations show that the imputed values of the gap and climax habitat after each harvest are related to the "stock effect" in the harvesting costs. The potential harvest is equal to

$$h_k = \frac{\lambda_1(t_k^+) - \lambda_3(t_k^-) + (p - Cx_3^{-\alpha})e^{-rt}}{-\alpha Cx_3^{\alpha-1}e^{-rt}} \tag{26}$$

We numerically computed the harvesting strategies following a forwards process like the iterative process proposed in Termansen (2007). We first calculated the time of harvest and the harvest intensity, and then identified the initial internal value of the habitats (the co-state variables for each of the habitats). In the numerical simulation the harvest moments and harvest intensity were calculated using the following steps: first, we estimated the evolution of the fraction of habitats in the landscape using the Markov matrix above and the dynamics of the imputed values (equation 14); second, we calculated the potential harvest if this were to take place using equation (26); and finally, we determined the terms of cutting rule (22) using (2)-(4), (24) and (25), to identify the optimal times of harvest. The internal values of the three habitats -that correspond to the given initial conditions- were calculated using a Latin Hyper Cube approach (LHC) (Saltelli et al., 2000). This is a sampling method that selects samples of parameter combinations from a multi-dimensional parameter space. It is a generalisation of the Latin Square Method, in which sample values are chosen from a square grid in such a way that only one value in each row and each column can be selected.

3. Results

3.1 The optimal rotation rule

An illustration of the optimal harvesting rule, equation (15), is represented in Figure 2. As explained in Section 2.1, this condition requires that the difference between the marginal change in the habitats before and after the harvesting activities be equal to the forgone interests. The Hamiltonian before the jump, $H(t^-)$, the value of habitats' *growth* before harvest, is negative and an increasing function of time since last harvest. It is negative mainly because the forest fraction occupied by gap habitat is decreasing between rotations (see Figure 1), and the imputed value of intermediate habitat is negative as this habitat dominates the landscape. It increases because the percentage of transition habitat that changes to old-growth forest also increases. $H(t^-)$ can thus be interpreted as the marginal increase in the forest returns by postponing harvesting associated with changes in the forest conditions to generate climax habitat.

The Hamiltonian after the jump, $H(t^+)$, the value of the post-harvest situation, which represents the contribution to the objective function gained by prolonging the start of the next rotation, is also negative (Figure 2b). It increases at the beginning of the rotation and then it levels off and finally decreases. This is because as climax habitat increases, and the potential harvest increases: (a) the percentage of climax habitat post-harvest is reduced significantly, (b) the fraction of gap habitat levels off or even increases (because the increase in gap habitat associated with harvesting is equal or higher than the decrease in gap habitat due to forest succession), and (c) the value of transition habitat decreases as its post-harvest growth increases at an increasing rate. Therefore, when $H(t^+)$ decreases the potential forest conditions after harvesting deteriorate with time. $H(t^+)$ can be interpreted as a marginal change in the forest returns by postponing the next rotation. This is therefore the change in the ability of the post-harvest stand to generate climax habitat. The opportunity costs, related to forgone interests from delaying the logging operations (FOC) increase through the growth cycle (Figure 3c). At the beginning of the rotation they take negative values because the potential benefits from selling the timber are lower than the planting costs.

The optimal cutting condition, called here $c(t) = H(t^+) - H(t^-) + FOC$, is represented in Figure 2d. This condition therefore states that harvest takes place when the marginal improvement in the forest conditions to yield climax habitat equals the sum of the forgone interest payments plus the marginal worsening of conditions in the following rotation to generate old-growth forest. When $c(t)$ is negative, all the components are negative, and $H(t^+) < H(t^-)$, which implies that the value of the post-harvest forest conditions are lower than the value of the pre-harvest forest conditions. When $c(t)$ is positive, $H(t^+) > H(t^-)$, the value of the post-harvest forest conditions are higher than those before harvest, but it is not optimal to undertake harvesting operations because these are increasing. In fact, harvesting takes place in the downwards sloping part of $H(t^+)$ when given the forest conditions after logging, the capacity to generate climax habitat decreases.

3.2 Habitat composition under optimal economic management

A numerical example where the forest state converges into a stationary solution is illustrated in Figure 3a. At $t=0$ the relative frequency of habitats is 60%, 30% and 10% for the gap, intermediate and climax state respectively. The first rotation period is after 25 years, and 26% of the forest landscape is harvested, then after five rotations the harvesting periods are near the steady-state optimal path. There seems to be convergence towards a forest with increasing dominance of intermediate habitat, and temporal trade-offs between gap and climax habitat in the remaining proportion of the landscape. Around 70% of the landscape is covered by intermediate habitat; gap habitat reaches values about 20% and 15% before and after harvest; the fraction of patches occupied by climax habitats is even smaller with 10% before harvest, and is reduced to around 3% just after harvests. Figures 3b & 3c show that steady-state management strategy does not depend on the initial conditions, as we get similar path for different initial forest conditions. These results also show that it is economically optimal to cut practically all the patches of climax habitats at every harvest operation for the parameters used. This is because in this model there is not reason to hold into the climax stock, given that gap and intermediate habitat are more productive because they generate the succession process. The results show thus that it is optimal to follow a rotation programme that leads to a

highly uneven distribution of the forest habitats maintaining the fraction occupied by intermediate habitat very high and fairly constant.

In Figure 4 we focus on the steady-state path and the dynamics of the proportion of gap and climax habitats to analyse the sensitivity of the results to changes in the model parameters. First we observe that in all parameter combinations tested the proportion of intermediate habitat is around 70%. Higher costs imply longer rotations because it takes longer to compensate for the costs, and the remaining proportion of climax habitat after harvesting is higher than in the base case scenario. There is therefore a trade-off between rotation length and remaining climax patches, the forest manager leaves some climax habitat for not having to wait too long between harvesting operations. An increase in the price makes harvest operations more frequent, and the same happens if there is a decrease in the stock effect (i.e. a reduction in the influence of climax abundance in the harvesting costs).

Even though these variations are small compared to the general pattern that the forest is dominated by intermediate habitat, they can have important implications for forests non-timber services such as biodiversity conservation. High timber prices may lead to management strategy in which there exist periods without climax patches, and this can have serious implications for the ability of survival of a key species which depends on this type of habitat. This risk does not seem to occur in the other scenario shown here with higher harvesting costs.

4. Conclusions

If the diversity of forest habitats at a large spatial scale is an objective of forest policy, it is important to know how this is affected by harvesting decisions. This paper presents a bioeconomic model for exploring how harvesting regimes influence the distribution of habitats in a forest landscape managed for timber production. The results suggest that the economically optimal harvest moment depends on the potential difference in the forest conditions to generate climax habitat with and without harvest. It depends therefore on the transition probabilities that characterise succession between forest's habitats and on the relative frequency of the different habitats in the landscape. It will be optimal to harvest when the marginal improvement in the conditions to generate old-growth forest if harvest is

delayed by one instant equals the opportunity costs of waiting given by a potential worsening in the forest conditions in the following rotation and the forgone interests.

The analysis is based on an ecological model that describes the successional dynamics in a forest landscape. A forest patch can be in one of three states: gap, intermediate state and climax state. The transitions between the state are modelled as a Markov process. Given the Markov matrix for the tropical forest in Malaysia, and the timber benefit function, the results of the simulations indicate that maximisation of timber benefit will lead to forest conditions dominated by transition habitat and small fractions of gap and climax forest. This forest habitat structure implies that it is optimal to harvest when the percentage occupied by the intermediate habitat is near its maximum, i.e. when the rate of increase of climax habitat is also at its maximum. Given the transition model used in the simulations, for lower levels of intermediate habitat, climax habitat is either growing at an increasing marginal rate or even has zero rate.

Our results are based on a Markov model which ignores waiting times, i.e. the minimum time before gap and intermediate habitat can change to intermediate and climax habitat, respectively. This implies the ecological assumption that the transitions are not dependent on the time spent in a given state. Accounting for this time delays for the transitions would allow for a better estimation of the forest succession dynamics (Acevedo et al. 1996), and will lead to longer periods between harvest moments, but optimal proportion of habitats in the landscape associated with harvest activities will not be affected.

Our results demonstrate that forests managed only for timber have low diversity at the landscape scale. Intermediate habitats are dominant. This is consistent with bioeconomic models for uneven aged forest where the timber stock is maintained constant before tree growth reaches its sustainable yield. The sensitivity analysis conducted showed that tax policies that increase the costs of harvesting will not influence much in the resulting overall habitat structure, i.e. the average proportion of habitats in the forest. However, they have an effect on the dynamics of climax habitat, as higher costs lead to strategies in which certain level of climax habitat is always left in the landscape after harvesting. Nevertheless, regulatory policies may be necessary, fixing for example a minimum quantity of climax habitat. Given that biodiversity conservation objectives involve a dynamic balance of diverse

habitats in the landscape, old-growth forest patches are required to satisfy biodiversity goals (O'Hara, 1998, and Hansen et al., 1991). Identifying this balance and how best to promote biodiversity conservation in managed forest ecosystems is an important area for future research.

References

Acevedo M. F., Urban D.L. and Ablan M. 1995. Transition and gap models of forest dynamics. Ecological Applications, 5(4):1040-1055.

Baskent E. Z. and Yolasigmaz H. A. (1999). Forest landscape management revisited. Environmental Management, 24(4): 437–448.

Clark C. W. (1990), *Mathematical bioeconomics: the optimal management of renewable resources*. Second Edition, Wiley, New York.

European Commission (2003). *Sustainable forestry and the European Union: Initiatives of the European Comission*. European Communities, Luxembourg.

Faustmann, M. (1849), 'On the determination of the value which forest land and immature stands possess for forestry,' English edition edited by M. Gane, Oxford Institute Paper 42, 1968. Reprinted in Journal of Forest Economics (1995) 1(1):7-44.

Franklin, J. F. (1993), 'Preserving biodiversity: species, ecosystems, or landscapes?' Ecological Applications, 3(2), 202–205.

Hansen A. J., Spies T. A., Swanson F. J., and Ohmann J. L. (1991). Conserving biodiversity in managed forests. Lessons from natural forests. BioScience, 41(6): 382–392.

Horn H.S. 1975. Markovian properties of forest succession. pp. 196-211 In: M.L. Cody and J.M. Diamond. (eds.) *Ecology and evolution of communities*. Belknap, Cambridge, MA.

Hunter M. L. (1990). *Wildlife, forest and forestry: principles of managing forests for biological diversity*. Prentice Hall, New Jersey.

Huth A., Drechsler M., and Köhler P. (2005). Using multicriteria decision analysis and a forest growth model to assess impacts of tree harvesting in dipterocarp lowland rain forests. Forest Ecology and Management 207: 215–232.

Johst K., and Huth A. (2005). Evaluation of the intermediate disturbance theory - two peaks are possible. Diversity and Distributions 11: 111-120.

Köhler P., Reinhard K., and Huth A. (2002). Simulating anthropogenic impacts to bird communities in tropical rain forests. Biological Conservation, 108: 35-47.

Lin, C.-R. and J. Buongiorno (1998), 'Tree diversity, landscape diversity, and economics of Maple-Birch forests: implication of Markovian models,' Management Science, 44(10), 1351–1366.

Liu, J., F. W. Cubbage, and H. R. Pulliam (1996), 'Ecological and economic effects of forest landscape structure and rotation length: simulation studies using ECOLECON,' Ecological Economics, 10, 249–263.

O'Hara, K. L. (1998). Silviculture for structural diversity. A new look at multi-aged systems. Journal of Forestry, 96(7): 4–10.

Ohlin, B. (1921), 'Till fr¨agan om skogernes omloppdtid (Concerning the question of the rotation period in forestry),' Ekonomisk Tidskrift, 22. Reprinted in Journal of Forest Economics (1995) 1(1):88-114 .

Oliver C. D. (1992). A landscape approach: achieving and maintaining biodiversity and economic productivity. Journal of Forestry, 90: 20–25.

Pearse, P. (1967), 'The optimum forest rotation,' Forestry Chronicle, 43 (2), 178–195.

Pimentel, D., U. Stachow, D. A. Takacs, H. W. Brubaker, A. R. Dumas, J. J. Meaney, J. A. S. O'Neil, D. E. Onsi, and D. B. Corzilius (1992), 'Conserving biological diversity in agricultural/forestry systems. Most biological diversity exists in human-managed ecosystems,' BioScience, 42(5), 354–362.

Pressler, M. R. (1860), 'Aus der holzzuwachslehre,' Allgemeine Forst- und Jagdzeitung, 36. Reprinted in Journal of Forest Economics (1995) 1(1):45-87.

Rose S. K., and Chapman D. (2003). Timber harvest adjacency economies, hunting, species protection, and old growth value: seeking the dynamic optimum. Ecological Economics, 44: 325-344.

Saltelli A., K. Chan and E. M. Scott (eds.). *Sensitivity Analysis*. John Wiley & Sons Ltd.

Seierstad, A., Sydsaeter, K. (1987). *Optimal control theory with applications*. Advanced textbooks in economics, Vol.24, North-Holland, Amsterdam.

Shugart H. H., and Crow T. R., and Hett J. M. (1973). Forest succession models: a rationale and methodology for modelling forest succession over large regions. Forest Science, 19(3):203-212-

Swallow S. K., Talukdar P., and Wear D. N. (1997). Spatial and temporal specialization in forest ecosystem management under sole ownership. American Journal of Agricultural Economics, 79: 311–326.

Swallow S. K. and Wear D. N. (1993). Spatial interactions in multiple-use forestry and substitution and wealth effects for the single stand. Journal of Environmental Economics and Management, 25: 103–120.

Tahvonen O., and Salo S. (1999). Optimal forest rotation with *in situ* preferences. Journal of Environmental Economics and Managemen*t* 37:106-128.

Termansen M. (2007). Economies of scale and the optimality of rotational dynamics in forestry. Environmental and Resource Economics (in print).

Touza J., (2003). Biodiversity in forest landscape management: a case study of Galician collective forests in Spain. D.Phil Thesis, Environment Department, University of York, UK.
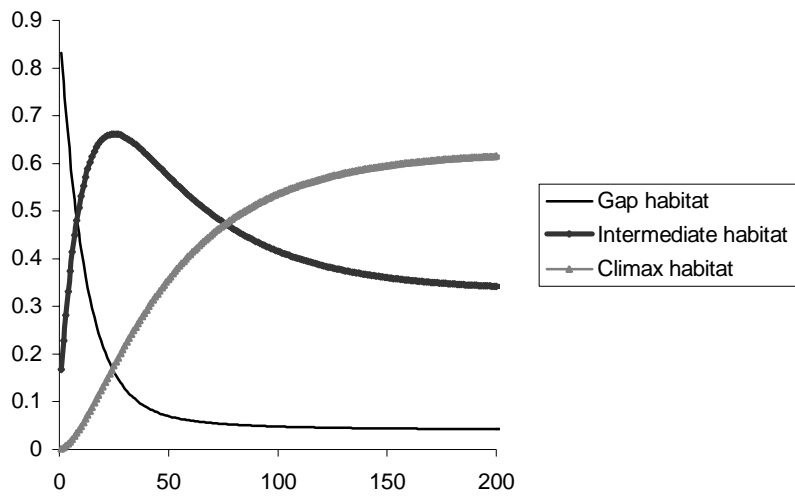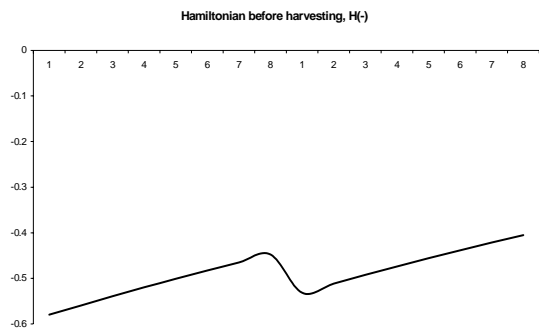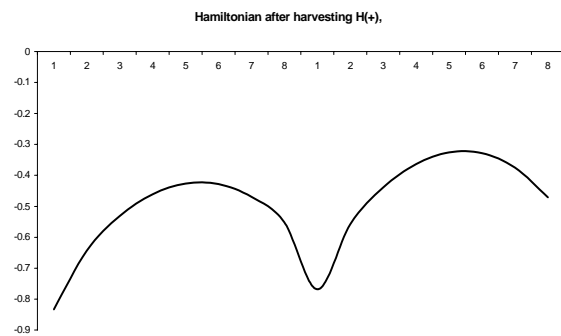
Figure 1: Relative frequency of the different habitat types (gap, intermediate, and climax) in the simulation of the Markov model. Source: Köhler et al. (2002)
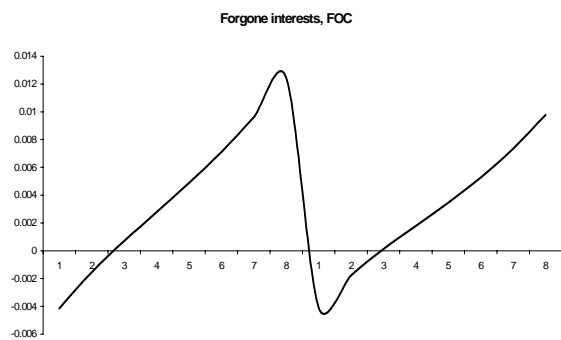
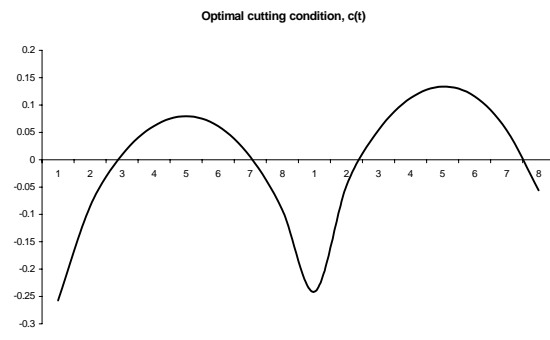Figure 2: Illustration of cutting condition for two rotations. Note: initial conditions in the forests: gap=60%, intermediate=30%, and climax=10%. r=0.02, p=50, α=1, η=1, C=6, b=0.3.
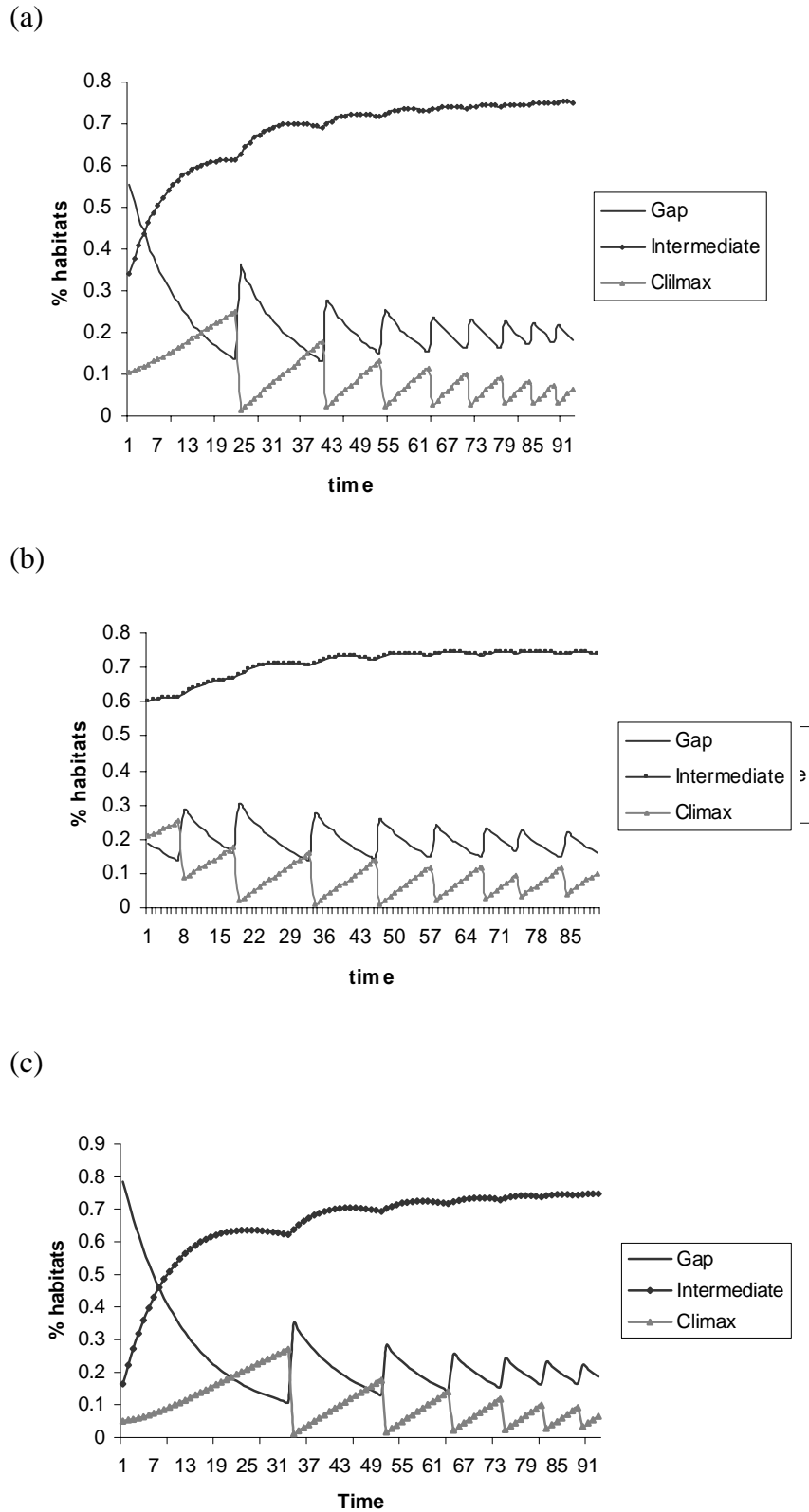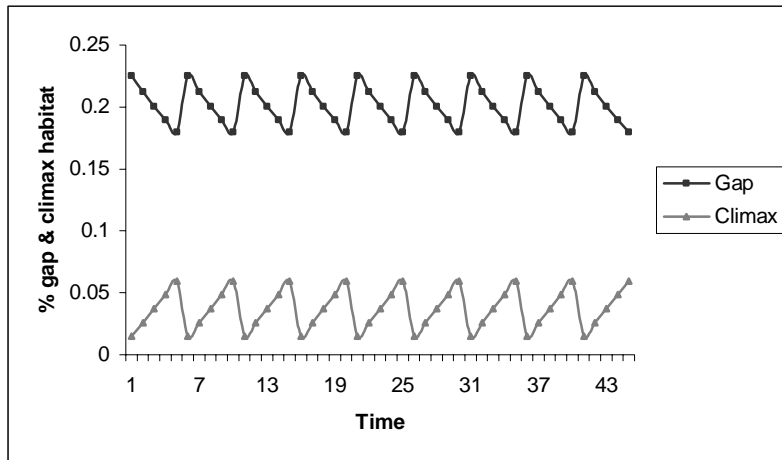
(a)

(b)

(c)

Figure 3: Optimal development of the harvesting decisions when the initial conditions in the forests are in (a): gap=60%, intermediate=30%, climax=10%; in (b): gap=60%, intermediate=20%, climax=20% and in (c): gap=80%, intermediate=15%, climax=5%. Note: r=0.02, p=50, α=1, C=6.
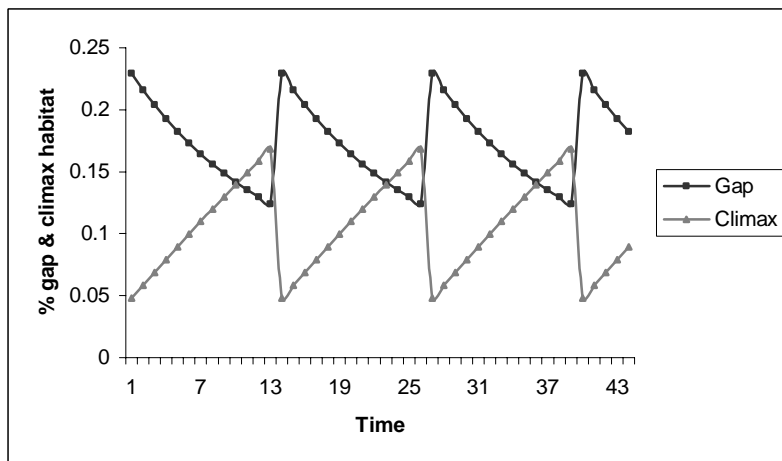
(a)

(b)

Figure 4: Optimal proportion of gap and intermediate habitat at steady-state (a) with increasing price, p=60 and (b) with increased harvesting costs, C=30.