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Coupled ecological–social dynamics in a forested landscape: Spatial interactions and information flow

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Abstract

We develop an agent-based model for forest harvesting to study how interactions between neighboring land parcels and the degree of information flow among landowners influence harvesting patterns. We assume a forest is composed of a number of land parcels that are individually managed. Each parcel is either mature forested, just-harvested, or immature forested. The state transition of each parcel is described by a Markov chain that incorporates the successional dynamics of the forest ecosystem and landowners' decisions about harvesting. Landowners decide to cut trees based on the expected discounted utility of forested vs. harvested land. One landowner's decision to cut trees is assumed to cause the degradation of ecosystem services on the downstream forested parcels. We investigated two different scenarios: in a strongly-connected society, landowners are familiar with each other and have full information regarding the behavior of other landowners. In a weakly-connected society, landowners do not communicate and therefore need to make subjective predictions about the behavior of others without adequate information. Regardless of the type of society, we observed that the spatial interaction between management units caused a chain reaction of tree harvesting in the neighborhood even when healthy forested land provided greater utility than harvested land. The harvest rate was higher in a weakly-connected society than that in a strongly-connected society. If landowners employed a long-term perspective, the harvest rate declined, and a more robust forested landscape emerged. Our results highlight the importance of institutional arrangements that encourage a long-term perspective and increased information flow among landowners in order to achieve successful forest management.

Keywords: Tree harvesting; Agent-based models; Expected utility; Land use; Externality

1. Introduction

Forested ecosystems provide many ecosystem services to human beings, including timber, fuel, charcoal, and non-timber forest products as well as subsistence resources for many communities (Daily, 1997; Millennium Ecosystem Assessment (MA), 2005). Forests also play vital roles in global biogeochemical processes and climate regulation. In addition, they play important roles in hydrological cycles by regulating water flow (thereby reducing soil erosion and nutrient leaching), maintaining water quality and providing freshwater for both human and non-human uses.

In the last 8000 years, an estimated 40% of original forest cover has been lost globally; this has occurred primarily during the last two centuries (Matthews et al., 2000). Deforestation occurs for a wide range of reasons (Geist and Lambin, 2001; Lambin et al., 2001). Lambin et al. (2003) proposed five fundamental causes: (1) resource scarcity leading to an increase in the pressure of production on resources, (2) changing opportunities created by markets, (3) outside policy intervention, (4) loss of adaptive capacity and increased vulnerability, and (5) changes in social organization, resource access, and attitudes. Angelsen and Kaimowitz (1999) reviewed the economic aspects of deforestation.

Ultimately, deforestation can be considered the outcome of decisions by landowners who try to maximize their utility associated with deforestation (i.e. by evaluating the

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costs and benefits of the activity; e.g. Bockstael, 1996). Economic models that describe the behavior of individual landowners have been developed in order to understand such decision-making processes. For example, in forest economics, the Faustmann model (Faustmann, 1849) addresses the question of 'when to harvest, if the harvesting of one stand of timber is to be followed by immediate replanting?' (Perman et al., 2003). Extending the deterministic Faustmann model, which focuses on profit maximization in a single stand, forest economists have incorporated various factors such as uncertainty of timber prices (Brazee and Mendelsohn, 1988), forest growth (Willanssen, 1998; Buongiomo, 2001), the policy environment (Zhang, 2001), and the interactions between different stands (Swallow, 1993; Amacher et al., 2004), to investigate how these drivers influence harvest timing. In these economic models, the behavior of a single landowner is emphasized.

Alternatively, there are agent-based models that consider landowners as a part of the ecosystem, and explore how system-level properties emerge from the interactions of individual landowners (Grimm et al., 2006). These models consist of autonomous decision-making entities (i.e. agents), an environment in which agents interact, a set of rules defining the relationship between agents and their environment, and the sequencing of actions (Evans et al., 2005). Recently, there has been a growing interest in the application of agent-based (or multi-agent system) models to the study of land-use change and ecosystem management (Bousquet and Page, 2004; Doran, 2001; Gimblett, 2001; Janssen, 2002; Parker et al., 2003; Walker, 1999, 2003; Walker et al., 2004). These studies explore how global land-use or resource-use patterns result from the decisions of individual actors.

The aim of this paper is to develop a simple agent-based model of forest harvesting. We focus on two aspects: (1) spatial interaction between different management units and (2) information flow among landowners. The first aspect deals with the correspondence (or lack thereof) between the scales of social and ecological dynamics. For example, the physical boundaries of forests often cross local political and administrative boundaries, which can lead to the optimal use of one ecosystem service at a particular place, yet cause erosion of another ecosystem service at a different parcel through edge effects (Murcia, 1995; Harper et al., 2005). Economists refer to this general situation as an externality, i.e. an unintended or uncompensated loss or gain by one actor, resulting from the actions of another.

Given spatial interactions among management units, the landowner must anticipate the actions of her neighbors in order to make a rational decision about forest harvesting. Ideally, this individual has full information regarding the behavior of other landowners. But, in many cases, it is likely that a landowner will make subjective predictions about the behavior of others without adequate information, if information is not readily exchanged among landowners.

Using the simple agent-based model, we investigate how spatial interactions and the degree of information flow among landowners influences landowners' decision making, and explore how global landscape patterns emerge from individual decisions. Based on these results, we discuss the implications of this work for forest policy and management.

2. Model description

2.1. Land-use change at a single parcel: a three-state Markov chain

We assume that a forest is composed of multiple land parcels arranged in a regular square lattice located along a river in a one-dimensional space (Fig. 1). The landowner of each parcel may be a single person, a household, or a group of people. Let x_i be the land-use state at a land parcel i ($i = 1, 2, \ldots, N$). x_i is in a mature forested (F), just-harvested (H), or immature forested (D) state, each of which differ in utility. We assume that land upstream of parcel 1 is covered with forest.

We describe the tree harvesting and forest succession processes at a single land parcel i as a three-state cyclic Markov chain (Fig. 2a). A mature forested parcel (F) becomes a just-harvested parcel following the harvesting decision of the landowner with probability r_i. Once a forested parcel (F) is harvested, the state changes from F to H. The just-harvested parcel (H) changes to the immature forested parcel (D) in one time step. Immature forest may develop secondary vegetation. Such reforestation helps to restore nutrient and water cycling, and can lead to the development of a forest with rates of biomass accumulation that resemble the original forest. In addition, human activities such as enhanced regeneration or enrichment tree planting may promote the restoration of the forest ecosystem. Therefore we assume that the immature forest finally becomes mature forest, through ecological succession and/or restoration. μ represents the rate of forest

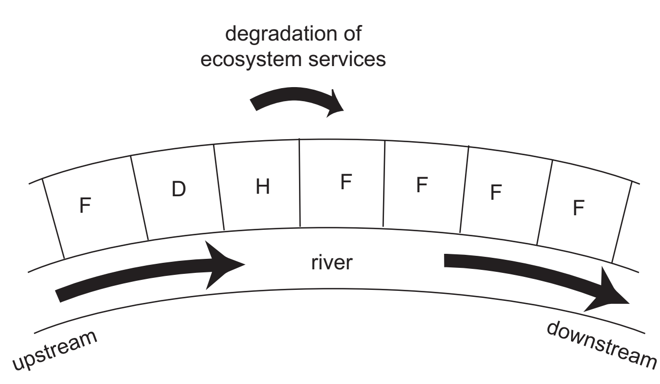

Fig. 1. A diagram explaining the unidirectional spatial interaction between neighboring land parcels. Land parcels are located along a river. Each parcel is in a mature forested (F), just-harvested (H), or immature forested state (D). The utility of the mature forested parcel is degraded by harvesting on the neighboring parcel upstream.

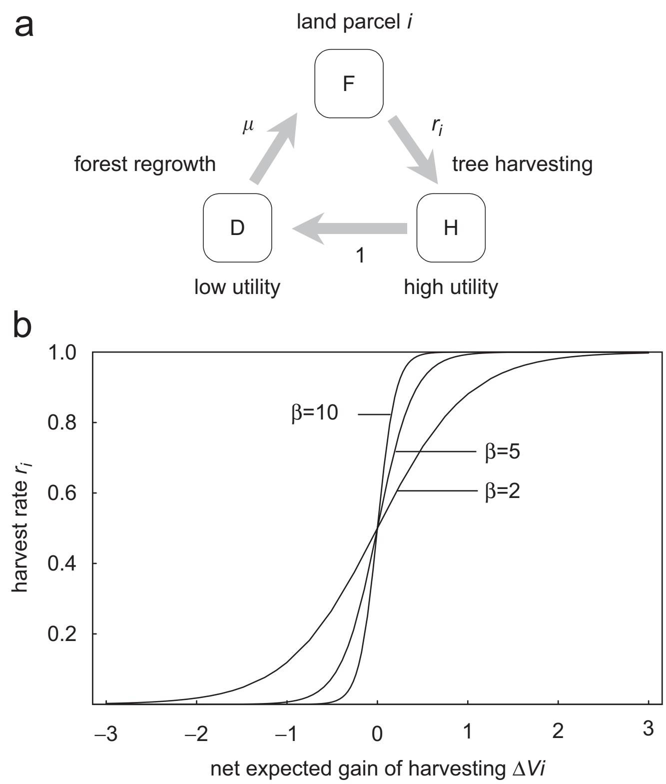

Fig. 2. (a) A diagram of the three-state cyclic Markov chain model for harvesting dynamics at land parcel i. F: mature forest, H: just-harvested parcel, and D: immature forest. F changes to H with probability r_i. H changes to D with probability 1. D changes to F due to forest regeneration with probability μ. (b) The harvest rate, r_i, plotted against the net expected gain of harvesting, ΔV_i. β is a positive constant.

regrowth per year that ranges from 0 to 1. We assume that μ is space-independent, although this assumption can be relaxed to allow heterogeneous land quality.

2.2. Utilities of mature/immature forest and harvested parcel

The decision of a landowner regarding whether or not to cut her trees is influenced by the utility of her parcel. We assume that the current utility of a land parcel depends on the current land-use state at the focal site and also at the neighboring upstream land parcel. Let $u(x_i|x_{i-1})$ be the utility of land parcel i in state x_i given that the neighboring upstream land parcel $i-1$ is in state x_{i-1}. For example, $u(F|F)$ is the utility of mature forested parcel that also has mature forest upstream neighbor. We call $u(F|F)$ the utility of "healthy" forested land (Fig. 1). A land parcel provides three sources of value to its owner. λ is a baseline value that is independent of the status of either the parcel or its upstream neighbor. For example, λ is considered as the utility received by a landowner by just owning a land parcel. All parcels, whether mature, just-harvested, or immature, provide this value, and immature forests provide no other value. If both a parcel and its upstream neighbor are in the mature forested state, then the parcel provides an additional value b, for a total of $\lambda + b$

$$u(F|F) = \lambda + b: \tag{1}$$

We assume b is generated by ecosystem services associated with the forest ecosystem.

A just-harvested parcel provides a utility of c in addition to the baseline value of λ:

$$u(H) = \lambda + c, \tag{2}$$

c is the total revenue generated by timber sales minus the costs for harvesting and transportation incurred when the landowner engaged in deforestation. A larger c indicates that cutting trees is more profitable. We simplify $u(H|F)$, $u(H|H)$, and $u(H|D)$ as $u(H)$ because the utility of the just-harvested parcel is independent of the neighbors.

After harvest, the value of the land parcel declines to a level even lower than that of mature forested land, because immature forested land does not provide the same range of ecosystem services. Therefore the utility of a land parcel two or more years after harvesting is given by

$$u(D) = \lambda. \tag{3}$$

In the above equation, we express $u(D|F)$, $u(D|H)$, and $u(D|D)$ simply by $u(D)$ because the utility of immature forest is also independent of the neighboring parcels.

We assume spatial interaction between adjacent land parcels. Specifically, just-harvested (H) and immature forested parcels (D) degrade the ecosystem and consequently jeopardize ecosystem services provided by the neighboring forested parcels downstream (Fig. 1). We assume that this local-scale interaction occurs in a uni-directional manner (only from upstream to downstream: Fig. 1). This resembles situations where the degradation of ecosystem services occurs primarily through alterations of stream flow. For example, the reduction of forest cover on an upstream parcel increases the speed of water runoff, which can increase the rate of soil erosion and leaching of nutrients in soils not only on the upstream parcel but also on neighboring parcels down slope. Increased soil erosion and leaching following tree harvesting have been reported in temperate (Likens et al., 1970), Mediterranean (Hooke, 2006), and in tropical regions (Williams et al., 1997). We recognize that there are other ecological interactions among parcels that operate bi-directionally or in other ways; but as a starting point, we begin by considering this unidirectional case.

Therefore the additional value of forested land is reduced to $b - \varepsilon$ if the upstream parcel is in a just-harvested or immature forested state:

$$u(F|H) = u(F|D) = \lambda + b - \varepsilon, \tag{4}$$

where ε represents the degree of degradation induced by harvesting of the upstream forested parcel. We call $u(F|H)$ and $u(F|D)$ the utilities of "degraded" forested land.

Once a mature forested parcel (F) is converted to a just-harvested parcel (H) the landowner enjoys high utility, $u(H)$. But the just-harvested parcel (H) changes to the

immature forested parcel (D), which has low utility, $u(D)$. Thus, in order to receive high utility in the future, the landowner has to wait until the immature forested parcel (D) finally reverts back to a mature forested parcel (F) (Fig. 2a). Although the utility of the immature forested parcel may also be degraded by harvesting upstream, here we only consider the erosion of ecosystem services on the mature forested parcels.

2.3. Decision making about tree harvesting

Each landowner decides whether or not to cut her trees. We assume that the probability that a landowner i will harvest a mature forested parcel in a year, denoted by r_i, is an increasing function of the net expected gain of harvesting, ΔV_i. In this section, we explain how to calculate ΔV_i, and how r_i is determined by ΔV_i. In the following, we call r_i the "harvest rate" at parcel i.

ΔV_i is defined as the change in the expected discounted utility of the land parcel associated with harvesting. The expected discounted utility is given as a cumulative sum of the current and the future utilities that is discounted over time. Let $V(x_i|x_{i-1})$ be the expected discounted utility of a land parcel i that is in state x_i and has an upstream neighbor in state x_{i-1}. $V(x_i|x_{i-1})$ is formalized as

$$V(x_i|x_{i-1}) = \sum_{n=0}^{\infty} \omega^n U_n^i(x_i|x_{i-1}), \tag{5}$$

where $U_n^i(x_i|x_{i-1})$ is the expected utility to be received after n years in the future when the focal parcel is in state x_i and the neighboring upstream land is in state x_{i-1} at the present time. The land-use state may change in the future, and $U_n^i(x_i|x_{i-1})$ includes all possible contributions from different land-use states as explained later. ω is the discount factor $(0 \leqslant \omega < 1)$. The discount factor ω is defined as $1/(1+\hat{i})$ where $\hat{i}$ is the discount rate. When ω is close to 1 (or $\hat{i}$ is close to 0), the landowner identifies the future utility of the land as being as important as the current utility. In contrast, if ω is close to 0 (or $\hat{i}$ is large), the landowner attaches the most importance to the current utility received from the land.

The net expected gain of harvesting is given by

$$\Delta V_i = \begin{cases} V(H|F) - V(F|F) & \text{if} \quad x_{i-1} = F \\ V(H|H) - V(F|H) & \text{if} \quad x_{i-1} = H \\ V(H|D) - V(F|D) & \text{if} \quad x_{i-1} = D \end{cases}. \tag{6}$$

The harvest rate at land parcel i, r_i, is given as follows (Satake and Iwasa, 2006):

$$r_i = \frac{1}{1 + \mathrm{e}^{-\beta(\Delta V_i)}}, \tag{7}$$

where β is a positive constant. Eq. (7) indicates that harvesting occurs more frequently if it results in a larger ΔV_i. β is a parameter that controls the degree of stochasticity (Fig. 2b). As β becomes infinitely large, the landowners' behavior resembles a deterministic decision (i.e. with little stochasticity), and she chooses the land-use state that represents the highest expected discounted utility. As β decreases, the decision about harvesting becomes more stochastic according to attitudinal heterogeneity (i.e. heterogeneity in the need for immediate income, preferred level of risk, and interest in conservation) and the errors in evaluating the utility of forested and just-harvested land. This decision dynamic is the same as the logit dynamic used in a game theoretic setting (Hofbauer and Sigmund, 2003), and also is used in a behavioral model for landscape change in Amazon basin (Walker et al., 2004).

2.4. No interaction between different land parcels

If a landowner expects landscape change in the future, the formalization of the expected discounted utility requires consideration of all possible changes of land-use state in the future. In this paper, the utility of a land parcel depends on the neighbor (i.e. the degradation of ecosystem services due to harvest in the neighborhood), which makes evaluation of the expected discounted utility even more complex. In order to clearly explain, we first describe how the expected discounted utility is calculated when land parcels are independent, as analyzed by Satake and Iwasa (2006). If the decisions of different landowners are independent, $u(F|F) = u(F|H) = u(F|D) = u(F)$ holds since no degradation of ecosystem services is incorporated (i.e. $\varepsilon = 0$). The expected discounted utility of a land parcel i in state x_i is now simply given by $V(x_i)$ instead of $V(x_i|x_{i-1})$.

We consider that the landowner of parcel i expects that mature forested land will be harvested with probability r_i in a year, and that immature forested land will revert back to forested land with probability μ (Fig. 2a). The expectation for future landscape change is represented by a transition matrix $\mathbf{P}_i$ as follows (Satake and Iwasa, 2006):

$$\mathbf{P}_i = \begin{array}{c} \\ \\ \end{array} \begin{array}{cccc} F & H & D & \\ \end{array}$$
$$\mathbf{P}_i = \begin{pmatrix} 1-r_i & r_i & 0 \\ 0 & 0 & 1 \\ \mu & 0 & 1-\mu \end{pmatrix} \begin{matrix} F \\ H \\ D \end{matrix}. \tag{8}$$

The kl-element of $\mathbf{P}_i$, denoted by p_{kl}^i, represents the transition probability that the land parcel i initially in state k will change to state l in the next time step. For example, $p_{FF}^i = 1 - r_i$ represents the probability that mature forested land (F) will remain forested (i.e. will not be harvested) in a year.

Let $\mathbf{u} = (u(F), u(H), u(D))^T$ be a column vector composed of the utilities of land-use states F, H, and D. Let $\mathbf{U}_n^i = (U_n^i(F), U_n^i(H), U_n^i(D))^T$ be a column vector composed of the utilities to be received after n years in the future when the land parcel i is in state F, H, D at the present time (in the following, we remove superscript i). $\mathbf{U}_n$ changes according to $\mathbf{U}_{n+1} = \mathbf{P}_i\mathbf{U}_n$. Since the utility to be received at the present time, $\mathbf{U}(0)$, is simply given by $\mathbf{u}$, we

have the following relationship; $\mathbf{U}_n = \mathbf{P}_i^n \mathbf{u}$. Using this relationship, the expected discounted utilities for each land-use state denoted by a vector, $\mathbf{V}_i = (V_i(F), V_i(H), V_i(D))^T$, is given as

$$\mathbf{V}_i = \mathbf{U}_0 + \omega \mathbf{U}_1 + \omega^2 \mathbf{U}_2 + \omega^3 \mathbf{U}_3 + \dots = \sum_{n=0}^{\infty} \omega^n \mathbf{P}_i^n \mathbf{u}, \tag{9}$$

where ω is the discount factor as given in Eq. (5). Using Eq. (9), we find that the net expected gain of harvesting, ΔV_i, is given by

$$\Delta V_i = V_i(H) - V_i(F). \tag{10}$$

2.5. Incorporating spatial interactions

When we consider spatial interactions between the land parcels, the expected discounted utility of the focal parcel i depends on whether the neighboring upstream land parcel $i-1$ is in a mature forested state or not (Fig. 1). Therefore we need to take into account the land-use cycle at parcel $i-1$ in addition to that at the focal parcel i. We represent this interrelated land-use cycle at neighboring parcels by introducing the transition matrix $\mathbf{A}_i$. $\mathbf{A}_i$ is now 9×9 matrix given by the tensor product of the transition matrix at parcels i and $i-1$ as follows:

$$\mathbf{A}_i = \mathbf{P}_i \otimes \mathbf{P}_{i-1} = \begin{pmatrix} (1-r_i)\mathbf{P}_{i-1} & r_i \mathbf{P}_{i-1} & 0\mathbf{P}_{i-1} \\ 0\mathbf{P}_{i-1} & 0\mathbf{P}_{i-1} & \mathbf{P}_{i-1} \\ \mu \mathbf{P}_{i-1} & 0\mathbf{P}_{i-1} & (1-\mu)\mathbf{P}_{i-1} \end{pmatrix}, \tag{11}$$

where $\mathbf{P}_i$ is defined in Eq. (8) and $\mathbf{P}_{i-1}$ is similarly defined with i replaced by $i-1$.

Let (x_i, x_{i-1}) be the pair of land-use states of the parcels i and $i-1$. There are nine possible combinations for (x_i, x_{i-1}) because each land parcel can be in one of three different states (F, H, or D). Let $\mathbf{V}_i = (V_i(F|F), V_i(F|H), V_i(F|D), \dots, V_i(D|D))^T$ be the column vector of the expected discounted utility for each combination. Given the transition matrix for future land conversion, $\mathbf{A}_i$, $\mathbf{V}_i$ is calculated as follows:

$$\mathbf{V}_i = \sum_{n=0}^{\infty} \omega^n \mathbf{A}_i^n \mathbf{u}, \tag{12}$$

where $u = (u(F|F), u(F|H), u(F|D), \dots, u(D))^T$ is the column vector of the utilities for nine different combinations of land-use states in the parcels i and $i-1$. Note that the utilities of just-harvested (H) and immature forested parcels (D) are independent of the state of the land upstream (i.e. $u(H|F) = u(H|H) = u(H|D) = u(D)$ and $u(D|F) = u(D|H) = u(D|D) = u(D)$). Now Eq. (12) is slightly different from Eq. (9) because the matrix $\mathbf{P}_i$ is replaced by $\mathbf{A}_i$. From Eq. (12), the net expected gain of harvesting, ΔV_i, is given by Eq. (6), and the landowner at parcel i decides to cut her trees with probability r_i (Eq. (7)).

Note that the expected discounted utility at parcel i is influenced not only by the land-use cycle at parcel $i-1$ but also the land-use cycle at all other parcels upstream. These complex linkages among land parcels make it difficult to evaluate the expected discounted utility of the focal parcel. We discuss how to deal with this problem in Section 2.6.

2.6. Influence of information flow: strongly-connected and weakly-connected societies

The harvest rate by landowner i is determined by the expected net gain of harvesting at parcel i (Eqs. (6) and (7)). The expected net gain of harvesting at parcel i depends on the land-use state and the harvest rate at land parcels i and $i-1$ (i.e. (x_i, x_{i-1}) and (r_i, r_{i-1}): see Eqs. (8), (11), and (12)). The harvest rate at parcel $i-1$, in turn, depends on the land-use state and the harvest rate at parcels $i-1$ and $i-2$ (i.e. (x_{i-1}, x_{i-2}) and (r_{i-1}, r_{i-2}). Therefore the landowner needs to take into account the land-use pattern and the harvest rate of all landowners upstream to appropriately evaluate the expected net gain of harvesting and then make her decision whether or not to cut her trees.

First, we assume that landowners have access to full information about the land uses and harvest rates of other landowners in the community. This situation could represent a society in which landowners are familiar enough with each other to obtain information about the current land-use state and future harvest rate of each landowner. Alternatively, landowners could file publicly available forest management plans. We refer to this situation as the "strongly-connected society." In a strongly-connected society, given the land-use state on the most upstream parcel, all landowners will make rational decisions about harvest due to full information exchange.

For example, the most upstream landowner (landowner 1) at parcel #1 accurately calculates the net gain of harvesting at that parcel without information about others' behavior because her parcel is not affected by any externality induced by harvesting by others. By noting that the parcel upstream of parcel #1 is in a forested state, landowner 1 determines r_1 by considering the current land-use state at her parcel. The landowner 1 communicates the harvest rate (r_1) to landowner 2, her nearest downstream neighbor. Landowner 2 then determines his harvest rate (r_2) by considering the current land-use states at parcels 1 and 2. Landowner 2 communicates r_2 to landowner 3, and so on. This information exchange from upstream to downstream continues until the landowner furthest downstream receives information about the harvest behavior of his upstream neighbor.

We also consider the situation where a landowner does not have access to full information about the land-use states and harvest rates of others. This represents the situation where landowners do not communicate, and therefore need to anticipate the behavior of others without adequate information. We call this situation the

"weakly-connected society." In this case, the landowner makes a subjective assessment about how she and all other landowners will engage in harvesting in the future, assuming that the harvest rate in the future will be the same, i.e. $r_1 = \cdots = r_i = \cdots = \hat{r}$. $\hat{r}$ is independent of the current land-use state, and therefore is given as a constant that satisfies $0 \leqslant \hat{r} \leqslant 1$. The expectation for the future harvest rate of others may not necessarily be a product of individual calculi, but rather is considered as a product of norms. The concept of norms has been at the core of several branches of the social sciences, and is basically defined as expectations about behavior that are at least partially shared by a group of decision makers (Gibbs, 1981; Moch and Seashore, 1981; Thibaut and Kelley, 1959). For the weakly-connected society, the transition matrix for future land-use change introduced in Eqs. (8) and (11) is now space invariant and is rewritten as follows:

$$\mathbf{A} = \mathbf{P} \otimes \mathbf{P}, \tag{13}$$

where

$$\mathbf{P} = \begin{pmatrix} 1-\hat{r} & \hat{r} & 0 \\ 0 & 0 & 1 \\ \mu & 0 & 1-\mu \end{pmatrix}. \tag{14}$$

Note that the landowner in the weakly-connected society obtains knowledge about the current land-use state of her own parcel and the neighboring parcel upstream by direct observation even if information flow is very limited.

3. Method to classify spatio–temporal landscape patterns

In order to classify the spatio–temporal patterns generated by the model, we introduce two quantities that can be calculated. They are the average harvest rates of healthy and degraded forested lands. We defined "healthy" forested land as mature forested land that also has mature forested land on the nearest upstream parcel. On the other hand, "degraded" forested land is defined as a parcel that has a just-harvested or immature forested parcel upstream. We denote them as $\bar{r}^F$ and $\bar{r}^D$, respectively. Note that $\bar{r}^D > \bar{r}^F$ because reduction of the utility of a degraded forested parcel leads to an increase in harvest rate.

In the following calculation, we consider 10 landowners in a community. The expected discounted utility and the transition matrix for future landscape change are interrelated (see Eqs. (8) and (9) or Eqs. (11) and (12)). To cope with this interdependence between $\mathbf{V}_i$ and $\mathbf{A}_i$ (or $\mathbf{P}_i$), we performed a recursive calculation (see Appendix A).

4. Results

4.1. Classification of landscape patterns

The combination of two types of transition processes—the conversion from a mature forested to just-harvested parcel ("tree harvesting") and the succession from an immature forested to mature forested parcel ("forest recovery": see Fig. 2a)—created unique spatio–temporal patterns of land-use at the landscape scale (Fig. 3). Based on the simulation described in the previous section, the model produced three distinct landscape patterns characterized by differing average harvest rates ($\bar{r}^F$ and $\bar{r}^D$) and forest recovery rates (μ). These three landscape patterns were observed regardless of the type of society (i.e. whether it was a strongly- or weakly-connected society).

(1) Robust forested landscape: This landscape type occurred when the forest recovery rate was larger than the average harvest rate (i.e. $\mu > \bar{r}^F, \bar{r}^D$). Even if harvesting occurred upstream, immature forested land quickly reverted back to a forested state (Fig. 3a). Therefore this landscape type was robust to harvesting upstream.
(2) Fragile forested landscape: When the forest recovery rate was smaller than the average harvest rate at the degraded forested parcel, but larger than the average harvest rate at the healthy forested parcel (i.e. $\bar{r}^D > \mu > \bar{r}^F$), harvesting on the most upstream parcel resulted in a chain reaction of harvesting downstream (Fig. 3b). Therefore the second landscape type was vulnerable to harvesting upstream. This landscape pattern does not emerge if land parcels are independent (Satake and Iwasa, 2006).

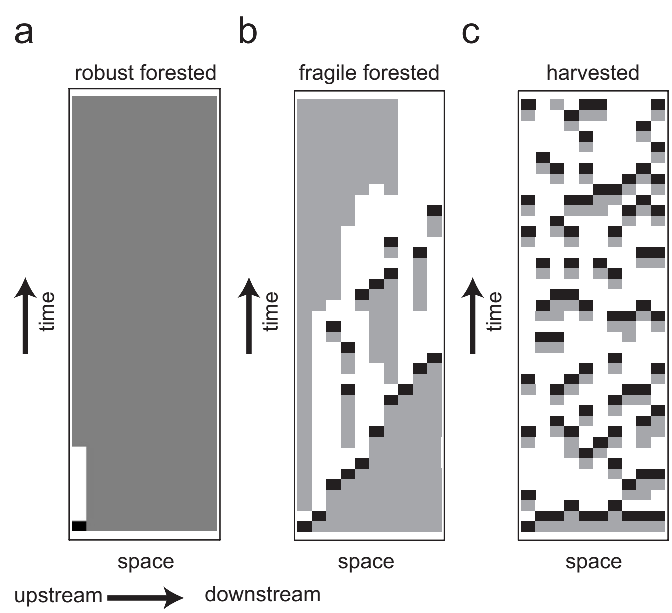

Fig. 3. Three landscape types. The horizontal axis is space (left-hand side represents upstream), and the vertical axis is time. (a) Robust forested landscape. $\omega = 0.9$, (b) fragile forested landscape. $\omega = 0.64$, and (c) harvested landscape. $\omega = 0.2$. Gray, black, and white parcels represent mature forested (*F*), just-harvested (*H*), and immature forested parcels (*D*). Other parameters are: $\lambda = 1.0$, $b = 0.5$, $c = 0.8$, $\varepsilon = 0.2$, $\mu = 0.1$, and $\beta = 10$. The strongly-connected society was considered. We assumed, for the initial conditions, that the most upstream land parcel was just-harvested (*H*), and the downstream parcels were in the mature forested state (*F*).

(3) Harvested landscape: When the forest recovery rate was smaller than the average harvest rates on both the healthy and the degraded forested land (i.e. $\bar{r}^F > \mu$), tree harvesting occurred everywhere, and therefore the immature forested state dominated the landscape (Fig. 3c).

4.2. Landscape patterns in the strongly-connected society

In this section, we report when these three different landscape types were realized depending on the parameter values. Three cases were considered, depending on the magnitude of the utility of mature forested and just-harvested parcels. For each case, we simulated the spatio–temporal dynamics of land use at the landscape level (with ten landowners) for a range of parameter combinations of the discount factor ω and forest recovery rate μ. We then related the emergent landscapes to the three different patterns defined in Section 4.1. Here, we focus on the results generated for the strongly-connected society.

Case 1, $c>b$: The utility of tree harvesting (c) is larger than that of mature forest (b). We illustrate how the expected discounted utility and harvest rate changed as the discount factor (ω) increased (Fig. 4). The expected discounted utility of healthy ($V_i(F|F)$ and degraded forested land ($V_i(F|H)$ did not change much, but the expected discounted utility of harvested land $V_i(H|F)$ showed a clear reduction as ω increased (Fig. 4a). Consequently, the average harvest rate on both healthy and degraded forested land, $\bar{r}_F$ and $\bar{r}_D$, decreased as ω increased (Fig. 4b). Therefore the harvested landscape appeared in the parameter region with the small discount factor (ω). As ω increased, the landscape type switched from the harvested to the fragile forested, and then from the fragile to the robust forested landscape (Fig. 5a). As the forest recovery rate (μ) increased, the region of robust forested landscape decreased slightly, but the influence was not drastic.

Case 2, $b>c>b-\varepsilon$: The utility of the healthy forested parcel (b) is larger than that of the just-harvested parcel (c), but the utility of the degraded forested parcel ($b-\varepsilon$) is smaller than c. This represents the situation in which edge effects are significant. In this case, the average harvest rate was low on the healthy forested land, but high on the degraded forested land. Consequently, the fragile forested landscape emerged when the discount factor (ω) was small. As ω increased, the fragile forested landscape switched to the robust forested landscape (Fig. 5b).

Case 3, $b-\varepsilon>c$: The utility of the mature forested parcel (b) is larger than the utility of the just harvested parcel (c), even if the ecosystem services of mature forested land are degraded by ε. Therefore edge effects are not significant. In this case, the harvest rate stayed at a very low level even if immature forested land existed upstream. Consequently this always resulted in the robust forested landscape regardless of the magnitude of the discount factor (ω) and the forest recovery rate (μ) (plot not shown).

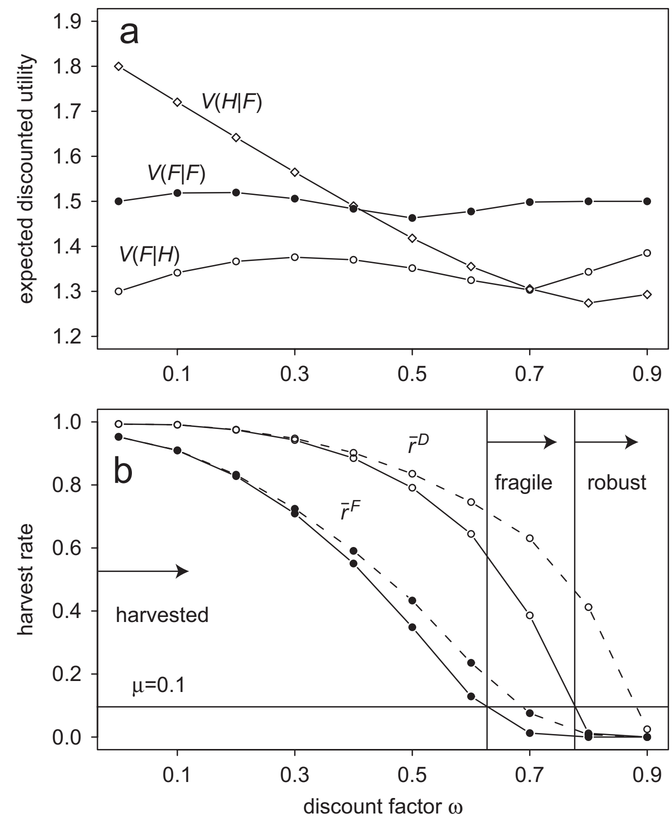

Fig. 4. (a) The expected discounted utility plotted against the discount factor, ω. Open triangles: the expected discounted utility of just-harvested land that has forested land upstream (i.e. $V(H|F)$). Solid circles: the expected discounted utility of healthy forested land (i.e. $V(F|F)$). Open circles: the expected discounted utility of degraded forested land (i.e. $V(F|H)$). (b) The harvest rate plotted against the discount factor, ω. Open circles: the average harvest rate on healthy forested land (i.e. $\bar{r}^F$). Solid circles: the average harvest rate on degraded forested land (i.e. $\bar{r}^D$). Solid lines; the forest recovery rate (μ) is 0.1. Dashed lines; $\mu = 0.3$. The solid horizontal line represents the value at which the harvest rate equals 0.1. Parameters are: $\lambda = 1.0$, $b = 0.5$, $c = 0.8$, $\varepsilon = 0.2$ and $\beta = 10$.

Overall, the influence of the discount factor (ω) on landscape pattern was significant: as ω increased, the robust forested landscape was more easily realized. In addition, a change in the forest recovery rate (μ) altered the average harvest rate (Fig. 4b). The harvest rates on healthy ($\bar{r}^F$) and degraded forested land ($\bar{r}^D$) increased as μ increased (Fig. 4b). Therefore, we conclude that the average harvest rate increases as the forest recovery rate increases.

4.3. Landscape patterns in the weakly-connected society

When a landowner does not have access to full information about others' harvest rates by others, she predicts that all landowners will engage in the same rate of harvest in the future. This prediction is given as $\hat{r}$. In this section, we investigate how landscape types differ

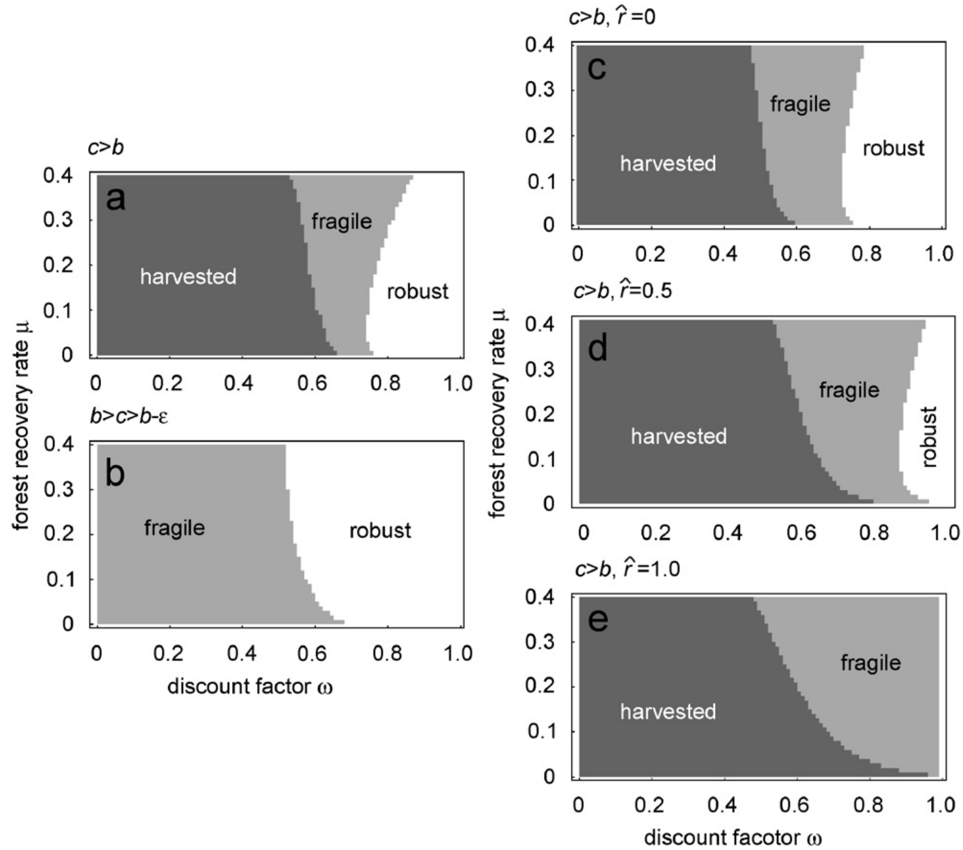

Fig. 5. Phase plot representing the three different types of landscape patterns. White, gray and black regions indicate the robust forested, fragile forested, and harvested landscapes (see text for detailed classification). (a) $c>b$: the utility of harvesting is larger than that of mature forest. $b=0.5$, $c=0.8$, $\varepsilon=0.2$; (b) $b>c>b-\varepsilon$: the utility of healthy forested land is larger than that of harvested, but the utility of degraded forested land is smaller. $b=1.0$, $c=0.5$, and $\varepsilon=0.7$. The strongly-connected society was considered in (a) and (b). (c) $c>b$ and $\hat{r}=0$: the landowners anticipate that no one will harvest trees in the future (“no-harvest expectation”). $b=0.5$ and $c=0.8$; (d) $c>b$ and $\hat{r}=0.5$: the landowners anticipate that the harvest rate is 0.5 in the future; (e) $c>b$ and $\hat{r}=1.0$. The landowners anticipate that everyone will harvest trees in the future (“extreme-harvest expectation”). The weakly-connected society was considered in (c), (d) and (e). Other parameters are $\lambda=1.0$, and $\beta=10$. We assumed, for the initial conditions, that the most upstream land parcel was in the just-harvested state (H), and other parcels downstream were in the mature forested state (F).

depending on $\hat{r}$. When $\hat{r}=0$, landowners expect that no one will harvest trees in the future (we call this the “no-harvest expectation” situation). In this case, the resultant landscape pattern created by individual decisions (Fig. 5c) was very similar to that created by the landowners with full information (Fig. 5a). However, as $\hat{r}$ increased, the region of robust forested landscape decreased (Fig. 5d), and finally disappeared when the landowners expected that everyone would harvest trees in the future (i.e. $\hat{r}=1$: we call this the “extreme-harvest expectation” situation: Fig. 5e). The result implies that varying expectations regarding the harvest rates of others can lead to very different landscape configurations overall.

For two extreme cases, we derived the conditions under which harvesting occurred (Appendix B).

(i) when $\hat{r}=1$ and $\mu=0$: This situation occurs when all landowners employ extreme-harvest expectation and anticipate that immature forest created after harvesting will not revert back to mature forest. When β is infinitely large, tree harvesting occurs when the following condition is satisfied (Appendix B):

$$\begin{cases} c-b>\omega c & \text{if} \quad x_{i-1}=F, \\ c-b+\varepsilon>\omega c & \text{if} \quad x_{i-1}=H. \end{cases} \tag{15}$$

The left-hand side of Eq. (15) represents the net gain of harvesting at the present time because harvest leads to the gain of utility of harvesting (c) but the loss of utility of forested land (b). On the other hand, the right-hand side of Eq. (15) describes the net gain of harvest at the next time step, and therefore it is discounted by ω. Eq. (15) means that when the present net gain of harvesting exceeds the future gain, the landowner decides to harvest her trees. The decision depends critically on the magnitude of the discount factor (ω); if the utility from future harvest is uncertain (e.g. because the landowner is not sure that he or she will still be alive), then ω would be small (i.e. the landowner takes a short-term management perspective), and consequently the landowner harvests her trees now. On the contrary, if the utility from future harvest is quite reliable, ω

would be large (i.e. a long-term management perspective), and therefore the landowner may not cut her trees now. Eq. (15) also implies that as the degradation of ecosystem services (ε) increases, harvesting occurs more frequently.

(ii) when $\hat{r}=0$ and $\mu=0$: This situation occurs when all landowners employ a no-harvest expectation and anticipate that immature forest created after harvesting will not revert back to mature forest. We calculated the condition of harvesting (see Appendix B) and obtained the following:

$$\begin{cases} c-b>\frac{\omega}{1-\omega}b & \text{if} \quad x_{i-1}=F, \\ c-b+\varepsilon>\frac{\omega}{1-\omega}(b-\varepsilon) & \text{if} \quad x_{i-1}=H. \end{cases} \tag{16}$$

The above equation represents a similar situation to that explained in Eq. (15); the landowner will harvest trees when the present gain of harvesting exceeds the future gain, though the right-hand side is now replaced by the cumulative sum of the utility of forested land. By rewriting Eq. (16), we found that the Eq. (16) is exactly the same as Eq. (15). Therefore, we conclude that under the assumption of no forest recovery, no-harvest and extreme-harvest expectations lead to the same decision about harvesting although this does not hold when landowners anticipate forest regrowth in the future (i.e. $\mu\neq 0$; see Figs. 5c–e).

We also calculated the condition of harvesting when forest recovery is expected to occur in the future (i.e. $\mu\neq 0$) under the no-harvest expectation (i.e.$\hat{r}=0$) and then obtained the following (see Appendix B):

$$c>\frac{1+\omega\mu}{1-\omega+\omega\mu}b. \tag{17}$$

Eq. (17) implies that harvesting becomes more likely as the forest recovery rate (μ) increases. This prediction, although naive, is consistent with the simulation results generated under the assumption of strongly-connected society (Fig. 4b).

5. Discussion

5.1. Main findings

Our results demonstrate how both ecological and social variables influence landowners' decisions about forest harvesting and how these decisions alter landscape patterns. First, in our model, harvesting by an upstream landowner was assumed to degrade the value of the forested land downstream, which was managed by a different landowner. The spatial linkage between management units caused a chain reaction of harvesting downstream when the degree of degradation was large (Fig. 3b). These results suggest that forest management based solely on an individual-property regime will not yield optimal results for all landowners when ecological dynamics operate at a larger scale than social dynamics.

Second, our findings highlight that under conditions of limited information about the harvesting behavior by other landowners, different predictions of future harvest rates can lead to varying decision-making and resultant landscape patterns. When landowners have "no-harvest expectations" (i.e. they predict that no one will harvest trees in the future), the landscape pattern resembles that created by a strongly-connected society where landowners are familiar each other and have full information regarding the harvesting behavior of others (Figs. 5a and c). In contrast, when landowners have "extreme-harvest expectations" (i.e. everyone will harvest trees in the future), the resulting pattern tends to favor fragile forested and harvested landscapes rather than a robust forested landscape (Fig. 5e) because landowners anticipate that the future benefits that they will receive from forest conservation will be less due to degradation of ecosystem services caused by others. The extreme-harvest expectation leads to the decision, "clear before anyone else does," that is, in fact, considered a widespread behavior associated with deforestation (Geist and Lambin, 2001).

Third, landowners who are focused on short-term economic gains tended to engage in harvesting at significantly higher rates than those who have longer-term perspectives (Figs. 4 and 5; Eqs. (15), (16), and (17)). This is because the lower the anticipated future benefit, the greater the focus on the short-term gains from harvesting. This result is consistent with the long-standing result that high discount rates promote high rate of resource exploitation (Clark, 1976).

5.2. Policy implications

The model results demonstrate the importance of matching the scales of ecological and social dynamics. When forest ecosystems include multiple, ecologically connected management units, establishment of higher-level institutions such as community or state-level institutions are necessary in order to mitigate the effects of negative externalities (McKean, 2000). By establishing market transactions between downstream and upstream agents, the downstream effects would be taken into account when upstream landowners make decisions about their own land use. One example is payment for ecosystem services (Pagiola et al., 2002). For example, downstream landowners could compensate upstream landowners for maintaining forest cover. This scheme would work (1) if the compensation of upstream landowners is at least equal to the opportunity cost of land use, and (2) if the amount of payment by downstream landowner is lower than the economic value of the externality. If landowners are myopic (i.e. $\omega=0$), the condition that should be satisfied in order to make that scheme be efficient is $c-b\leqslant q<\varepsilon$, where q is the amount of payment. This type of payment for ecosystem services has been proven to be economically efficient (Coase, 1960).

Our findings also suggest that institutional arrangements that encourage a long-term perspective and increased

information flow among landowners are more likely to result in successful forest management. A long-term perspective can be enhanced by secure land tenure, improved participation in resource governance, and increased economic and social well being (World Resources Institute et al., 2005). For example, a survey of Amerindian households in the Honduran rain forest showed that the longer households lived in a village, the less likely they were to clear old-growth forest. This finding can be interpreted as a negative relationship between secure land tenure rights and harvest rate (Godoy et al., 1997). Also, a negative association between the security of land tenure and harvest rate also was reported in Ecuador (Southgate et al., 1991) and in a cross-country comparison (Deacon, 1999). Godoy et al. (1997) also showed that levels of education and wealth (potential indicators of well-being) negatively influenced the harvest rate of households, i.e. the households with higher education and wealth levels were less likely to deforest their land.

In addition, information exchange itself may play a key role in establishing trust among different agents. Trust, in turn, may enhance the likelihood of successful resource management. For instance, groups of people who can identify with one another and develop dense social networks—sometimes called social capital—are more likely than groups of strangers to trust one another (Ostrom et al., 1999; Pretty, 2003; Pretty and Smith, 2003). This axiom is exemplified by a study in southern Sweden, where Olsson et al. (2004) found that social networks were essential to achieving adaptive co-management of the area's ecosystems. The degree of information exchange and the structure of the information network has been shown to be important in many other cases of natural resource management, as well (Schneider et al., 2003; Bodin and Norberg, 2005; Lambin, 2005).

These three components—matching the scales of ecological and social dynamics, encouraging a long-term perspective, and increasing information flow—are influenced by multiple dimensions of the organization and dynamics of societies. Therefore, in addition to ecological monitoring, social and economic monitoring also is needed in order to inform forest policy and management decisions (Stem et al., 2005).

5.3. Future research

We anticipate several extensions of this work. First, we have assumed that the spatial interactions between different management units are unidirectional (i.e. only from upstream to downstream) at a local scale in one-dimensional space. Although this simple assumption was useful to clearly understand the conditions under which harvesting can occur, we plan to investigate the situation in which interactions occur in more complex spatial settings (e.g. interactions within a multi-directional, complex network or cross-scale interactions that involve both local and global scales).

Second, we are interested in exploring how the uncertainty of social and ecological dynamics is altered by the learning and experience of landowners. This article focused on the behavior of agents who employ forward-looking rationality (i.e. maximization of expected utility with foresight). In addition, backward-looking alternatives need to be explored in order to investigate how local and historical knowledge of resources influences the behavior of agents. Here we assumed that the landowner expected that she and other landowners would engage in a time-invariant rate of harvesting in the future. However, the landowner could update her expectation of others' harvest rate by learning from past experience. For instance, Satake et al. (2007) demonstrated that long-term memory about past experiences can play a key role in preventing reemergence of overexploitation. Learning-theoretic approaches have been applied to solve social dilemmas (Macy and Flache, 2002) and to investigate landscape management, as well (Bodin and Norberg, 2005).

Finally, we are investigating the role of sanctions in creating sustainable forest management. The role of sanctions or punishment to maintain cooperative behavior in a group has been identified as important (Ostrom, 1990) and has been recently supported experimentally (Fehr and Gachter, 2002; Fehr and Fischbacher, 2004) and theoretically (Sigmund et al., 2001, Boyd et al., 2003; Nakamaru and Iwasa, 2005). In our model, one landowner's behavior could negatively impact another (through the decision to deforest her land), but we did not consider how the affected actor responded to this event. This situation can be changed to allow symmetric interactions between actors, so that an affected actor punishes a neighbor who deforests her land. This situation represents one in which downstream landowners have a right to determine the status of upstream parcels.

These theoretical studies on coupled social and ecological systems will further understanding of the social and ecological elements that are needed to achieve successful resource management, and provide opportunities for developing hypotheses for further empirical research as well as frameworks for more effective forest management.

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Appendix A

The expected discounted utility $\mathbf{V}_i$ and the transition matrix for future landscape change $\mathbf{A}_i$ at the land parcel i are dependent on each other—the harvest rate at the land parcel i, r_i, is a function of $V_i(F|x_{i-1})$ and $V_i(H|x_{i-1})$, where x_{i-1} is a land-use state at a land parcel i–1 and is in either a mature forested (F), just-harvested (H), and immature forested state (D) (see Eq. (7) in the text). $V_i(F|x_{i-1})$ and $V_i(H|x_{i-1})$ in turn depend on $\mathbf{A}_i$ (Eq. (11) in the text); but elements of $\mathbf{A}_i$ include r_i (Eq. (12) in the text). We explain a method of recursive calculation that is performed to cope with the interdependence between $\mathbf{V}_i$ and $\mathbf{A}_i$. Although r_i is influenced by r_{i-1}, r_{i-1} is now treated as a constant because the landowner at the land parcel i is assumed to be able to anticipate r_{i-1} before she makes a decision.

The problem of interdependence can be solved by the following recursive calculation. Let $\mathbf{A}_i[\mathbf{V}_i]$ be the transition matrix given the expected discounted utility $\mathbf{V}_i$. We started with a simple set of the expected discounted utility, such as $\mathbf{V}^{(0)} = \mathbf{u}$ in which there is no contribution of future utility. $\mathbf{u}$ is defined as the utilities of land-use states F, H, and D, as denoted by $\mathbf{u} = (u(F), u(H), u(D))^T$ (see the text). The expected discounted utility changes according to the following dynamics: $\mathbf{V}_i^{(n+1)} = \mathbf{u} + \omega\mathbf{A}_i[\mathbf{V}_i^{(n)}]\mathbf{V}_i^{(n)}$. Using these dynamics, we obtained a series of $\mathbf{V}_i^{(1)}, \mathbf{V}_i^{(2)}, \ldots, \mathbf{V}_i^{(n)}$. When it converges (i.e. $\mathbf{V}_i^{(n+1)} = \mathbf{V}_i^{(n)}$), $\mathbf{V}_i$ and $\mathbf{A}_i$ satisfy both Eqs. (7) and (12) in the text.

Appendix B

Here we explain how to derive the condition of harvesting on healthy and degraded forested lands in a strongly-connected society for the following two extreme cases.

(1) When $\hat{r} = 1$ and $\mu = 0$: Since the forest recovery rate μ is 0, D is an absorbing state (see Fig. 2a). Now we explain how to calculate the harvest rate at land parcel i. Let $r_i(F|x_{i-1})$ be the harvest rate at land parcel i in F state when the land-use state of parcel i–1 is in $x_{i-1} \in \{F, H, D\}$. Since the harvest rate $r_i(F|H)$ and $r_i(F|D)$ do not differ much, we simply focus on the problem of calculating $r_i(F|F)$ and $r_i(F|H)$. $r_i(F|F)$ and $r_i(F|H)$ are determined by Eq. (7) in the text, and we need to calculate the expected discounted utility, $(V_i(F|F), V_i(F|H), V_i(H|F), V_i(H|H))$ to obtain these harvest rates. When $\hat{r} = 1$ and $\mu = 0$, we obtain $(V_i(F|F), V_i(F|H), V_i(H|F), V_i(H|H))$ as follows:

$$V_i(F|F) = u(F|F) + \omega u(H) + \sum_{n=2}^{\infty} \omega^n u(D), \tag{B.1a}$$

$$V_i(F|H) = u(F|D) + \omega u(D) + \sum_{n=2}^{\infty} \omega^n u(D), \tag{B.1b}$$

$$V_i(H|F) = V_i(H|H) = u(H) + \omega u(D) + \sum_{n=2}^{\infty} \omega^n u(D). \tag{B.1c}$$

From Eq. (7), when β is infinitely large, the harvest rate is given as follows:

$$r_i(F|F) = \begin{cases} 1 & \text{if } V_i(H|F) > V_i(F|F), \\ 0 & \text{otherwise,} \end{cases} \tag{B.2}$$

$$r_i(F|H) = \begin{cases} 1 & \text{if } V_i(H|H) > V_i(F|H), \\ 0 & \text{otherwise.} \end{cases} \tag{B.3}$$

After simple calculation, we derived the condition when the inequalities $V_i(H|F) > V_i(F|F)$ and $V_i(H|H) > V_i(F|H)$ are satisfied. These conditions are given in Eq. (15) in the text.

(2) When $\hat{r} = \mu = 0$.
In this case, the net present value $(V_i(F|F), V_i(F|H), V_i(H|F), V_i(H|H))$ is given as follows:

$$V_i(F|F) = u(F|F)\sum_{n=0}^{\infty} \omega^n = (\lambda + b)/(1-\omega), \tag{B.4a}$$

$$V_i(F|H) = u(F|H)\sum_{n=0}^{\infty} \omega^n = (\lambda + b - \varepsilon)/(1-\omega), \tag{B.4b}$$

$$V_i(H|F) = V_i(H|H) = u(H) + \sum_{n=1}^{\infty} \omega^n u(D) = \lambda/(1-\omega) + c. \tag{B.4c}$$

By noting the sum of geometric series, we derived the condition when the inequalities $V_i(H|F) > V_i(F|F)$ and $V_i(H|H) > V_i(F|H)$ are realized. These conditions are given by Eq. (16) in the text.

(3) When $\hat{r} = 0$ and $\mu \neq 0$
When $\hat{r} = 0$, and if the current land-use at the neighboring upstream parcel is in the mature forested state, no future land-use change is expected at that parcel. Therefore future land-use change is expected to be completely independent of the neighboring land-use dynamics. In this case, we can calculate the condition of harvesting when $\mu > 0$.

We denote the expected discounted utility of mature forested, just-harvested, and immature forested parcels as $V(F)$, $V(H)$, and $V(D)$, respectively, because neighboring forested parcels are expected not to change in the future. $V(F)$, $V(H)$, and $V(D)$ are given as follows:

$$V(F) = b + \omega V(F), \tag{B.5a}$$

$$V(H) = c + \omega V(D), \tag{B.5b}$$

$$V(D) = \omega[\mu V(F) + (1-\mu)V(D)]. \tag{B.5c}$$

From these we have

$$V(H) - V(F) = c - \frac{1+\omega\mu}{1-\omega+\omega\mu}b. \tag{B.6}$$

The condition when $V(H) > V(F)$ is satisfied is given in Eq. (17) in the text.

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