Chapter 7
Theoretical Models as a Tool to Derive Management Strategies for Sustainable Natural Resource Management

Joung-Hun Lee

Abstract Biodiversity hot spots cannot be preserved successfully unless human activities such as illegal logging and grazing are properly controlled and cooperation is achieved among resource users to reduce anthropogenic impacts. We explore strategies for sustainable use of common resources by studying resource users' behaviors together with resource dynamics, because ecological and social factors are known to interact strongly. By showing three systems dealing with the risk of illegal logging, grazing pressure, and increasing catching effort respectively, we show the advantages of a mathematical model as a management tool.

Keywords Biodiversity · Natural resource management · Sustainable use · Social-ecological dynamics · Mathematical modeling · Sustainable use

1 Introduction

Many of the ecosystems are maintained under the strong influence of human activities. Without proper control of prevalent illegal logging, hunting, and resource overuse and also with lack of cooperation of local inhabitants, we cannot achieve our goals: successful conservation of biodiversity and ecosystem management, in other words, sustainable resource management.

To resolve such problems, an interdisciplinary approach embracing natural sciences and social sciences is required. Natural sciences are for understanding the biological mechanisms under which natural resource behaves. Social sciences help us understand how individual resource users behave and make decisions which may make a tremendously huge impact on the resource and ecosystem.

In addition to the traditional academic fields, we also actively embrace new approaches to facilitate our understanding on human behaviors or dynamics of

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interactions among decision-makers. As an example, we would like to introduce theoretical biology as a tool to enhance such roles toward sustainable society: to test/derive strategies which promote cooperative behavior for public goods, to couple social/ecological aspects for comprehensive ecosystem management, and to support decision makings through testing possible scenarios. In the following sections, we provide three examples which handle different ecosystems and sustainable use of the resource in the ecosystem and show how a theoretical modeling approach can contribute to our shared goal of a sustainable society.

2 Connecting the Understanding of Mechanism for Human Cooperation to Strategies for Cooperation in Real Setting

As we briefly mentioned in Chap. 1, theoretical biology has been accumulated understanding on the mechanism of cooperation building or maintenance among people such as direct/indirect reciprocity, reputation, and punishment. By specifying the strategies of agents who apply those mechanisms to games, especially the public or common goods game, theoretical models help us understand in which conditions cooperative behavior (leading to good results for whole participants) can stay and defective behavior (exploit cooperative player) can be suppressed. Besides deepening our understanding on the fundamental questions on human cooperation, the explorational feature of the theoretical approach can be used for more field-related tests such as policy making or rule application to the common good managements. Models for the tests need not be fully realistic; we can have reasonable expectations about how the idea or thoughts will work by the test.

2.1 Illegal Logging Suppression

As an example, we would like to provide a game theoretical model of a self-regulating community in which rules are invented to suppress illegal logging in their communal forest (Lee and Iwasa 2011). Illegal logging is a serious problem for some countries, such as Cambodia, Indonesia, and Bolivia. Indicative estimates of illegal logging even exceed 80% (Food and Agriculture Organization (FAO) 2005; European Forest Institute 2005), and illegal logging occurs widely and persistently, at both state and community levels (World Bank Group 2006). In this model, we focus on the community-level illegal logging considering these countries usually suffer from the lack of administrative power so that if the community can regulate autonomously, it would be more effective prevention for smaller-scale illegal logging.

Illegal logging is a typical example of a crisis of management of a common good threatened by the tragedy of the commons. Each individual resource user (tree harvester) gains from harvesting more trees or resources from the forest than other users. Thus, preventing the overuse of the forest requires establishing standards for sustainable level of harvesting. The standard requires the tasks of monitoring and sanctioning harvesters who break rules. However, those tasks cannot be always implemented by community members, so if the tasks are delegated to the third party who is relatively free from social pressure inside the community, corruption may arise. As corruption is known to be positively correlated with illegal logging in many places around the world (Seneca Creek Associates and Wood Resources International 2004), we believe that the model could give us important insights on how to reign corruption and eventually illegal logging.

2.2 Model

To reflect the autonomous community management setting, we consider a situation in which a group of harvesters establish a rule to restrain the harvesting amount. Hired enforcers monitor the harvesters who comply to the rule and fine defectors who harvest trees excessively. We assume that rule enforcers are paid by the harvesters, rather than being funded through an external source or organization. To investigate whether this rule enforcement system can emerge as a social institution in the modeled community, we use replicator dynamics describing social learning occurring through the imitation of successful role models (e.g., Sigmund 2010).

We specify three types of tree harvesters and two types of hired enforcers involved in this forest management: conditional cooperator, committing defector, non-committing defector, corrupt enforcer, and honest enforcer. A harvester is assumed to be a member of the community and free to choose either to hire an enforcer or not. A rule complier to the harvest amount is called a conditional cooperator who hires an enforcer (pay for hired enforcer). The conditional cooperator won't cooperate with the player who doesn't pay for the enforcement system. A committing defector is one that does not comply to the harvest rule but pay for the hired enforcer to exploit conditional cooperator. This type of harvester can be successful when he meets corrupt enforcers by bribing them otherwise punished harshly by an honest enforcer. By being hired by a pair of harvesters given that both are committing harvesters, enforcers may earn their salary. By setting the parameters such as benefit from cooperative behavior (b), cost of the cooperation (c), salary of hired enforcer (s), bribery from excessively harvesting defector to corrupt enforcer (B), and punishment to the defector (A), we can summarize the payoff for each type of player of the game as shown in Table 7.1. On this basis, we investigate conditions sustaining cooperative behaviors of harvesters and suppressing corrupt enforcers.

Table 7.1 Payoffs for harvesters and enforcers

	Conditional cooperator	Committing defector	Non-committing defector
a. Payoffs for harvesters accompanied by an honest enforcer			
Conditional cooperator	*b-c-s*	*-c-s*	0
Committing defector	*b-s-A*	*-s-A*	0
Non-committing defector	0	0	0
b. Payoffs for harvesters accompanied by a corrupt enforcer			
Conditional cooperator	*b-c-s*	*-c-s*	0
Committing defector	*b-s-B*	*-s-B*	0
Non-committing defector	0	0	0
c. Payoffs for an honest enforcer			
Conditional cooperator	2*s*	2*s*	0
Committing defector	2*s*	2*s*	0
Non-committing defector	0	0	0
d. Payoffs for a corrupt enforcer			
Conditional cooperator	2*s*	2*s*+*B*	0
Committing defector	2*s*+*B*	2*s*+2*B*	0
Non-committing defector	0	0	0

2.3 Findings

With the help of replicator dynamics based on the payoff (Table 7.1), we find the system may be faced with very different outcomes: full of cooperators leading to a very well-managed forest or full of illegal loggers leading to a devastated communal forest. It depends on whether the system retains a critical fraction of honest enforcers in the first beginning. With the fraction of honest enforcers higher than the critical fraction, the communal forest can be sustainably managed. If not, even with almost all cooperative harvesters, the forest finally ends up with deforestation by illegal loggers. This result implies that it is most important to ensure the quality of enforcers and also keep the quality by a sound educational system. Figure 7.1 shows how important the critical fraction is to maintain the forest sustainable. If the critical fraction of honest enforcers is larger, then the fraction of undesirable resultant outcomes is increased.

We also find that the critical fraction is denoted by the model parameters as a formula, (*c*-*B*)/(*A*-*B*). This formula says that with the same level of bribe (*B*) if the punishment to rule breaker (*A*) is larger or the cost of cooperative behavior (*c*) is small, the system requires smaller fraction of honest enforcers in the beginning than the opposite cases.

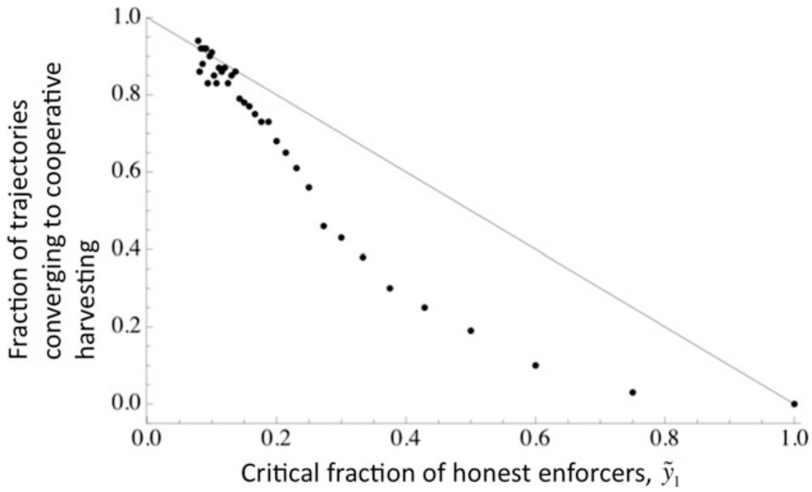

Fig. 7.1 Importance of an initial fraction of honest enforcers. A total of 100 different initial conditions consisting of different fractions of harvesters and enforcers are tested. Each condition converges to either cooperative harvesting or devastating harvesting. Larger critical fraction of honest enforcers means smaller cooperative harvesting in that any initial condition less that the fraction goes to the defective harvesting. The figure is adapted from Lee et al. (2015b)

3 Incorporating Social and Ecological Knowledge: Coupled Dynamics for Sustainable Resource Management

Hot spots or areas worthy of preservation identified by ecologists and evolutionary biologists cannot be properly preserved without proper management of anthropogenic impacts. Needless to say, biodiversity will be in danger under the presence of prevalent overuse of resources and lack of managing strategy in achieving the cooperation of local inhabitants. In this respect, it is important to incorporate the way to manage these aspects and to plug it into the ecosystem management that should be also based on ecology too. This is a point where we need the concept of social-ecological systems or human-environmental systems for successful conservation. Here we provide an example of the coupled dynamics of social-ecological systems (Lee et al. 2015b).

3.1 Mongolian Rangeland Management

The Mongolian rangeland is one of the terrestrial ecosystems affected by intensive human activities, cattle grazing. Precipitation here fluctuates greatly year to year, herders should cope with environmental uncertainty caused by such fluctuation (Smith et al. 2007). Herders, who are especially based on the southern part of Mongolia and have limited access to the northern area due to the traveling cost suffer from environmental uncertainty than herders in the northern area with more abundant, stable precipitation. During drought, the rangeland grasses disappear except in small areas called "key resource," and those provide refuge and forage for the herders and their animals in the very dry season (Kakinuma et al. 2013). Thus it is essential to keep key resource areas and to understand how it could be maintained for the herders in southern herders.

3.2 Model

To understand how herders' choice interacts with plant dynamics in key resource areas, we study the coupled dynamics of grasses of key resource areas and herders who choose between staying at the same site and moving to an alternative rangeland during drought. With strong grazing pressure, grass biomass in the focal rangeland is decreased, and then more herders move to an alternative rangeland rather than staying in the focal rangeland. Thus, plant biomass is influenced by its intrinsic growth rate, caring capacity, and grazing pressure from the animals in the site (Fig. 7.2).

Herders are assumed to choose the foraging site giving the higher payoff. We assume that the payoff in the southern area (U_{stay}) depends on the level of grass biomass (consumed by animals) and the payoff in the northern area (U_{move}) is constant reflecting that it has a more stable environment. Herders choose to either stay or move considering each payoff and are assumed to do it in accordance with stochastic best-response dynamics. Besides stochastic best-response dynamics, we incorporate the aspect of inertia or delay of human decision-making in herder's choice which reflects that people could maintain their current choice with many

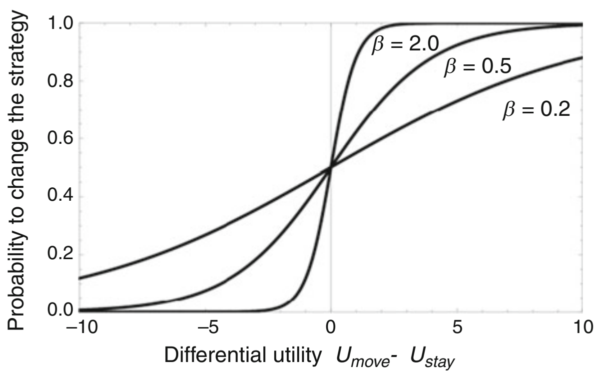

Fig. 7.2 Stochastic best-response dynamics. Herders compare the payoff difference of two options (stay/move). Herders (people) prefer options with higher payoff, but not always, and immediately change their current choice because of the positive margin. Their switch can be smooth and sometimes very slow depending on the sensitivity to the difference (compare three different beta values)

reasons, such as lack/distrust of new information (For more detailed model formulation, see Lee et al. 2015a).

3.3 Findings

We find that when the social dynamics is coupled with the grass biomass dynamics, the system generates typical nonlinear behaviors, such as bistability displaying a strong dependence on the initial condition or perpetual large-amplitude fluctuation. Fluctuation means plant biomass and herders in the southern area are not stabilized and continuously changing.

The fact that the system can oscillate has two interesting implications. First, traditionally such fluctuation is regarded as a result derived from environmental change, such as precipitation. However, our model shows that without the well-known environmental factors, the coupling of ecological dynamics and herders' choice dynamics can make such fluctuation (Fig. 7.3).

Second, the fluctuating system may cause more hardship to herders who cannot plan their lives under stable economic conditions, especially with large amplitude. By studying the model, we find how quickly people respond to the expected utility which is one key factor in controlling the fluctuation. As they make a quick decision (more herders decide to stay or move depending on their expectation about the utility from their choice rather than just keeping their current choice), the fluctuation may be dampened (see Fig. 7.4). If we find limiting factors to create such delay, the fluctuation could be prevented. Our model implies that limiting factors might be the lack of accurate information on plant conditions of the focal area and alternative area, unaffordable traveling cost to the northern area, and potential conflicts between herders in the northern area and herders from the southern area.

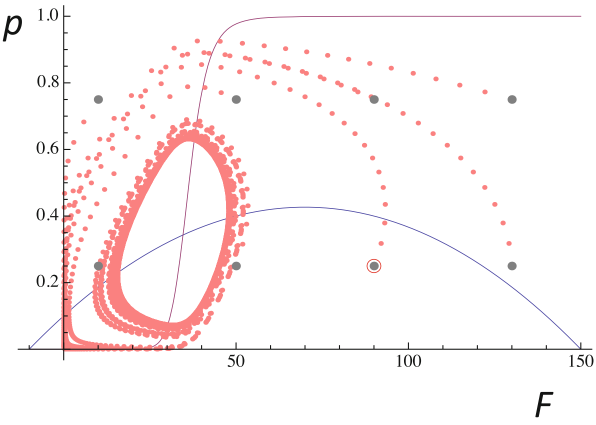

Fig. 7.3 Coupled social and ecological dynamics fluctuation. The x-axis is the level of plant biomass. The y-axis is the fraction of herders who stay in the southern area. p–F phase plane. The equilibrium is unstable, and all trajectories converge to a limit cycle showing a perpetual oscillation . The figure is adapted from Lee et al. (2015a)

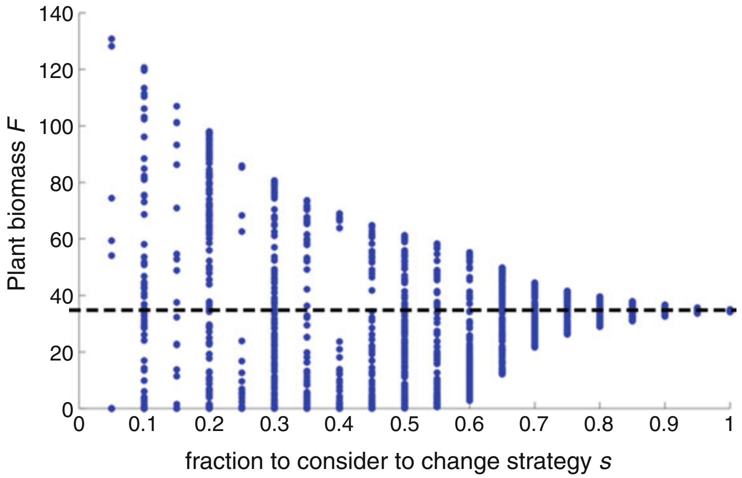

Fig. 7.4 Plant biomass fluctuation depending on the fraction of herders who consider changing their strategy depending on the utility difference between two options. A larger fraction means a larger fraction of herders adjust their strategy to move by comparing utilities

4 Testing Influences of New Stakeholders in Resource Use

Membership is an important factor to sustain stewardship of people over the resource in their use. With the existence of membership, the long-term use of the resource is guaranteed, and also mechanisms to enhance cooperation such as reputation, reciprocity, and social pressure might work well among the members. Despite the advantages, the system may face challenges to disturb it such as introducing a new stakeholder. Often the possible disturbance causes conflicts among people who have different opinions over the challenges. In such cases, a theoretical approach can play a role as a decision support tool by clarifying questions to be asked, stakes of each stakeholder, change of benefit distribution, impact to the ecosystem (level of focal resource), etc. The following example shows how we use a theoretical model as the decision support tool for the challenge.

4.1 Tourists and Traditional Divers in a Common Fishing Ground

The coastal area of Jeju island in South Korea has been utilized only by traditional divers. As the number of traditional divers decreased and they get aged, the local government has been thinking of introducing tourists into the coastal area called common fishing ground for an additional income source for the villagers in the island. Such policy may change resource dynamics and benefit distribution through introducing new stakeholders, tourists, into the current system consisting of mainly traditional divers and marine resources. Especially when it is considered that traditional divers are known to be concerned about the environment, new stakeholders, for example, tourists, may affect the environment more than the traditional divers.

4.2 Model

We describe the common fishing ground system by marine resource population dynamics, tourists introduced into the fishing ground, and total benefit for the fishing association consisting of benefits from tourists and traditional divers' marine resource catch. As the goal of tourism introduction to the fishing ground is to increase the income for fishing villages, it is required to get benefits from tourists' visits to the fishing ground. In the model, we assume that the entrance fee is collected from tourists who might respond to the level of the fee as well as the abundance of marine products they can access. Because tourists can also catch the resource, now the traditional divers compete with tourists in the fishing ground for the resource such as octopus, seashells, etc. The key is to choose to optimize the entrance fee level. If the fee is too high, tourists might not visit the fishing ground. If it is too low, tourists might catch more resources to the extent that the traditional divers' catch is decreased significantly. The fishing association consisting of traditional divers, fishermen in fishing villages, and retired traditional divers is assumed to have the right to choose the fee level for the model. It reflects the fact that it has the legal right to manage the fishing ground although traditional divers utilize it (for more detailed formulation, see Lee and Iwasa 2011).

4.3 Findings

Decisions made regarding tourism derived from the model are shown to affect the claimed resource depletion of the Jeju island fishing ground. The fishing association can maximize its economic benefit by using the model, which might be quite plausible. However, the resource level may be apart from the sustainable level. The fishing association may seek a short-term benefit to maximize their own profit at the expense of resource sustainability more than traditional divers whose concerns are more about the long-term use of the resource (Ostrom 1990).

The adequacy of the optimal choice, therefore, should be discussed in light of values other than the economic benefits to the fishing village. The result denotes the potential conflict caused by tourists' resource use in competition with the traditional divers (Fig. 7.5). This result suggests that the stakeholders among the fishing association should come to some agreement before introducing tourists. The fact that tourism can negatively affect resources more than traditional diving requires thinking of an alternative tourism in accord with it such as a diver training program.

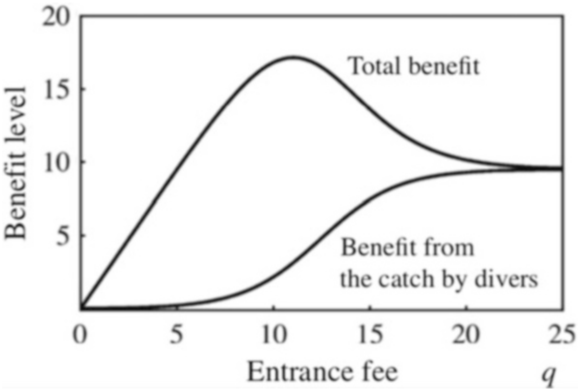

Fig. 7.5 Potential conflict between traditional divers and other members of the fishing association. The optimal entrance fee maximizing the total benefit for the fishing association is lower than the fee level which maximizes the benefit from divers' catch. The figure is adapted from Lee and Iwasa (2011)

It can be an opportunity to recruit new divers as well as to provide interesting experience to tourists.

5 Conclusion

Through the theoretical study of ecosystem management including rule making, coupled social-ecological dynamics, and policy making, we can combine our knowledge on ecological and social sciences in a manner useful for management. We discovered several unexpected behaviors of the social-ecological dynamics, such as a big oscillation in herder-grass systems, abrupt switches between deforestation and forestation, or the potential conflicts among stakeholders. With the help of the model, key factors to control the destruction of the ecosystem service can be identified, and then policy implication is provided.

For its wider use, in the near future, the importance of accumulating and extending knowledge to incorporate social sciences to demonstrate people's behavior into the robust management of common goods may be greatly emphasized. Then social-ecological models strengthened by the knowledge can deal with large-scaled, complicated management challenges with multiple stakeholders over our common resources.

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