Principal-Agent Relationship in Resource Management, Multiple Principals and Spatial Dynamics

Philippe Delacote[*,†,‡], Arnaud Dragicevic[*,†,¶], Serge Garcia[*,†]

Abstract

Public authorities (often local) frequently mandate public or private agencies to manage their natural resources. Contrary to the agency, which is an expert in resource management, public authorities usually do not know the sustainable harvest level. In this paper, we model the contractual relationship between a principal, who owns the resource, and an agent, who holds private information on its sustainable harvest level, and look for the Pareto-optimal allocations. The agent can strategically use his private information to harvest outside the sustainability interval. We consider the case where the agent simultaneously interacts with several principals. From a simple dynamic spatial game, we show how the existence of multiple interacting principals with diverse qualities on information can help the least well-informed principals to reduce the information rent and lead to the Pareto-optimal allocation.

Keywords: Resource management; Sustainable harvesting; Principal-agent model; Spatial dynamics

JEL classification: D82, Q20

[*] Agro ParisTech – Laboratoire d'Économie Forestière, 54042 Nancy Cedex, France
[†] INRA – Laboratoire d'Économie Forestière [UMR 356], 54000 Nancy, France
[‡] Chaire Économie du Climat [Université Paris-Dauphine–CDC Climat], 75002 Paris, France
[§] Chaire Forêts pour Demain [Agro ParisTech–Office National des Forêts], 54042 Nancy Cedex, France
[¶] Contact. Tel. (+33)383396896 | Fax. (+33)383373645 | Email. arnaud.dragicevic@agroparistech.fr

1 Introduction

States, regions and municipalities frequently mandate public or private agencies to manage their natural resources. This paper analyzes this type of principal-agent relationship. Principals and agents can have diverse preferences and objectives when it comes to resource management: harvest rates, investment, provision of amenities or ecosystem services, etc. Usually, the agent holds some private information on the way to manage the resource: Which are the boundaries that condition sustainability? Which actions should undertaken in order to insure the long-term stability of the resource? Could the ecosystem services and amenities really be provided?

Sometimes the agent has several contracts of resource management with several partners (also called *Common agency*). It can be observed that the expected results about inefficiency and rent extraction are not always verified. We argue that it is because a principal may observe the principal-agent relationships from his neighborhood in order to capture a piece of information rent from the agent. Should this be the case, two kinds of heterogeneity matter: Either the principals have different preferences and objectives or their resources are uneven. The latter leads to distinguishing between management practices and information rents.

The prime consideration of this paper is to understand how the agent's private information may come into conflict with the principal's objective, jeopardizing the Pareto-optimal allocations. The second consideration is to analyze how the neighborhood scrutiny facilitates the capture of the information rent. Through spatial dynamics, our ultimate aim is to observe spatial reconfigurations and surplus turnovers. Our study is thus different from the classical literature on multiple principals, which directly model the interactions between an agent and several principals (Martimort 1992, Martimort and Stole 2002).[1]

We first model the contractual relationship between a principal and an agent for the resource management, and then study the interactions between principals. The innovation is that we consider that these interactions can be described by a spatial game (Nowak and May 1992, Nowak et al. 1994, Schweitzer and Mach 2006). In a spatial game, each player interacts with neighbors in some spatial array. In each step, each player evaluates the payoff of everyone and compares his own payoff with that of his neighbors. And in the next step, he adopts the strategy of whoever has the highest score. In this paper, we study the evolution of harvesting behavior at a particular location and how it is influenced by the payoffs obtained in the neighborhood (Jun and Sethi 2007).

For this purpose, we conduct a study carried by the classic principal-agent game. Once the multiple principals have offset their contracts with the sole agent, our study construes the

[1]See also Bernheim and Whinston (1986) for a multiprincipal approach with moral hazard.

interactions between multiple principals in a spatial dynamics game.

After this starting section, we describe the model assumptions in Section 2. Section 3 covers the principal-agent relationship in perfect information. Section 4 derives the optimal contracting when the agent owns private information on the sustainable harvesting. We present the spatial game played between the principals in Section 5. Section 6 discusses our findings and concludes.

2 A principal-agent model of resource management

We consider a principal who delegates the management of a natural resource of stock s to an agent. The principal and the agent have to agree upon a quantity to be harvested q from the resource owned by the principal. The stock s is considered as a proxy of the resource amenities, which are all non-market goods and services related to the existence of this resource (e.g., environmental and social services).

Sustainable harvesting of resources matches to cutting the natural growth of the renewable resource, such that the stock remains unchanged or $\frac{ds}{dq} = 0$. Unsustainable harvesting can be envisaged in two ways. When $\frac{ds}{dq} > 0$, the scenario corresponds to over-stocking due to the absence of implementation of the management plan. When $\frac{ds}{dq} < 0$, the scenario implies over-harvesting and deforestation, given that the resource stock decreases.

Finally, the principal gives a revenue share to the agent for the resource management r, harvesting included, such that $\frac{dr}{dq} > 0$.

The principal and the agent can have different preferences on how to conduct the resource management. For instance, the agent could have stronger preferences for income from harvesting, while the principal could have stronger preferences for preserving the resource amenities. In the knowledge that resource harvesting must not jeopardize sustainability, the interval $[\underline{q}, \overline{q}]$ defines the set of possible actions to be undertaken in purpose of the sustainable resource management: Minimum and maximum harvest levels for a sustainable resource management. There is a maximum level of harvesting beyond which the resource is depleted, cannot be renewed and does no longer provide amenities. There is a minimum level of harvesting below which environmental and social services are decreasing. Therefore, q has to lie somewhere within this interval. These assumptions implicitly mean that resource and amenities can be complementary goods, at least for a specific range of harvest levels.

If we assume that the principal has stronger preferences for the stock conservation (i.e., for resource amenities) than the agent, the objectives of parties should differ: The principal's harvesting objective will tend to be a low level of harvest, running the risk of being below the minimum sustainable harvest level $\underline{q}$, whereas the agent will seek to harvest beyond this level.[2]

The knowledge of the interval of sustainable harvests is crucial and the key issue of the contract setting is the information gap between the principal and the agent as to this interval. We will thus consider that this interval can correspond to public (section 2.3) or private (section 2.4) information held by the agent.

2.1 The principal - resource owner

Let V_p be the value function of the risk-neutral principal. This value function is decreasing in revenue transfer r paid to the agent. However, the effect of resource stock s and harvesting q on the value function is ambiguous, since harvesting brings revenues from resource harvesting but, at the same time reduces utility by diminishing resource amenities and environmental services. While the principal is willing to harvest less than the agent, the question is whether the principal's optimal harvest level q_p^* lies or not within the sustainability interval $[\underline{q}, \overline{q}]$. The principal's value function is defined by:

$$V_p = V_p \left(s(q), I_p \left(q \right), r(q) \right) \tag{1}$$

where $I_p \left(q \right)$ represents the principal's identity function such that:

$$I_p \left(q \right) := \begin{cases} q_p^* > \underline{q} \text{ if } V'_{p_q} \leq 0 \\ q_p^* \leq \underline{q} \text{ if } V'_{p_q} > 0 \end{cases} \tag{2}$$

with q_p^* the (optimal) harvest quantity that maximizes the function defined by equation (1). In particular, equation (2) states that $V'_{p_q} > 0$, which means that the principal's optimal harvest level lies within the sustainability interval, and does not otherwise.

From the foregoing, it can be written that:

- $V'_{p_s} \gtreqless 0$, based on the principal's preferences toward the non-market goods and services;
- $V'_{p_r} < 0$, for the principal pays the agent to execute the management plan;
- $V'_{p_q} \gtreqless 0$, depending on the principal's identity function $I(q)$.

Let us now analyze the conditions in which the principal's optimal harvest level q_p^* lies within the sustainability interval $[\underline{q}, \overline{q}]$, from the variation of the value function in quantity.

Lemma 1 *The condition for the principal's optimal harvest level q_p^* to lie within $[\underline{q}, \overline{q}]$ is $V'_{p_q} = -V_{p_r} \frac{dr}{dq}$.*

[2]The opposite assumption yields symmetric results with respect to the maximum level $\overline{q}$.

Proof See the Appendix.

Thereby, the optimal harvest level implies that the marginal value from the resource harvest equals the marginal remuneration for the resource management.

2.2 The agent - resource manager

Let V_a be the value function of the risk-neutral agent. We have assumed that the agent in charge of the resource management is more willing to harvest than the principal. And we are interested in where the agent's optimal harvest level q_a^* lies within the sustainability interval $[\underline{q}, \overline{q}]$. The agent has the following value function:

$$V_a = V_a\left(s(q), r(q), c(q)\right) \tag{3}$$

where c expresses the harvesting costs, and q depends on $\underline{q}$ following the simple functional form $q = \underline{q} + v$, where v can be a positive or negative deviation from this level of harvesting.

The agent's value function increases in resource stock s, in harvest quantities q and in revenue transfer r, and decreases in harvest costs c. Put another way:

- $V_{a_s}^{'} \gtreqless 0$, based on the agent's preferences toward the non-market goods and services;
- $V_{a_r}^{'} > 0$, for the agent is paid by the principal to execute the management plan;
- $V_{a_c}^{'} \leq 0$, which involves increasing returns from the resource management.

Lemma 2 *The condition for the agent's optimal harvest level q_a^* to lie within $[\underline{q}, \overline{q}]$ is $-V_{a_c}^{'}\frac{dc}{dq} = V_{a_r}\frac{dr}{dq}$.*

Proof See the Appendix.

The optimal harvest level implies that the marginal remuneration from the resource management equals the marginal loss from the embedded management costs.

3 The optimal contract with public information on the sustainability interval

We assume that both the principal and the agent have the knowledge of the sustainability interval $[\underline{q}, \overline{q}]$. The principal then chooses the harvest level such that he maximizes his utility, subject to the agent's participation constraint (or individual rationality IR) and to the minimum harvesting level $\underline{q}$ of this sustainability interval:[3]

$$\begin{aligned} &\max_{q,r} V_p\left(s(q), I_p\left(q\right), r(q)\right) \\ &\text{s.t. (IR) } V_a\left(s(q), c(q), r(q)\right) \geq 0 \end{aligned} \tag{4}$$

The program means that the principal binds the agent to his participation constraint, that is, he sets the revenue transfer so that the harvest costs are covered and the agent is not in deficit. Although the principal might want to harvest less than the minimum sustainable level ($q_p^* < \underline{q}$), he has to comply with the sustainability constraint.

The Lagrangian can be written:

$$L = V_p + \lambda_{\text{IR}}\left[V_a\right] \tag{5}$$

The first-order conditions implicitly give the harvest level q^* and the revenue transfer r^*:

$$L_q^{'} = V_{p_q}^{'} + \lambda_{\text{IR}}\left[V_{a_q}^{'}\right] = 0 \tag{6}$$

$$L_r^{'} = V_{p_r}^{'} + \lambda_{\text{IR}}\left[V_{a_r}^{'}\right] = 0 \tag{7}$$

$$L_{\lambda_{\text{IR}}}^{'} = 0 \tag{8}$$

In case where additional harvesting provides for the principal increasing marginal utility ($V_{p_q}^{'} > 0$) while grants the agent with diminishing marginal utility ($V_{a_q}^{'} < 0$), equations (6) and (7) give:

$$\lambda_{\text{IR}} = -\frac{V_{p_q}'}{V_{a_q}'} \neq 0 \tag{9}$$

$$\frac{V_{p_r}^{'}}{V_{p_q}^{'}} = \frac{V_{a_r}^{'}}{V_{a_q}^{'}} \tag{10}$$

From equation (8), we know that the agent's participation constraint is binding, that is, the information rent is set to zero. The sign in Equation (9) indicates that an optimum exists. At last, equation (10) means that the first-best contractual harvesting is when the principal's and the agent's ratios of marginal values equate.

The complete information efficient harvesting level is such that:

$$q^* = \underline{q} \tag{11}$$

[3] As written above, this is the minimum sustainable harvesting $\underline{q}$ at stake, for the principal is willing to harvest less (beyond this level) and the agent fights to reach this level at least.

Indeed, the principal cannot request to harvest outside the sustainability interval, so that the agent harvests up to the minimum sustainable level. Besides, harvesting diminishes the principal's marginal utility outside the sustainability interval.

The following proposition ensues.

Proposition 1 *In case of perfect information setting, the Pareto-optimal contracting implies a level of harvest at least equal to the lower bound of – and thus inside – the sustainability interval, such that the principal's value function remains unchanged.*

Proof See the Appendix.

Proposition 1 uncovers the fact that the optimal contracting does not affect the principal's value function, so that the marginal costs and benefits from harvest cancel each other.[4]

4 The optimal contract with private information on the sustainability interval

In the imperfect information case, the principal does not know what the sustainable harvest interval is, which is now held by the agent in the form of private information. This time, the agent announces an interval $[\underline{q}, \overline{q}]$ to the principal, where the bounds depend on his optimal harvest. The private knowledge of the sustainability interval gives the agent an opportunity to over-estimate the minimum harvest level.[5] This in turn acts as an incentive for a more intensive harvesting on the principal.

We assume that $F(.)$ is a continuous distribution function, with a positive density $f(.)$, that describes the prior of the principal over the set of potential minimum levels of sustainable harvesting $[0, s]$.[6] The principal maximizes his expected value function subject to the agent's individual rationality (IR) and incentive compatibility (IC) constraints:

$$\max_{q,r} \int_0^s V_p\left(s\left(q\right), I_p\left(q\right), r\left(q\right)\right) f\left(\underline{q}\right) d\underline{q} \tag{12}$$
$$\text{s.t. (IR) } V_a\left(s\left(q\right), c\left(q\right), r\left(q\right)\right) \geq 0$$
$$\text{s.t. (IC) } V_a\left(s\left(q\right), c\left(q\right), r\left(q\right)\right) - V_a\left(s\left(\tilde{q}\right), c\left(\tilde{q}\right), r\left(\tilde{q}\right)\right) \geq 0$$

Based on the above, the principal is maximizing his surplus by integrating his payoff function

[4] This property only holds because we study the case of renewable resources.

[5] It is our only variable of interest, since we assume that the principal is less willing to harvest than the agent.

[6] The possible set of harvest goes from no harvesting ($q = 0$) to clear-cutting of the whole stock ($q = s$), even if the latter is never reached.

over $\underline{q}$. Although this value is provided by the agent, the principal reveals his preferences regarding $\underline{q}$.

The risk is that the agent attempts to signal a level of $\underline{q}$ which maximizes his payoff function at a cost to the principal. Indeed, the agent sends a signal of the minimal sustainable harvesting level, but the principal ignores whether this signal is the real one. Since the agent knows that both players disagree on the harvest level, and that the interval defining sustainable harvest is his private information, he might want to belie on $\underline{q}$ and choose a level that can lower the principal's payoff for the sake of contracting. In consequence, the principal has to maximize his value function over density $f(\underline{q})$, knowing that the real $\underline{q}$ is somewhere between 0 and s.

Two cases are possible:

- In case $q_p^* \geq q_a^*(\underline{q})$, the principal and the agent implicitly agree on the harvesting volume. Therefore, both the principal and the agent enter into a contract that optimizes their respective payoff functions. Indeed, $q_a^*(\underline{q})$ at least saturates the participation constraint and at most provides him with some surplus.

- In case $q_p^* < q_a^*(\underline{q})$, the principal and the agent implicitly disagree on the harvesting volume. Given that $q_a^*(\underline{q}) > 0$, for resource management includes some non-null resource maintenance, we have $0 < q_p^* < q_a^*$. This time, the contract does not provide for the agent a non-negative payoff, and therefore does not give him incentive to contract.

The IC constraint is a maximizing argument. Hence, we have to look at the optimal conditions. The optimal condition of the IC constraint $v\left(q(\underline{q}), q(\underline{q})\right) \geq v\left(q(\underline{q}), q(\tilde{q})\right) \; \forall \, [0, s]$ is given by:

$$\left.\frac{\partial v\left(q(\underline{q}), q(\tilde{q})\right)}{\partial q(\tilde{q})}\right|_{q(\tilde{q})=q(\underline{q})} = 0$$

The second-order condition of the IC constraint is:

$$\left.\frac{\partial^2 v\left(q(\underline{q}), q(\tilde{q})\right)}{\partial q(\tilde{q})^2}\right|_{q(\tilde{q})=q(\underline{q})} \leq 0$$

We define the Hamiltonian of the associated maximization problem:

$$H = V_p f\left(\underline{q}\right) + \lambda_{\mathrm{IR}}\left[V_a\right] + \lambda_{\mathrm{IC}}\left[V_{a_q}^{'}\right] \quad (13)$$

The contract variables q and r must satisfy:

$$\begin{aligned} H_q^{'} &= V_{p_q}^{'} f\left(\underline{q}\right) + \lambda_{\text{IR}}\left[V_{a_q}^{'}\right] + \lambda_{\text{IC}}\left[V_{a_{qq}}^{''}\right] = 0 \\ H_r^{'} &= V_{p_r}^{'} f\left(\underline{q}\right) + \lambda_{\text{IR}}\left[V_{a_r}^{'}\right] + \lambda_{\text{IC}}\left[V_{a_{rq}}^{''}\right] = 0 \end{aligned}$$

The boundary at $\underline{q} = 0$ is unconstrained, meaning that $\underline{q}$ could take any value on the interval. Hence the transversality condition is $\lambda_{\text{IC}}(\underline{q}) = 0$, that is, the shadow price of $\underline{q}$ is zero. Therefore, $\frac{\partial H}{\partial \lambda_{\text{IC}}(\underline{q})} = f(\underline{q})$ yields $\lambda_{\text{IC}}(\underline{q}) \equiv \int \frac{\partial H}{\partial \lambda_{\text{IC}}(\underline{q})} = F(\underline{q})$, which gives:

$$\lambda_{\text{IR}} = -\frac{V_{p_q}^{'} f(\underline{q}) + V_{a_{qq}}^{''} F(\underline{q})}{V_{a_q}^{'}} \tag{14}$$

The second-best optimal condition is therefore:

$$\frac{V_{p_r}^{'}}{V_{p_q}^{'}} - \sigma = \frac{V_{a_r}^{'}}{V_{a_q}^{'}} \tag{15}$$

where

$$\sigma = \frac{V_{a_{qq}}^{''} - V_{a_{rq}}^{''} V_{a_q}^{'}}{V_{a_q}^{'}} \frac{F(\underline{q})}{f(\underline{q})} \tag{16}$$

In comparison to the perfect information case, an additional term σ arises.[7] The optimal condition for contracting is when the principal's and the agent's ratios of marginal values equate modulo σ. As the sustainability interval is not known to the principal, the agent announces a level which maximizes his own payoff. In this sense, σ represents the information rent captured by the agent or the loss in payoff inflicted to the principal.

The second-best optimal harvesting q^{SB} induces the following probability over $\underline{q}$:

$$F(\underline{q}) = \left(\frac{V_{p_r}^{'}}{V_{p_q}^{'}} - \frac{V_{a_r}^{'}}{V_{a_q}^{'}}\right) \frac{V_{a_q}^{'} f(\underline{q})}{V_{a_{qq}}^{''} - V_{a_{rq}}^{''} V_{a_q}^{'}} \tag{17}$$

If $F(\underline{q}) = 0$, we fall on the perfect information case and $q^* = \underline{q}$. Should this not be the case, the consequential proposition can be stated.

Proposition 2 *In case of imperfect information setting, the Pareto-optimal contracting depends on the probability that the level of harvest is less than or equal to the lower bound of – and thus outside – the sustainability interval.*

Proof See the Appendix.

[7] Assuming the concavity of the agent's value function with respect to q and $V_{a_{rq}}^{''} > 0$ implies $\sigma < 0$.

The rent represents the use made by the agent of his private information on the sustainability interval and is increasing under the Jensen's inequality (Rogerson 1985):

$$\frac{V''_{a_{rq}}}{V''_{a_{qq}}} \geq \frac{1}{V'_{a_q}} \tag{18}$$

Corollary 1 *Given the agent's preferences toward contracting, there is information rent.*

Proof See the Appendix.

On the assumption that $F(\underline{q}) \neq 0$, the only way to fall on the perfect information case and thus to fall on the lower bound of the sustainability interval is to set $\sigma = 0$, which implies that the Jensen's relative inequality becomes a strict equality. To get there, the inverse of the agent's marginal value from harvesting should be equal to his ratio of critical points over revenue transfer and harvesting. This implies that V_a should be linear.

Provided that assuming linear preferences for the agent is unreasonable, we now study whether a spatial game with multiple principals could reduce the information asymmetry and rent in the contractual relationship.

5 A spatial game of resource harvest with multiple principals

5.1 The model behind the game

In this section, we consider that spatial dynamics can help a principal to reduce the information asymmetry on the true sustainability interval, and thus to decrease the agent's information rent or to move towards his first-best optimum, that is, $\underline{q}$. Following the work by Nowak et al. (1994) and Schweitzer and Mach (2006), we consider n principals. Let i be a principal interacting with his $n-1$ neighbors. Neighbors different from i are indexed $j = 1, ..., n-1$.

Each principal i can observe what happens in his neighborhood, especially the harvesting level q_j^*. Before the observation, we assume that $q_j^* = q_j^{SB}$ at the initial period of contracting between the principal and the agent. Differences in q_j^* may come either from diverse preferences of principals or diverse resource characteristics reflecting diverse sustainability intervals or diverse information rents. We therefore distinguish between three kinds of heterogeneity: preference-related heterogeneity via $V_j = V_j(s, q, r)$, resource-related heterogeneity via $[\underline{q_j}, \overline{q_j}]$, and information-related heterogeneity via σ_j. More specifically, we can expect that:

$$q_i^* > q_j^*,\ \forall\ V'_{i_q} > V'_{j_q} \tag{19}$$

$$q_i^* > q_j^*,\ \forall\ \underline{q_i} > \underline{q_j} \tag{20}$$

$$q_i^* > q_j^*,\ \forall\ \sigma_i > \sigma_j \tag{21}$$

Equation (19) states that a greater harvesting level has been contracted with principals with stronger preferences for harvesting (yet smaller than those of the agent himself). Equation (20) implies that the contracted harvesting level is greater when the sustainable harvest level is itself greater. Finally, equation (21) tells us that larger information rent implies greater level of minimal harvest.

Therefore, when principal i observes a neighbor with smaller harvest level, this can be due to (a) weaker preferences for harvesting; (b) more fragile resource stock, (c) smaller uncertainty on the sustainability interval.

The interactions between principals is thus an n-person game. We have $n-1$ two-principal games that occur simultaneously and independently. Let q_i^* be the strategy of principal i from the strategy set, i.e., $q_i^* \in [0, s]$. The spread of strategy q_i^* in principal i's neighborhood is given by:

$$k_i^q = \sum_{j=1}^{n-1} \delta_q q_j^* \tag{22}$$

where δ_q is the Kronecker delta equal to 1 when $i = j$ and 0 otherwise. k_i^q describes the contagion of strategy q_i^* in the neighborhood of principal i and depends on the number of principals playing this strategy.

Principal i confronts each neighbor's strategy q_j^*, from which it would receive the payoff of $V_i(s_i, q_j^*, r_i)$. Principal i's total payoff is then:

$$\pi_i(s, q, r) = \frac{1}{n-1} \sum_{j=1}^{n-1} V_i(s_i, q_j^*, r_i) \cdot k_i^q \tag{23}$$

Let us consider a principal i observing a neighbor j. If i is aware that principal j has identical preferences ($V_i(s, q, r) = V_j(s, q, r)$) and similar resources ($\underline{q_i} = \underline{q_j}$, $s_i = s_j$), while he observes $q_j^* < q_i^*$, i knows that this comes from j's smaller uncertainty over the sustainability interval ($\sigma_j < \sigma_i$). Moreover, he knows that he would have been better had he chosen j's harvest level, i.e. $V_i(s_i, q_j^*, r_i) > V_i(s_i, q_i^*, r_i)$. If that were the case, principal i should switch from q_i^* to q_j^*.

In order to analyze the dynamic spread of a strategy, we consider the game to be repeated through a recursive framework. We call generation the number of times any principal can observe his $n-1$ neighbors' strategies. During a given generation t, strategy $q^*_{i_t}$ cannot be changed by the principal while he interacts. Based on a comparison of the payoffs received, principal i can change once generation t is completed and before generation $t+1$ has started. Therefore, principal i compares the payoff from his strategy to the payoff he would have obtained had he followed his $n-1$ neighbors' strategies. If principal i has received the highest payoff from his neighbors, he keeps $q^*_{i_t} = q^*_{i_{t-1}}$ from one generation to another. If one of the neighbors j has received the highest payoff, principal i switches to the strategy of the relevant principal:

$$q^*_{i_t} = \arg \max_{j=0,\ldots,n-1} q^*_{j_{t-1}} \tag{24}$$

The switching process leads to an evolution of the spatial distribution of strategies and should reduce the information rent of the agent. Indeed, the agent receives at each generation t a total payoff of:

$$\omega_{a_t}(s,q,r,c) = \sum_{i=1}^{n} V_{a_t}(s_{i_t}(q^*_{i_t}), r_{i_t}(q^*_{i_t}), c_{i_t}(q^*_{i_t})) \tag{25}$$

This payoff has to be compared to the payoff he would have obtained without the repeated spatial game between principals:

$$\omega_a(s,q,r,c) = \sum_{i=1}^{n} V_a(s_i(q_i^{SB}), r_i(q_i^{SB}), c_i) \tag{26}$$

In the special case in which the only source of heterogeneity among principals comes from their level of information about the true sustainability interval, our intuition is that less informed principals will observe and mimic more informed ones, until the information spreads out in the whole community. This case is developed in the next section.

5.2 Illustration of the Spatial Game

5.2.1 Case 1: Homogeneous Preferences and Homogeneous Land Quality

We assume that principals have homogeneous preferences over the resource harvesting, and that they only differ in their levels of uncertainty on the sustainability interval. Moreover, we assume that the land is also of homogeneous quality, implying the same sustainability interval for all squares of the map.

Let us consider the land map in Figure 1. Following our framework, red squares represent the uninformed principals (U) or principals with large uncertainty about the sustainability interval, and blue squares represent the informed principals (I) or principals with low uncertainty about the sustainability interval. The uncertainty about this sustainability interval is the only difference between the blue and red-type principals. Each cell represents a principal that has already offset his contract with the sole agent, that is, his harvesting level has been decided. Considering our previous results, we have:

$$V_i(s_i, q_{\mathrm{I}}^*, r_i) \geq V_i(s_i, q_{\mathrm{U}}^*, r_i) \tag{27}$$

The principals now play between them. Each principal plays the game with all of his neighbors. In this example of square lattice, a principal can have up to 8 neighbors, that is, the Moore neighborhood. He compares his own payoff with that of his neighbors and adopts the strategy of whoever has the highest payoff, be it his own strategy. The future of each principal depends on the state of all 25 squares in the square lattice.

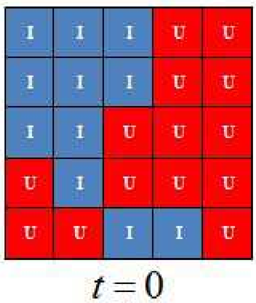

Figure 1: Hypothetical Land Map

Consider now the payoff matrix in Figure 2.

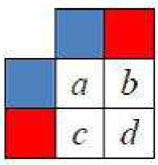

Figure 2: Case 1 Payoff Matrix

If two neighboring principals have low uncertainty, both receive a. If a principal with high uncertainty meets a neighbor with low uncertainty, he gets payoff c, while the principal with low uncertainty gets b. The interaction between two principals with high uncertainty leads to payoff d. We have $a \geq b \geq c > d$. Let $\frac{z}{Z}$ be the proportion of neighboring principals with low uncertainty and $\frac{Z-z}{Z}$ the proportion of neighboring principals with high uncertainty. Given the payoff matrix, we obtain the spatial game in Figure 3.

$\frac{3}{3}a + \frac{0}{3}b$	$\frac{5}{5}a + \frac{0}{5}b$	$\frac{3}{5}a + \frac{2}{5}b$	$\frac{2}{5}c + \frac{3}{5}d$	$\frac{0}{3}c + \frac{3}{3}d$
$\frac{5}{5}a + \frac{0}{5}b$	$\frac{7}{8}a + \frac{1}{8}b$	$\frac{4}{8}a + \frac{4}{8}b$	$\frac{2}{8}c + \frac{6}{8}d$	$\frac{0}{5}c + \frac{5}{5}d$
$\frac{4}{5}a + \frac{1}{5}b$	$\frac{5}{8}a + \frac{3}{8}b$	$\frac{4}{8}c + \frac{4}{8}d$	$\frac{1}{8}c + \frac{7}{8}d$	$\frac{0}{3}c + \frac{5}{5}d$
$\frac{3}{5}c + \frac{2}{5}d$	$\frac{3}{8}a + \frac{5}{8}b$	$\frac{4}{8}c + \frac{4}{8}d$	$\frac{2}{8}c + \frac{6}{8}d$	$\frac{1}{5}c + \frac{4}{5}d$
$\frac{1}{3}c + \frac{2}{3}d$	$\frac{2}{5}c + \frac{3}{5}d$	$\frac{2}{5}a + \frac{3}{5}b$	$\frac{1}{5}a + \frac{4}{5}b$	$\frac{1}{3}c + \frac{2}{3}d$

Figure 3: Case 1 Spatial Game

As we repeat the game until some steady-state occurs, we obtain the following dynamic mapping.

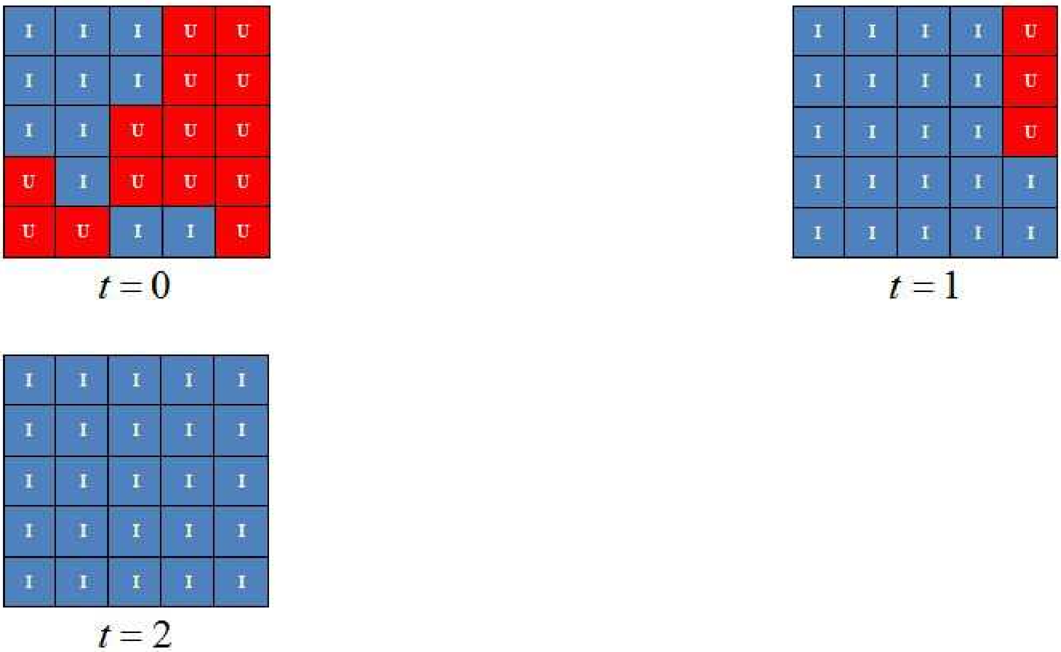

Figure 4: Dynamic Mapping for $a = 4, b = 3, c = 2, d = 1$

Figure 4 shows the temporal distribution of principals. Despite the early outnumber of uninformed principals, the spatial game reverses the trend and propagates information among principals, simply because, in this simulation, it provides the highest payoff. Indeed, although the East resists against the information dissemination at $t = 1$, it only takes one generation more to end up with the steady-state of the population.

Result 1 *When principals have homogeneous preferences over harvesting and when the land is of homogeneous quality, the map evolves such that all principals reduce the uncertainty over their sustainability interval by getting up informed.*

In the basic case of complete homogeneity, we observe that the information disseminates up to the point where every principal gets the most accurate information.

5.2.2 Case 2: Heterogeneous Preferences and Homogeneous Land Quality

We consider the fact that principals may have heterogeneous preferences over the resource harvesting. A principal can have high (H) or low (L) preferences for harvesting. He adopts the blue strategy when he has low-harvesting preferences, but can maintain the red strategy, has he had poor knowledge of his sustainability interval. With high-harvesting preferences, the principal prefers to keep the red strategy, he to be informed or uninformed. This is summarized in the following payoff matrix.

	L	L
L	a	b
L	a	c

	H	H
H	d	d
H	d	d

Figure 5: Case 2 Payoff Matrix

As the principal observes a blue neighbor, he assumes that this neighbor (i) is well informed about his sustainability interval; (ii) has low-harvesting preferences. In contrast, if a principal observes a red neighbor, he presumes that this neighbor is uninformed and/or has high preferences for harvesting. It follows that (i) the principal with low preferences for harvesting should choose the blue strategy when he is informed or has some blue neighbor; (ii) the uninformed principal with low preferences for harvesting will select the blue strategy only if he observes some blue neighbor; he will always keep the red strategy when his preferences go for high harvesting.

Let d represent the invariable payoff of a principal with high-harvesting preferences. We have $d \geq a \geq b > c$. Given the hypothetical land map, we can observe the subsequent spatial game.

$\frac{3}{3}a + \frac{0}{3}b$	$\frac{5}{5}a + \frac{0}{5}b$	$\frac{3}{5}a + \frac{2}{5}b$	d	$\frac{0}{3}a + \frac{3}{3}c$
$\frac{5}{5}a + \frac{0}{5}b$	$\frac{7}{8}a + \frac{1}{8}c$	$\frac{4}{8}a + \frac{4}{8}c$	d	d
$\frac{4}{5}a + \frac{1}{5}b$	$\frac{5}{8}a + \frac{3}{8}b$	$\frac{4}{8}a + \frac{4}{8}c$	d	$\frac{0}{3}a + \frac{5}{5}c$
d	$\frac{3}{8}a + \frac{5}{8}b$	d	$\frac{2}{8}a + \frac{6}{8}c$	d
$\frac{1}{3}a + \frac{2}{3}c$	d	$\frac{2}{5}a + \frac{3}{5}b$	$\frac{1}{5}a + \frac{4}{5}b$	d

Figure 6: Case 2 Spatial Game

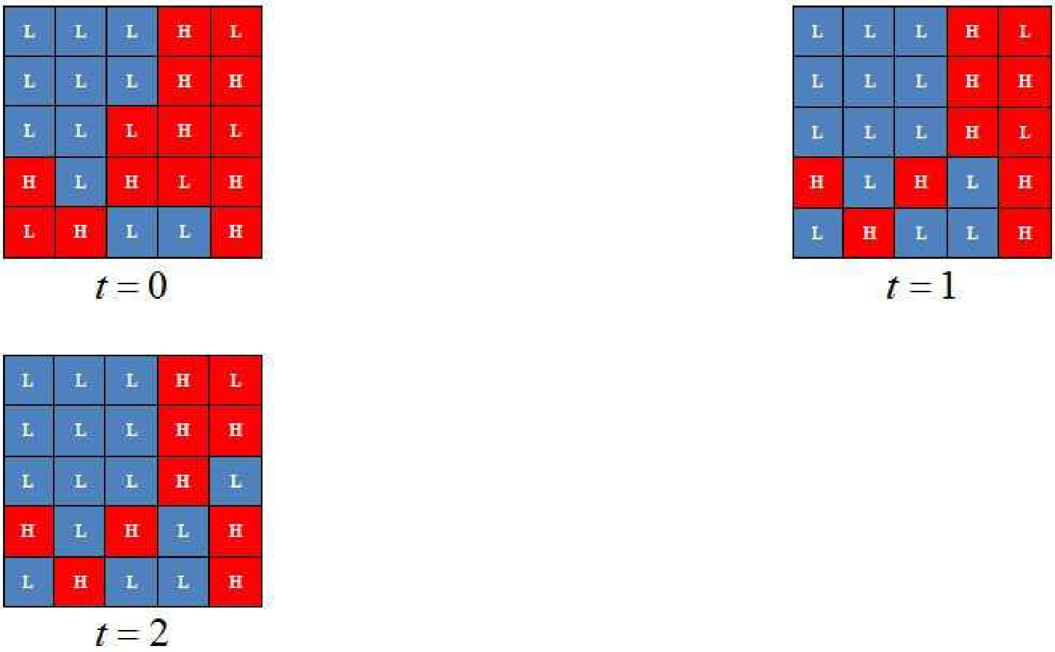

Figure 7: Dynamic Mapping for $a = 4, b = 4, c = 2, d = 4$

Figure 7 shows the temporal distribution of principals with heterogeneous preferences over the resource harvesting. As can be observed, the East homogenizes as the blue strategy gains ground. It takes two generations to end up with the steady-state of the population. This is due to the fact that both the informed and the uninformed principals with low-harvesting preferences opt for the blue strategy provided they encounter a blue principal in their neighborhood. Note also that the principal with low-harvest preferences at the very North-East of the map keeps a red strategy, as he is surrounded by principals with high-harvest preferences, who prevent him from getting information from his neighbors.

Result 2 *When principals have heterogeneous and unobservable preferences over harvesting, the map evolves such that the uninformed principals with high-harvesting preferences maintain their initial strategy, whereas the principals with low-harvesting preferences switch their strategy for that of the informed low-harvesting neighbor. Nevertheless, an uniformed principal with low-harvesting preferences will be unable to update his strategy when he is surrounded by high-harvesting neighbors.*

Thereby, due to the heterogeneous unobservable preferences, a principal with low-harvesting preferences surrounded by principals with high-harvesting preferences remains unaffected until his neighbors meet an informed principal.

5.2.3 Case 3: Homogeneous Preferences and Heterogeneous Land Quality

In the previous section, heterogeneity focused on the principals' preferences. In this section, we assume that principals may own lands of heterogeneous qualities. This means that some parcels detain a large sustainability interval or solid resource (S), while others have a tight sustainability interval or fragile resource (F).

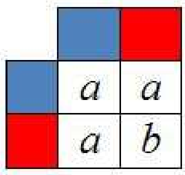

Figure 8: Case 3 Payoff Matrix

When a principal observes higher harvesting in the neighborhood, he does not know if this is due to better knowledge of the sustainability interval or a solid resource. This can lead to unsustainable harvesting and, as an extreme case, to the resource depletion. In our simulation, the cost of unsustainable harvest is quite low (small difference between a and b). We can expect that if this cost is larger, this would influence the overall dynamics of the map. Let β be the probability that the uninformed principal has the same quality of resource as his neighbors and $(1-\beta)$ that he does not. We have $a > b$. Given the hypothetical land map, we can observe the subsequent spatial game.

$\frac{3}{3}a + \frac{0}{3}\left[\beta a + (1-\beta)b\right]$	$\frac{5}{5}a + \frac{0}{5}\left[\beta a + (1-\beta)b\right]$	$\frac{3}{5}a + \frac{2}{5}\left[\beta a + (1-\beta)b\right]$	$\frac{2}{5}a + \frac{3}{5}\left[\beta a + (1-\beta)b\right]$	$\frac{0}{3}a + \frac{3}{3}\left[\beta a + (1-\beta)b\right]$
$\frac{5}{5}a + \frac{0}{5}\left[\beta a + (1-\beta)b\right]$	$\frac{7}{8}a + \frac{1}{8}\left[\beta a + (1-\beta)b\right]$	$\frac{4}{8}a + \frac{4}{8}\left[\beta a + (1-\beta)b\right]$	$\frac{2}{8}a + \frac{6}{8}\left[\beta a + (1-\beta)b\right]$	$\frac{0}{5}a + \frac{5}{5}\left[\beta a + (1-\beta)b\right]$
$\frac{4}{5}a + \frac{1}{5}\left[\beta a + (1-\beta)b\right]$	$\frac{5}{8}a + \frac{3}{8}\left[\beta a + (1-\beta)b\right]$	$\frac{4}{8}a + \frac{4}{8}\left[\beta a + (1-\beta)b\right]$	$\frac{1}{8}a + \frac{7}{8}\left[\beta a + (1-\beta)b\right]$	$\frac{0}{5}a + \frac{5}{5}\left[\beta a + (1-\beta)b\right]$
$\frac{3}{5}a + \frac{2}{5}\left[\beta a + (1-\beta)b\right]$	$\frac{3}{8}a + \frac{5}{8}\left[\beta a + (1-\beta)b\right]$	$\frac{4}{8}a + \frac{4}{8}\left[\beta a + (1-\beta)b\right]$	$\frac{2}{8}a + \frac{6}{8}\left[\beta a + (1-\beta)b\right]$	$\frac{1}{5}a + \frac{4}{5}\left[\beta a + (1-\beta)b\right]$
$\frac{1}{3}a + \frac{2}{3}\left[\beta a + (1-\beta)b\right]$	$\frac{2}{5}a + \frac{3}{5}\left[\beta a + (1-\beta)b\right]$	$\frac{2}{5}a + \frac{3}{5}\left[\beta a + (1-\beta)b\right]$	$\frac{1}{5}a + \frac{4}{5}\left[\beta a + (1-\beta)b\right]$	$\frac{1}{3}a + \frac{2}{3}\left[\beta a + (1-\beta)b\right]$

Figure 9: Case 3 Spatial Game

Figure 10 shows the temporal distribution of principals with heterogeneous qualities of resources. Equiprobable heterogeneity leads to the maintenance of both strategies. This is due to the fact that principals compare themselves with neighbors whose resources are heterogeneous. The West and the South stabilize their red strategy, independently of the hidden resource quality. In Case 3, it takes five generations to end up with the steady-state of the population.

Result 3 *When principals have heterogeneous and unobservable qualities of their lands, the map evolves such that the uninformed principals mimic both the informed and the uninformed principals, based on the proportion of informed principals in their neighborhood.*

As can be seen, taking the risk to mimic a neighbor's strategy while not being certain of the resource homogeneity may sometimes lead to the resource depletion. This can be observed when the uninformed principals with fragile resources act as if their resources were solid. Accordingly, we can argue that the spatial observation of neighbors allows for the information dissemination about the sustainability interval only when the resources are homogeneous enough. In case of heterogeneity, the agent may want to keep the benefit of the doubt about his sustainability interval and apply the precautionary principle. It follows that heterogeneity or the cost of harvesting outside the sustainability interval reduces the possibility of information dissemination. Simple observation of the neighbors' strategies is no longer sufficient.

We can expect that mimicking will be more widespread when unsustainable harvest brings a larger cost (larger difference between a and b) and in case of a small proportion of solid lands (low β) on the map.

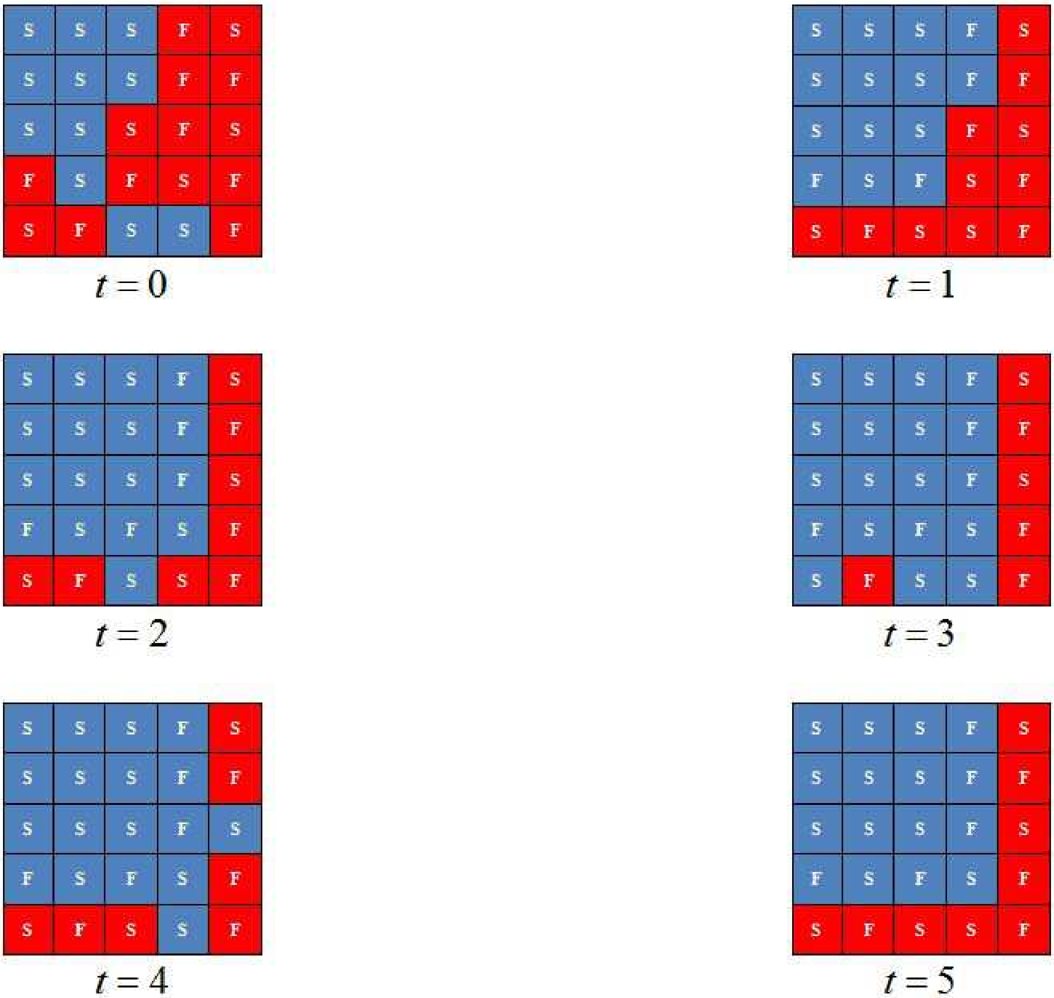

Figure 10: Dynamic Mapping for $\beta = 0.5, a = 4, b = 3$

6 Discussion

The management of natural resources often takes the form of management delegation from the resource owner to the resource manager. In presence of asymmetric information on the sustainable harvesting interval and different preferences between the owner and the manager, a principal-agent game may take place. In this paper, we show that if the manager has higher propensity to harvest than the owner, he may be tempted to manipulate his private information on the true sustainability interval against the owner, so that the latter accepts a larger harvest level (a similar approach could be done in the opposite direction).

In this context, we show that the existence of multiple interacting principals with diverse information qualities can help the least well-informed principals to reduce the cost of asymmetric information they bear. Through the repeated spatial game of the information spread, our findings show that even a small number of informed owners can disseminate the information among the population. This result gives the insight that, in a world where resource owners delegate their resource management to an agent with divergent preferences and private information, improving the quality of information held by some owners is sufficient to decrease the extend of the moral hazard problem.

However, information dissemination is facilitated when principals have homogeneous preferences and resource characteristics. In contrast, if principals have unobservable and diverse preferences for harvest, an uninformed principal with low preference for harvest may not benefit from information dissemination if he is surrounded by principals with high preferences for harvest. Moreover, if the resource is of heterogeneous and unobservable characteristics among principals, information dissemination may no longer be possible. This is especially the case when the degree of heterogeneity is very large, or when the resource is very fragile, that is, if stepping outside the sustainability interval implies rapid resource depletion.

7 Acknowledgment

This work was financially supported by a grant overseen by the French National Forestry Office through the Forests for Tomorrow International Teaching and Research Chair. It was also supported by the French National Research Agency through the Laboratory of Excellence ARBRE, a part of the Investments for the Future Program (ANR 11 – LABX-0002-01). The authors would like to thank the discussants from the Journées Louis-André Gérard-Varet, the World Congress of Environmental and Resource Economists and the International Symposium on Dynamic Games. They are also grateful to the participants of the EQUIPPE and LAMETA seminars for their comments toward this work.

Appendix

Proof of Lemma 1. The total differentiating of V_p with respect to q yields:

$$\frac{\partial V_p\left(s, I_p\left(q\right), r\right)}{\partial s}\frac{ds}{dq} + \frac{\partial V_p\left(s, I_p\left(q\right), r\right)}{\partial q}\frac{dq}{dq} + \frac{\partial V_p\left(s, I_p\left(q\right), r\right)}{\partial r}\frac{dr}{dq} = 0$$

Ceteris paribus, the marginal rate of technical substitution (MRTS) between forest stock and harvesting can be analyzed. We have:

$$\frac{ds}{dq} = -\frac{V'_{p_q} - V'_{p_r}\frac{dr}{dq}}{V'_{p_s}}$$

When $\frac{ds}{dq} = 0$, we fall on $V'_{p_q} = -V_{p_r}\frac{dr}{dq}$.

A contrario, we have $\frac{ds}{dq} > 0$ for $q_p^* < \underline{q}$ or $\frac{ds}{dq} < 0$ for $q_p^* > \underline{q}$. When $\frac{ds}{dq} > 0$, we have $V'_{p_s} > 0$ for $-V'_{p_q} > 0$ and $-V_{p_r}\frac{dr}{dq} > 0$. When $\frac{ds}{dq} < 0$, we have $V'_{p_s} < 0$ for $V'_{p_q} < -V_{p_r}\frac{dr}{dq}$. ■

Proof of Lemma 2. We are interested in the variation V_a with respect to q. Hence:

$$\frac{\partial V_a\left(s(q), c(q), r(q)\right)}{\partial s}\frac{ds}{dq} + \frac{\partial V_a\left(s(q), c(q), r(q)\right)}{\partial c}\frac{dc}{dq} + \frac{\partial V_a\left(s(q), c(q), r(q)\right)}{\partial r}\frac{dr}{dq} = 0$$

Ceteris paribus, the relationship between forest stock and harvesting can be analyzed. From the total differentiating, we obtain:

$$\frac{ds}{dq} = -\frac{V'_{a_c}\frac{dc}{dq} + V'_{a_r}\frac{dr}{dq}}{V'_{a_s}}$$

As in the case of the principal, sustainable harvesting corresponds to $\frac{ds}{dq} = 0$. We fall on $-V'_{a_c}\frac{dc}{dq} = V_{a_r}\frac{dr}{dq}$.

Conversely, $\frac{ds}{dq} > 0$ is verified for $q_a^* < \underline{q}$ and $\frac{ds}{dq} < 0$ for $q_a^* > \underline{q}$. When $\frac{ds}{dq} > 0$, we have $V'_{a_s} > 0$ for $-V'_{a_c}\frac{dc}{dq} > V_{a_r}\frac{dr}{dq}$. When $\frac{ds}{dq} < 0$, we have $V'_{a_s} < 0$ for $-V'_{a_c}\frac{dc}{dq} > V_{a_r}\frac{dr}{dq}$. ■

Proof of Proposition 1. By Lemma 1, we know that $V'_{p_q} = -V_{p_r}\frac{dr}{dq}$. Equation (10) can thus be written as $-\frac{dr}{dq} = \frac{V'_{a_q}}{V'_{a_r}}$. Given that r and q vary in a complementary way, their technical marginal rate of substitution equals zero, which implies that $-\frac{dr}{dq} = 0 = dV_p$. ■

Proof of Proposition 2. Straightforward from equation (16), we know that $\sigma = 0$ if $\frac{F(\underline{q})}{f(\underline{q})} = 0$ or $\frac{V''_{a_{qq}} - V''_{a_{rq}}V'_{a_q}}{V'_{a_q}} = 0$. If one of these two conditions were verified, Lemma 1 and Lemma 2 complete the proof. ■

Proof of Corollary 1. The Jensen's inequality is verified when V_a is convex over both of its arguments. From (20), we have

$$\begin{aligned} \frac{V''_{a_{rq}}}{V''_{a_{qq}}} &\geq \frac{1}{V'_{a_q}} \\ \Leftrightarrow V''_{a_{qq}} &\leq V'_{a_q} V''_{a_{rq}} \\ \Leftrightarrow \frac{V''_{a_{qq}}}{V''_{a_{rq}}} &\leq V'_{a_q} \end{aligned}$$

Through complementarity, we know that $V''_{a_{rq}} > 0$. When $V'_{a_q} > 0$, the opening relative inequality implies that $V''_{a_{qq}} \geq 0$. In this case, both arguments give convexity of V_a, which ends the proof. When $V'_{a_q} < 0$, the information rent is useless, for the agent does not wish to harvest more than what has been fixed by the management plan. At that time, the risk involved is the lack of harvest. ■

References

Bernheim, B. D., and M. D. Whinston (1986): "Common Agency," *Econometrica*, 54(4), 923–942.

Jun, T., and R. Sethi (2007): "Neighborhood structure and the evolution of cooperation," *Journal of Evolutionary Economics*, 17(5), 623–646.

Martimort, D. (1992): "Multi-principaux avec anti-sélection," *Annales d'Economie et de Statistique*, (28), 1–37.

Martimort, D., and L. Stole (2002): "The Revelation and Delegation Principles in Common Agency Games," *Econometrica*, 70(4), 1659–1673.

Nowak, M. A., S. Bonhoeffer, and R. M. May (1994): "Spatial games and the maintenance of cooperation," *Proceedings of the National Academy of Sciences*, 91(11), 4877–4881.

Nowak, M. A., and R. M. May (1992): "Evolutionary games and spatial chaos," *Nature*, (6398), 826–829.

Rogerson, W. P. (1985): "Repeated Moral Hazard," *Econometrica*, 53(1), 69–76.

Schweitzer, F., and R. Mach (2006): "Distribution of Strategies in a Spatial Multi-Agent Game," in *Proceedings from the 8th International Workshop on Game Theoretic and Decision Theoretic Agents (GTDT), Hakodate, Japan*, pp. 46–51.