Quasi-option Value under Strategic Interactions

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Abstract

We consider a simple two-period model of irreversible investment under strategic interactions between two players. In this setup, we show that the quasi-option value may cause some conceptual difficulties. In case of asymmetric information, decentralized investment decisions fail to induce first-best allocations. Therefore a regulator may not be able to exercise the option to delay the decision to develop. We also show that information-induced inefficiency may arise in a game situation and that under certain assumptions inefficiency can be eliminated by sending asymmetric information to the players, even when the regulator faces informational constraints. Our model is potentially applicable to various global environmental problems.

Keywords: Biodiversity, Irreversibility, Quasi-option value, Uncertainty, Value of information.

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1. Introduction

Irreversibility is one of the most fundamental characteristics of the environmental problems we currently face. Extinction of an endangered species is one obvious example. Because we cannot restore a species that has become extinct, the action that entails a loss of species can be considered irreversible.[1] When there is uncertainty about future states, the impacts of irreversible actions must be carefully evaluated. For example, if a project drives an economically valuable but yet-to-be-discovered species to extinction, opportunity cost arises due to the loss of that species. However, such cost is typically ignored in project evaluation because of the lack of information about the species at the time of evaluation.

One can appropriately account for the potential loss of species by taking into consideration the quasi-option value (QOV), or the Arrow-Fisher-Hanemann-Henry option value due to Arrow and Fisher (1974), Henry (1974), Fisher and Hanemann (1987), and Hanemann (1989). The quasi-option value can be viewed as the value associated with the mere prospect of obtaining better information in the future. This concept is related to the (unconditional) expected value of information (EVI) but is generally different from it (Conrad, 1980; Hanemann, 1989). Fisher (2000) argued that QOV is also equivalent to the option value for investment under uncertainty proposed by Dixit and Pindyck (1994), though Mensink and Requate (2005) showed that they differ by the postponement value irrespective of uncertainty.

Previous studies of the QOV have generally assumed the presence of a single decision-maker. Given that strategic interactions are almost always absent in a standard cost-benefit analysis, this is a reasonable starting point. Yet, many of the situations to which the concept of the QOV is relevant involve strategic interactions among relevant players.

For example, consider an open-access forest that potentially contains undiscovered genetic resources, the existence of which may only become known in the future as a result of scientific research. Because there is open access to the forest, each logger may find the immediate benefits from logging more attractive than conservation of the forest's genetic resources, even if conservation is a better option for the society at large; this results in a "prisoners' dilemma" situation.

It is important to take strategic interactions into account when conducting the cost-benefit analysis because it may alter the conclusion. For example, in the case of a single decision-maker, the information that becomes available in the future never hurt the decision-maker. However, in the presence of strategic interactions, a prisoners' dilemma situation can be induced by public information.

To see this, consider a case when there is a follower advantage (and a leader disadvantage) in development.[2] In this case, the prospect of future information gives players a strong incentive to hold back development because future information helps the players to make an informed decision and because the players can avoid the leader disadvantage by holding back development. As a result, both players may choose to conserve the forest, even if it is socially efficient to develop the forest now. As shown below, an efficient outcome can be achieved in this case by giving information asymmetrically. That is, the perfect information about the true state is given to one player and a noisy message is given to the other player.

This finding has important implications for policies. It is widely believed that making additional information to the public is generally desirable. Therefore, we often tend to hold the opinion that new information and knowledge accumulated by the public sector, for example through publicly-funded research activities, should be made widely available. However, our results warns against mindless public disclosure of information. It may be better to keep some

[1] In this paper, we say that an action is irreversible when it is impossible or prohibitively expensive to undo the action.

[2] A more precise definition of this is given later.

players more informed than others. Based on this, public information disclosure must be accompanied by careful consideration of the possibility of information-induced inefficiency.

This argument creates obvious and immediate concerns regarding equity issues. It may be difficult to justify informing one player but not the other. However, even in cases of this type, we can ensure equity *ex ante* by randomly assigning the player who receives the perfect information before current actions are taken. Incorporating this twist into our model would not change our results in any significant manner.

Beside contributing to the existing literature on the QOV mentioned above, this study also contributes to the body of literature on value of information. Our definition of the value of information is different from the definitions used in previous studies such as Levine and Ponssard (1977), Bassan et al. (2003), and Kamien et al. (1990). For example, Kamien et al. (1990) essentially define the value of information as the maximum transfer that an external agent (maven) can extract from the players of the game. In contrast, our definition is based on the expected social gains that information brings about.

This paper has two purposes. The first is to highlight some conceptual difficulties with the QOV under strategic interactions. As will be shown later, it is possible to define generalized version of EVI in the presence of strategic interaction. However, the same cannot said about the QOV because the option to delay decisions to exploit future information may not exist. For example, when the best response to conserve the forest is to develop the forest today, conservation will not be supported as an equilibrium.

The second purpose of the paper is to investigate the potential importance of information-induced inefficiency. We demonstrate that all the players could be hurt if they know that they will know more in the future. In cases where this applies, the regulator should carefully disseminate information. In particular, we show that sending information about the state asymmetrically across players may be useful for achieving a socially efficient outcome.

This paper is organized as follows. In Section 2, we introduce strategic interactions into the standard framework of the QOV. We then discuss the conceptual difficulty with the QOV under strategic interactions. In Section 3, we consider a case in which information is given to the players asymmetrically to achieve an efficient outcome. It is shown in this section that manipulating information about the state by providing noisy message about the state may be socially desirable. Section 4 provides some discussions.

2. Setup

Building upon the existing literature on QOV, we set up a model of irreversible investment that includes the possibility of strategic interactions among players. Whenever possible, we use notations similar to Hanemann (1989).

Following the previous literature, we assume that there are two time periods, of which period 1 is the current period and period 2 is the future period. Previous studies typically assumed, often implicitly, that there is a single decision-maker who can choose the action to be taken in each period. We regard this decision-maker as a social planner in this study.

In line with the standard model, we consider the following situation: a forest can be developed in each period. The forest may contain biological resources that will be lost if the forest is developed (clear-cut). A key assumption in the previous QOV literature and in this study is that development is irreversible; forest that has been developed in period 1 cannot be reversed to the original state in period 2 (i.e., the lost biological resources cannot be recovered).

We shall denote by $S \equiv \{s_1, s_2\}$ the set of all possible states; s_1 represents the state in which there are no biological resources, and s_2 is the state in which biological resources exist. Hence, opportunity cost due to the loss of biological resources arises only when the state is s_2. In period 1, the state is not known. However, it is known *ex ante* that s_1 and s_2 occur with probability π and $1 - \pi$ respectively. In period 2, the state may be known before an action is taken because of, for example, (exogenous) scientific research. To keep the model simple, we shall only consider independent learning. That is, the state is revealed in period 2 regardless of the actions taken in period 1.

An important difference between this study and previous QOV studies is that we incorporate strategic interactions. We assume that the society has two risk-neutral players, α and β, and a risk-neutral regulator. The value of π is common knowledge. The two players in this setup may be thought of as forest loggers or private land developers. We shall discuss various outcomes that depends on the degree of control the regulator has over the players.

In each period $t \in \{1, 2\}$, each player $i \in \{\alpha, \beta\}$ chooses an action, $d_t^i \in \{0, 1\}$, where $d_t^i = 0$ represents conservation and $d_t^i = 1$ represents development. We assume that conservation is always chosen when the decision-maker is indifferent between conservation and development.

Because the action to develop is irreversible, we must have $d_1^i \leq d_2^i$. Notice that modeling the choice between conservation and development as a discrete choice is not as restrictive as it may appear because a corner solution almost always arises when there is a constant returns to scale technology of development, as shown by Arrow and Fisher (1974). Hence, our analysis can readily be extended to a case of continuous development on a unit interval. In this study, we use a discrete-choice model to avoid unnecessary complications.

In what follows, players may be allowed to take an action in period 2 after they have learned the state. In such a case, the action in period 2 is state-dependent. Therefore, we shall write $d_2^i(s)$ when we need to make clear that the action is state-dependent. With a slight abuse of notation, we denote the action profile at time t by $d_t \equiv (d_t^\alpha, d_t^\beta)$, the sequence of actions taken by player i by $d^i \equiv (d_1^i, d_2^i)$, and the sequence of the action profile by $d \equiv (d_1, d_2)$.

Let $A_1^i = \{0, 1\}$ and $A_2^i(d_1^i) \equiv \{1\} \cup \{d_1^i\}$ represent the set of permissible actions for player i in periods 1 and 2, respectively. Note that A_2^i depends on d_1^i because conservation cannot be chosen in period 2 if the player has already chosen development in period 1. We let $A_1 \equiv A_1^\alpha \times A_1^\beta$ be the set of permissible action profiles in period 1 and define the set A of the sequence of permissible action profiles by the following:

$$A \equiv \left\{ \left((d_1^\alpha, d_1^\beta), (d_2^\alpha, d_2^\beta) \right) | d_1^\alpha \leq d_2^\alpha, d_1^\beta \leq d_2^\beta, \text{ and } d_1^\alpha, d_1^\beta, d_2^\alpha, d_2^\beta \in \{0, 1\} \right\}. \tag{1}$$

We also assume that the forest is subject to open access. When at least one player chooses to develop, the biological resources in the forest will be lost. We also assume that the total payoff from development (i.e., the sum of payoffs for the two players) depends only on the timing of development and not on who develops. Therefore, who develops only affects the distribution of individual payoffs for the two players.

We make the following assumptions about the distribution of the payoffs from development: When both players choose to develop at the same time, they share the payoffs from development equally. If one player chooses to develop in period 1 and the other in period 2, then the leader in development (i.e., the player who develops in periods 1 and 2) takes all of the per-period payoff from development in period 1 and a share $k \in (0, 1)$ in period 2. The follower (i.e., the player who develops only in period 2) receives no payoff in period 1 and a share $1 - k$ of the payoff from development in period 2. We assume that the value of k is common knowledge. The interpretation of the parameter k will be presented subsequently.

We normalize the payoffs so that the per-period payoff from conservation is equal to zero. Further, we assume that the total payoff from development to the society in period 1 is positive. If not, it is always best for the society to wait until period 2 to develop and the problem is not interesting. For a similar reason, we assume the per-period payoff from development in period 2 is negative in one state and positive in the other. Given these assumptions, we can permit the total per-period payoff from development to the society be equal to a in period 1, b in period 2 if the state is s_1, and $-c$ in period 2 if the state is s_2, where a, b, and c are positive constants

Table 1: The per-period payoff matrix $(v_1^\alpha(d_1), v_1^\beta(d_1))$ in period 1.

	$d_1^\beta = 0$	$d_1^\beta = 1$
$d_1^\alpha = 0$	$(0, 0)$	$(0, a)$
$d_1^\alpha = 1$	$(a, 0)$	$(\frac{a}{2}, \frac{a}{2})$

Table 2: The per-period payoff matrix $(v_2^\alpha(d, s), v_2^\beta(d, s))$ in period 2 when $s = s_1$ (top) and $s = s_2$ (bottom).

$s = s_1$	$d^\beta = (0, 0)$	$d^\beta = (0, 1)$	$d^\beta = (1, 1)$
$d^\alpha = (0, 0)$	$(0, 0)$	$(0, b)$	$(0, b)$
$d^\alpha = (0, 1)$	$(b, 0)$	$(\frac{1}{2}b, \frac{1}{2}b)$	$((1-k)b, kb)$
$d^\alpha = (1, 1)$	$(b, 0)$	$(kb, (1-k)b)$	$(\frac{1}{2}b, \frac{1}{2}b)$

$s = s_2$	$d^\beta = (0, 0)$	$d^\beta = (0, 1)$	$d^\beta = (1, 1)$
$d^\alpha = (0, 0)$	$(0, 0)$	$(0, -c)$	$(0, -c)$
$d^\alpha = (0, 1)$	$(-c, 0)$	$(-\frac{1}{2}c, -\frac{1}{2}c)$	$(-(1-k)c, -kc)$
$d^\alpha = (1, 1)$	$(-c, 0)$	$(-kc, -(1-k)c)$	$(-\frac{1}{2}c, -\frac{1}{2}c)$

expressed in present value. In this section, the values of a, b, and c are common knowledge. In the next section, however, they are known only to the players, but not necessarily to a regulator.

We denote player i's per-period payoff in periods 1 and 2 by $v_1^i : A_1 \to \mathbb{R}$ and $v_2^i : A \times S \to \mathbb{R}$, respectively. Note here that the payoff in period 2 is state-dependent. We present $v_1^i(d_1)$ and $v_2^i(d, s)$ in the form of payoff matrices in Tables 1 and 2.

The rows and columns of each matrix represent, respectively, player α's and player β's strategies (action or sequence of actions). The first entry in each parenthesis represents player α's per-period payoff, and the second entry represents player β's per-period payoff. Note that, regardless of who chooses to develop, the total payoff always sums to a in period 1 when development takes place in that period. Similarly, the total payoff from development in period 2 is b when $s = s_1$ and $-c$ when $s = s_2$, respectively. An important parameter in Table 2 is k. When $k > 1/2$, the leader takes a larger share of the total payoff from development than the follower, and the opposite is true when $k < 1/2$. Therefore, k can be considered a measure of leader advantage in getting a larger share of the total payoff than the follower.

There is no reason *a priori* to assume that k is larger than, equal to, or smaller than $1/2$. It would be possible for the leader in development to retain a large share of forest in period 2, because he already has a footing in the forest. However, it would also be possible for the follower to obtain a larger share of the forest if the institution is designed to favor the follower in period 2 to ensure dynamic equality with regard to the use of open-access resources.

It should also be noted that the share k is fixed regardless of the state in this model. There are two reasons for this choice. First, by fixing k, the responsibility for the (potential) loss of biological resources is proportionate to the (potential) gain from development. In this way, we can shut off the externality due to the loss of biological resources. Second, by fixing k, we can keep the number of model parameters small.

Having said this, however, it is plausible that in practice the benefits and costs of development may be shared differently by the players. When biological resources are lost, everyone in the society may be hurt. On the other hand, logging would only benefit the loggers. Therefore, depending on the situation, it may be appropriate to let k depend on the state.

In the remainder of this paper, we assume that the regulator is able to transfer the payoffs between the players in a lump-sum manner. Therefore, the social welfare function that the regulator tries to maximize is simply the expected total payoff in the society (i.e., the sum of the payoffs for players α and β) for the two periods.

We shall consider the following three cases in which the regulator r has different degrees of control over the actions of the players and sends different type of information about the true state:

(I) The regulator is a social planner who can stipulate the actions taken by each player. This is the first-best case and is equivalent to a single decision-maker case.

(II) The regulator is merely an informant. He simply tells the players the true state in period 2 before their actions are taken; he has no control over the actions taken by each player. This case is used to introduce the EVI for the society.

(III) The regulator has no control over the actions taken by each player and also has no knowledge of the values of a, b, and c, except that they satisfy a certain condition. He can, however, send a (potentially noisy) message about the state to each player to achieve an efficient outcome. The regulator may vary the message across players.

In each of these cases, the regulator learns the state in period 2 and may pass to the players some information about the true state.

In the next subsections, we shall discuss the QOV as well as a related concept of the EVI for Cases (I) and (II). Comparison of these cases allows us to see the importance of strategic interactions in the model of irreversible investment. It also permits us to highlight some conceptual difficulties with the QOV under conditions where strategic interactions occur.

We shall delay the discussion of Case (III) until the next section, in which we discuss the possibility of sending messages about the state to the players in an asymmetric manner to achieve an efficient outcome. We will demonstrate that the EVI for the society depends critically on how the information is disseminated. For example, making better information available to everyone hurts everyone when the prospect of better information induces a prisoner's dilemma situation. In such cases, social welfare may be improved by providing information to the public asymmetrically so that one player gets better information than the other. Therefore, Case (III) points to the possibility that the government may be able to improve efficiency by manipulating the information given to the players.

2.1. Case (I): Social Planner

In Case (I), we shall consider a social planner, who can stipulate the actions taken by the players. Because the social planner is the sole decision-maker in this case, Case (I) is equivalent to the standard single-person setup. Therefore, the definitions of the QOV and EVI in Case (I) are also equivalent to the standard definitions. Note that the parameter k is not relevant in this case because this parameter affects only the distribution and not the expected total payoff.

Let $d_t^r \equiv d_t^\alpha + d_t^\beta - d_t^\alpha d_t^\beta$; this expression takes a value of zero if both players choose to conserve in period $t \in \{1, 2\}$ and a value of one otherwise. From the social planner's perspective, d_t^r provides sufficient statistics, because the expected total payoff depends only on whether and when development takes place, and not on who chooses to develop. Using d_t^r, we can also define the per-period payoff for the social planner as follows:

$$
\begin{aligned}
v_1^r(d_1^r) &= v_1^\alpha(d_1) + v_1^\beta(d_1) = a d_1^r && (2)\\
v_2^r(d_2^r, s) &= v_2^\alpha(d, s) + v_2^\beta(d, s) = (b \cdot \mathrm{Ind}(s = s_1) - c \cdot \mathrm{Ind}(s = s_2))\, d_2^r, && (3)
\end{aligned}
$$

where $\mathrm{Ind}(\cdot)$ is an indicator function that takes a value of one if the statement inside the parentheses is true and zero otherwise and where $d_1^i \leq d_2^i$ is satisfied for $i \in \{\alpha, \beta, r\}$.

To define the QOV and EVI, we need to consider two scenarios. In the first, no information about the state is available to the players or the social planner in period 2. Hence, all decisions can be made in period 1, and these decisions correspond to the open-loop strategy. In this scenario, the objective function that the social planner wishes to maximize in period 1 is the following:

$$\begin{aligned} V^*(d_1^r) &\equiv v_1^r(d_1^r) + \max_{d_2^r(\geq d_1^r)} \mathbf{E}_s[v_2^r(d_2^r, s)] && (4) \\ &= v_1^r(d_1^r) + \max_{d_2^r(\geq d_1^r)} \{B - C, 0\}, && (5) \end{aligned}$$

where $B \equiv \pi b$, $C \equiv (1-\pi)c$, and $\mathbf{E}_s[\cdot]$ is an expectation operator taken over all the possible states. We use an asterisk (*) to emphasize that the decisions are made in the absence of information in period 2. B and C may be interpreted as the expected payoff for period 2, decomposed into the s_1- and s_2-components.

The social planner chooses d_1^{r*} in period 1 to maximize $V^*(\cdot)$. Because $V^*(0) = \max\{B - C, 0\}$ and $V^*(1) = (a + B - C)$, we have:

$$\begin{aligned} W_I^* &\equiv \max_{d_1^r} V^*(d_1^r) && (6) \\ &= V^*(d_1^{r*}) && (7) \\ &= \begin{cases} V^*(1) = a + B - C & \text{if } C < a + B \\ V^*(0) = 0 & \text{if } C \geq a + B, \end{cases} && (8) \end{aligned}$$

with $d_1^{r*} = \text{Ind}(C < a + B)$.

In the second scenario, information about the state becomes available before actions are taken in period 2 but after actions are taken in period 1. In general, information about the state may consist of a message that contains some information about the state. However, in this section, we consider only the simplest case, in which the information is perfect (i.e., the players and the social planner learn the true state in period 2). Therefore, in the second scenario, the players are allowed to take state-contingent actions in period 2, and the strategy in this scenario corresponds to the closed-loop strategy. The objective function in this scenario can be written as follows:

$$\begin{aligned} \hat{V}(d_1^r) &\equiv v_1^r(d_1^r) + \mathbf{E}_s\big[\max_{d_2^r(s)} v_2^r(d_2^r(s), s)\big] && (9) \\ &= v_1^r(d_1^r) + (B - C)d_1^r + B(1 - d_1^r) && (10) \\ &= (a - C)d_1^r + B. && (11) \end{aligned}$$

We use the hat $(\hat{\ })$ notation to emphasize that the decisions are made in the presence of information in period 2. The social planner chooses $\hat{d}_1^r$ to maximize $\hat{V}(\cdot)$. Because $\hat{V}(0) = B$ and $\hat{V}(1) = a + B - C$, we have:

$$\begin{aligned} \hat{W}_I &\equiv \max_{d_1^r} \hat{V}(d_1^r) && (12) \\ &= \hat{V}(\hat{d}_1^r) && (13) \\ &= \begin{cases} \hat{V}(1) = a + B - C & \text{if } C < a \\ \hat{V}(0) = B & \text{if } C \geq a, \end{cases} && (14) \end{aligned}$$

with $\hat{d}_1^r = \text{Ind}(C < a)$.

Following Arrow and Fisher (1974), Henry (1974), Fisher and Hanemann (1987), and Hanemann (1989), the QOV in Case (I) is the difference in the expected net present value of development relative to conservation between the two scenarios. That is:

$$\text{QOV}_I \equiv (\hat{V}(0) - \hat{V}(1)) - (V^*(0) - V^*(1)) = \min(B, C). \tag{15}$$

The QOV can be interpreted in the following way. Suppose we evaluate the conservation (relative to development) in period 1 while ignoring the prospect of new information in period 2. The net present value of conservation is then $V^*(0) - V^*(1)$. However, this is not a correct calculation. To obtain the correct net present value of conservation (i.e., $\hat{V}(0) - \hat{V}(1)$), we need to add an adjustment term. This adjustment term is the QOV.

In this model, the information in period 2 is valueless when development starts in period 1 because the decision to develop is irreversible. This point is reflected in the fact that $V^*(1) = \hat{V}(1)$. Using this relationship, we can rewrite Eq.(15) as $\text{QOV}_I = \hat{V}(0) - V^*(0)$. Therefore, as Hanemann (1989) has shown, QOV can be interpreted as the value of information conditional on conservation in period 1.

The EVI should be defined as the expected gains in the objective function from the information that becomes available in period 2. Following Hanemann (1989), we define EVI as follows:

$$\text{EVI} \equiv \hat{W}_I - W_I^* = \begin{cases} 0 & \text{if } C < a \\ -a + C & \text{if } a \leq C < a + B \\ B & \text{if } a + B \leq C. \end{cases} \tag{16}$$

The definitions of QOV and EVI in Case (I) are equivalent to the standard definitions. Therefore, Case (I) serves as a benchmark case for this study and is used as a basis for comparison with the two cases presented below.

2.2. Case (II): Social EVI resulting from decentralized decision making

Case (II) is the same as Case (I) except that in Case (II) the regulator has no control over the players' actions. In other words, the players can freely choose their actions. The regulator in Case (II) simply informs the players of the state in period 2 before their actions are taken.

A major difference between Case (I) and Case (II) is that in Case (II), each player has to take into account the direct consequences of his own action (i.e., if he chooses to develop in period 1, then he must choose to develop in period 2 as well) as well as his opponent's response to his action. In our model, player i assumes that his opponent $-i \equiv \{\alpha, \beta\} \setminus \{i\}$ always plays the best response to his action in each period, and this is common knowledge. We also assume that the players know exactly whether and how the information is transmitted from the regulator; this assumption is maintained for the rest of this paper.

Because, given the action profile $d_1 = (d_1^\alpha, d_1^\beta)(\in A_1)$ in period 1, each player freely chooses his own action, a Nash equilibrium is played in period 2. With this equilibrium, we can go back to period 1, and find the subgame perfect Nash equilibrium. By comparing the equilibrium outcome that occurs with and without the prospect of information in period 2, we can consider the QOV and EVI for Case (II). As we argue below, it turns out to be difficult to define the QOV in the presence of strategic interactions. However, by comparing the EVI for Case (I) and Case (II), we can see the impacts of strategic interactions.

Note that the equilibrium is not necessarily unique. Because equilibrium selection is not the focus of this paper, we simply assume that an equilibrium that is efficient under the potential compensation criterion (i.e., the equilibrium that has the highest expected total payoff) will be chosen. Even with this restriction, the possibility of multiple equilibria remains. However, once this restriction is imposed, the multiplicity of equilibria is irrelevant for our purpose because the total equilibrium payoff is unique. Further, as described in the Appendix, we have a unique equilibrium for most combinations of parameters. Therefore, even if we drop the assumption of efficient equilibrium, the main findings of our study will hold. We shall briefly consider the consequences of relaxing this assumption in the Appendix.

Let us now formally consider the QOV and EVI under strategic interactions with some additional notations. As with the previous subsection, we need to consider two scenarios. In the first, the information is not available to the players in period 2. Therefore, the players are not allowed to take state-contingent actions in period 2.

To solve the game using backward induction, we first define the best response BR_2^{i*} in period 2 for player $i (\in \{\alpha, \beta\})$ as a function of the action profile d_1 in period 1 and of the opponent's action $d_2^{-i} (\in A_2^{-i}(d_1^{-i}))$ in period 2, as follows:

$$BR_2^{i*}(d_2^{-i}; d_1) \in \arg \max_{d_2^i \in A_2^i(d_1^i)} \mathbf{E}_s[v_2^i((d_1, (d_2^\alpha, d_2^\beta)), s)]. \tag{17}$$

Given d_1, the Nash equilibrium in period 2 can be described as a pair d_2^* that satisfies the following:

$$d_2^*(d_1) \equiv \left(d_2^{\alpha*}(d_1), d_2^{\beta*}(d_1)\right) = \left(BR_2^{\alpha*}(d_2^{\beta*}; d_1), BR_2^{\beta*}(d_2^{\alpha*}; d_1)\right). \tag{18}$$

Using the Nash equilibrium action profile $d_2^*(d_1)$ in period 2, the best response BR_1^{i*} for player i in period 1 can be defined as follows:

$$BR_1^{i*}(d_1^{-i}) \in \arg \max_{d_1^i \in A_1^i} \left\{ v_1^i(d_1) + \mathbf{E}_s[v_2^i((d_1, d_2^*(d_1)), s)] \right\}. \tag{19}$$

Hence, the action profile d_1^* in a subgame perfect Nash equilibrium satisfies the expression:

$$d_1^* = \left(d_1^{\alpha*}, d_1^{\beta*}\right) = \left(BR_1^{\alpha*}(d_1^{\beta*}), BR_1^{\beta*}(d_1^{\alpha*})\right). \tag{20}$$

The sequence of the equilibrium action profile is given by $d^* \equiv (d_1^*, d_2^*(d_1^*))$.

Let us now illustrate the solution procedure described above. The top panel of Table 3 provides the expected payoff profile for all the possible action profiles. The bold rules define the four subgames determined by each of the four action profiles $d_1 \in \{(0,0), (0,1), (1,0), (1,1)\}$. For example, when the action profile in period 1 is $d_1 = (0,0)$, the cells a*), b*), d*), and e*) belong to the same subgame. The cell i*), on the other hand, is a subgame in itself. Therefore, given $d_1 = (1,1)$, this cell is trivially an equilibrium in period 2

Let us now describe how backward induction works in our model when $C > a + B$. The lightly shaded cells in the top panel of Table 3 provide the equilibrium in each subgame. Going back to period 1, we have the bottom panel of Table 3. When $C > a + B$, both players choose $d_1^i = 0$, so that the sequence of the action profile in the subgame perfect Nash equilibrium is $((0,0), (0,0))$. Hereafter, we shall use the payoff matrix to describe the equilibrium. For example, when $C > a + B$, the equilibrium is given by the cell a*) in the top panel of Table 3.

One might argue that the analysis could be simplified by taking the Nash equilibrium in the top panel instead of considering the equilibrium in each subgame. It turns out that doing so makes no difference for the analysis in this subsection. However, in general, the players cannot commit to the action taken in period 2, and this point is relevant in the next section. Therefore, the subgame perfect Nash equilibrium is a more appropriate solution concept in our model.

Table 3: The *ex ante* expected payoff matrix when no information is available in period 2 (top), and the reduced payoff matrix using backward induction (bottom). The lightly shaded cells represent the Nash equilibria in the subgames in period 2, and the heavily shaded cell the subgame perfect Nash equilibrium for $C > a + B$.

	d_1^β	0				1	
d_1^α	d_2^α \ d_2^β	0		1		1	
0	0	a^*)	$(0,0)$	b*)	$(0, B-C)$	c*)	$(0, a+B-C)$
	1	d*)	$(B-C, 0)$	e*)	$((B-C)/2, (B-C)/2)$	f*)	$((1-k)(B-C), a+k(B-C))$
1	1	g*)	$(a+B-C, 0)$	h*)	$(a+k(B-C), (1-k)(B-C))$	i*)	$((a+B-C)/2, (a+B-C)/2)$

$\downarrow$

d_1^α \ d_1^β	0		1	
0	a*)	$(0,0)$	c*)	$(0, a+B-C)$
1	g*)	$(a+B-C, 0)$	i*)	$((a+B-C)/2, (a+B-C)/2)$

Table 4: The *ex ante* payoff matrix when the players learn the true state in period 2 before they take actions

	d_1^β	0		1	
d_1^α	$d_2^\beta(s)$ \ $d_2^\alpha(s)$	$\text{Ind}(s = s_1)$		1	
0	$\text{Ind}(s = s_1)$	â)	$(B/2, B/2)$	b̂)	$((1-k)B, a+kB-C)$
1	1	ĉ)	$(a+kB-C, (1-k)B)$	d̂)	$((a+B-C)/2, (a+B-C)/2)$

Let us now consider the second scenario, in which the uncertainty about the state is resolved after players have taken actions in period 1 but before actions are taken in period 2. Because both players know the state before they take their actions in period 2, each player i is able to take his actions $d_2^i(s)$ contingent on the state $s(\in S)$ in this scenario. To obtain the equilibrium action profile, we need to define the best response $\widehat{BR}_2^i$ of player i in period 2 as a function of the action profile $d_1(\in A_1)$ in period 1, the opponent's action $d_2^{-i}(s)(\in A_2^{-i})$, and the state s as follows:

$$\widehat{BR}_2^i(d_2^{-i}(s); d_1, s) \in \arg\max_{d_2^i(s)\in A_2^i(d_1^i)} \left\{ v_2^i((d_1, (d_2^\alpha(s), d_2^\beta(s))), s) \right\} \quad \text{for} \quad i \in \{\alpha, \beta\}. \tag{21}$$

With this definition and given $d_1(\in A_1)$, the Nash equilibrium action profile in period 2 can be described as a pair of best response actions $\hat{d}_2(d_1, s)(\in A_2(d_1))$ in the following manner:

$$\hat{d}_2(d_1, s) \equiv (\hat{d}_2^\alpha(s; d_1), \hat{d}_2^\beta(s; d_1)) = \left(\widehat{BR}_2^\alpha(\hat{d}_2^\beta(s; d_1); d_1, s), \widehat{BR}_2^\beta(\hat{d}_2^\alpha(s; d_1); d_1, s) \right). \tag{22}$$

We can now go back to period 1 and define the best response in period 1 as a function of the opponent's action as follows:

$$\widehat{BR}_1^i(d_1^{-i}) \in \arg\max_{d_1^i \in A_1^i} \left\{ v_1^i(d_1) + \mathbf{E}_s[v_2^i((d_1, \hat{d}_2(d_1, s)), s)] \right\} \quad \text{for} \quad i \in \{\alpha, \beta\}. \tag{23}$$

Given this, the subgame perfect Nash equilibrium action profile in period 1 is $\hat{d}_1$:

$$\hat{d}_1 = (\hat{d}_1^\alpha, \hat{d}_1^\beta) = \left(\widehat{BR}_1^\alpha(\hat{d}_1^\beta), \widehat{BR}_1^\beta(\hat{d}_1^\alpha) \right) \tag{24}$$

Thus, the sequence of the equilibrium action profile in the presence of information in period 2 is given by $\hat{d}(s) \equiv (\hat{d}_1, \hat{d}_2(\hat{d}_1, s))$.

When the players can take state-contingent actions, they always choose to develop if the state is s_1 and never choose to develop if the state is s_2 regardless of the parameter values. Therefore, $(d_2^i(s_1), d_2^i(s_2)) = (1, 0)$ dominates $(0, 0)$, $(0, 1)$, and $(1, 1)$. After eliminating the dominated strategies, we can write the *ex ante* payoff matrix, as shown in Table 4. As the table shows, there is only one cell in each of the four subgames in period 2. As a result, the subgame-perfect Nash equilibrium is identical to the Nash equilibrium for a one-shot game with the same payoff matrix.

Let us now revisit the concepts of the QOV and EVI. The standard QOV measures the difference in the payoff of conservation relative to development between the two scenarios with and without information about the state in period 2. Therefore, if $\hat{V}(0)$, $\hat{V}(1)$, $V^*(0)$, and $V^*(1)$ for the society could somehow be defined (hereafter, we denote these with the subscript S), then the social QOV could be defined as $\mathrm{QOV}_S \equiv (\hat{V}_S(0) - \hat{V}_S(1)) - (V_S^*(0) - V_S^*(1))$.

However, the problem is that it is difficult to meaningfully define $\hat{V}_S(0)$ and so on. Ideally, $\hat{V}_S(0)$ should be defined as the total payoff when conservation takes place in period 1. However, if the regulator is unable to stipulate the players' actions and if conservation in period 1 is not supported as an equilibrium, then the regulator does not really have an option to delay development decision until period 2. Therefore, without additional restrictions on the equilibrium, it would not be possible to meaningfully define the social QOV.

Unlike the social QOV, it is possible to meaningfully define the EVI for the society in the presence of strategic interactions. The idea is simple; we take the change in the expected total payoff in the equilibrium due to the information that becomes available in period 2. Formally, we can define the social EVI (EVI_S) as follows:

Definition 1 Let $\hat{W}_{II} \equiv \mathbf{E}_s\left[\left(v_1^\alpha(\hat{d}_1) + v_1^\beta(\hat{d}_1) + v_2^\alpha(\hat{d}(s), s) + v_2^\beta(\hat{d}(s), s)\right)\right]$ be the expected total payoff with information about the true state in period 2. Similarly, we let $W_{II}^* \equiv \mathbf{E}_s\left[v_1^\alpha(d_1^*) + v_1^\beta(d_1^*) + v_2^\alpha(d^*, s) + v_2^\beta(d^*, s)\right]$ be the expected total payoff without information about the true state in period 2. We define the social EVI under strategic interactions as follows:

$$\mathrm{EVI}_S \equiv \hat{W}_{II} - W_{II}^*. \tag{25}$$

The social EVI is not uniquely defined if there are multiple equilibria. Therefore, as discussed earlier, we shall take the most efficient equilibrium. With this restriction, the full description of EVI_S is given in the Appendix.

One important point to notice from Definition 1 is that the social EVI may or may not be positive. Remember that the players are informed of the true state in period 2 before the actions are taken. Therefore, if the social EVI is negative, making more information available to everyone decreases the efficiency. For the payoff structure described in Tables 1 and 2, it is possible to show the following proposition:

Proposition 1 *The social EVI is negative if and only if*

$$k < \frac{1}{2}, \quad C < a, \quad \text{and} \quad \frac{2(a-C)}{1-2k} < B < C + \frac{2a}{1-2k} \tag{26}$$

A complete description of EVI_S for all possible combination of parameters is provided in the Appendix, and it also serves as an informal proof of this proposition. We shall discuss below why the prospect of additional information is possibly harmful to everyone.

When $k < 1/2$, we have a situation where a larger share of the benefits (and costs) will be obtained if the player is a follower in development. Therefore, if $B > C$, each player has the incentive to hold back development until period 2 so that he does not have to suffer from the leader disadvantage. Obviously, this point must be weighed against the opportunity cost (a) of conservation in period 1.

When $C < a$ holds, it is efficient for the society to develop in period 1 because the opportunity cost of conservation in period 1 is large relative to the potential gains from information (C is the expected loss that could be avoided by utilizing the information in period 2). This efficient outcome is achieved in the absence of information in period 2 if development is sufficiently attractive but B is not large enough for the players to try to be followers in development. This occurs when $0 < B < C + 2a/(1-2k)$. Therefore, the upper bound on B in Eq.(26) reflects the condition for the efficient outcome in the absence of information.

Now consider the scenario in which the players learn the state in period 2. In this scenario, the players have more to lose by choosing development in period 1. Because the opponent can take state-contingent actions in period 2, players suffer from a larger cost when the state is $s = s_2$, whereas they enjoy a smaller fraction of benefit when the state is $s = s_1$, because $k < 1/2$. Therefore, the prospect of future information gives each player an additional incentive to conserve in period 1. The lower bound on B ensures that both players choose to conserve in period 1 in this scenario. As a result, when Eq.(26) holds, conservation takes place in period 1 even if it is not socially efficient to conserve.

In short, the situation described in Eq.(26) shows that the prospect of future information induces a prisoner's dilemma situation. There are other situations in our model where such a situation arises in the presence of information (② and ⑥ in Figure A.2 and Table A.7 in the Appendix), but the situation described in Proposition 1 is unique in the sense that the prisoner's dilemma is induced by the prospect of better information.

This point begs another question. Would it be possible for the regulator to manipulate the information given to the players in such a way as to improve the efficiency (by avoiding the prisoner's dilemma situation)? It is clear from Proposition 1 that the regulator can improve efficiency by not passing information to players when Eq.(26) holds (the regulator announces in period 1 that he does not give any information on the state in period 2). Therefore, when the regulator knows the values of a, B, and C, he can simply choose to pass information if and only if Eq.(26) does not hold.

However, it is possible that some of the parameters are not known to the regulator in some practical settings. For example, the benefits from developing the forest may be better known to the loggers than to the regulator. Therefore, it is useful to consider a situation in which a, B, and C are known only to the two players, and the regulator has only some vague ideas about their values. We demonstrate in the next section that, even in such a situation, the regulator may be able to induce an efficient equilibrium by giving information to the players asymmetrically.

3. Case (III): Optimal regulation under strategic interactions and informational constraints

Thus far, the players have been treated completely symmetrically (i.e., players α and β have been treated in the same way). However, under certain assumptions stated below, it is socially desirable to give perfect information to one of the players and less-than-perfect information (noisy message about the true state) to the other player. Without loss of generality, we let the former player be player β and the latter player α.

With perfect information, player α chooses to develop if and only if the social planner in Case (I) would choose to develop. Put differently, player β makes the right decision about development. At the same time, the incentive for player α to wait until period 2 is smaller in this case than in Case (II), where there is a prospect of future information. Therefore, the prisoner's dilemma situation due to the prospect of future information described in the previous section can be avoided.

Sending information in this way would raise the following question: Why does one of the players have to learn the true state? The answer is that if neither player knows the true state, there is always a small probability that an inefficient outcome is supported as an equilibrium. Therefore, we need at least one player to know the true state.

We hereafter focus on cases in which sending information asymmetrically can help improve efficiency. Therefore, in this section, we make the following assumptions: (A-i) $k < 1/2$, (A-ii) $B < 2a/(1-2k)$, and (A-iii) a, B, and C are known to the players but not to the regulator.

Assumption (A-i) is required to have a situation in which information-induced inefficiency occurs. Assumption (A-ii) is also necessary. When B is very large relative to other parameters, the regulator cannot keep the players from choosing to conserve in period 1 because the cost of the leader disadvantage is simply too large. Therefore, we need an upper bound on B. We include Assumption (A-iii) to make the possibility of sending information asymmetrically meaningful. This assumption is not essential and can be dropped without any major modifications. However, if the values of a, B, and C are also known to the regulator, the regulator can achieve an efficient outcome by sending the information to neither or both players. Hence, the regulator does not gain anything from the possibility of sending information asymmetrically.

We can now formalize the idea described above. Suppose that the regulator informs player β of the true state in period 2 before an action is taken. Player α, on the other hand, receives a message $m \in \mathcal{M}$ from the regulator, where $\mathcal{M}$ is the message space. In period 2, player α can take a message-contingent action and player β a state-contingent action, if they have chosen to conserve in period 1. This structure is common knowledge.

There are five possible strategies for player β: (a) $d^\beta = (0,0)$, (b) $d^\beta = (0,1)$, (c) $d^\beta = (0, \mathrm{Ind}(s = s_1))$, (d) $d^\beta = (0, \mathrm{Ind}(s = s_2))$, and (e) $d^\beta = (1,1)$. Because strategy (c) dominates strategies (b), (d) and (e), the only strategies that can possibly be chosen in an equilibrium are (a) and (c). As a result, the regulator does not need more than two messages because there are at most two Nash equilibria in general except for some corner cases that have measure zero on the $B - C$ plane. Therefore, we can let $\mathcal{M} = \{m_1, m_2\}$ without loss of generality.

We assume that the message sent to player α has the following structure: the regulator can choose the probability of sending a message conditional on the state. That is, the regulator can choose q_1 and q_2, where $\Pr(m = m_1|s_1) = q_1$ and $\Pr(m = m_1|s_2) = q_2$ before the players choose their actions in period 1. We assume that the players know q_1 and q_2. Because player α always receives a m_1 or m_2, we also have $\Pr(m = m_2|s_1) = 1 - q_1$ and $\Pr(m = m_2|s_2) = 1 - q_2$. As with player β, there are five possible strategies for α, though player α can only take a message-contingent action instead of a state-contingent action. Unlike the case of player β, none of these five strategies are trivially dominated by others.

With a slight abuse of notation, we can define the best response functions for players α and β in period 2 in a way similar to that presented previously:

$$\widetilde{BR}_2^\alpha(d_2^\beta(s); d_1, m) \in \arg\max_{d_2^\alpha(m) \in A_2^\alpha(d_1^\alpha)} \mathbf{E}_s \left[v_2^\alpha((d_1, (d_2^\alpha(m), d_2^\beta(s))), s)|m \right] \tag{27}$$

$$\widetilde{BR}_2^\beta(d_2^\alpha(m); d_1, s) \in \arg\max_{d_2^\beta(s) \in A_2^\beta(d_1^\beta)} \mathbf{E}_m \left[v_2^\beta((d_1, (d_2^\alpha(m), d_2^\beta(s))), s)|s \right] \tag{28}$$

Now, given $s \in \{s_1, s_2\}$ and $m \in \{m_1, m_2\}$, we can define the equilibrium action profile in period 2 as follows:

$$\tilde{d}_2(d_1, (s, m)) = (\tilde{d}_2^\alpha(m; d_1), \tilde{d}_2^\beta(s; d_1)) \tag{29}$$

$$= \left(\widetilde{BR}_2^\alpha(\tilde{d}^\beta(s; d_1); d_1, m), \widetilde{BR}_2^\beta(\tilde{d}_2^\alpha(m; d_1); d_1, s) \right). \tag{30}$$

By going back to period 1, we can define the best response in period 1 in the following manner:

$$\widetilde{BR}_1^i(d_1^{-i}) \in \arg\max_{d_1^i \in A_1^i} v_1^i(d_1^\alpha, d_1^\beta) + \mathbf{E}_{(s,m)} \left[v_2^i(d_1, \tilde{d}_2(d_1, (s, m)), s) \right] \quad \text{for} \quad i \in \{\alpha, \beta\} \tag{31}$$

Given this, the equilibrium action profile in period 1 is characterized by the following:

$$\tilde{d}_1 = (\tilde{d}_1^\alpha, \tilde{d}_1^\beta) = (\widetilde{BR}_1^\alpha(\tilde{d}_1^\beta), \widetilde{BR}_1^\beta(\tilde{d}_1^\alpha)). \tag{32}$$

Using this, the sequence of equilibrium profile can be written as $\tilde{d}(s,m) \equiv (\tilde{d}_1, \tilde{d}_2(\tilde{d}_1,(s,m)))$.

Based on this, we can define as follows the expected value of information for the society when the regulator gives information asymmetrically:

$$\widetilde{EVI}_S \equiv \tilde{W}_{III} - W^*_{II}, \tag{33}$$

where $\tilde{W}_{III} \equiv \mathbf{E}_{(s,m)}\left[v_1^\alpha(\tilde{d}_1) + v_1^\beta(\tilde{d}_1) + v_2^\alpha(\tilde{d}(s,m),s) + v_2^\beta(\tilde{d}(s,m),s)\right]$ is the expected total payoff when the information is asymmetrically sent.

Let us now create the *ex ante* expected payoff matrix similar to Tables 3 and 4. To show how this is done, let us consider cell $\tilde{d}$) in Table 5. Suppose that player β always chooses to develop in both periods and that player α chooses to conserve in period 1 and develop in period 2 if and only if $m = m_1$. When $(s,m) = (s_1, m_1)$, the sum of payoffs over the two periods for the two players is $((1-k)b, a+kb)$, and this occurs with probability πq_1. Similarly, the sum of payoffs for the two players is $(-(1-k)c, a-kc)$, $(0, a+b)$, and $(0, a-c)$ when (s,m) is (s_2, m_1), (s_1, m_2), and (s_2, m_2), respectively. These occur with probabilities $q_2(1-\pi)$, $\pi(1-q_1)$, and $(1-\pi)(1-q_2)$, respectively. Therefore, the expected payoff in this example is:

$$\begin{aligned} & \pi q_1((1-k)b, a+kb) + q_2(1-\pi)(-(1-k)c, a-kc) && (34)\\ & \quad +\pi(1-q_1)(0,a+b) + (1-\pi)(1-q_2)(0,a-c) \\ = \; & ((1-k)(Bq_1 - Cq_2)), (a + (kq_1 + (1-q_1))B - (kq_2 + (1-q_2))C)) \, . && (35) \end{aligned}$$

Carrying out similar computations for other strategy profiles, we have Table 5. As with the previous tables, the bold rules define the subgames. Thus, we can solve the game using backward induction as with Case (II).

The regulator can choose q_1 and q_2 appropriately so that an efficient outcome is supported as an equilibrium. It turns out that an efficient outcome can be always supported as an equilibrium under Assumptions (A-i) and (A-ii) regardless of the values of a, b, and c:

Proposition 2 . *Suppose that Assumptions (A-i) and (A-ii) hold. Then, except for some corner cases with measure zero on the $B - C$ plane, a necessary and sufficient condition for the subgame perfect Nash equilibrium to be efficient (i.e., $\hat{W}_I = \tilde{W}_{III}$) is $(q_1, q_2) = (2k, 0)$.*

Proof. Let us first discuss the necessary condition. Notice first that $\hat{W}_I = B$ when $C \geq a$. Therefore, we must have $\tilde{W}_{III} = B$ for $C \geq a$. This can only occur when the equilibrium is either in cell ã), or in cell c̃) when $q_2 = 0$ in Table 5. However, ã) cannot be an equilibrium if, for example, $B/2 > C \geq a$, because $d_2^\alpha(m) = 1$ dominates $d_2^\alpha(m) = 0$ for player α in this case. Therefore, $q_2 = 0$ is necessary.

Notice that $\max\left\{0, \frac{(1-q_1)B}{2} - (1-q_2)C, \frac{B}{2} - C, a + kB - C\right\} = a + kB - C$ for $B \leq \frac{2a}{1-2k}$. Therefore, for c̃) to be an equilibrium if and only if $C \geq a$, we want to have the following:

$$\frac{q_1 B}{2} \geq a + kB - C \Longleftrightarrow C \geq a \tag{36}$$

The above condition holds if and only if $q_1 = 2k$.

Table 5: The *ex ante* expected payoff matrix when player α receives a message about the state and player β learns the (true) state in period 2

	d_1^β		0		1
d_1^α	$d_2^\alpha(m)$ \ $d_2^\beta(s)$		$\mathrm{Ind}(s = s_1)$		1
0	0	ã)	$(0, B)$	$\tilde{\text{b}}$)	$(0, a + B - C)$
	$\mathrm{Ind}(m = m_1)$	c̃)	$(q_1B/2 - q_2C, (1 - q_1/2)B)$	$\tilde{\text{d}}$)	$((1 - k)(Bq_1 - Cq_2), a + (kq_1 + (1 - q_1))B - (kq_2 + (1 - q_2))C)$
	$\mathrm{Ind}(m = m_2)$	ẽ)	$((1 - q_1)B/2 - (1 - q_2)C, (1 + q_1)B/2)$	$\tilde{\text{f}}$)	$((1 - k)(B(1 - q_1) - C(1 - q_2)), a + (k(1 - q_1) + q_1)B - (k(1 - q_2) + q_2)C)$
	1	g̃)	$(B/2 - C, B/2)$	$\tilde{\text{h}}$)	$((1 - k)(B - C), a + k(B - C))$
1	1	ĩ)	$(a + kB - C, (1 - k)B)$	$\tilde{\text{j}}$)	$((a + B - C)/2, (a + B - C)/2)$

.

For the sufficiency, we have provided a complete description of the equilibrium for various combinations of a, B, and C when $(q_1, q_2) = (2k, 0)$ in Table A.9 and in Figure A.4 of the Appendix. This description also shows that $\tilde{W}_{III} = \hat{W}_I$ when $(q_1, q_2) = (2k, 0)$ under assumptions (A-i) and (A-ii). $\square$

Notice that there still remain some combinations of a, B, and C (①, ②, ④, and ⑤ in Figure A.4 of the Appendix) that lead to inefficient outcome. This is expected because the cost of the leader disadvantage is high when B is high, and this cannot be changed by manipulating the message. However, the figure also shows that Assumption (A-ii) can be slightly relaxed. We can replace it by Assumption (A-ii') $B < 2\max\{a, C\}/(1-2k)$.

The results reported in Table A.9 of the Appendix show that sending information with $(q_1, q_2) = (2k, 0)$ is good even when Assumption (A-ii') may not be satisfied, because $\widetilde{EVI}_S$ is always non-negative. Therefore, even if the regulator has no knowledge about a, b, and c, the regulator can still potentially improve the efficiency by sending information asymmetrically. Proposition 2 and this point underscore the importance of careful dissemination of information to achieve an efficient outcome.

4. Discussion

In this study, we have introduced strategic interactions into the analysis of QOV. In so doing, we have highlighted some conceptual difficulties with the QOV when the regulator (or the cost-benefit analyst, for that matter) has to take strategic interactions as given.

We have shown that information may be harmful to the society as a whole because it may induce a prisoner's dilemma situation. For example, when there is a follower advantage in development, there are always some incentives for players to conserve in period 1 even when it is inefficient to develop in period 1. By giving perfect information about the true state to player β and a noisy message to player α, we can exploit the value of information to the society in the first-best case (i.e., EVI_I) while avoiding the inefficiency induced by strategic interactions. Proposition 2 provides the conditions for this to occur.

Notice that two conditions needs to be satisfied for efficiency. First, if it is efficient for the society to develop in period 1, then development should take place in period 1. Second, if conservation is chosen in period 1 in the society, then development should take place in period 2 if and only if the state is s_1.

Provided that Assumptions (A-i) and (A-ii') hold, the sufficiency of the second condition is satisfied, because development is always chosen by player β in period 2 when the state is s_1. For the necessity part, it is clear that player β chooses to develop only if the state is s_1. Noting that the message m_1 is never sent when the state is s_2, we see that player α chooses to develop only if the state s_1. Therefore, the second condition is satisfied.

The first condition is also satisfied by giving a noisy message to player α. Because player α receives only less-than-perfect information about the state in period 2, the expected gains from delaying development is smaller for player α. As a result, conservation is not as attractive to player α as it is to player β in period 1. Hence, we can induce player α to choose to develop in period 1 when it is efficient for the society to do so.

Because the primary goals of this paper is to highlight some conceptual difficulties of the QOV and to demonstrate the potential importance of information-induced inefficiency, we tried to keep the model as parsimonious as possible. However, it is useful to discuss qualitatively what happens if our model allows for the possibility of state-dependent.

We consider an alternative setup, in which $k < 1/2$ if the state is s_1 and $k = 1/2$ if the state is s_2, because it is one of the most interesting cases. In this case, as with Case (III), the follower advantage is still present. However, the cost is equally shared when the two players choose to develop.

This setup could be interpreted in the context of climate change. Suppose that each player represents a country (*e.g.,* the US and China). We can regard $d_t^i = 0$ as "stringent environmental policy," and $d_t^i = 1$ as "business as usual." When $s = s_1$, a technology to cheaply eliminate the damages from climate change (by, say, removing greenhouse gases from the atmosphere) is found. Because the follower country may be able to adopt such a technology faster and more effectively than the other country, there may be a follower advantage (i.e., $k < 1/2$) when the state is s_1. On the other hand, when the state is s_2, no such technology is found. In this case, the damages from climate change would be felt equally by both countries so that $k = 1/2$. It would be reasonable to assume that B is bounded and that B and C are not very well known to the policy-makers of global climate policies.

Obviously, the example given represents a gross simplification of strategic interactions in the arena of global climate policy. Our model nevertheless offers some insights into how information should be handled in this context. In fact, the basic argument in Case (III) holds even in this alternative setup; The leader disadvantage is exacerbated by the fact that the follower never shares C with the leader with a prospect of perfect information, but the regulator can mitigate this by giving a noisy message to one of the players. Therefore, although the state dependence of k alters the incentive structures, the reason that giving a noisy message about the state helps ensure an efficient equilibrium remains the same.

Applications of our model to important environmental problems would potentially require careful calibration of parameters, extension of the number of players and the action space, and perhaps incorporation of the possibility of dependent learning. Yet, given that many global environmental problems feature irreversibility, strategic interactions and scientific uncertainty, we believe that the possibility of information-induced inefficiency is an area that deserves more attention than it has received.

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Table A.6: EVI and QOV when $k = 1/2$. (See also Figure A.1.)

	d^*	$\hat{d}(s)$	QOV_I	EVI_I	EVI_S
①	i*)	$\hat{\text{d}}$)	C	0	0
②	i*)	â)	C	$C-a$	$C-a$
③	i*)	$\hat{\text{d}}$)	B	0	0
④	i*)	â)	B	$C-a$	$C-a$
⑤	a*)	â)	B	B	B

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Appendix A. Appendix

In this appendix, we provide a complete description of the QOV and EVI for Cases (I) and (II) in Table A.6 and Figure A.1 for $k = 1/2$, in Table A.7 and Figure A.2 for $k > 1/2$, and in Table A.8 and Figure A.3 for $k < 1/2$. Note that the conditions in Proposition 1 correspond to ④, ⑧, and ⑫ in Table A.8 and Figure A.3.

We also provide in Table A.9 and Figure A.4 a complete description of the expected social welfare and EVI when the conditions in Proposition 2 are satisfied. In Assumption (A-ii) corresponds to ⑦, ⑧, ⑨, and ⑩ in Table A.9 and Figure A.4, whereas Assumption (A-ii') corresponds to ③ and ⑥ in addition to these. The shaded areas in Figures A.2-A.4 represent inefficient outcomes in the equilibrium (when information or message is provided by the regulator).

For Tables A.6 through A.9, we describe the combinations of parameters a, B, and C on the $B - C$ plane in Figures A.1-A.4, respectively. For example, ⑤ in Figure A.1 refers to the condition $C > a + B$ when $k = 1/2$. Reading the corresponding row in Table A.6, we have:

$$\text{QOV}_I = \text{EVI}_I = \text{EVI}_S = B. \tag{A.1}$$

In these tables, we also provide a complete description of the sequence of action profile in the equilibrium. To describe the sequence, we refer to the payoff matrices for Case (II) without information in period 2 in Table 3, for Case (II) with information in Table 4, for Case (III) when the condition in Proposition 2 is satisfied (i.e., $(q_1, q_2) = (2k, 0)$) in Table 5.

If there are multiple equilibria, the choice of the equilibrium potentially affects the computation of EVI_S. We have used brackets to indicate the inefficient equilibria (③ and ⑦ in Table A.2) that are not used for the computation of EVI_S. There are other cases with multiple equilibria that are equally efficient (③, ④, ⑤, ⑦, and ⑪ in Table A.3). In these cases, the choice of the equilibrium does not affect the values of EVI_S.

To show how the tables should be read, let us consider again ⑤ in Table A.6 (or $C > a+B$). The table indicates that d^* and $\hat{d}(s)$ are a*) and â) respectively. Referring to Tables 3 and 4, we see that $d^* = ((0,0),(0,0))$ and $\hat{d}(s) = ((0,0),(\text{Ind}(s = s_1), \text{Ind}(s = s_1)))$. Other cells should be interpreted in a similar manner.

Table A.7: EVI and QOV when $k > 1/2$. (See also Figure A.2.)

	d^*	$\hat{d}(s)$	QOV_I	EVI_I	EVI_S
①	i*)	$\hat{\text{d}}$)	C	0	0
②	i*)	$\hat{\text{d}}$	C	$C-a$	0
③	i*)	$\hat{\text{d}}$), [$\hat{\text{a}}$)]	C	$C-a$	$C-a$
④	i*)	$\hat{\text{a}}$)	C	$C-a$	$C-a$
⑤	i*)	$\hat{\text{d}}$)	B	0	0
⑥	i*)	$\hat{\text{d}}$)	B	$C-a$	0
⑦	i*)	$\hat{\text{d}}$), [$\hat{\text{a}}$)]	B	$C-a$	$C-a$
⑧	i*)	$\hat{\text{a}}$)	B	$C-a$	$C-a$
⑨	a*)	$\hat{\text{a}}$)	B	B	B

Table A.8: EVI and QOV when $k < 1/2$. (See also Figure A.3.)

	d^*	$\hat{d}(s)$	QOV_I	EVI_I	EVI_S
①	e*)	$\hat{a}$)	C	0	C
②	e*)	$\hat{a}$)	C	$C-a$	C
③	f*), h*)	$\hat{b}), \hat{c})$	C	0	0
④	f*), h*)	$\hat{a}$)	C	0	$C-a(<0)$
⑤	f*), h*)	$\hat{a}$)	C	$C-a$	$C-a$
⑥	i*)	$\hat{d}$)	C	0	0
⑦	i*)	$\hat{b}), \hat{c})$	C	0	0
⑧	i*)	$\hat{a}$)	C	0	$C-a(<0)$
⑨	i*)	$\hat{a}$)	C	$C-a$	$C-a$
⑩	i*)	$\hat{d}$)	B	0	0
⑪	i*)	$\hat{b}), \hat{c})$	B	0	0
⑫	i*)	$\hat{a}$)	B	0	$C-a(<0)$
⑬	i*)	$\hat{a}$)	B	$C-a$	$C-a$
⑭	a*)	$\hat{a}$)	B	B	B

Table A.9: EVI and the expected total payoff when the conditions in Proposition 2 are satisfied. (See also Figure A.4.)

	$\tilde{d}(s,m)$	$\tilde{W}_{III}$	W^*_{II}	$\widetilde{\text{EVI}}_S$	$\hat{W}_I$
①	$\tilde{\text{g}}$)	$B-C$	$B-C$	0	$a+B-C$
②	$\tilde{\text{g}}$)	$B-C$	$B-C$	0	B
③	$\tilde{\text{c}}$)	B	$B-C$	C	B
④	$\tilde{\text{g}}$)	$B-C$	$a+B-C$	a	$a+B-C$
⑤	$\tilde{\text{g}}$)	$B-C$	$a+B-C$	a	B
⑥	$\tilde{\text{c}}$)	B	$a+B-C$	$C-a(>0)$	B
⑦	$\tilde{\text{i}}$)	$a+B-C$	$a+B-C$	0	$a+B-C$
⑧	$\tilde{\text{h}}), \tilde{\text{i}})$	$a+B-C$	$a+B-C$	0	$a+B-C$
⑨	$\tilde{\text{j}}$)	$a+B-C$	$a+B-C$	0	$a+B-C$
⑩	$\tilde{\text{c}}$)	B	0	B	B

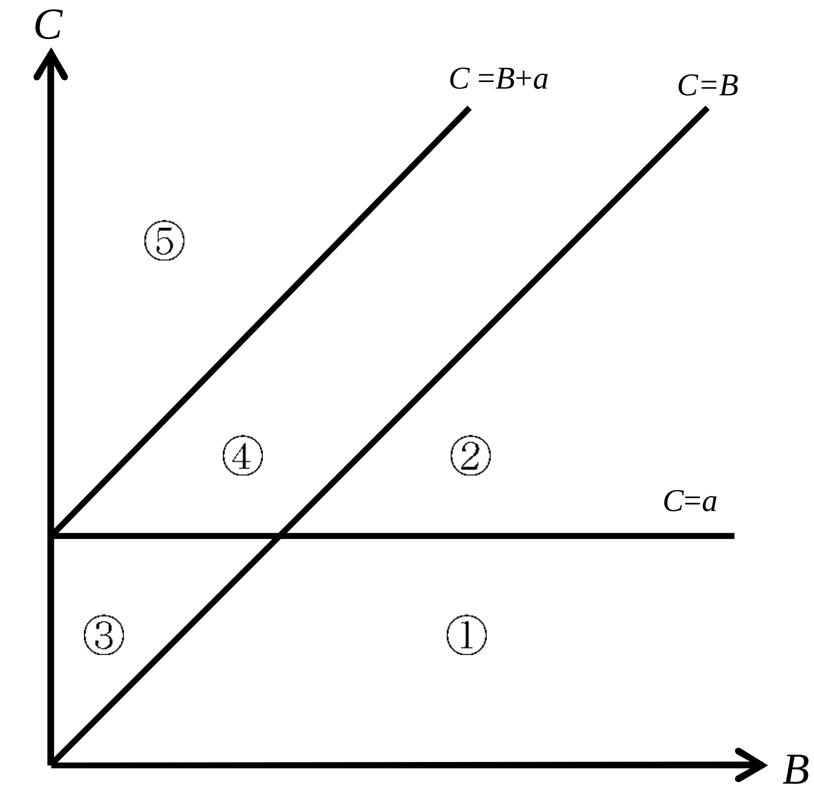

Figure A.1: Parameter combinations when $k = 1/2$.

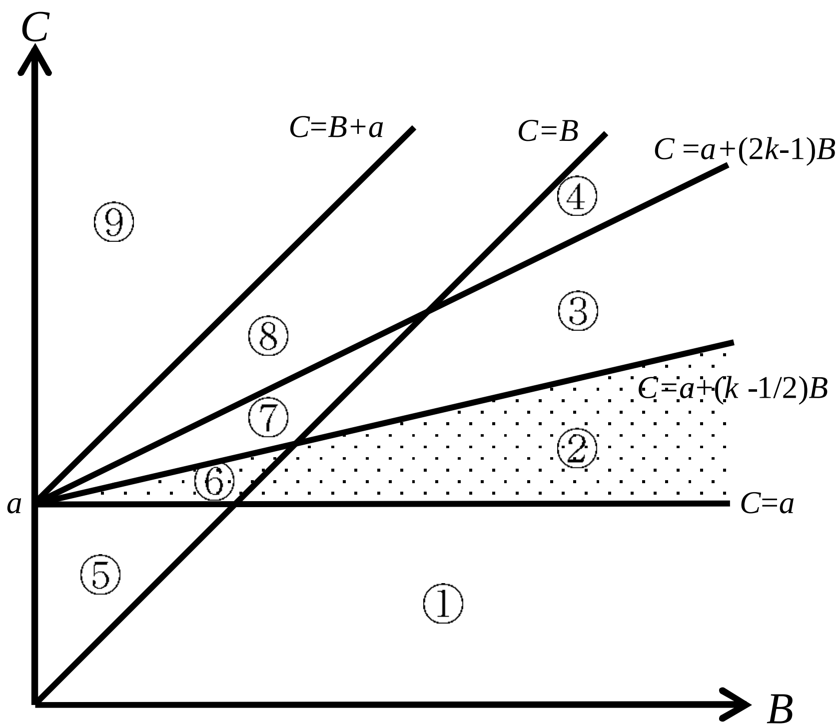

Figure A.2: Parameter combinations when $k > 1/2$.

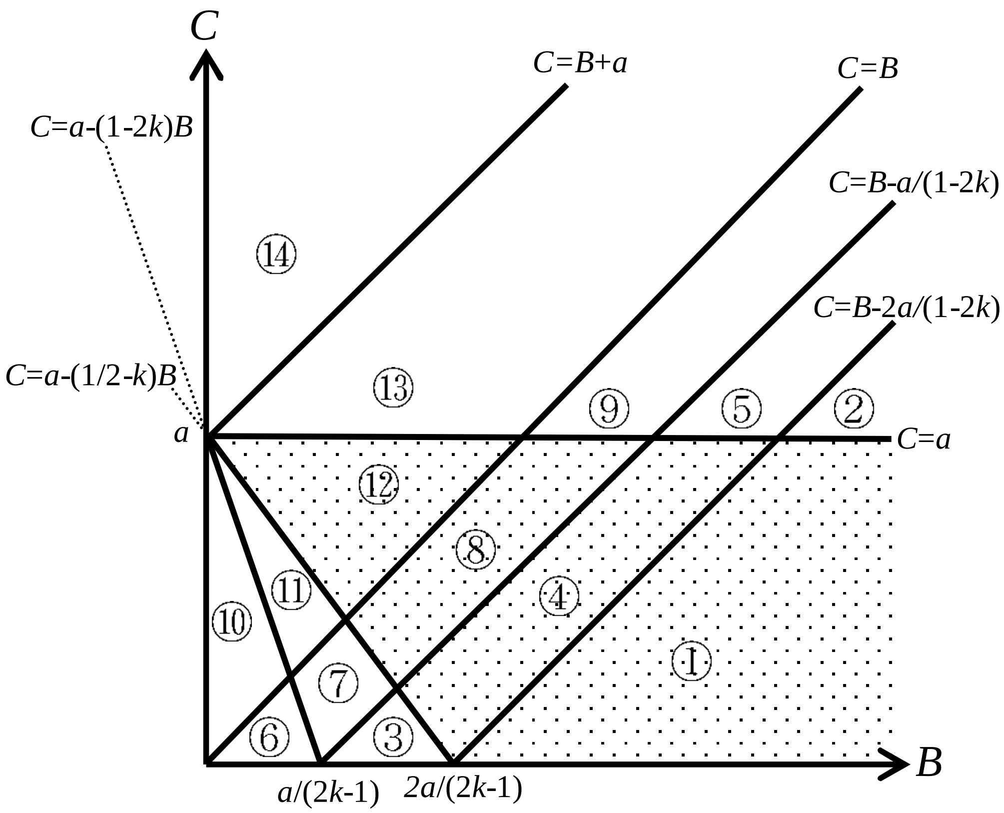

Figure A.3: Parameter combinations when $k < 1/2$.

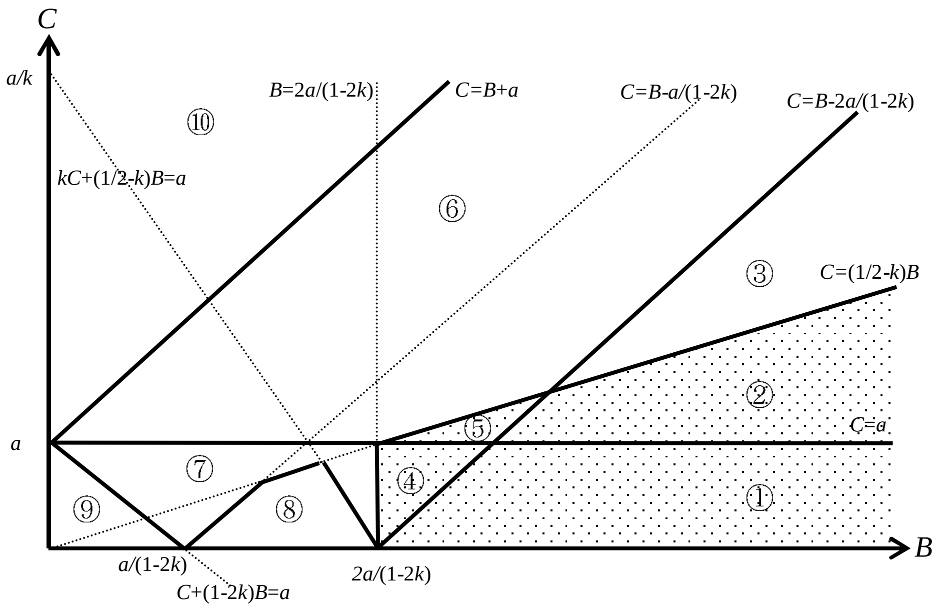

Figure A.4: Parameter combinations when the conditions in Proposition 2 are satisfied.