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Abstract

We consider a simple two-period model with irreversible investment with strategic interactions. In this setup, we try to extend the concept of the quasi-option value (QOV) by Arrow and Fisher (1974), Henry (1974), Fisher and Hanemann (1987) and Hanemann (1989) to a game-theoretic situation. In doing so, we demonstrate some conceptual difficulties with the QOV, and stress the potential importance of information-induced inefficiency. We also show that this inefficiency can be remedied by incorporating sophisticated control of information flow. Our model is potentially applicable to various global environmental problems.

JEL classification codes: C72, H43, Q50.

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

1 Introduction

Irreversibility is one of the most fundamental characteristics of environmental problems we are facing. Biodiversity is one example that features irreversibility. Extinction of a species is irreversible at least with the current technology, so that conservation of biodiversity is undoubtedly important. However, conservation of biodiversity is also a tricky policy objective because of the scientific uncertainties involved. We don't know very precisely how diverse the global biological resources are and how much of them are at risk. Estimates of the total number of species in existence on earth today greatly vary, though they commonly fall between 5 million and 30 million. It is estimated that only 1.8 million species, or less than 20 percent of the best working estimate of 8 to 9 million, have been described (See, Vié et al., eds (2009)). Further, out of these 1.8 million species, only about 2.7 percent have been assessed for the IUCN Red List, which is probably the most well-known and systematic efforts to catalogue the species facing a high risk of extinction.

These facts also have significant implications for the current climate debate. For example, the Interngovernmental Panel on Climate Change (2007) reports that 40 to 70 percent of species assessed is projected to go extinct as global average temperature increases by more than about 3.5 degrees relative to 1980-1999 period. Given this, it is likely that a number of species that are economically valuable are lost when the future rise in the Earth surface temperature is significant. Because greenhouse gases are stock pollutants and difficult to remove from the atmosphere in a short period of time, current economic activities may lead to irreversible (and negative) consequences.

Should we always avoid a project (or a course of actions) that entails irreversible consequences? The answer to this question is clearly no at least in the standard framework of the cost-benefit analysis. Irreversibility may affect the future states and possible future actions, but that alone does not affect the basic principle of project evaluation.

However, when there is uncertainty, project evaluation requires a careful assessment of the information that becomes available in the future. For example, some of the species that are yet to be described may be discovered and found economically valuable in the future. If a project drives such species to extinction by, say, clear-cutting a forest, the opportunity cost due to the lost species arises. However, the economic loss due to the extinction of unknown species is typically ignored in the project evaluation due to 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 better information in the future. This concept is related to the unconditional expected value of information (Conrad, 1980) but generally different from it (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 the they are different by the postponement value irrespective of uncertainty.

Since the quasi-option value is non-negative by the standard definition, ignoring the QOV (or opportunities due to better information available in the future) tends to bias decisions. In case of biodiversity conservation, ignoring the QOV would bias decisions against conservation in favor of immediate development.

The previous studies on the QOV mentioned above have generally assumed the presence of a single decision maker. This is a reasonable starting point, given that strategic interactions are almost always absent in a standard cost-benefit analysis. Yet, many of the situations where the concept of the QOV is useful involve strategic interactions among relevant players.

For example, suppose that an open-access forest potentially contains undiscovered genetic resources. In such a situation, the immediate benefits of logging to each logger may be large compared with the conservation of the forest. On the other hand, conservation may be a better option to the society at large, because the expected potential benefits from useful genetic resources—the existence of which may be known only in the future as a result of scientific research—are large enough. Therefore, a situation similar to the tragedy of commons may arise.

For the rest of the paper, we consider an action to be irreversible when it is prohibitively expensive to quickly restore the original state before the action was taken. Whether or not it is technologically feasible to restore the original state is irrelevant here. Once this definition of irreversibility is accepted, it can be seen that a number of environmental problems, in addition to an open-access forestry problem described above, involve irreversible actions taken by more than one players. We discuss two examples below to further motivate our analytical framework.

The first example is climate change. In addition to the potential loss of genetic resources, climate change may lead to a number of other consequences, including sea-level rises, increased incidence of extreme climatic events and changes in the pattern of rainfall. These consequences could be reversed in the long run. However, because it may take decades, if not centuries, to undo climate change, the present action to emit greenhouse gases can be deemed irreversible at least in the short run. Since the decision to emit greenhouse gases is made by more than one players, an appropriate treatment of strategic interactions is important and thus our analytical framework is relevant.

The second example to which our analytical framework is relevant is what is known as the brownfield problem. This problem originates from the enactment of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) in the United States. Under the CERCLA, developers may be liable for the cleaning-up cost of the brownfields—those properties *potentially* contaminated with hazardous substances, if such substances are found after the beginning of development. Further, the developers may be liable for the cleanup cost even after selling the land to someone else when the polluter cannot be identified. Hence, the decision to develop the land is irreversible in the sense that the potential liability cannot be undone.

As a result of the CERCLA, developers have become reluctant to develop the lands suspected with contaminants. This led to excessive development of greenfields and underdevelopment of brownfields, though this issue has been mitigated after the enactment of the Small Business Liability Relied and Brownfields Revitalization Act in 2002.[1]

The brownfield problem is more serious when there are positive spillovers to development. That is, potential developers may be discouraged from developing the brownfields not only because of the potential liability for the cleanup costs but because other developers are also in the same situation. Therefore, if a developer decides to develop a brownfield, he may run into the risk of developing a plot of land surrounded by completely empty plots. A proper analysis of this situation again requires an appropriate treatment of strategic interactions.

This paper has two purposes. The first purpose is to highlight some conceptual difficulties of the QOV under strategic interactions. The second purpose is to emphasize the potential importance of information-induced inefficiency. We demonstrate that everyone could be hurt if everyone knows that everyone will know more in the future. Therefore, the way information is disseminated is essential to best exploit the information that becomes available in the future.

This point is relevant to various global environmental problems, because the necessary actions

[1]See, for instance, Blakely and Leigh (2010) and Sterner (2002) for further discussion of the brownfield problem.

at present may be delayed to take advantage of the opportunities that arises due to the better information in the future. As we shall argue, this also means that information control may benefit the society under some circumstances.

This study is related to the aforementioned literature on the QOV, but it is obviously different, because we model strategic interactions explicitly. This study is also related to the value of information literature including Levine and Ponssard (1977), Bassan et al. (2003) and Kamien et al. (1990). However, the way we define the value of information is different from the previous studies. For example, Kamien et al. (1990) essentially define the value of information as the maximum sum of the gains that an external agent (maven) can extract from the players of the game. However, we define the value of information from the perspective of social gains.

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 associated with the QOV when strategic interactions exist. In Section 3, we consider a case where information is given to the players asymmetrically to achieve efficient outcome. This section shows that controlling the information flow is potentially socially desirable. Section 4 provides some discussions.

2 Setup

Built upon the previous literature on QOV, we set up a model of irreversible investment that features a possibility of strategic interactions among players. Whenever possible, we use notations similar to Hanemann (1989). Note that it is not our goal to model strategic interactions in the most general way. We shall, instead, construct a parsimonious model that allows to highlight some of the conceptual difficulties of QOV.

Following Arrow and Fisher (1974), Henry (1974), Fisher and Hanemann (1987), and Hanemann (1989), we assume that there are two time periods, where period 1 is the current period and period 2 is the future period. These studies implicitly assume 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, which will be lost if the forest is developed (clear-cut). A key assumption in the QOV literature and this study is that development is irreversible so that the forest that has already been developed in period 1 cannot be reversed to the original state in period 2 (*i.e.* the biological resources cannot be recovered).

We shall denote by $S \equiv \{s_1, s_2\}$ the set of all the possible states, where s_1 the state in which there is no biological resources and s_2 the state in which there is. Hence, the opportunity cost due to the lost biological resources arises only when the state is s_2. The state is not known in period 1. 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, the (exogenous) scientific research. To keep the model simple, we shall only consider the independent learning (*i.e.* the state is learned in period 2 regardless of the actions taken in period 1).

An important difference of this study from others is that we incorporate strategic interactions. We assume that the society has two risk-neutral players, α and β and a risk-neutral social planner. The two players in this setup may be thought of as loggers of the forest or private land developers. We shall discuss various outcomes depending on the degrees of control that the social planner 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 $d_t^i = 1$ development. We assume that conservation is always chosen when the decision-maker is indifferent between conservation and development.

Since 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 development as shown by Arrow and Fisher (1974). Hence, our analysis can be readily extended to a case of continuous development a unit interval. We use a discrete-choice model in this study 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 it 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 $d \equiv (d_1, d_2)$.

We let $A_1^i = \{0, 1\}$ and $A_2^i(d_1^i) \equiv \{1\} \cup \{d_1^i\}$ be the set of permissible actions for player i in periods 1 and 2. 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:

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

We also assume that the forest is open access. Therefore, when at least one player chooses to develop, the biological resources in the forest will be lost. We also assume that the total payoffs from development only depend on the timing of development and not on who develops. Therefore, who develops only affect the distribution in the society.

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 a 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 period 1) takes all the per-period payoff from development in period 1 and a share $k \in (0,1)$ in period 2. We shall discuss the interpretation of this parameter k subsequently.

We normalize the payoffs so that the per-period payoff from conservation is equal to zero. Further, we assume 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 write the total payoff from development to the society equal to a in period 1, b in period 2 if the state is s_1, and $-c$ if the state is s_2, where a, b and c are positive constants expressed in present value.

We denote the payoff of player i 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 can present $v_1^i(d_1)$ and $v_2^i(d, s)$ in the form of payoff matrices in Tables 1 and 2.

Table 1 provides the payoff of each player in period 1. The rows and columns of the matrix mean player α's and β's actions, respectively. The first entry in each parenthesis represents player α's payoff and the second entry player β's payoff. Note that, regardless of who chooses to develop, the total payoff always sums up to a when development takes place.

Table 2 give the payoffs in period 2 for each of the two possible states. The interpretation of this table is similar to Table 1. Notice that the total payoff from development is b when $s = s_1$ and $-c$ when $s = s_2$, respectively. An important parameter in this tables is k. When $k > 1/2$,

Table 1: The payoff profile $(v_1^\alpha(d_1), v_1^\beta(d_1))$ 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 payoff profile $(v_2^\alpha(d, s), v_2^\beta(d, s))$ in period 2 when $s = s_1$ (top) and $s = s_2$ (bottom).

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

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

the leader takes a larger share than the follower, and the opposite is true when $k < 1/2$.

There is no reason *a priori* to assume that k is larger, equal, or smaller than 1/2. It would be possible that the leader in development may be able to retain a large share of forest in period 2. It would also be possible that the follower could get a larger share of the forest if the institution is designed to favor the follower in period 2 in order to ensure dynamic equality with regard to the use of open-access resource.

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 the benefits and costs of development may be shared differently by the players in practice. When biological resources are lost, everyone in the society may be hurt potentially. On the other hand, logging would only benefit the loggers. In the case of climate change, anthropogenic emissions of greenhouse gases may hurt the society at large, whereas only the greenhouse gas emitters would benefit from the gas emitting activities. Therefore, depending on applications, it may be appropriate to let k depend on the state.

In the rest of the paper, we assume that the social planner is able to transfer the payoffs between the players in a lump-sum manner. Therefore, the social welfare function that the social planner 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 where the social planner p has different degrees of control over the actions of the players and the information flow:

(I) The social planner is a benevolent dictator. He can stipulate the actions taken by the players. This is *de facto* a single decision-maker case.

(II) The social planner is just an informant. He simply let the players know the state in period 2 before the actions are taken.

(III) The social planner is a manipulator of information flow. He does not have a direct control over the actions taken by the players, but can influence them by deliberately controlling the flow of information.

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

In the next subsections, we shall discuss the QOV and EVI for Cases (I) and (II). The comparison of these cases allows us to see the importance of strategic interactions in the calculation of the QOV and EVI. It also allows us to highlight some conceptual difficulties associated with the QOV.

We shall defer to the next section the discussion of Case (III), where we discuss the possibility that the social planner sends messages about the state to the players in an asymmetric manner. We will demonstrate that the expected value of information to the society critically depends on how the information is held. 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, the 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 the efficiency by manipulating the information flow.

2.1 Case (I): Social planner is a benevolent dictator

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

Let $d_t^p \equiv d_t^\alpha + d_t^\beta - d_t^\alpha d_t^\beta$, which takes zero if both players choose to conserve in period $t \in \{1, 2\}$, and one otherwise. From the social planner's perspective, d_t^p 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^p, we can also define the per-period payoff for the social planner as follows:

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

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

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

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

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^{p*} in period 1 to maximize $V^*(\cdot)$. Since $V^*(0) = \max\{B - C, 0\}$ and $V^*(1) = (a + B - C)$, we have:

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

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

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

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

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

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

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

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:

$$
\begin{aligned}
\text{QOV}_I &\equiv (\hat{V}(0) - \hat{V}(1)) - (V^*(0) - V^*(1)) \\
&= \min(B, C). \qquad (1)
\end{aligned}
$$

The QOV term can be understood in the following manner. Suppose we evaluate the conservation (relative to development) in period 1 ignoring the prospect of new information in period 2. Then the net present value of conservation is $V^*(0) - V^*(1)$. However, this is not a correct calculation. In order 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(1) 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:

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

Since the definitions of QOV and EVI in Case (I) are equivalent to the standard definitions, Case (I) serves as a benchmark base for this study. In what follows, we will define QOV and EVI under strategic interactions, and compare against those in Case (I).

2.2 Case (II): Social planner is just an informant

Case (II) is the same as Case (I) except that the social planner has no control over the players' actions. In other words, the players freely choose their actions. The social planner 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 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 has to 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 a common knowledge.

Therefore, for a given action profile $d_1 = (d_1^\alpha, d_1^\beta)(\in A_1)$ in period 1, a Nash equilibrium is played in period 2. Given this, we can go back to period 1, and find the subgame perfect Nash equilibrium. By comparing the equilibrium outcome with and without the prospect of information in period 2, we can define the QOV and EVI for Case (II). By comparing these with the standard QOV and EVI defined in Case (I), we can see the impacts of strategic interactions.

Note that the equilibrium is not necessarily unique. However, since equilibrium selection is not the focus of this paper, we simply assume that an efficient equilibrium under the potential compensation (*i.e.* the equilibrium that has the highest total payoff) will be chosen. We shall subsequently discuss why this may be a reasonable choice. While the possibility of multiple equilibria remains even with this restriction, it is irrelevant once this restriction is imposed.

The assumption of efficient equilibrium is arbitrary, but it does not alter the main findings of our study. Furthermore, for most combinations of parameters, we have a unique equilibrium as described in the Appendix. We shall consider the consequences of relaxing this assumption in Section 4.

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

To solve the game using the 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 the opponent's action $d_2^{-i}(\in A_2^{-i}(d_1^{-i}))$ as follows:

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

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

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

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:

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

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

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

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, the cells a*), b*), d*), and e*) belong to the same subgame when the action profile in period 1 is $d_1 = (0,0)$. 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 the backward induction works in our model when $C > a + B$. The yellow 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 simply 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.

Let us now move on to the second scenario where the uncertainty about the state is resolved after players have taken actions in period 1 but before actions are taken in period 2. Since both

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). Colored cells represent the Nash equilibria in the subgames in period 2, and the red cell the subgame perfect Nash equilibrium when $C > a + B$.

	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*)	$((a+B-C)/2, (a+B-C)/2)$

↓

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 state in period 2 before they take actions

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

players know the state before they take their actions in period 2, each player i is able to take their actions $d_2^i(s)$ contingent on the state $s(\in S)$ in this scenario. To obtain the equilibrium action profile in this scenario, 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:

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

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:

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

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

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

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

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

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 $(0,0)$, $(1,0)$ and $(1,1)$. We have provided the *ex ante* payoff matrix in Table 4 similar to the top panel of Table 3. Note that we have eliminated the strategies that are never chosen in the equilibrium. As can be seen in Table 4, there is only one cell in each of the four subgames in period 2 after eliminating the dominated strategies. As a result, the subgame-perfect Nash equilibrium is identical to the Nash equilibrium in Table 4 when it is taken as a one-shot game.

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 scenarios with and without information about the state in period 2. Thus, the QOV measure in a game-theoretic situation would require us to specify the hypothetical sequence of action profiles in the two periods when a particular action is chosen by a player in period 1, so that the net present value of conservation and development in period 1 with and without information (*i.e.* $V^{i*}(0), V^{i*}(1), \hat{V}^i(0)$, and $\hat{V}^i(1)$) can be computed.

Since each player takes into account the response to the action he takes, it is convenient to define the action profile when a certain action is taken by player i. We let $D_1^{\alpha*} \equiv (d_1^\alpha, BR_1^{\beta*}(d_1^\alpha))$ and $D_1^{\beta*} \equiv (BR_1^{\alpha*}(d_1^\beta), d_1^\beta)$. Likewise, we let $\hat{D}_1^\alpha \equiv (d_1^\alpha, \widehat{BR}_1^\beta(d_1^\alpha))$ and $\hat{D}_1^\beta = (\widehat{BR}_1^\alpha(d_1^\beta), d_1^\beta)$.

Using these, the net present value $V^{i*}(d_1^i)$ associated with action d_1^i for player i in period 1 in the absence of additional information in period 2 can be written as follows:

$$V^{i*}(d_1^i) \equiv v_1^i(D_1^{i*}) + \mathbf{E}_s[v_2^i((D_1^{i*}, d_2^*(D_1^{i*})), s)]. \tag{2}$$

Similarly, the net present value $\hat{V}^i(d_1^i)$ when information is available before the action is taken in period 2 can be written as follows:

$$\hat{V}^i(d_1^i) \equiv v_1^i(\hat{D}_1^i) + \mathbf{E}_s\left[v_2^i((\hat{D}_1^i, \hat{d}_2(\hat{D}_1^i, s)), s)\right]. \tag{3}$$

Given these definitions, one reasonable way to define the QOV and EVI for each individual would be as follows:

$$\begin{aligned} QOV_{II}^i &= (\hat{V}^i(0) - \hat{V}^i(1)) - (V^{i*}(0) - V^{i*}(1)) \\ EVI_{II}^i &= \max\left[\hat{V}^i(0), \hat{V}^i(1)\right] - \max\left[V^{i*}(0), V^{i*}(1)\right] \end{aligned}$$

Once these definitions are accepted, we may calculate the QOV and EVI for the society as a sum of QOV_{II}^{i} and EVI_{II}^{i} over $i \in \{\alpha, \beta\}$ following the standard procedure of the cost-benefit analysis. Therefore, we may be tempted to define QOV and EVI as follows:

$$QOV_{\Sigma} = QOV_{II}^{\alpha} + QOV_{II}^{\beta} \quad (4)$$

$$EVI_{\Sigma} = EVI_{II}^{\alpha} + EVI_{II}^{\beta} \quad (5)$$

A complete description of $\text{QOV}_{\sum}$, and $\text{EVI}_{\sum}$ as well as QOV_{I}, EVI_{I} and the sequence of action profiles in the equilibrium for possible combinations of parameters is given in the Appendix.

We argue that QOV_{Σ} defined in this way would not be particularly meaningful. From the social planner's perspective, we would like to see the value of conservation relative to development with and without the information in period 2. This is, however, a tricky question when the best response to a player's action is different from that player's action. For example, when we compute $V^{i*}(0)$, we are evaluating the stream of payoffs when the player i chooses to conserve (in the absence of information). However, the player $-i$'s response to player i's conservation is not necessarily development. For example, when $k \leq 1/2$ and $B > C$, the best response to conservation is development (See ①, ②, ③, and ④ in Figure 2 and Table 7 in the Appendix). In this case, the forest is never conserved in an equilibrium. Therefore, summing $V^{i*}(0)$ over i does not lead to the net present value of conservation in the society,

A more fundamental question here would be what the social QOV should really measure in the presence of strategic interactions. The net present value of conservation relative to development in the society is not well defined when either conservation or development is not supported as a Nash equilibrium. Therefore, it is difficult to define the social QOV that is comparable to Eq.(1) when there are strategic interactions among players.

There is another potential problem with Eqs.(4) and (5). These definitions use Eqs.(2) and (3), which in turn implicitly assume that the player i is a first-mover in period 1. Hence, he will take the action such that the resulting Nash equilibrium is most favorable to him, which turns out to be an efficient equilibrium in our model as we shall discuss below.

This definition poses no problem if both players take the same action in an efficient Nash equilibria. Otherwise, however, the QOV and EVI will not be correct as Eqs.(4) and (5) incorrectly assume that both players are first-movers. This occurs, for example, when $B - a/(1-2k) <$

$C < B$ and $k < 1/2$ (See ⑥, ⑦, ⑧ and ⑨ in Figure 3 and Table 8) in the absence of information in period 2. This problem can be easily avoided by introducing the order of moves. However, there appears no obvious way to handle this problem in simultaneous-move games. One possible approach would be to employ additional equilibrium selection criteria. This, however, would require some alterations to Eqs.(2) and (3).

When we are concerned about the EVI for the society, it is possible to define the EVI directly at the level of society. 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 The social EVI in the presence of strategic interactions is defined as follows:

$$\mathrm{EVI}_S \equiv \mathbf{E}_s\left[\left(v_1^\alpha(\hat{d}_1) + v_1^\beta(\hat{d}_1) + v_2^\alpha(\hat{d}(s), s) + v_2^\beta(\hat{d}(s), s)\right)\right] - W_{II}^*,$$

where $W_{II}^* \equiv \mathbf{E}_s\left[v_1^\alpha(d_1^*) + v_1^\beta(d_1^*) + v_2^\alpha(d^*, s) + v_2^\beta(d^*, s)\right]$ is the expected social welfare when no information becomes available in period 2.

The social EVI is not uniquely defined if there are multiple equilibria. As discussed earlier, we shall take the most efficient equilibrium in this case. This choice is be reasonable, because the equilibrium chosen by the first-mover is always an efficient equilibrium in our model. This point is obvious for symmetric equilibria. Since there are at most two asymmetric equilibria in our model, the equilibrium that is most favorable to the first-mover is (one of) the most efficient equilibria as well.

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 state in period 2 before the actions are taken. Therefore, if the social EVI is negative, more information that is made available to everyone hurts 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*

$$k < \frac{1}{2}, \quad C < a, \quad \text{and} \quad \frac{2(a-C)}{1-2k} < B < C + \frac{2a}{1-2k} \tag{6}$$

A complete description of EVI_S for all the 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.

The reason why information may hurt the society in a situation described in Proposition 1 is as follows. First, notice that we have a situation where a larger share of the benefits (and costs) will be obtained if the player is a follower in development, because $k < 1/2$. 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 the conditions in Proposition 1 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 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 a follower in development. This occurs when $0 < B < C + 2a/(1 - 2k)$ when $C < a$. Therefore, the upper bound on B in Eq.(6) reflects the condition for the efficient outcome in the absence of information.

Now, consider the scenario where the players learn the state in period 2. In this case, the players have more to lose by choosing development in period 1. Since the opponent can take state-contingent actions in period 2, they 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, each player has a stronger incentive to conserve in period 1, even if it is not socially efficient to do so. In fact, both players are better off by jointly choosing to develop in period 1 when Eq.(6) holds.

In short, the situation described in Eq.(6) shows that the prospect that information will be made available to everyone induces a prisoner's dilemma situation. There are other situations where prisoner's dilemma situation arise in the presence of information (② and ⑥ in Figure 2 and Table 7 in the Appendix) in our model, 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 social planner to manipulate the information given to the players to improve the efficiency (by avoiding the prisoner's dilemma situation)? It is clear from Proposition 1 that the social planner can improve the efficiency by not passing information to players when Eq.(6) holds. Therefore, if the social planner knows the values of a, B, C and k, he can simply choose to pass information if and only if Eq.(6) does not hold.

However, it is possible that some of the parameters are not known to the social planner in some practical settings. For example, the benefits of the development of the forest may be better known to the players than the social planner. Or, the cleanup cost of the brownfield may be better understood by the private land developers. Therefore, it is useful to consider a situation where B and C are private information, and the social planner only has some vague ideas about their values. We demonstrate in the next section that the social planner may be able to induce an efficient equilibrium even in such a situation by giving information to the players asymmetrically.

3 Case (III): The social planner is a manipulator of information flow

Thus far, the players have been treated completely symmetrically (*i.e.* players α and β have been treated in the same way). However, it may be the case that the efficiency in the society may be improved if the perfect information is given to one of the players and less-than-perfect information to the other.

Intuitively, this possibility can be understood in the following manner. Information that becomes available in period 2 is potentially valuable. The analysis of Case (I) makes clear that having additional information never hurts, when the social planner can stipulate the actions taken by the players,

However, as discussed in Case (II), the prospect of better information in the future can induce prisoner's dilemma situation. The players have an extra incentive to conserve compared when $k < 1/2$ with when $k = 1/2$, so that they can avoid the leader disadvantage or enjoy the follower advantage. Thus, when Eq.(6) holds, this extra incentive is too strong for the equilibrium outcome to be efficient. In such a case, having no information at all may be actually better for the society if the social planner has to take as given the strategic interactions between the players.

The extra incentive can be mitigated by giving a noisy signal about the state instead of telling the true state. We achieve this by sending a message (noisy signal) about the state to player α and informing player β of the true state. We show that it is possible to strike a balance between the extra incentives to conserve due to information and the gains from information.

Sending information in this way would immediately raise the following question: Why does one player still learn the true state while the other player only gets a noisy signal? The answer is that, if both players do not know the true state, there is always a small probability that inefficient action profile is supported as an equilibrium. Therefore, we need at least one player to know the true state. We let that player to be player β.

We focus on the case where sending noisy information asymmetrically can help improve efficient outcome. Therefore, we make the following assumptions in this section: (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 social planner.

Let us discuss why these assumptions are important. First, we need Assumption (A-i) to have a situation where information gives the players extra incentives to conserve, even when it is inefficient to develop in period 1. Assumption (A-ii) is also necessary, because when B is very large relative to other parameters, the social planner 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. Finally, we make Assumption (A-iii), because the social planner does not necessarily have to send information asymmetrically otherwise. However, this assumption is not essential and can be dropped without any major modifications in the discussion below.

Let us now formalize the idea described above. Suppose that the social planner inform player β of the state in period 2 before an action is taken. Player α, on the other hand, receives a message $m \in \mathcal{M}$ from the social planner, 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.

Logically speaking, 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) $d^\beta = (1,1)$. However, strategy (c) dominates strategies (b), (d) and (e). Therefore, there are only two strategies (*i.e.* (a) and (e)) that can possibly be chosen in an equilibrium. As a result, the social planner 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 social planner can choose the probability of sending a message conditional on the state. That is, the social planner can choose q_1 and q_2, where $\Pr(m = m_1 | s_1) = q_1$ and $\Pr(m = m_1 | s_2) = q_2$. Since the player always receives a message, we also have $\Pr(m = m_2|s_1) = 1 - q_1$ and $\Pr(m = m_2|s_2) = 1 - q_2$. Without loss of generality, we can assume that $q_1 > q_2$. We assume that q_1 and q_2 are common knowledge. As with player β, there are logically 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 before:

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

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:

$$\begin{aligned}
\tilde{d}_2(d_1, (s, m)) &= (\tilde{d}_2^{\alpha}(m; d_1), \tilde{d}_2^{\beta}(s; d_1)) \\
&= \left(\widetilde{BR}_2^{\alpha}(\tilde{d}^{\beta}(s; d_1); d_1, m), \widetilde{BR}_2^{\beta}(\tilde{d}_2^{\alpha}(m; d_1); d_1, s) \right).
\end{aligned}$$

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

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

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

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

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 social planner gives information asymmetrically:

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

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 social welfare when the information is asymmetrically send.

Let us now create the *ex ante* expected payoff matrix similar to Tables 3 and 4. Just to show how this is done, let us consider one example. Suppose that player β always choose to develop in both periods, and 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 are $(-(1-k)c, a-kc)$, $(0, a+b)$ 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 probability $q_2(1-\pi)$, $\pi(1-q_1)$ and $(1-\pi)(1-q_2)$, respectively. Therefore, the expected payoff in this example is:

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

Doing 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 the backward induction as with Case (II).

The social planner can ensure an efficient outcome only by choosing q_1 and q_2 appropriately so that an efficient outcome is always supported as an equilibrium. It turns out that an efficient outcome can be supported as an equilibrium under Assumptions (A-i) and (A-ii) regardless 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, when $C \geq a$, we must have $\tilde{W} = B$ as well. This can only occur when the equilibrium is either in cell ã), or in cell c̃) when $q_2 = 0$. However, ã) cannot be an equilibrium if, for example

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

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	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)	$(0, B)$	$\tilde{\text{b}}$)	$(0, a+B-C)$
	$\mathrm{Ind}(m=m_1)$	č)	$(q_1B/2 - q_2C, (1-q_1/2)B)$	$\tilde{\text{d}}$)	$((1-k)(Bq_1 - Cq_2), a + (kq_1 + (1-q_1))B - (kq_2 + (1-q_2))C)$
	$\mathrm{Ind}(m=m_2)$	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)	$(a + kB - C, (1-k)B)$	$\tilde{\text{j}}$)	$((a+B-C)/2, (a+B-C)/2)$

$B/2 > C \geq a$, in which case $d_2^\alpha(m) = 1$ dominates $d_2^\alpha(m) = 0$ for player α. 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:

$$\frac{q_1 B}{2} \geq a + kB - C \Longleftrightarrow C \geq a \tag{7}$$

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

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

Notice that there still remain some combinations of a, B, and C (①, ②, ④, and ⑤ in Figure 4 in the Appendix) that lead to inefficient outcome. This is expected because the cost of leader disadvantage is high when B is high. 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 9 in 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 in this case. Proposition 2 and this point underscore the importance of careful control of information flow to achieve an efficient outcome.

4 Discussions

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

We have then shown that information may be harmful to the society as a whole because it may induce prisoner's dilemma situation. For example, when $k < 1/2$, there is a follower advantage in development. Therefore, there are always some incentives for players to conserve in period 1 even when it is inefficient to develop in period 1. This incentive is strong when both players have perfect information about the state in period 2.

Therefore, by giving perfect information about the state to player β and a noisy signal to player α, we can strike a balance between the "intrinsic" value of information (EVI_I) and the inefficiency that information may induced in the presence of strategic interactions. Proposition 2 provides the condition for this to occur.

This condition can be understood in the following manner. Notice that we need to satisfy three conditions for efficiency. First, when 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 $s = s_1$.

The sufficiency of the second condition is satisfied, because development is always chosen by player β in period 2 when $s = s_1$. For the necessity part, it is clear that player β never choose to develop if $s \neq s_1$. Noting $\Pr(m = m_1 | s = s_2) = 0$, we see that player α never choose to develop if $s \neq s_1$. Therefore, the second condition is satisfied.

Provided Assumptions (A-i) and (A-ii') hold, the first condition is satisfied by giving a noisy signal to player α. Because player α receives only less-than-perfect information about the state in period 2, the expected gains from delaying the development is smaller for player α. As a result, conservation is not as attractive to player α as 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.

This finding has important implications for policies. It is often believed that making additional information to the public is generally desirable. Therefore, we often tend to think new information and knowledge accumulated by the public sector, through publically-funded research activities for example, should be made widely available. However, our results warns against mindless public disclosure of information. It may be better to keep some players more informed than others. Therefore, public information disclosure must accompany a careful consideration of the possibility of information-induced inefficiency.

This obviously creates immediate concerns for equity issues. It may be hard to justify informing one player but not the other. However, even in this case, we can ensure equity *ex ante* by randomly assigning the player who receives the perfect information before actions are taken in period 1. Incorporating this twist into our model does not change our results in any significant manner.

Since the primary goals of this paper is to highlight some conceptual difficulties of the QOV and emphasize the potential importance of information-induced inefficiency, we tried to keep the model as parsimonious as possible. However, it is useful to discuss qualitatively when our model allows for the possibility that k is dependent on the state.

We consider the case where $k(s_1) < 1/2$ when $s = s_1$ and $k = 1/2$ when $s = s_2$, as it would be one of the most interesting cases. In this case, the follower advantage exists as is the case we considered in Case (III). 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 is a country (say, 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 eliminate the damages from climate change (by removing greenhouse gases from the atmosphere or otherwise) is found. Since the follower country may be able to adopt such a technology faster and more effectively, there may be a follower advantage (*i.e.* $k < 1/2$) when $s = s_1$. On the other hand, when $s = s_2$, no such technology is found. In this case, the damages from climate change would damages go to both countries so that $k = 1/2$. It would be reasonable to B is bounded and B and C are not very well known to the policy-makers of global climate policies (Each country knows them better).

Obviously, this would be a gross simplification of the strategic interactions that occur in the arena of the global climate policy-making. However, our model still offers some insights into how information should be handled in this context. In fact, the basic argument we have holds even when $k = 1/2$ when $s = s_2$. This point can be intuitively seen by noting that the follower never share C with the leader in an efficient equilibrium. Therefore, although k alters the incentive structures, the reason why giving a noisy signal about the state helps ensure an efficient equilibrium remains the same.

It should also be noted that our model allows for an alternative interpretation about the nature of uncertainty. We have interpreted the uncertainty about the state to be scientific uncertainty, but the uncertainty may come from the institutional uncertainty. For example, as we have shown in the discussion of the brownfield problem, the scope of the developer's liability for clean-up costs had changed when the new laws were enacted. It appears that developers and policy-makers did not anticipate such a change with a reasonable degree of certainty. Therefore, the possibility of such a change may well be treated as institutional uncertainty.

Applications of our model to the important environmental problems would potentially require careful calibration of parameters, extension of the number of players as well as the action space, and perhaps possibility of dependent learning. We do not, therefore, try to overstretch our findings. 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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Appendix

In this appendix, we provide a complete description of the QOV and EVI for Cases (I) and (II) in Table 6 and Figure 1 for $k = 1/2$; Table 7 and Figure 2 for $k > 1/2$; and Table 8 and Figure 3 for $k < 1/2$. We also provide a complete description of the expected social welfare and EVI for Case (III) in Table 9 and Figure 4. The shaded areas represent inefficient outcome in the equilibrium (when information or message is provided by the social planner).

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

$$\text{QOV}_I = \text{EVI}_I = \text{EVI}_\Sigma = \text{EVI}_S = B, \quad \text{and} \quad \text{QOV}_\Sigma = C + B - a.$$

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

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 one (③ and ⑦ in Table 2), which is 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 3). In these cases, the choice of the equilibrium does not affect the values of EVI_S. Note also that both QOV_Σ and EVI_Σ are not dependent on these choices.

Table 6: EVI and QOV when $k = 1/2$

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

Table 7: EVI and QOV when $k > 1/2$

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

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

Table 8: EVI and QOV when $k < 1/2$

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

Table 9: EVI when the condition in Proposition 2 is satisfied.

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

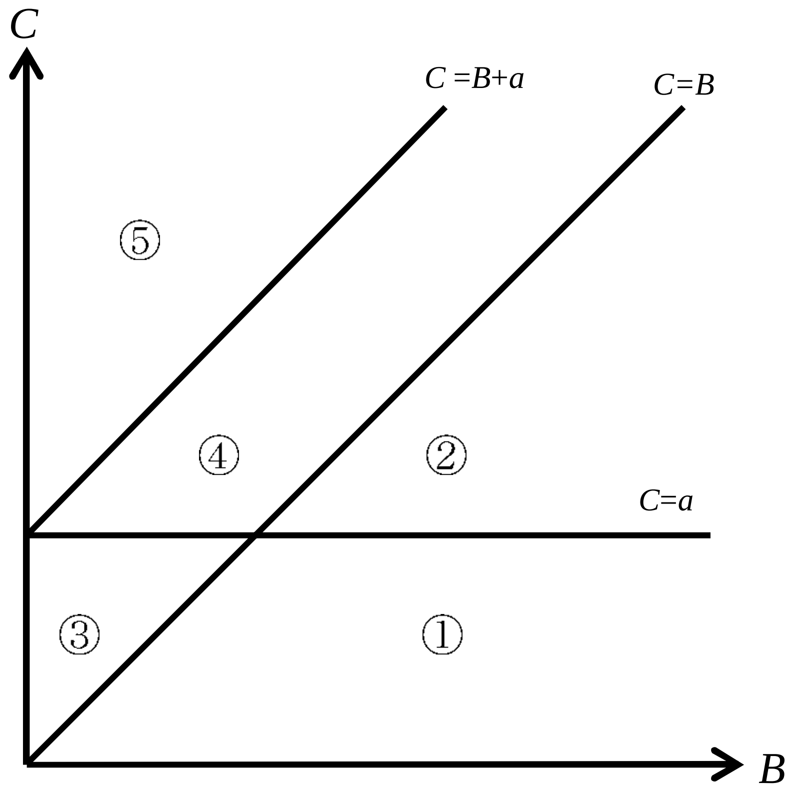

Figure 1: Parameter combinations when $k = 1/2$.

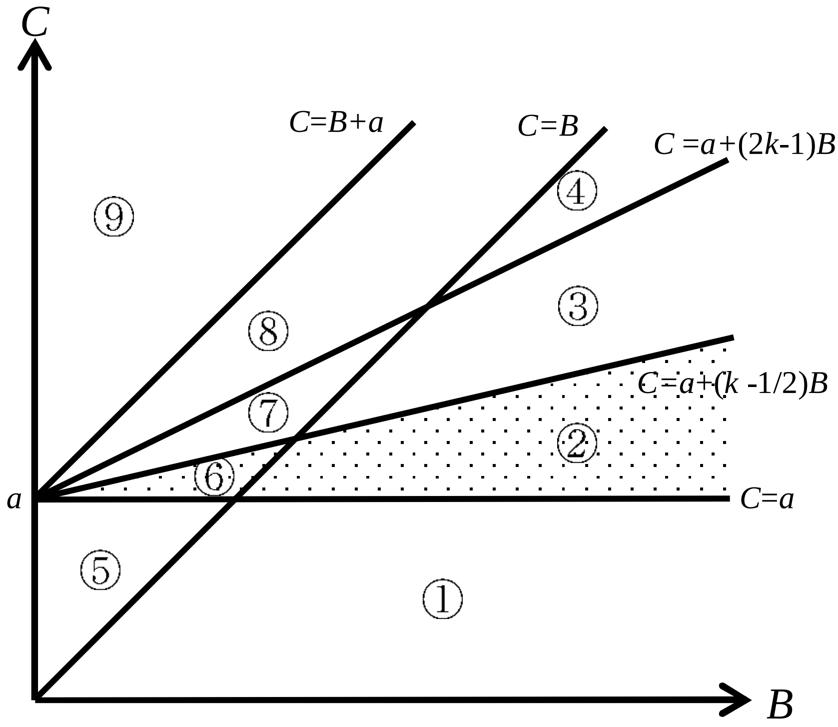

Figure 2: Parameter combinations when $k > 1/2$.

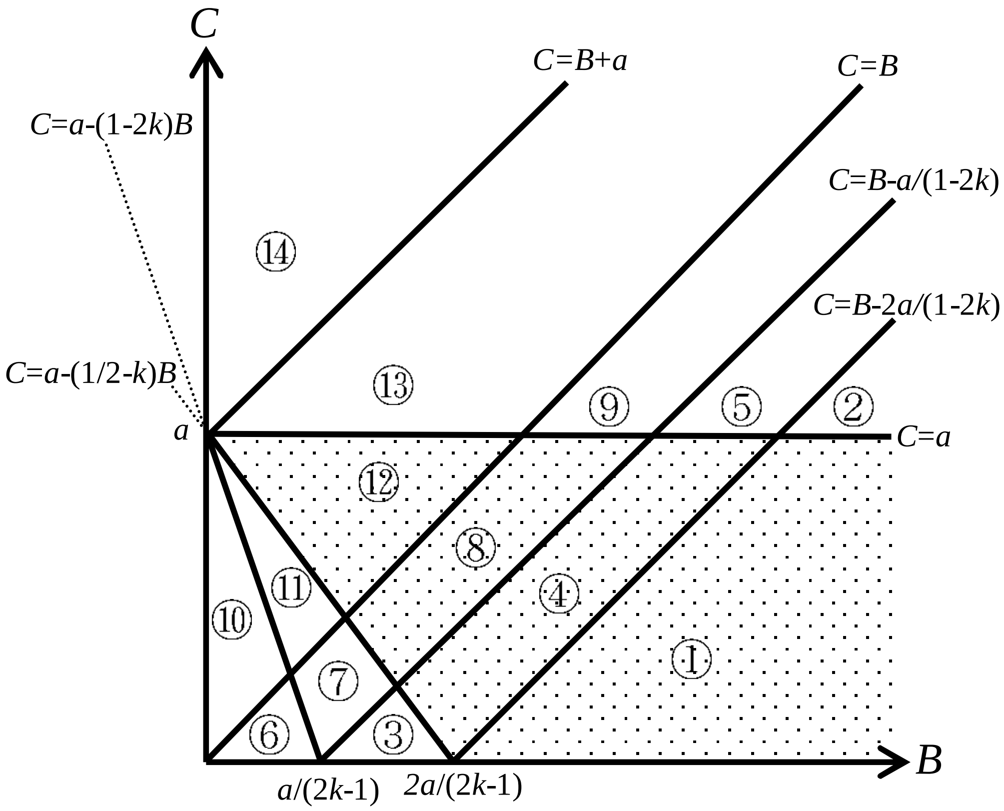

Figure 3: Parameter combinations when $k < 1/2$.

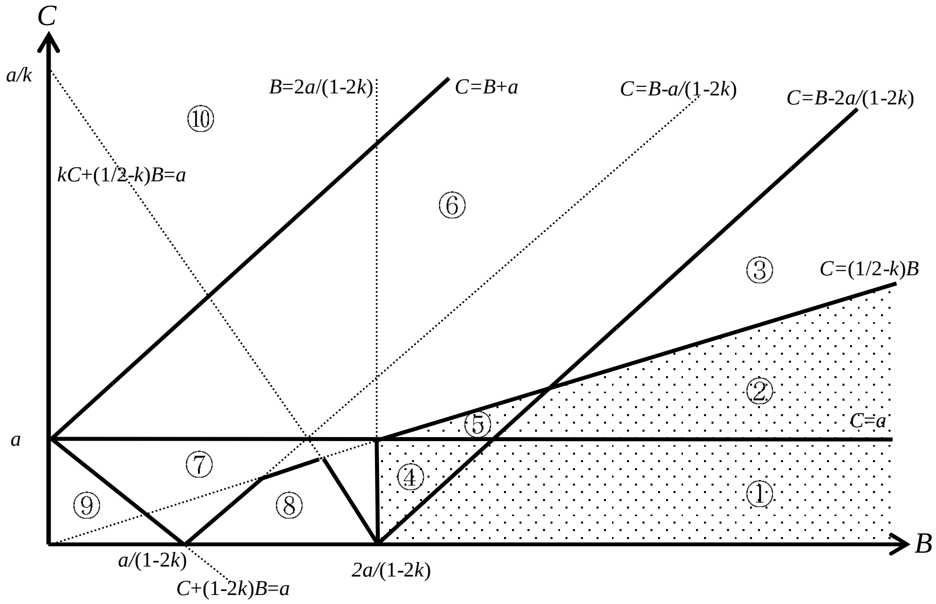

Figure 4: Parameter combinations when information is asymmetrically given (Case (III)).