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Precautionary Effect and Variations of the Value of Information

Laurent Gilotte and Michel de Lara

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CCMP – Climate Change Modelling and Policy

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Precautionary Effect and Variations of the Value of Information

Summary

For a sequential, two-period decision problem with uncertainty and under broad conditions (non-finite sample set, endogenous risk, active learning and stochastic dynamics), a general sufficient condition is provided to compare the optimal initial decisions with or without information arrival in the second period. More generally the condition enables the comparison of optimal decisions related to different information structures. It also ties together and clarifies many conditions for the so-called irreversibility effect that are scattered in the environmental economics literature. A numerical illustration with an integrated assessment model of climate-change economics is provided.

Keywords: Value of Information, Uncertainty, Irreversibility effect, Climate change

JEL Classification: D62, D63, H23, Q29

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1 Introduction

In relation to information, two issues are recurrent in the applied literature dealing with climate change¹. Firstly, the degree to which the emissions of greenhouse gases should be reduced today will hinge on our assumption on the extent of our future knowledge about the climate. Secondly, how much should we be ready to pay now through, for example, investment in scientific research, in order to acquire information in the future?

The second of these questions relates to the *value of information*, or more explicitly the *value of an information structure*². It is a familiar concept in the economics of uncertainty, which has been used for example in order to try and set an upper-bound to the value of a substantial research program to reduce climate-related uncertainties (Manne and Richels, 1992).

As for the first question, it is central to the theoretical literature on irreversibility and uncertainty³ and relates to the ‘irreversibility effect’ (Henry, 1974a). This effect states roughly that, when there is a source of irreversibility in the system we control, then the learning effect⁴ is precautionary. Most of the literature on the subject looks for conditions under which the effect holds. In one of the seminal papers, Arrow and Fisher (1974), noted the “increasing concentration of carbon dioxide in the global atmosphere” as an application for the reasoning. However, most of the theoretical findings, including theirs’, can hardly be used to help and interpret the results of integrated-assessment models (IAM) of climate and economics such as DICE (Nordhaus, 1994). In effect, analytical models usually involve simplifications that are extreme in regard to the climate change issue. For instance, environment is always captured by a scalar variable that follows a linear dynamic, whereas in DICE 98 (Nordhaus and Boyer, 2000) the environment is a five-component vector with a non-linear dynamic for the atmospheric temperature.

Moreover, as Ulph and Ulph (1997) noted, it is not possible to conclude in advance and “as a matter of principle” about the direction of the learning effect for the climate change issue. This would require the condition identified by Epstein (1980), which is not met even in the “simplest model of global warming” that they set out. It implies that, in complex numerical models that embed irreversibility sources, the direction of the learning effect may depend on the data. Moreover, it may depend on the prior beliefs of the decision maker. This idea is reinforced by more recent results by Gollier *et al.* (2000). In a two-period setting close to Ulph and Ulph’s, they show that the irreversibility effect is guaranteed for all risks if the utility function belongs to a restrictive class.

Concepts that can be used for interpreting (rather than conjecturing) the behaviour of complex models were sought. We found promising to follow Ha-Duong (1998), who proposed to rely on how, in the second-period problem, the value of information is modified by the initial decision. He argues it should be a better guide than the notion of quasi-option value, which is traditional to the irreversibility literature since introduced by Arrow and Fisher (1974). Moreover, results about quasi-option value do not hold in the general case (Hanemann, 1989). Ha-Duong implements this idea with a particular model: the initial decision is taken in a set of two elements (high or low abatement), uncertainty is described by two states of nature (dangerous or benign). Once the initial decision has been taken, he looks at the value of getting perfect information before the next decision and points that this value of information depends on the initial decision; the irreversibility effect takes place when the value of information, as a function of the initial decision, is greater for

¹See for example Manne and Richels (1992); Nordhaus (1994).

²We shall keep the terminology *expected value of information* for the case where the value of the information structure is a random variable, see section 4.

³Arrow and Fisher (1974); Henry (1974a,b); Freixas and Laffont (1984); Kolstad (1996); Ulph and Ulph (1997)

⁴By learning effect we refer to how the first-period optimal decision is modified when the decision maker considers that information will arrive in the future.

high initial abatement than for low initial abatement.

Until recently, the irreversibility literature had not really taken advantage of the observation that, once an initial decision is made, the value of information can be defined as a function of that decision. Conrad (1980) emphasized the value of future information from the point of view of the next generation but did not make this dependency explicit. Hanemann (1989) calls it value of information conditional on the initial decision⁵, but even in the case where the set of admissible decisions is a real interval, he considers this value only for some particular initial decisions (the optimal decisions with and without information). More recently, however, Rouillon (2001) defined for a particular model of climate-change the value of information as a function of the greenhouse gases (GHG) concentration. He found in one of his cases that, when this value of information (after the initial decision) is a monotone function of the pollution stock, then the optimal emission levels with and without information can be ordered.

We show that this result is in fact very general and ties together different pieces of the literature on uncertainty and irreversibility. It can also be applied properly in integrated assessment models with few modifications and thus connects two themes of the climate change literature, namely, the value of information and the irreversibility effect.

Section 2 presents a standard model of sequential decision under uncertainty. Practically all the specific models studied in the irreversibility literature from Arrow and Fisher to Gollier *et al.* can be seen as particular instance of our model. Formally it is not restricted to environmental problems. We define the ‘subsequent’ value of information as the value of the information structure once the initial decision has been taken. In section 3, we show that, when value of information is a (partially) monotone function of the initial decision, then the optimal initial decisions with or without information can be compared. With two different information structures, the same result applies to the value of exchanging one information structure for the other. The result does not require any convexity conditions. It is extended in section 4 to sequential decision problems including endogenous risk, active learning and stochastic dynamic. Section 5 shows how our result unifies and provides an interpretation for the conditions for the irreversibility effect that are given in the literature. Finally, section 6 uses Nordhaus’ DICE model to provide a practical application.

2 The standard model of decision with learning

2.1 The decision problem

We consider in this section a rather general model of optimal control under uncertainty, where decisions are taken at two periods of time, namely, at $t = 0$ and at $t = 1$. The decision maker aims at maximizing the expected present benefit

$$\begin{aligned} \max_{u_0, u_1} \mathbb{E} [l_0(u_0) + l_1(u_1, x_1, \gamma)] \\ \text{s.c.} \quad x_1 = f(x_0, u_0) \quad \text{and} \quad u_t \in \mathcal{U}_t(x_t), \quad t = 0, 1. \end{aligned} \tag{1}$$

$x_t \in \mathbb{R}^n$ is the *state of the system* at time t , which depends on the decisions u_t through the dynamics f ; its initial value x_0 is known; the decision u_t must be chosen in a admissible set $\mathcal{U}_t \subset \mathbb{R}^{m_t}$ that, in all generality, depends on t and on the state x_t . We make the restriction that the initial decision is a scalar ($\mathcal{U}_0 \subset \mathbb{R}$, i.e. $m_0 = 1$). Finally $l_t(\cdot)$ is the benefit of decision u_t when the system is in the state x_t . The function l_1 depends on γ , a parameter unknown at time $t = 0$ that we represent

⁵We shall avoid this terminology, which can be confusing. See footnote 2.

as a random variable over a probability space⁶ $(\Omega, \mathcal{F}, \mathbb{P})$, where the $\omega \in \Omega$ are the *states of the nature*. Note that, at this stage, randomness appears only through γ , though the dynamics may be taken as stochastic as we shall see in section 4.

We could actually write this standard model into a more compact form⁷ as it is the current practice in the literature on irreversibility and decision under uncertainty. However, the explicit distinction between state and control is convenient for handling the general model with stochastic dynamics presented in section 4.

In what follows, we shall always assume that, for the problems we consider, the *sup* is attained and we shall use the notation *max*.

2.2 Information structure

The decision maker eventually obtains information at time $t = 1$. A rather general way to describe information is to assume the reception at time $t = 1$ of a signal⁸ that allows to improve on the law \mathbb{P}_γ of the random variable γ by conditioning: in this case, Φ is a random variable (over the same sample space as γ) so that when the decision maker observes Φ , she uses the conditional probability law \mathbb{P}_γ^Φ of γ knowing Φ . More generally, information is a σ -algebra (the one generated by the signal, $\sigma(\Phi)$ in the case hereabove).

‘No information’ at time $t = 1$ can be represented by a constant signal over Ω or, equivalently, by the trivial σ -algebra $\{\Omega, \emptyset\}$. In the following, we shall denote by \perp a non-informative structure.

At time $t = 1$, the decision maker receives a given realization $\Phi(\omega)$ of the signal Φ before her choice u_1 . For any state x_1 , the decision u_1 can be seen as a function from Ω to $\mathcal{U}_1(x_1)$ and should be measurable with respect to the σ -algebra induced by the signal function Φ . We denote this requirement by $u_1 \preceq \Phi$:

$$u_1 \preceq \Phi \iff \sigma(u_1) \subset \sigma(\Phi). \quad (2)$$

For the problem with information structure Φ , define the ‘expected optimal benefit in state $x_1 = x$ ’ as the value function at $t = 1$:

$$V_\Phi(x) \stackrel{\text{def}}{=} \mathbb{E} \left[\max_{u_1 \in \mathcal{U}_1(x), u_1 \preceq \Phi} \mathbb{E} [l_1(u_1, x, \gamma) \mid \Phi] \right] \quad (3)$$

which allows to rewrite the decision problem (1) at $t = 0$ as:

$$\max_{u_0 \in \mathcal{U}_0(x_0)} [l_0(u_0) + V_\Phi(f(x_0, u_0))]. \quad (4)$$

⁶In the irreversibility literature Ω is a finite set of the possible values of γ , $\mathcal{F} = \mathcal{P}(\Omega)$, and \mathbb{P} is the prior used by the decision maker at time $t = 0$.

⁷Namely as

$$\begin{aligned} & \max_{u_0 \in \mathcal{U}_0, u_1 \in \mathcal{D}(u_0)} \mathbb{E} [l_0(u_0) + L(u_1, u_0, \gamma)] \\ & \text{where } L(u_1, u_0, \gamma) \stackrel{\text{def}}{=} l_1(u_1, f(x_0, u_0), \gamma) \\ & \text{and } \mathcal{D}(u_0) \stackrel{\text{def}}{=} \mathcal{U}_1(f(x_0, u_0)). \end{aligned}$$

⁸The irreversibility literature (for instance Freixas and Laffont, 1984; Kolstad, 1996) relies on a description of information through partitions. However partitions are less general in the non-finite case.

2.3 Subsequent value of the information structure

After any initial decision u_0 , the decision maker knows from the deterministic dynamics f what subsequent state of the system, x_1 , will enter her new decision problem at time $t = 1$. If she thinks she will not learn about γ (information structure \perp), she may be ready to pay to obtain information from a signal Φ . When buying Φ , she does not know which information she will receive, but she will be able to move from the expected benefit $V_{\perp}(x_1)$ to the expected benefit $V_{\Phi}(x_1)$. Let us define therefore⁹

$$\begin{aligned} I_{\Phi}(x) &\stackrel{\text{def}}{=} V_{\Phi}(x) - V_{\perp}(x) \\ &= \mathbb{E} \left(\max_{u_1 \in \mathcal{U}_1(x), u_1 \preceq \Phi} \mathbb{E} [l_1(u_1, x, \gamma) \mid \Phi] \right) - \max_{u_1 \in \mathcal{U}_1(x)} \mathbb{E} [l_1(u_1, x, \gamma)] \end{aligned} \quad (5)$$

as the *subsequent value of the information* structure Φ when the system will be in state x in $t = 1$. This value is clearly always non-negative.

The definition makes clear that the value of the information is a function of the state of the system. In applications (Manne and Richels, 1992; Nordhaus, 1994), the value of information is usually defined before decision u_0 has been taken ; therefore it can be considered to depend on x_0 .

In order to distinguish between these two notions, *initial* value of information will refer to the usual definition, and *subsequent* value of information to definition by (5). In the following, we shall indifferently use the expressions ‘value of information’ or ‘value of the information structure’.

More generally, when the state of the system in $t = 1$ is $x_1 = x$, the value of having an information structure Ψ rather than the information structure Φ is:

$$\Delta_{\Psi\Phi}(x) \stackrel{\text{def}}{=} I_{\Psi}(x) - I_{\Phi}(x) \quad (6)$$

If Ψ is finer¹⁰ than Φ , this value is also positive.

3 Learning effect and value of information

3.1 How value of information enters the decision problem

From (4) applied to the non-informative structure \perp , the program of the non-informed decision maker writes:

$$\max_{u_0 \in \mathcal{U}_0(x_0)} [l_0(u_0) + V_{\perp}(f(x_0, u_0))] \quad (7)$$

From (4) and (7) and the definition of the subsequent value of information in (5), the initial decision problem with information structure Φ writes:

$$\max_{u_0 \in \mathcal{U}_0(x_0)} [l_0(u_0) + V_{\perp}(f(x_0, u_0)) + I_{\Phi}(f(x_0, u_0))] \quad (8)$$

Comparing programs (7) and (8), it appears that the decision maker who expects information optimizes the same objective as the uninformed decision maker *plus* the value of the information, which depends on her initial decision. Her optimal decision can achieve a trade-off: it can be suboptimal from the point of view of the non-informed decision maker but compensate for this by an increase of the value of information.

⁹With general utility functions (instead of benefit functions), the value of information is measured in utility units. Equivalent or compensating variations in monetary values can also be defined (Laffont, 1989).

¹⁰Meaning that the σ -algebra induced by Φ is included in the one induced by Ψ .

Note also that I_Φ , the subsequent value of information, depends on the initial decision even though there is no active learning, i.e. what one expects to learn does not depend on u_0 .

More generally, replacing the information structure Φ by the information structure Ψ leads to a reformulation of the problem (4) as

$$\max_{u_0 \in \mathcal{U}_0(x_0)} [l_0(u_0) + V_\Phi(f(x_0, u_0)) + \Delta_{\Psi\Phi}(f(x_0, u_0))].$$

3.2 Comparison of initial and subsequent values of information

Before comparing first period optimal decisions with and without future information, it is easier to compare the subsequent values of information resulting from these decisions. The *initial* value of information enters the comparison laid out in the following proposition (the proof is in Appendix 8).

PROPOSITION 1

Denote by I^0 the initial value of acquiring the information structure Φ before any decision u_0 is made:

$$I^0 \stackrel{\text{def}}{=} \max_{u_0 \in \mathcal{U}_0(x_0)} [l_0(u_0) + V_\perp(f(x_0, u_0)) + I_\Phi(f(x_0, u_0))] - \max_{u_0 \in \mathcal{U}_0(x_0)} [l_0(u_0) + V_\perp(f(x_0, u_0))]. \quad (9)$$

Let u_0^\perp be an optimal solution of (7), the problem without learning, and u_0^Φ be an optimal solution of (8), the problem with learning. Then,

$$I_\Phi(f(x_0, u_0^\perp)) \leq I^0 \leq I_\Phi(f(x_0, u_0^\Phi)). \quad (10)$$

This comparison generalizes the relation between the initial value of information and the option value given by Hanemann (1989), who defines option value as $I_\Phi(f(x_0, u_0^\Phi)) - I_\Phi(f(x_0, u_0^\perp))$ for a family of problems where $I_\Phi(f(x_0, u_0^\perp)) = 0$.

The hereabove inequalities show that a decision maker who knows she will receive information in the future *chooses her first decision so as to increase the value of information*, whereas a decision maker who neglects the fact that she will receive information makes a decision that reduces the value she would be ready to pay for information.

We next derive sufficient conditions for the comparison of initial optimal decisions, a problem at the centre of the literature on irreversibility and uncertainty.

3.3 Comparison of optimal solutions; the learning effect

From Proposition 1, we obtain immediately:

$$\forall u > u_0^\perp, I_\Phi(f(x_0, u)) < I_\Phi(f(x_0, u_0^\perp)) \Rightarrow u_0^\Phi \leq u_0^\perp.$$

Hence, a *practical sufficient condition for comparison of optimal solutions is to know that $u_0 \mapsto I_\Phi(f(x_0, u_0))$ is a strictly decreasing or a strictly increasing function*¹¹.

DEFINITION 2

The eventual difference between u_0^Φ and u_0^\perp is the learning effect.

More generally we have the following, which is our main result.

¹¹Note here that we adopt the following terminology: a function f defined on an ordered set is *increasing* if $x \geq y \Rightarrow f(x) \geq f(y)$, and is *strictly increasing* if $x > y \Rightarrow f(x) > f(y)$; the same convention holds for decreasing and strictly decreasing functions.

PROPOSITION 3

Let Φ and Ψ be two information structures (not necessarily comparable in the sense that one is finer than the other).

Let u_0^Φ be any optimal initial decision with information structure Φ , that is

$$u_0^\Phi \in \arg \max_{u_0 \in \mathcal{U}_0(x_0)} [l_0(u_0) + V_\Phi(f(x_0, u_0))],$$

and let u_0^Ψ be any optimal initial decision with information structure Ψ :

$$u_0^\Psi \in \arg \max_{u_0 \in \mathcal{U}_0(x_0)} [l_0(u_0) + V_\Psi(f(x_0, u_0))].$$

If the value of substituting Ψ for Φ , $u_0 \mapsto \Delta_{\Psi\Phi}(f(x_0, u_0))$, is a strictly decreasing function, then

$$u_0^\Psi \leq u_0^\Phi.$$

The result is immediate from (13) in Appendix¹².

The results holds in fact under the weaker assumption that $u_0 \mapsto \Delta_{\Psi\Phi}(f(x_0, u_0))$ is strictly decreasing (respectively strictly increasing) when $u_0 < u_0^\Psi$ (respectively when $u_0 > u_0^\Psi$.)

A more general proposition can be made for non-strictly decreasing (or increasing) functions.

PROPOSITION 4

If the value of substituting Ψ for Φ , $u_0 \mapsto \Delta_{\Psi\Phi}(f(x_0, u_0))$, is a decreasing function, then comparisons are still possible under the form

$$\sup \arg \max_{u_0 \in \mathcal{U}_0(x_0)} [l_0(u_0) + V_\Psi(f(x_0, u_0))] \leq \sup \arg \max_{u_0 \in \mathcal{U}_0(x_0)} [l_0(u_0) + V_\Phi(f(x_0, u_0))].$$

The proof derives from Proposition 8, see appendix section 9.

As a consequence, if u_0^Φ is unique, it is sufficient that $u_0 \mapsto \Delta_{\Psi\Phi}(f(x_0, u_0))$ be decreasing to conclude that $u_0^\Psi \leq u_0^\Phi$.

Before applications in Sections 5 and 6, the following definition relates the comparison of u_0^Φ and u_0^\perp to the ‘irreversibility effect’ and more generally to the ‘precautionary effect of the learning’.

DEFINITION 5

Precautionary effect of learning

In the case where

1. l_0 is an increasing function (i.e. increasing u_0 yields benefits in $t = 0$)
2. $u_0 \mapsto l_1(u_1, f(x_0, u_0), \gamma)$ is a decreasing function (i.e. u_0 implies some future costs)

then a decision $u_0^\Phi \leq u_0^\perp$ is said to be ‘more precautionary’ than u_0^\perp and the learning effect from Φ is said to be ‘precautionary’. This is also referred to as the ‘irreversibility effect’ in some specific cases.

¹²Freixas and Laffont (1984) give sufficient conditions for the monotonicity of $\Delta_{\Psi\Phi}$ in a setting where the dynamics is reduced to $x_{t+1} = u_t$ and where the state of the system does not enter the benefits l_t but only the admissibility set. However, they do not provide the interpretation of Δ in terms of value of substituting information structures. Kolstad (1996) obtains necessary and sufficient conditions for a problem which is actually a sub-case of Freixas and Laffont though this does not appear at first glance from his notations but has to be derived from his hypotheses.

4 Extension to active learning and stochastic evolution

Possible extensions of the standard case appear in the literature. This section shows that the main result still apply in the general, extended case.

Stochastic dynamic. From period $t = 0$ on, the state of the system \tilde{x}_t is a random variable. Its evolution may depend on an other random variable w_t : $\tilde{x}_{t+1} = f(\tilde{x}_t, u_t, w_t)$. The model in Conrad (1980) is an occurrence of stochastic dynamic in the irreversibility literature.

Endogenous risk An example of endogenous risk can be found in Gjerde et al. (1999) where the law of the date of a climate catastrophe depends on the emission reductions. Endogenous risk arises when the random variable γ depends on the previous decisions, u_0 and u_1 . In stochastic control theory, γ is treated as a state variable. Endogenous risk is thus viewed as a particular case of stochastic dynamic.

Active learning Active learning (or dependent learning) takes place when the initial decision can modify the signal the decision maker will receive. It means that in addition to ω , Φ depends on u_0 , or more generally on \tilde{x}_1 (then the modification is also random). Rouillon (2001) studies a model of active learning in climate change economics and uses the variations of the value of information to conclude about the irreversibility effect.

Comparison in the general model

Consider the problem :

$$\begin{aligned} \max_{u_0, u_1} \mathbb{E} [l_0(u_0, \tilde{x}_0) + l_1(u_1, \tilde{x}_1)] \\ \text{s.c.} \quad \tilde{x}_1 = f(\tilde{x}_0, u_0, w_0) \quad \text{and} \quad u_t \in \mathcal{U}_t(y_t), t = 0, 1 \end{aligned}$$

where w_t is a random variable (r.v.) and y_t a non-stochastic subcomponent of \tilde{x}_t , so that the decision maker knows the admissible set $\mathcal{U}(y_1)$ when she makes her choice¹³ u_1 .

At time $t = 1$, when the state of the system is the r.v. \tilde{x} , the information structure Φ delivers a signal that depends on \tilde{x} . We denote by $\Phi_{\tilde{x}}$ the corresponding signal function $\Phi_{\tilde{x}} : \omega \mapsto s(\omega, \tilde{x}(\omega))$. The decision-problem can be written as:

$$\begin{aligned} \max_{u_0 \in \mathcal{U}_0(y_0)} \mathbb{E} [l_0(u_0, \tilde{x}_0) + V_{\Phi}(f(\tilde{x}_0, u_0, w_0))] . \\ \text{with} \quad V_{\Phi}(\tilde{x}) \stackrel{\text{def}}{=} \mathbb{E} \left[\max_{u_1 \in \mathcal{U}_1(y), u_1 \preceq \Phi_{\tilde{x}}} l_1(u_1, \tilde{x}) \mid \Phi_{\tilde{x}} \right] . \end{aligned}$$

As in previous section, the decision problem with information can be put under the form:

$$\max_{u_0 \in \mathcal{U}_0(x_0)} \mathbb{E} [l_0(u_0, \tilde{x}_0) + V_{\perp}(f(\tilde{x}_0, u_0, w_0)) + I_{\Phi}(f(\tilde{x}_0, u_0, w_0))]$$

and the comparisons of initial decisions now rely on the expectation of I_{Φ} or $\Delta_{\Psi\Phi}$ as follows.

¹³It is sufficient to assume that the decision maker gets full information at time $t = 1$ on a stochastic subcomponent \tilde{y}_1 ; then this information, \tilde{y}_1 should be explicitly included for conditioning the problem, even in the case where no additional information arrives.

PROPOSITION 6

If $u_0 \mapsto \mathbb{E} [\Delta_{\Psi\Phi}(f(\tilde{x}_0, u_0, w_0))]$ is monotone, comparison of the optimal decisions for the general problems with information structure Φ and Ψ will be possible. Precise conditions are the same as in Proposition 3.

It is self-explanatory that $\mathbb{E} I_{\Phi}(f(\tilde{x}_0, u_0, w_0))$ is the expected value of information after decision u_0 , and $\mathbb{E} \Delta_{\Psi\Phi}(f(\tilde{x}_0, u_0, w_0))$ the expected value of exchanging the information structure Φ for Ψ . It is also possible to define the value of information conditional on a realization of w_0 or of \tilde{x}_1 .

5 Value of information as a key to the irreversibility literature

A goal of the literature on irreversibility and uncertainty consists in identifying hypotheses or conditions under which the ‘irreversibility effect’ holds. Two kinds of conditions can be examined. A first thread follows Epstein (1980) and concentrates on determining the direction of the learning effect for all possible random vectors γ over a finite sample set and for all comparable information structures. As Ulph and Ulph (1997) noted, this restricts the conclusion to limited classes of problems, for example those later identified by Gollier et al. (2000). An other thread looks for specific problems where the irreversibility effect is verified when Epstein conditions do not apply. This for example the case in Ulph and Ulph (1997).

Though monotonicity of the value of information is only necessary for the irreversibility effect, it turns out that Epstein necessary and sufficient conditions imply a monotone value of information. Besides, many of the specific (necessary) conditions found in the literature also do. In particular, we have already seen (section 3.2) that Proposition 1 generalizes Hanemann’s statement on the quasi-option value (Hanemann, 1989) and that Proposition 3 provides an interpretation for the conditions examined by Freixas and Laffont (1984) for a simple model (section 3.3). We shall see it is also the case for many others, and moreover, this monotonicity is often intuitive without fully-fledged mathematical demonstration.

5.1 Epstein’s Theorem and the value of information

Epstein (1980) gave necessary and sufficient conditions that allow to conclude about the direction of the learning effect for all prior beliefs. We show that they also imply a monotone value of information.

For any distribution law ρ on Ω , let us define

$$J(x, \rho) \stackrel{\text{def}}{=} \max_{u_1 \in \mathcal{U}_1(x)} \mathbb{E}_{\rho}(l_1(u_1, x, \gamma)) = \max_{u_1 \in \mathcal{U}_1(x)} \int_{\Omega} l_1(u_1, x, \gamma(\omega)) \rho(d\omega) \quad (11)$$

Epstein’s Theorem states that initial decisions may be compared for any comparable information structures (one being more informative than the other) when $\frac{\partial J}{\partial x}(x, \rho)$ exists and is convex or concave in ρ varying among discrete probability laws.

We show that Epstein’s assumptions, extended to non-discrete probability and without necessarily differentiability in the first decision argument, are sufficient conditions for the value of information to be monotone and therefore to ensure the comparison of initial decisions.

PROPOSITION 7

Assume that

1. for any $u_+ \geq u_-$, $J(f(x_0, u_+), \rho) - J(f(x_0, u_-), \rho)$ is convex (concave) in ρ ,

2. Ψ is finer than Φ .

Then the value of substituting Ψ for Φ , $u_0 \mapsto \Delta_{\Psi\Phi}(f(x_0, u_0))$, is an increasing (a decreasing) function.

Thus, initial decisions may be compared (see the remarks following Proposition 3). The proof is in appendix.

5.2 Linear dynamics and costs; ‘all or nothing’ decision set

The seminal literature as well as more recent contributions often considers linear dynamics and costs, which imply all or nothing decisions, or hinges directly on a binary decision set (see for instance Arrow and Fisher, 1974; Henry, 1974a; Ha-Duong, 1998; Fisher, 2000 and Henry, 1974b, part 2). With a binary decision set, the monotonicity of the value of information becomes trivial. Moreover, the direction of variation is easily determined under the hypothesis of total irreversibility, *i.e.* when one of the two possible initial decisions affects the state or the second period cost so that it does not depend any longer on the second period decision. This is for example the case with the model of Arrow and Fisher (1974).

5.3 Value of information in Ulph and Ulph, 1997

The model examined in (Ulph and Ulph, 1997) can be rewritten with our formalism as follows

$$\max_{u_0} \left[l_0(u_0) + \mathbb{E} \max_{u_1 \preceq \Phi} [l_1(u_1) - \mathbb{E}[\gamma | \Phi] D(\delta x_1 + u_1)] \right] \quad (12)$$

with $x_{t+1} = \delta x_t + u_t$ and $u_t \in [0, A_t]$,

where u are greenhouse gases (GHG) emissions, x GHG concentrations, l_t utilities, and D a damage function. A_t is the unrestricted level of emissions¹⁴. Functions l_t are assumed to be strictly increasing and strictly concave, and D strictly increasing and strictly convex. The r.v. γ is assumed to be non-negative.

The authors compare u_0^\perp , the initial decision without information, and u_0^\top , the initial decision with perfect information structure (for example $\Phi = \gamma$). With our notations, their theorem 3 states that:

$$\text{if } (u_0^\perp, u_1^\perp) \text{ is such that } u_1^\perp = 0, \text{ then } u_0^\top \leq u_0^\perp.$$

Two features are essential to this result. On the one hand, the assumption that the optimal policy, $u_1^\perp = 0$, is a corner solution in second period. On the other hand, the shape of the the payoff, which is linear in the random variable.

We show (see Annex 11 for the proof) that, under their hypothesis and their condition $u_1^\perp = 0$, the conclusion about the irreversibility effect can be generalized to any information structure Φ because the second-period value of this information structure can be shown to be a decreasing function for $u_0 \geq u_0^\perp$.

This generalized result can even be obtained intuitively, because, under their conditions, monotonicity of the value of information becomes intuitive. Ulph and Ulph’s condition implies that when the GHG concentration in $t = 1$, x_1 , is above a certain level $\delta x_0 + u_0^\perp$, then it is optimal

¹⁴Ulph and Ulph do not make this hypothesis which is benign for the problem considered (greenhouse gases emissions cannot be infinite) and simplifies the demonstration.

to cut emissions to zero in $t = 1$ when no information is available. Therefore, if information is obtained when we are in the situation x_1 , it might open the opportunity to emit. The value of the information is then equal to the benefit of additional emissions in $t = 1$ minus the expected additional damages. From the envelope theorem, these expected additional damages are strictly increasing at the margin for a small increase of the concentration x_1 , whereas benefits do not depend directly of the concentration level. As a consequence, the value of information diminishes and the irreversibility effect applies.

6 Illustration with a modified stochastic version of dice

Here we produce a numerical illustration with a stochastic version of the standard integrated assessment model DICE 98 (Nordhaus et Boyer, 2000). Such a model is already complex compared to the analytical ones present in the literature. But it will appear that, strikingly, the value of information after initial policy choice behaves in a way that can support intuition.

The model is a stochastic optimal-growth model of the world economy. It is designed to maximize the discounted expected value of utility from consumption. The decisions variables are the rate of investment and the rate of emissions reductions in greenhouse gases. The model operates in time steps of 10 years. Perfect information about the uncertain climate parameter arrives in 2040. A simple adaptation of the original model ensures compatibility with the analytical framework of section 4. We make a parameterization of the paths of investment and abatement from now till 2030–2039 with a unique scalar. This scalar, the abatement rate targeted for 2030–2039, summarizes and entirely defines the policy choice in the initial period.

6.1 The climate-economy system

The dynamic evolution of the climate-economy system can be represented with the relation: $z_{i+1} = g(z_i, v_i, \gamma)$ where $i \in \{0, 1, \dots, T\}$ is the 10-year interval spanning from year $2000 + 10i$ to year $2009 + 10i$; $v_i \in [0, 1] \times [0, 1]$ is the couple of controls, which are the rate of reduction of greenhouse gases and the investment rate in time step i ; $z_i \in \mathbb{R}^6$ is the state of the climate-economy system in the beginning of period i comprising the stock of capital; concentrations of carbon in three reservoirs (atmosphere; biosphere and surface ocean; deep ocean); and oceanic and atmospheric global mean temperature rises with respect to pre-industrial times.

The temperature components of z are stochastic. Uncertainty enters their dynamics through the *climate sensitivity* γ . This random variable is equal to the atmospheric temperature rise for a permanent doubling of the carbon concentration in the atmosphere. The r.v. γ is constant through time with values 2.5°C , 3.5°C and 4.5°C and remains unobserved until year 2040. In the first step $i = 0$, the true atmospheric temperature rise with respect to pre-industrial times is also uncertain.

The detailed climate-economy equations are slightly changed from the original version of DICE. The temperature increase equation is an updated calibration that provides a better description of warming over forthcoming decades. A threshold damage function replaces the original quadratic one. Both modifications are taken from Ambrosi et al. (2003). The full description for the original DICE model can be found in Nordhaus (Nordhaus, 1994; Nordhaus and Boyer, 2000).

6.2 The decision problem

At each time step i , a control v_i and a state of the system z_i result in a discounted random utility $L_i(v_i, z_i)$. In fact we have two notions of time. The first notion, the time steps, describes the natural

time in the original problem. The second notion describes the decision periods. In accordance with the framework of section 4, there are two decisions period $t \in \{0; 1\}$. The initial period, $t = 0$, covers the time steps before learning, $i = 0, \dots, 3$; the next period, $t = 1$, covers the time steps $i = 4, \dots, T$. The decisions u_t define the controls v_i as follows. The initial decision $u_{t=0} \in [0, 1]$ is the level of abatement targeted for 2030; it parameterizes the investment and abatement path for time steps $i < 4$ through a function φ from $[0, 1]$ into \mathbb{R}^6 : $(v_i)_{i \in \{0, \dots, 3\}}$ is taken equal to $\varphi(u_{t=0})$. The next decision, $u_{t=1} \in [0, 1]^{2(T-3)}$, is the vector of investment and abatement rates for $i \geq 4$: $(v_i)_{i \in \{4, \dots, T\}} = u_{t=1}$. Details for the parameterization of the initial policy are in Appendix 12.

The decision problem is

$$\begin{aligned} \max_{u_0} \mathbb{E} & \left\{ \sum_{i < 4} L_i(v_i, z_i) + \mathbb{E} \left[\max_{u_1 \preceq \gamma} \sum_{i=4}^T L_i(v_i, z_i) \mid \gamma \right] \right\} \\ \text{with } & (v_0, \dots, v_3) = \varphi(u_0) \\ & (v_4, \dots, v_T) = u_1 \in [0, 1]^{2(T-3)} \\ & z_{i+1} = g(z_i, v_i, \gamma) \end{aligned}$$

where the path of controls before information is constrained to belong to the family of curves defined by φ . This decision problem clearly pertains¹⁵ to the framework described in section 4 but as far we know it is out of bounds for the rest of the analytical literature about irreversibility, learning and climate change.

6.3 How policy affects the value of information on the climate

The figure 1 page 13 plots the expected value of information as a function of the initial policy. Available initial decisions range from no effort until 2030 (0% emissions reduction) to targeting the maximum effort in 2030 (100% reduction). Three cases are presented corresponding to three different probability distributions for γ : optimistic case, centered case and pessimistic case (see Appendix 12).

In all cases, the expected value of information is strictly decreasing. Consistently, in all cases, the prospect of learning the true value of γ in 2040 is an opportunity to make initially less reduction efforts (u_0^\perp) than in the never-learn situation (u_0^\parallel). This is also consistent with the simulations made by Ulph and Ulph (1997). If no certainty can ever¹⁶ be obtained about the future evolution of the climate, the more cautious emission policy u_0^\perp would be preferred. Here, the learning effect is not precautionary.

In an analytical framework with a linear dynamic, Gollier et al. (2000) showed that logarithmic utility implies that the structure of information has no effect on the initial decision. They wondered whether this was the explanation for the little or nonexistent learning effect found in earlier results by Nordhaus (1994), Manne and Richels (1992) and others¹⁷. Our model departs from Nordhaus' DICE only with some specifications of the dynamics (see section 6.1). But the utility function of the model is logarithmic as it is in DICE. However, the 'learning effect' (the difference between u_0^\perp and u_0^\parallel) ranges from 9 to 21%. In terms of abatement costs this is even larger due to the

¹⁵With $\tilde{x}_0 = (z_0, \gamma)$ and $\tilde{x}_1 = (z_4, \gamma)$ so that $f(\tilde{x}_0, u_0, \gamma) = [g(\dots, (g(\tilde{x}_0, v_0, \gamma), \dots), v_3, \gamma); \gamma]$. Similarly l_0 and l_1 are defined through L_i and compositions of g .

¹⁶Kelly and Kolstad (1999) suggest that certainty on the true value of the climate sensitivity with less than 5% rejection might be available only after 2090.

¹⁷Ulph and Ulph used a quadratic specification for their numerical simulations and found that, for most parameter values, learning made little difference.

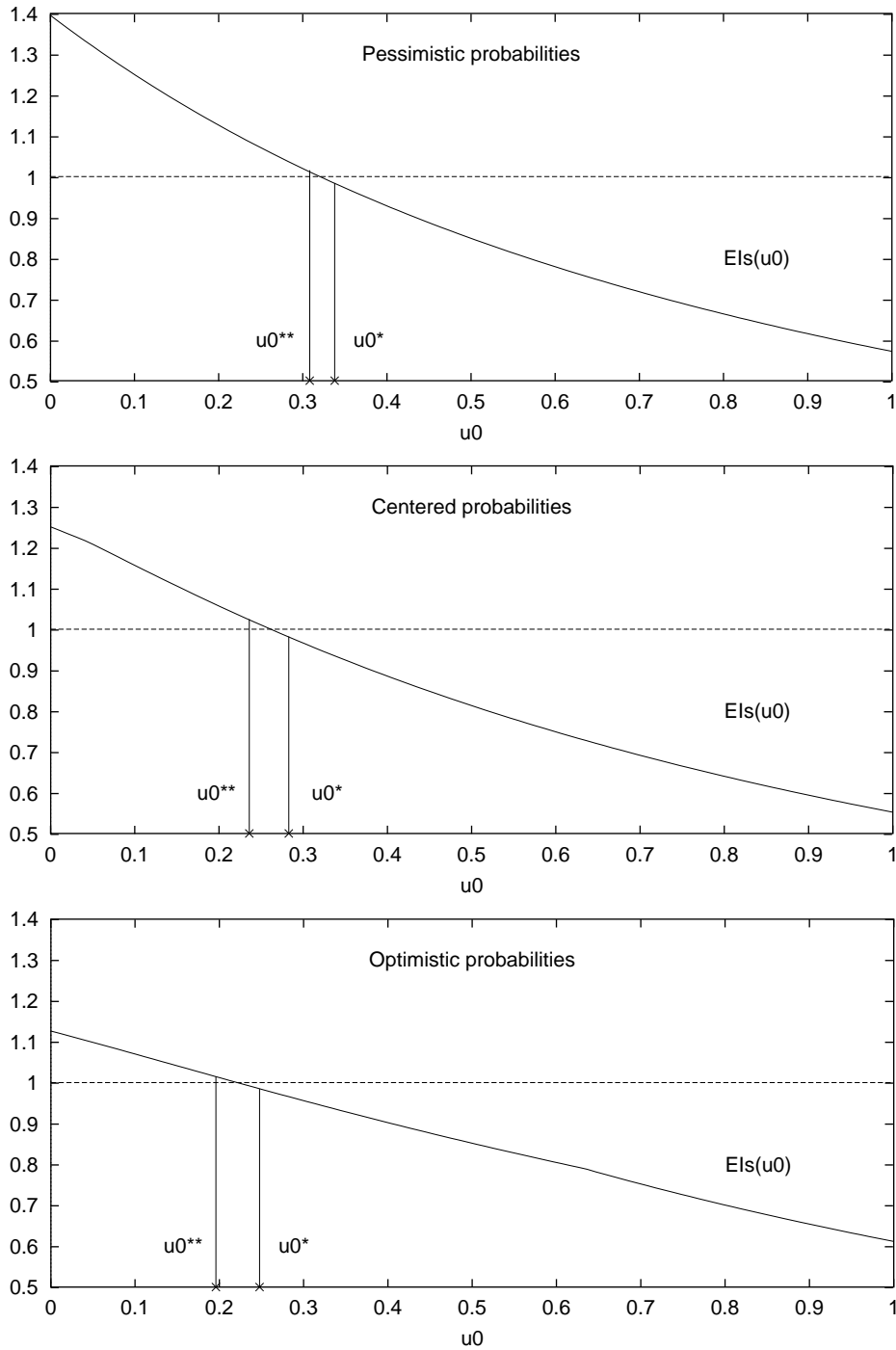


Figure 1: Variations of the expected value of information, $EIs(u_0)$, with u_0 . In each case, the expected value of information has been normalized with $\mathbb{E}I^0$, the expected value of information before any decision is made. Note that this normalization is different in each case.

specification of the abatement costs in DICE as a power function (with an exponent greater than 2). Clearly, learning has an effect on decision which is not negligible. Thus, our findings answer the question raised by Gollier *et al.* and show that the weak learning effect found by Nordhaus is also determined by his choice of a particular dynamic and not solely by his logarithmic objective function.

7 Conclusion

This article explored the role of the value of an information structure in analyzing general, sequential decision problems. The difference between value of future information before and after an initial decision is taken was made explicit. The monotonicity of the latter, the *subsequent value of information*, is sufficient for making a conclusion about the direction of the learning effect. Many of the conditions given in the literature as sufficient or as necessary and sufficient for the irreversibility effect can be understood as guarantees for this monotonicity. The present analysis shares a common limitation with the irreversibility literature: the initial decision is assumed to be scalar. But extension is readily available in theory. As long as the set of admissible initial decisions can be ordered even incompletely, Topkis' theorem (Topkis, 1978) leads to a similar conclusion. Extension to multi-scalar decisions would help the interpretation of empirical integrated assessment models. For example in the original DICE model (Nordhaus and Boyer, 2000), assuming that information arrives in 2040, the initial decision vector has eight components (four abatement and investment decisions). However, the difficulty is to find a meaningful order over the decision set.

For communication with policy-makers, there is a practical advantage in analyzing the learning effect in terms of growing or strictly decreasing value of information because value of information is a relatively self-explanatory concept (Ha-Duong, 1998). Finally, the intuitive simplicity of the notion of value of information also suggests application in experimental economics. It should be possible to design experimental tests of rationality under uncertainty that are based on how and whether individuals modify their estimation of the value of improved future knowledge as a consequence of their current decisions.

8 Appendix: Proof of Proposition 1

By definition, the initial value of information is

$$I^0 \stackrel{\text{def}}{=} \overbrace{\max_{u_0 \in \mathcal{U}_0(x_0)} [l_0(u_0) + V_{\perp}(f(x_0, u_0)) + I_{\Phi}(f(x_0, u_0))]}^{\mathcal{J}_{\Phi} \stackrel{\text{def}}{=}} - \underbrace{\max_{u_0 \in \mathcal{U}_0(x_0)} [l_0(u_0) + V_{\perp}(f(x_0, u_0))]}_{\mathcal{J}_{\perp} \stackrel{\text{def}}{=}} .$$

Since u_0^{\perp} is an optimal solution of the problem without information and since u_0^{Φ} is an optimal solution of the problem with information, we have, on the one hand,

$$\mathcal{J}_{\perp} = l_0(u_0^{\perp}) + V_{\perp}(f(x_0, u_0^{\perp})) \geq \underbrace{l_0(u_0^{\Phi}) + V_{\perp}(f(x_0, u_0^{\Phi}))}_{\mathcal{I}_{\Phi} - I_{\Phi}(f(x_0, u_0^{\Phi}))}$$

so that $\mathcal{I}_{\Phi} - \mathcal{J}_{\perp} \leq I_{\Phi}(f(x_0, u_0^{\Phi}))$.

On the other hand,

$$\mathcal{I}_\Phi = l_0(u_0^\Phi) + V_\perp(f(x_0, u_0^\Phi) + I_\Phi(f(x_0, u_0^\Phi))) \geq \underbrace{l_0(u_0^\perp) + V_\perp(f(x_0, u_0^\perp))}_{\mathcal{J}_\perp} + I_\Phi(f(x_0, u_0^\perp))$$

so that $\mathcal{I}_\Phi - \mathcal{I}_\perp \geq I_\Phi(f(x_0, u_0^\perp))$. Combining both inequalities, we obtain

$$I_\Phi(f(x_0, u_0^\perp)) \leq I^0 = \mathcal{J}_\Phi - \mathcal{J}_\perp \leq I_\Phi(f(x_0, u_0^\Phi))$$

which is Proposition 1.

Similarly we obtain easily:

$$\Delta_{\Psi\Phi}(f(x_0, u_0^\Phi)) \leq \mathcal{J}_\Psi - \mathcal{J}_\Phi \leq \Delta_{\Psi\Phi}(f(x_0, u_0^\Psi)) \quad (13)$$

where u_0^Ψ (respectively u_0^Φ) is any optimal initial decision for the problem with the information structure Ψ (respectively Φ). Note that, without specific hypothesis on the relative informativeness of Φ and Ψ , Δ can assume negative values and $\mathcal{J}_\Psi - \mathcal{J}_\Phi$ can be negative.

9 Appendix: Comparison of arg max

We recall here results on comparison between the arg max of two optimization problems. They may be seen as particular instances of results from a general theory with supermodular functions or functions with increasing differences as developed in Topkis (1998).

PROPOSITION 8

Let $\mathcal{D} \subset \mathbb{R}$, let $g : \mathcal{D} \rightarrow \mathbb{R}$ and $h : \mathcal{D} \rightarrow \mathbb{R}$. We denote

$$\mathcal{D}_g \stackrel{\text{def}}{=} \arg \max_{u \in \mathcal{D}} g(u) \subset \mathcal{D} \quad \text{and} \quad \mathcal{D}_{g+h} \stackrel{\text{def}}{=} \arg \max_{u \in \mathcal{D}} (g+h)(u) \subset \mathcal{D},$$

and we assume that $\mathcal{D}_g \neq \emptyset$ and $\mathcal{D}_{g+h} \neq \emptyset$.

1. If h is strictly increasing on $] -\infty, \sup \mathcal{D}_g]$, then

$$\sup \mathcal{D}_g \leq \inf \mathcal{D}_{g+h}.$$

2. If h is increasing on $] -\infty, \sup \mathcal{D}_g]$, then

$$\sup \mathcal{D}_g \leq \sup \mathcal{D}_{g+h}.$$

3. If h is strictly decreasing on $[\inf \mathcal{D}_g, +\infty[$, then

$$\sup \mathcal{D}_{g+h} \leq \inf \mathcal{D}_g.$$

4. If h is decreasing on $[\inf \mathcal{D}_g, +\infty[$, then

$$\inf \mathcal{D}_{g+h} \leq \inf \mathcal{D}_g.$$

Proof. We prove the first statement, the others being minor variations.

Let $u_g^\sharp \in \mathcal{D}_g$. For any $u \in \mathcal{D}$, we have $g(u) \leq g(u_g^\sharp)$. For any $u \in]-\infty, u_g^\sharp[$, we have $h(u) < h(u_g^\sharp)$ if h is strictly increasing. Thus

$$u \in]-\infty, u_g^\sharp[\Rightarrow g(u) + h(u) < g(u_g^\sharp) + h(u_g^\sharp).$$

We conclude that $\mathcal{D}_{g+h} \subset [u_g^\sharp, +\infty[$, so that

$$\mathcal{D}_{g+h} \subset \bigcap_{u_g^\sharp \in \mathcal{D}_g} [u_g^\sharp, +\infty[= [\sup \mathcal{D}_g, +\infty[.$$

This proves that $\sup \mathcal{D}_g \leq \inf \mathcal{D}_{g+h}$. □

The proof of Proposition 3 is a straightforward consequence with $u_0 \mapsto l_0(u_0) + V_\Phi(f(x_0, u_0)) + \Delta_{\Psi\Phi}(f(x_0, u_0))$ as function g and $u_0 \mapsto -\Delta_{\Psi\Phi}(f(x_0, u_0))$ as function h .

Freixas et Laffont (1984) propose a similar proof for a case with simplified dynamics and criteria (see section 3.3).

10 Appendix: Proof of Proposition 7

Let $\mathcal{P}(\Omega)$ be the set of all distributions on Ω , the states of the world. By classical arguments (Breiman, 1993, p. 77) (as soon as Ω is a complete separable metric space for instance), there exists a regular conditional probability of \mathbb{P} given Φ , denoted by $\mathbb{P}^\Phi : \Omega \times \mathcal{F} \rightarrow [0, 1]$ and characterized by:

1. $\forall \omega \in \Omega, \mathbb{P}^\Phi(\omega, \cdot) \in \mathcal{P}(\Omega)$;
2. $\forall A \in \mathcal{F}, \omega \mapsto \mathbb{P}^\Phi(\omega, \cdot)$ is measurable with respect to Φ ;
3. for all bounded random variable $Z, \mathbb{E}(Z \mid \Phi)(\omega) = \int_\Omega Z(\omega') \mathbb{P}^\Phi(\omega, d\omega')$, for \mathbb{P} -almost ω .

The sensor¹⁸ associated to \mathbb{P} and Φ is the random measure $S^\Phi \in \mathcal{P}(\mathcal{P}(\Omega))$ defined by

$$\forall M \in \mathcal{B}(\mathcal{P}(\Omega)), \quad S^\Phi(M) \stackrel{\text{def}}{=} \mathbb{P}\{\omega \in \Omega, \mathbb{P}^\Phi(\omega, \cdot) \in M\}. \quad (14)$$

Equivalently, S^Φ is also the image of the measure \mathbb{P} by the mapping

$$\omega \in \Omega \mapsto \mathbb{P}^\Phi(\omega, \cdot) \in \mathcal{P}(\Omega). \quad (15)$$

It is shown in Artstein and Wets (1993) that

$$\begin{aligned} \mathbb{E} \left(\max_{u_1 \in \mathcal{U}_1(x), u_1 \preceq \Phi} \mathbb{E} [l_1(u_1, x, \gamma) \mid \Phi] \right) &= \int_\Omega \mathbb{P}(d\omega) \left(\max_{u_1 \in \mathcal{U}_1(x), u_1 \preceq \Phi} \int_\Omega l_1(u_1, x, \gamma(\omega')) \mathbb{P}^\Phi(\omega, d\omega') \right) \\ &= \int_{\mathcal{P}(\Omega)} dS^\Phi(\rho) \left(\max_{u_1 \in \mathcal{U}_1(x)} \int_\Omega l_1(u_1, x, \gamma(\omega')) \rho(d\omega') \right) \\ &= \int_{\mathcal{P}(\Omega)} dS^\Phi(\rho) J(x, \rho). \end{aligned}$$

¹⁸A sensor is a probability law on the set $\mathcal{P}(\Omega)$ of all distributions on the states of the world, *i.e.* an element of $\mathcal{P}(\mathcal{P}(\Omega))$, the Borel space of probability measures on $\mathcal{P}(\Omega)$. Following Artstein (1999), an information structure can be defined by a sensor since it governs which posterior beliefs will be materialized at the time of decision. Chapter ?? offers more recalls and developments on sensors. See especially section ?? page ??.

Thus, by (6) and (5), we have

$$\begin{aligned}\Delta_{\Psi\Phi}(x) &= \mathbb{E} \left(\max_{u_1 \in \mathcal{U}_1(x), u_1 \preceq \Psi} \mathbb{E} [l_1(u_1, x, \gamma) \mid \Psi] \right) - \mathbb{E} \left(\max_{u_1 \in \mathcal{U}_1(x), u_1 \preceq \Phi} \mathbb{E} [l_1(u_1, x, \gamma) \mid \Phi] \right) \\ &= \int_{\mathcal{P}(\Omega)} dS^\Psi(\rho) J(x, \rho) - \int_{\mathcal{P}(\Omega)} dS^\Phi(\rho) J(x, \rho).\end{aligned}$$

Still following Artstein and Wets (1993) and Artstein (1999), we have that if Ψ is finer than Φ , then S^Ψ is more refined than S^Φ in the sense that for all $\phi : \mathcal{P}(\Omega) \rightarrow \mathbb{R}$ convex,

$$\int_{\mathcal{P}(\Omega)} \phi(\rho) dS^\Psi(\rho) \geq \int_{\mathcal{P}(\Omega)} \phi(\rho) dS^\Phi(\rho). \quad (16)$$

Thus, under the assumptions, the value of substituting Ψ for Φ , $u_0 \mapsto \Delta_{\Psi\Phi}(f(x_0, u_0))$, is an increasing (a decreasing) function.

11 Appendix: Variations of the value of information in Ulph and Ulph, 1997

We express $\frac{dI_\Phi}{dx_1} = \frac{dV_\Phi}{dx_1} - \frac{dV_\perp}{dx_1}$ for the problem (12).

Denote by $\hat{u}_1(x_1)$ the optimal feedback without information:

$$\hat{u}_1(x_1) \stackrel{\text{def}}{=} \arg \max_{u_1 \geq 0} \overbrace{[l_1(u_1) - \mathbb{E}\gamma D(u_1 + \delta x_1)]}^{V_\perp(x_1)}.$$

Unicity of the arg max results from the strict concavity of the mapping $u_1 \mapsto l_1(u_1) - \mathbb{E}\gamma D(u_1 + \delta x_1)$ since, by assumption, l_1 is strictly concave, D is strictly convex, and $\gamma \geq 0$.

Denoting $x_1^\perp \stackrel{\text{def}}{=} \delta x_0 + u_0^\perp$, we have then $u_1^\perp = \hat{u}_1(x_1^\perp)$ by definition. From Euler's characterization of the maximum of a concave function, the assumption $u_1^\perp = 0$ implies that $l'(0) - \delta \mathbb{E}\gamma D'(\delta x_1^\perp) \leq 0$. Now, for any $x_1 \geq x_1^\perp$, we have

$$l'(0) - \delta \mathbb{E}\gamma D'(\delta x_1) \leq l'(0) - \delta \mathbb{E}\gamma D'(\delta x_1^\perp) \leq 0$$

since $-D'$ is decreasing (D is convex). Thus, by Euler's condition, $\hat{u}_1(x_1) = 0$. Replacing in $V_\perp(x_1)$ and differentiating with respect to x_1 , we obtain

$$\frac{dV_\perp}{dx_1}(x_1) = -\mathbb{E}[\gamma] \delta D'(\delta x_1).$$

We now turn to $\frac{dV_\Phi}{dx_1}(x_1)$. Let

$$u_1^\Phi(x_1) \stackrel{\text{def}}{=} \arg \max_{u_1 \preceq \Phi} l_1(u_1) - \mathbb{E}[\gamma \mid \Phi] D(u_1 + \delta x_1)$$

which is a random variable.

By the Danskin theorem (see Clarke, 1990)), we have that

$$\frac{d}{dx_1} \max_{u_1 \preceq \Phi} l_1(u_1) - \mathbb{E}[\gamma \mid \Phi] D(u_1 + \delta x_1) = -\mathbb{E}[\gamma \mid \Phi] \delta D'(\delta x_1 + u_1^\Phi(x_1)).$$

By differentiating under the integral sign, we get that

$$\frac{dV_{\Phi}}{dx_1}(x_1) = \mathbb{E}[-\mathbb{E}[\gamma | \Phi] \delta D'(\delta x_1 + u_1^{\Phi}(x_1))]$$

Finally,

$$\begin{aligned} \frac{dI_{\Phi}}{dx_1}(x_1) &= \mathbb{E}[-\mathbb{E}[\gamma | \Phi] \delta D'(\delta x_1 + u_1^{\Phi}(x_1))] + \mathbb{E}[\gamma] \delta D'(\delta x_1) \\ &= \mathbb{E}[-\mathbb{E}[\gamma | \Phi] \delta D'(\delta x_1 + u_1^{\Phi}(x_1))] + \mathbb{E}[\mathbb{E}[\gamma | \Phi]] \delta D'(\delta x_1) \\ &= \mathbb{E}[\mathbb{E}[\gamma | \Phi] (D'(\delta x_1) - D'(\delta x_1 + u_1^{\Phi}(x_1)))] \end{aligned}$$

which is non-positive since $u_1^{\Phi}(x_1, s) \geq 0$ and D is convex. Therefore $u_0 \mapsto I_{\Phi}(\delta x_0 + u_0)$ is decreasing for all u_0 greater than u_0^{\dagger} : the value of information diminishes with initial GHG emissions above their optimal level without information.

12 Appendix: Details for the numerical model

12.1 Summarized description of the modified dice model

The model solve the following problem.

$$\max_{v_0, \dots, v_{d-1}} \mathbb{E} \left\{ \sum_{i=0}^{d-1} L_i(v_i, z_i) + \mathbb{E} \left[\max_{(v_d, \dots, v_T) \preceq \gamma} \sum_{i=d}^T L_i(v_i, z_i) \mid \gamma \right] \right\} \quad (17)$$

$$\text{with } z_{i+1} = g(z_i, v_i, \gamma) \quad (18)$$

The time horizon is $T = 40$. Time step $i = 0$ corresponds to the period 2000–2009. The date of arrival of information, d , belongs to $\{0, \dots, T + 1\}$.

Variables

Controls		
v_i	a_i	GHG reduction rate
	b_i	investment rate
State variables		
z_i	K_i	Capital stock
	$M_i \in \mathbb{R}^3$	Stocks of carbon in 3 reservoirs
	$\theta_i \in \mathbb{R}^2$	Mean temperature rises for atmosphere and ocean
γ	r.v. $\in \{L, C, H\}$	Climate sensitivity
Intermediary, transfer variable		
	Y	Available economic output

Relations

$$\text{Output} \quad Y_i = F_i(K_i)(1 - C_i(a_i))(1 - D(\theta_i)) \quad (19)$$

$$\text{Capital accumulation} \quad K_{i+1} = G(K_i, b_i Y_i) \quad (20)$$

$$\text{Carbone cycle} \quad M_{i+1} = H(a_i, K_i, M_i) \quad (21)$$

$$\text{Reduced-form climate model} \quad \theta_{i+1} = \Theta(\theta_i, M_i, \gamma) \quad (22)$$

$$\text{Discounted utility} \quad L_i(z_i, v_i) = U_i((1 - b_i)Y_i)$$

$$\text{Admissibility domain for } b_i \quad b_i \in [0, 1 - \varepsilon]$$

$$\text{Admissibility domain for } a_i \quad a_i \in [0, 1] \quad (C_i(1) < 1 \quad \text{for all } i)$$

The dynamics summarized by function g in Eq. (18) is composed with the four relations (19–22).

Detailed functional forms can be found in Nordhaus (1994) or Nordhaus and Boyer (2000) except for two modifications from Ambrosi et al. (2003) — function Θ in Eq. (22) and damage function D in Eq. (19) — that are reproduced in section 12.5 below.

Random variable Three different distributions are used for the random variable $\gamma \in \{L, C, H\}$

Probability	Climate sensitivity γ		
	L(2.5 °C)	C(3.5 °C)	H(4.5 °C)
optimistic	2/3	1/3	1/3
centered	1/3	2/3	1/3
pessimistic	1/3	1/3	2/3

12.2 Parameterization of the controls in time steps 0 to 3

The goal is to compute the value of information in 2040 ($d = 4$) as a function of a scalar policy decision describing abatement and investment choices from 2000 to 2039. We chose the abatement rate targeted for 2030 as the key policy decision. The problem is to chose a sensible parameterization of investment and abatement before and up to 2030 with this scalar. We propose one that approximates for $i \in \{0, \dots, 3\}$ the optimal trajectories of the model under the different hypotheses available on the climate sensitivity. Afterwards, the parameterization allows to describe a wider range of trajectories, including non-optimal ones (bad policy choices) in a coherent and continuous manner.

For calibration purposes, we have therefore computed the numerical optimal values for $(v_i)_{i \in \{0, \dots, 3\}}$ in problem (17) under four different hypotheses :

- H1: no uncertainty ($d = 0$) and $\gamma = L$
- H2: no uncertainty ($d = 0$) and $\gamma = C$
- H3: no uncertainty ($d = 0$) and $\gamma = H$
- H4: information in 2040 ($d = 5$). $\gamma \in \{L, C, H\}$, pessimistic probabilities (see above) are used.

Hypothesis	Abatement rate in year				Investment rate in year			
	2000	2010	2020	2030	2000	2010	2020	2030
	a_0	a_1	a_2	a_3	b_0	b_1	b_2	b_3
H1	0.059	0.075	0.093	0.115	0.239	0.232	0.228	0.225
H2	0.092	0.123	0.163	0.215	0.239	0.231	0.227	0.224
H3	0.138	0.194	0.266	0.361	0.238	0.231	0.226	0.223
H4	0.121	0.168	0.230	0.310	0.238	0.231	0.226	0.224

Table 1: Optimal abatement and investment rates under H1–4

The GAMS code for solving numerically problem (17) is ‘dice_response_art.gms’ provided in attachment. See also section ???. The numerical model has actually $i = -1$ as first time step corresponding to 1990–1999, but abatement is fixed to $a_{-1} = 0$. Investment is fixed as well with value $b_{-1} = 0.250$. We obtain the following results, displayed below in Table 1

The parameterization chosen, $\varphi : u_0 \mapsto (a_i, b_i)_{i \in \{0..3\}}$, is defined by

$$a_i = \varphi_i^a(u) = \lambda u + \mu u i + \nu u i^2$$

with $\lambda = 0.3006 \quad \mu = 0.0724 \quad \nu = 0.0256$

and

$$b_i = \varphi_i^b$$

with $\varphi_0^b = 0.239 \quad \varphi_1^b = 0.231 \quad \varphi_2^b = 0.227 \quad \varphi_3^b = 0.224$

Both parameterizations are chosen to approximate the optimal numerical solutions of problem (??) under hypotheses H1–H4. Figure 2 displays how φ approximates the optimal decisions in Table 1.

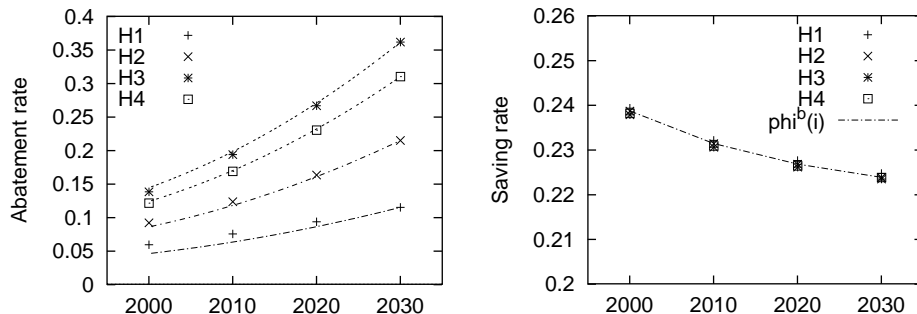


Figure 2: Parameterization of policy before 2040

The left panel of figure 2 shows as dots the optimal abatement rates a_i in time steps $i = 0, \dots, 3$ under hypotheses H1–4. The lines trace the corresponding parameterizations φ^a where u_0 assume in turn the preceding values of a_3 in hypotheses H1–4.

The right panel of Figure 2 displays the optimal investment rates b_i for $i = 0 \dots 3$ under hypotheses H1–H4 and the parametrization φ_i^b as a line. Note that it depends only of the time step and not of u .

12.3 Optimal initial policies with and without learning

After parameterization, the problem is simplified into

$$\begin{aligned} \max_{0 \leq u_0 \leq 1} \mathbb{E} \left\{ \sum_{i < 4} L_i(\varphi_i(u_0), z_i) + \mathbb{E} \left[\max_{(v_4, \dots, v_T) \preceq \gamma} \sum_{i=4}^T L_i(v_i, z_i) \mid \gamma \right] \right\} \\ \text{with } z_{i+1} = g(z_i, \varphi_i(u_0), \gamma) \quad \text{for } i < d \\ \text{and } z_{i+1} = g(z_i, v_i, \gamma) \quad \text{for } i \geq d \end{aligned} \quad (23)$$

This problem is solved with MINOS 5 using the GAMS code ‘u0opt_dicersp.gms’. For each probability distribution, we obtain the following optimal values for u_0 with information arrival in 2040 or without arrival of information. We have computed the *initial* value of information, I^0 (the difference between the optimal value of the objective with $d = 0$ and with $d = 4$)

Optimal abatement target in 2030 with and without learning			
	Information in 2040	Never learn	Initial value of information
Probability distribution	u_0^{**}	u_0^*	(in utility units)
Optimistic	0.196	0.248	462
Centered	0.236	0.283	284
Pessimistic	0.308	0.338	193

Table 2:

The values for u_0^{**} and u_0^* are reported into Figure 1 of the main paper.

12.4 Computed value of information

By definition,

$$\begin{aligned} I_s(u_0) = \mathbb{E} \left[\max_{(v_d, \dots, v_T) \preceq \gamma} \sum_{i=d}^T L_i(v_i, z_i) \mid \gamma \right] - \max_{(v_d, \dots, v_T)} \mathbb{E} \sum_{i=d}^T L_i(v_i, z_i) \\ \text{with } z_{i+1} = g(z_i, v_i, \gamma) \quad \text{for } i \geq d \\ \text{and the r.v. } z_d \text{ determined by } z_0, \gamma \text{ and } u_0 \text{ through:} \\ z_{i+1} = g(z_i, \varphi_i(u_0), \gamma) \quad \text{for } i < d \end{aligned} \quad (24)$$

We screen $[0, 1]$ for values of u_0 . For each value of u_0 , the problems in Eq. 24 are solved with MINOS 5 using the GAMS code ‘vlinfinfo_dicersp.gms’.

An extract of the results is given in the next table.

12.5 Detailed modifications to the original dice model

These modifications are taken and reproduced from Ambrosi et al. (2003)

Reduced-form climate model

We detail here the Eq. (22): $\theta_{i+1} = \Theta(\theta_i, M_i, \gamma)$

$$\theta_{i+1} = \Sigma(\gamma) \theta_i + \sigma_1 \begin{bmatrix} F_i(M_i) \\ 0 \end{bmatrix}$$

Value of information as a function of initial policy			
Initial policy u_0	Probability distribution		
	pessimistic	centered	optimistic
	Value of information <i>(in utility units)</i>		
0.000	269	355	520
0.051	255	343	507
0.101	241	328	494
0.152	228	314	481
0.202	217	300	467
0.253	206	286	454
0.303	196	274	441
0.354	187	262	428
0.404	178	250	416
0.455	170	240	404
0.505	163	230	392
0.556	156	220	381
0.606	150	212	370
0.657	143	203	359
0.707	138	195	346
0.758	132	188	333
0.808	127	181	322
0.859	122	174	311
0.909	118	167	300
0.960	114	161	290
1.000	110	157	283

Table 3: Initial policy is the abatement targeted for 2030

where

- $\theta_i = {}^t(\theta_i^{At}, \theta_i^{Oc})$ is the vector of global mean temperature rise ($^{\circ}\text{C}$) with respect to pre-industrial times for the atmosphere and the ocean.
- $F_i(M_i)$ is the radiative forcing defined by

$$F_i(M_i) = F_{2X} \log(M_i^{\text{atm}}/280) / \log 2$$

where M_i^{atm} , subcomponent of M_i , is the CO_2 atmospheric concentration in time step i . M_{PI} is the CO_2 atmospheric concentration at pre-industrial times, set at 280 ppm. F_{2X} is the instantaneous radiative forcing for an atmospheric concentration of $2 \times M_{PI}$, set at 3.71 W.m^{-2} .

- the transfer matrix $\Sigma(\gamma)$ is

$$\Sigma(\gamma) = \begin{bmatrix} 1 - \sigma_1(F_{2X}/\gamma + \sigma_2) & \sigma_1\sigma_2 \\ \sigma_3 & 1 - \sigma_3 \end{bmatrix}$$

with coefficient values $\sigma_1 = 0.479 \text{ C.W}^{-1}.\text{m}^{-2}$, $\sigma_2 = 0.109 \text{ C}^{-1}.\text{W.m}^{-2}$, $\sigma_3 = 0.131$ and γ is the climate sensitivity.

Damage function

We detail here the function D of Eq. (19) that defines the damages in share of GWP.

$$D(\theta_i) = b(\theta_i^{At} - \theta_0^{At}) + \frac{d}{1 + \exp\left[\frac{K+Z-2(\theta_i^{At}-\theta_0^{At})}{K-Z} \ln\left(\frac{2-e}{e}\right)\right]}$$

where $b = 0.005\text{ }^\circ\text{C}^{-1}$ is the linear trend of the damage; $d = 0.03$ is the magnitude of the jump ; $e = 0.1$ controls the steepness of the jump ; $K = 1.3\text{ }^\circ\text{C}$ and $Z = 2.7\text{ }^\circ\text{C}$ are the temperatures where the non-linear transition begins and ends.

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