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Decision-Making Under Scientific Uncertainty: The Economics of the Precautionary Principle

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Abstract

The Precautionary Principle has provided the foundations for building a new risk regulatory pattern under scientific uncertainty. This paper investigates how classical economic theory may, or may not, justify the Precautionary Principle. It examines the link between irreversibility, the prospect of increasing information over time and risk management. In doing so, it brings closer the notion of option value to that of precaution. Using a general modelling framework, it identifies the conditions so that the Precautionary Principle is an efficient economic guideline. It also explains why precautionary policies are not likely to emerge in a competitive economy or in the presence of a global pollution problem.

Keywords: Precautionary Principle, option value, scientific uncertainty, irreversibility

JEL Classification: D81, Q28, H43

1. Introduction

As recently illustrated by the beef crisis in Europe or by the debates on genetic manipulations, the Precautionary Principle (PP) is becoming increasingly prominent in the environmental protection and health safety debate. The basic premise of the PP is that one should not wait for conclusive evidence of a risk before putting control measures in place designed to protect the environment or consumers.

Despite the seemingly clear meaning of this premise, the question of how to interpret the PP has engendered endless controversies. There is no single accepted interpretation of the PP.[1] In its most extreme formulation, the PP requires absolute proof of safety before allowing innovations to be adopted. Its various interpretations has been the source of international tensions between the US and the European Union, as in the hormone-treated beef affair for example. A critical editorial in the Wall Street Journal has said that the "*PP is an environmentalist neologism, invoked to trump scientific evidence and move directly to banning things they don't like—biotech, wireless technology, hydrocarbon emissions*."

At the root of these tensions is the difficult question of how to manage a risk under conditions of imperfect scientific knowledge. Intuitively, there is an argument for postponing costly preventive efforts until more scientific evidence sustaining the existence of a high risk is made available. The sequential aspect of the decision process is thus central to the problem

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of risk management under conditions of scientific uncertainty. For the sake of illustration, research on policies for limiting climate change due to greenhouse gases emissions have emphasized the need to develop such a sequential approach to decision-making. The choice between a moderate or an aggressive emissions reduction is determined today by the future improvement of scientific understanding of climate change and by our ability to switch to other sources of energy in the future.

Yet, economists have not been waiting till we face the global warming issue to think about decision-making under conditions of evolving knowledge. In 1974, Kenneth Arrow and Anthony Fisher examined the effect of learning more over time about uncertain benefits of preserving an area of wilderness land when its development would be irreversible. They identified an additional (quasi-) *option value* that raises the opportunity cost of development due to the prospect of forthcoming information. The same year, Claude Henry proved that taking account of forthcoming information together with the irreversible nature of most investment decisions prevents the use of the net present value method. This insight was applied to the valuation of irreversible investment projects in France, such as developing a circumferential highway around Paris over forests or ancestral properties.

Given the prominent literature on the PP in social sciences in general,[2] the purpose of the paper is thus to develop a coherent view of the economic approach of the PP. We build on the option value literature to provide an interpretation of the PP, that, we believe, is shared by most economists. In short, we consider a sequential framework and examine the conditions so that scientific uncertainties lead to a more precautionary rule in the short-run. In doing so, the paper also summarizes recent research of the option value literature and points out the strengths of this approach as well as its limits in order to raise some promising research trends.[3] In particular, this paper discusses various implementation issues raised by the PP.

We organize this paper as follows. In the Section 2, we shall begin by stressing some typical features of new technological or environmental risks. We argue that the interplay among those features suggest to develop sequential regulatory policies. This will permit to adapt future decisions to scientific progress. We then introduce the PP as a new guideline that appeared in international treaties in the early 90s.

In Section 3, with the help of a simple example, we introduce the theory of sequential decision-making (Arrow and Fisher, 1974; Dixit and Pindyck, 1994). We bring closer the notion of option value to that of precaution. We set up the general model and define the notions of information structures and that of irreversibility. We also make use of that model to distinguish the notion of precaution from that of prevention.

In Section 4, we examine the interplay between information and flexibility. We demonstrate that the prospect of forthcoming information always biases decisions in favor of more flexibility (Epstein, 1980). In doing so, this paper presents in a summary fashion the literature on the ‘irreversibility effect’ in order to integrate the most recent developments in investment theory and its interactions with environment policy. In particular, we show that when long-term effects of risks are unknown, it may be optimal to be more prudent at the initial stage of the risk management process. This allows us to put forward a normative economic basis for the PP (Gollier, Jullien, and Treich, 2000).

In Section 5, we show that the results derived from the literature on option values may not carry over to a world where several actors act non-cooperatively. We give three typical illustrations of such market failures. We discuss the strength of competition in innovative markets, the effect of time-inconsistencies and that of global environmental externalities. For these three illustrations, we show that decision-makers may not select precautionary policies at the equilibrium, while these policies should be adopted in the global economy. There is thus a need to implement the PP by designing appropriate regulatory policies together with the suitable institutions to enforce these policies.

In Section 6, we conclude the paper by a broader discussion on risk regulatory institutions. We argue that scientific uncertainty introduces a considerable room for discretion and self-interested biases through the channels of risk management. Experts may more easily provide biased recommendations. Politicians may rely more easily on the scientific theory that matches their interests. Liability rules are more difficult to set up due to imperfect knowledge and the long run effects in presence. Also, scientific uncertainty may enhance public misperceptions. The presence of scientific uncertainty thus drastically complicates the decision-making process. The challenge then will be to design the PP to reduce the opportunism of some agents in situation of imperfect and changing risk information.

2. A new guideline for regulating new risks

The perception of risks has profoundly changed in the last three decades. As illustrated by the development of cancers from abestos, by the drama of contaminated blood transmitting AIDS, or by the recent ‘mad cow affair’, damages generated by decisions taken under scientific uncertainty may affect millions of people with wide regional variations. Examples abound of risks sharing those characteristics: hazardous wastes, species extinction, global warming, electromagnetic fields, cellular phones, transgenic food; and the list could go on. Analysis of regulatory policies to deal with those new risks is complicated by several features.

First, the consequences may arise in a time-span of several decades to centuries. Typically damages are generated by the stock of pollutants present in the environment, rather than by its flow which can be controlled more easily. The concentration of the pollutant can respond only slowly to the change in the annual rate of emission. As a result, one cannot readily reverse or mitigate physical degradation other than letting the natural rate of decay operate. The Montréal protocol, establishing a schedule to reduce the consumption of CFCs and halons, was signed as of March 1987. Yet, one will have to wait until the end of this new century for the rate of chlorine to be lower than its level of 1970. In this sense, past decisions to emit pollutants will have some strong impact on the risk borne by future generations.

In addition to this inertia linked to physical processes, there exist more radical types of irreversibility. For instance, the Creutzfeldt-Jakob disease, that may result from eating ‘mad cows, is irreversible. The loss of some animal species due to climate change or the diffusion of some genetically modified species may also be readily irreversible. Another kind of irreversibility comes from the time needed for adaptation of the socio-economic system. Rapid changes in the turnover of capital imply higher costs than a smooth adaptation, as the time necessary for developing low-cost substitutes of the pollutants. This time lag will involve further complications related to technical changes as well as population and consumption patterns.

Also, there is typically a large degree of uncertainty in predicting the severity of such catastrophic events. For instance, scientists do not know how ‘mad cows’ became infectious and how long humans incubate the disease. As a result current estimates of human victims in the U.K. over the next two decades vary from 100 to more than 100,000. In the current debates on global warming or on El Nino phenomenon, complexity is a dominant characteristic of the problem. The interactions between atmosphere, clouds, oceans and polar ice sheets are still not well understood. IPCC (1995) estimated that for a doubling atmospheric concentration of carbon dioxide the increase in the temperature may lie between $+1.8^{\circ}$C and $+5.4^{\circ}$C. This represents a considerable scientific uncertainty.

However, while at first uncertainty may loom very large, there is high potential for rapid resolution of uncertainty. There is ongoing research on these new risks. Recall that in the 1960s, ozone alarms began with an attack against supersonic flights, wrongly suspected by some US scientists to deplete ozone layer. In 1974, Molina and Rowland published their famous theory in *Nature*. Then, in the fall 1985, two teams of scientists discovered the ozone hole over the antarctic.

To sum up, decision-making related to new environmental or technological risks must take into account these important characteristics of the problem: long time horizon, stock externalities, possible irreversibilities (physical and socio-economic), large uncertainties and future scientific progress.

As opposed to various forms of regular risks commonly addressed by standard prevention or insurance activities, the interplay among those characteristics has emphasized the need to develop dynamic approaches to regulation strategies. Timing becomes the key issue.

This underlies the need to identify optimal short-term strategies in the face of long-term uncertainties. These strategies should permit to respond to new information with mid-course corrections. As a result, “[preventing] *measures should be periodically reviewed in the light of scientific progress, and amended as necessary*” (CEC, 2000). The advantages of a so-called *sequential approach* has been often advocated as a strategy for abating climate change (Hammitt, Lempert, and Schlesinger, 1992). For instance, IPCC (1995) states that *“the challenge is not to find the best policy today for the next* 100 *years, but to select a prudent and flexible strategy and to adjust it over time.”*

The economic approach may then be of significant help. Considerable work has been done in economic theory on the question of uncertainty and learning. The economic criteria of decision-making under uncertainty potentially permit to select among the various scientific experts’ scenarios. As an illustration, Manne and Richels (1992) or Nordhaus (1994) combined Ramsey growth economic models together with elaborated climatic modules. Those “integrated assessment” models have identified optimal climate policies given climatic uncertainties.

One of the difficulty to implement a sequential approach comes from the danger to take decisions with a limited confidence on the underlying mechanism generating the risk faced by the population. The costs of developing early preventive actions is often very high compared to the do-nothing strategy, just waiting for better scientific evidence. Uncertainty and irreversibility may precisely be used as an argument in favor of the status quo. For instance, in the early 1980s, the American Chemistry Society complained that any restriction on CFCs reduction would constitute *“the first regulation to be based entirely on an unverified* *scientific prediction."* A DuPont spokesperson protested that *"we are going a very long way into the regulatory process before scientists know what's really going on"* (Morone and Woodhouse, 1986, p. 82).

The key point here is that there is a tension between the rapid resolution of uncertainty and the slow entropy of the system, e.g. climate evolves slowly compared to rate of the resolution of spatio-temporal climate models. As stated for instance by the IPCC (1995): *"The choice of abatement paths involves balancing the economic risks of rapid abatement now (that premature capital stock retirement will later proved unnecessary) against the corresponding risk of delay (that more rapid reduction will then be required, necessitating premature retirement of future capital stock)."*

In this context, the PP takes a committed stand against "learn-then-act," "wait-and-see" or "business-as-usual" strategies and in favor of premature preventive actions. The PP has its beginnings in the early 1970s as the German principle of Vorsorge, or foresight. The PP was first introduced in 1984 at the First International Conference on Protection of the North Sea. It has then flourished in international statements of policy, as in the Maastricht Treaty, or at the Conference of Rio. Principle 15 of the 1992 Rio Declaration states *"Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."*[4]

Although devoid of practical content, the PP is formulated in such a manner as to provide the basis for regulatory policies. Considering that the absence of evidence is not the evidence of absence, the main message of the PP is conceptually clear: scientific progress do not justify the delay of measures preventing environmental degradation. The PP is the most notable anticipatory principle existing in the national and international law with special relevance for human-induced environmental problems. In practice, its scope is even much wider and there are reasonable grounds for applying it to regulate the protection of human, animal and plant health issues (CEC, 2000). Nowadays, this principle is often said to be the solid foundation on which to base decision-making under conditions of large uncertainty (e.g. Godard, 1997).

Yet, the PP cannot stand out through decrees or discussions only. Our objective is to examine whether the PP is an efficient economic guideline. Hence we will investigate in the next section a sequential decision problem. As time passes, information about the true scientific theory comes. We will examine optimal sequential policies, i.e. policies that are robust to the timing of the resolution of scientific uncertainty. We will check whether these policies induce a bias towards premature investments in prevention, as suggested by the PP.

3. Presentation of the framework

The previous section has presented the historical context in which the PP has emerged. We have seen that since the first environmental threats developed in the mid-70s the concept of precaution has become increasingly prominent in environmental or health safety protection debates. Interestingly, during the same period, economists have performed a new theoretical approach to cost-benefit analysis, stressing the irreversibility and the uncertainty inherent to the future benefits of development decisions (Arrow and Fisher, 1974). This option value literature has then been developed intensively in the investment literature (Dixit and Pindyck, 1984).

In this section, we will proceed as follows. We will first introduce the notion of option value through a simple example. We will then set up the general model and define the notions of irreversibility and that of information structure. We then make use of that framework to formally distinguish the notion of prevention to that of precaution.

3.1. *Option values: Introductory example*

An economy of risk-neutral agents is considering the possibility of developing a wild area. There is a once for all sunk cost I to implement the project. The benefit from developing the area is uncertain because the area might contain some rare species or some plant with important medicine properties in the future. Given the current scientific uncertainty about these future benefits, the project's expected benefit for the Society per period is P. In fact, there are two competing theories which can be true with equal probabilities given our current beliefs. But one expects scientific progress to be made over the first period which will reveal the true theory and the corresponding true added value of the development project.[5] With equal probability it may rise to $1.5P$ or fall to $0.5P$. The discount factor is $\beta \in]0, 1[$. The problem is to determine the optimal timing for developing the area.

If one develops it immediately, the expected net present value of the project is

$$NPV_1 = \frac{P}{1-\beta} - I, \tag{1}$$

since the project generates a cost I in the current period and an expected benefit P in each period forever. The classical method consists in developing the project immediately if NPV_1 is positive. This, however, may not be optimal. An alternative decision rule would be to decide whether or not to develop after the scientific uncertainty has been resolved. To make the problem interesting, let us assume that

$$\frac{0.5P}{1-\beta} \leq I \leq \frac{1.5P}{1-\beta}, \tag{2}$$

so that the project is socially valuable only if the good theory is true. As a consequence, conditionally on the fact that the decision to develop is delayed in the first period, the project is developed in the second period if and only if the good theory is revealed to be the true one. This implies that the expected present value of this alternative strategy is

$$NPV_2 = 0.5\beta\left(\frac{1.5P}{1-\beta} - I\right). \tag{3}$$

Obviously, the risk neutral Society will find it optimal to delay the project until period 2 if and only if $NPV_2 \geq NPV_1$. There is a negative and a positive effect of delaying the project. The negative effect comes from the loss of the initial expected value P. The benefit comes from the opportunity to abandon the project if the bad theory happens to be the true one. This is only when this benefit is larger than the loss of the first period cash-flow that the option is valuable. The quantity $\max(0, NPV_2 - NPV_1)$ is called the *option value* of delaying the investment, which can be positive or zero. Thus, the decision of whether it is optimal to invest in the first period or to remain uncommitted depends upon the relative values of the three parameters: P, I and β. Specifically, suppose as in the introductory example in Dixit and Pindyck (1994) that these parameters take respectively 200, 1600 and 1/1.1. Then the option value is equal to 173.

This positive option value reflects the cost of an irreversible decision: investing with no possibility of "dis-investing". Note that if the cost I was fully recoverable, then it would be always optimal to invest in the first period and then to recover this cost if one learns that the project is not socially valuable. But a decision like the one of developing a wild area is often very costly to reverse. This choice makes the future position inflexible. Yet since the opportunity to develop is not a take-it-or-leave-it option, one may choose to do nothing first. By doing so, one keeps the option of developing later on. This flexibility in the decision process makes possible for the decision-maker to use the information to come, which is valuable.

There is thus a trade-off between receiving the current period cash-flow of the project and waiting for the future scientific information arrival. This is the irreversible nature of investment decisions together with the information value that is at the origin of the option value as first recognized by Arrow and Fisher (1974) and Henry (1974a).[6] This option value provides a strong argument in favor of the PP, if it is interpreted as the idea that scientific uncertainty should induce us to preserve flexibility for the future.

3.2. *The model*

We now introduce a general model that includes the previous one. Our objective will be to exhibit the general conditions that control the sensitiveness of the current decision to the prospect of forthcoming information.

A decision-maker (DM) lives for two periods:

- At the beginning of period one, he must choose α_1 within an opportunity set D that affects his first period utility $u(\alpha_1)$;
- After decision α_1 is made, he receives a message $\tilde{y} = y$. He revises his beliefs according to the Bayes'rule;
- At the beginning of period 2, he takes another decision α_2 within an opportunity set $D(\alpha_1)$;
- Finally the true state of the world $\tilde{\theta} = \theta$ is revealed and the DM enjoys a discounted felicity $v(\alpha_1, \alpha_2, \theta)$.

The DM maximizes his lifetime expected utility:

$$\max_{\alpha_1 \in D} u(\alpha_1) + \beta E_{\tilde{y}} \max_{\alpha_2 \in D(\alpha_1)} E_{\tilde{\theta}/\tilde{y}} v(\alpha_1, \alpha_2, \tilde{\theta}). \tag{4}$$

We assume that solutions of (4) exist and are unique.[7] This model includes the introductory example above. To see that, just take

$$u(\alpha_1) = \alpha_1\left(\frac{P}{1-\beta} - I\right), \tag{5}$$

$$v(\alpha_1, \alpha_2, \theta) = \alpha_2\left(\frac{\theta P}{1-\beta} - I\right), \tag{6}$$

and assume that θ may take 0.5 or 1.5 with equal probability.

In the example presented in the previous section, irreversibility may be represented as a reduction of the future opportunity set implied by the first period decision,

$$D(\alpha_1) = \{0, 1 - \alpha_1\}. \tag{7}$$

In words, taking action "1" in the first period means "investing". Then, the future opportunity set would become $D(1) = \{0\}$, so that there is only one possible choice let for the future, "no investing". As a consequence, investing now kills the option of investing in the future. This represents the fact that developing the project is 'irreversible'. More generally, we will say that decision α_1 is more irreversible than α_1' when

$$D(\alpha_1) \subseteq D(\alpha_1'). \tag{8}$$

This definition captures the notion of *choice irreversibility*. Undertaking an irreversible action, such as the development of a wildland area results in a more inflexible position than leaving the area undeveloped today and having the choice of the development or preservation tomorrow. In our framework, this choice is irreversible since it will reduce the set of choices $D(\alpha_1)$ available later on.[8] For instance, when the opportunity takes the form of a constraint on period 2 decision, i.e. so that $f_1(\alpha_1) \leq \alpha_2 \leq f_2(\alpha_1)$, larger α_1 is more irreversible only if $f_1'(\cdot) \geq 0$ and $f_2'(\cdot) \leq 0$.[9]

Let us now turn to another crucial question. As explained earlier, our aim is to determine the impact of scientific uncertainty on the optimal timing of risk-taking. Scientific uncertainty differs from natural risks by the fact that the first is subject to be resolved over time, at least partially. We will examine the effect of an increase in the scientific uncertainty. The problem is thus to characterize more scientific uncertainty.

We will say that there is more scientific uncertainty today if we expect scientific research to be more informative in the future, i.e. if we face a better information structure. We hereafter present the concept of a better information structure introduced by Blackwell (1951).

It is convenient here to assume that $\tilde{\theta}$ is discrete with m atoms of probability. We then denote $\pi_y(\theta_i)$ for the probability that $\tilde{\theta} = \theta_i$ conditional to receiving signal y and $\pi_y = (\pi_y(\theta_1), \ldots, \pi_y(\theta_m))$ (resp. $\pi'_{y'}$) the probability distribution conditional to the message y of $\tilde{y}$ (resp. y' of $\tilde{y}'$). Let us also define

$$S = \left\{ \pi_y \in R_+^m \;\middle|\; \sum_{i=1}^{m} \pi_y(\theta_i) = 1 \right\},$$

as the set of all conditional distributions on $\tilde{\theta}$.

In the standard terminology of Blackwell (1951), $\tilde{y}$ in model (4) describes an "experiment", but what we have in mind is scientific research in general. We will consider the following intuitive definition of a better experiment first proposed by Bohenblust, Shapley, and Sherman (1949). We say that the experiment $\tilde{y}$ is better than experiment $\tilde{y}'$ if and only if every DM prefers a priori observing $\tilde{y}$ than $\tilde{y}'$:

$$E_{\tilde{y}} \max_{\alpha_2 \in D(\alpha_1)} E_{\tilde{\theta}/\tilde{y}} v(\alpha_1, \alpha_2, \tilde{\theta}) \geq E_{\tilde{y}'} \max_{\alpha_2 \in D(\alpha_1)} E_{\tilde{\theta}/\tilde{y}'} v(\alpha_1, \alpha_2, \tilde{\theta}), \tag{9}$$

or equivalently,

$$E_{\tilde{y}} j(\alpha_1, \pi_{\tilde{y}}) \geq E_{\tilde{y}'} j(\alpha_1, \pi'_{\tilde{y}'}),$$

where $j(\alpha_1, \pi_y)$ is the period-2 value function conditional of observing signal $\tilde{y} = y$. It is defined as

$$j(\alpha_1, \pi_y) = \max_{\alpha_2 \in D(\alpha_1)} E_{\tilde{\theta}/y} v(\alpha_1, \alpha_2, \tilde{\theta}). \tag{10}$$

Note that this function is convex in the vector of posterior probabilities since it is the maximum of linear functions of π_y. Importantly, this result holds independently of the decision problem under consideration. Indeed by (10), function j is the upper envelop of a set of functions $f(\alpha_1, \pi_y) = E_{\tilde{\theta}/y} v(\alpha_1, \alpha_2, \tilde{\theta})$, $\alpha_1 \in D(\alpha_1)$, that are linear in π_y. Therefore it is a convex function of π_y.

Reciprocally, one can prove that any convex function $\rho(\pi_y)$ on S can be obtained from the operation (10) when appropriately choosing the decision-making environment. This is due to the well-known separating hyperplane theorem which implies that, to any convex surface, there exists a set of hyperplanes for which this surface is the upper envelope. Following Marschak and Miyasawa (1968), this leads to another equivalent definition of a better information structure which will prove to be extremely useful in the rest of the paper.

Definition 1. Information structure $\tilde{y}$ is better than information structure $\tilde{y}'$ if and only if:

$$\text{for any } \rho \text{ convex on } S: E_{\tilde{y}} \rho(\pi_{\tilde{y}}) \geq E_{\tilde{y}'} \rho(\pi'_{\tilde{y}'}). \tag{11}$$

Note that (11) implies that the two economies have the same beliefs ex ante

$$E_{\tilde{y}} \pi_{\tilde{y}} = E_{\tilde{y}'} \pi'_{\tilde{y}'}.$$

As a consequence (11) defines a mean-preserving spread of posterior beliefs. This means that the increase in scientific uncertainty is obtained without changing the ex ante distribution of the real risk $\tilde{\theta}$. Suppose for instance that there are two states of the world, $m = 2$ and denote $\pi \equiv \pi(\theta_1)$ for the prior belief on state 1. Then any convex function $\rho(\pi)$ on $\Re$ is a measure of information. Take for instance the inverse of the entropy function[10]

$$\rho(\pi) = \pi \log \pi + (1 - \pi) \log(1 - \pi).$$

Entropy or uncertainty is maximal for $\pi = 0.5$ and minimal for 0 or 1. Any experiment that will lead to move ex post probabilities away from π also diminish the ex ante uncertainty faces by the DM.

3.3. Prevention versus precaution

Since Knight (1921) it is standard to make a distinction between a *risk*, characterized by an objective probability distribution, and *uncertainty*, which is not related to any precise statistical estimates. From this point of view, the previous model distinguishes the risk, tied to the realizations of $\tilde{\theta}$, from uncertainty tied to the realizations of $\tilde{y}$. Making this distinction leads to recognizing that uncertainty is not independent of knowledge and thus is not a static concept. With the accumulation of knowledge, uncertainty resolves, at least partially, allowing for a revision of beliefs. Hence, we interpret the fact that the future probability distribution $\pi_{\tilde{y}}$ is unknown to the DM in the initial period as the *lack of full scientific certainty* advocated by the PP. Initially the DM ignores both θ and y. There are two sources of risk represented in the model. The second source of risk, tied to scientific uncertainty $\tilde{y}$, is at the root of the precautionary motive.

What is the effect of scientific uncertainty on decision-making? Using definition (11), we will answer this question in the sense of the comparative statics analysis. We consider two economies $\tilde{y}$ and $\tilde{y}'$ that are equivalent except for the flow of information, i.e., except for the degree of scientific uncertainty. In which economy is it optimal to be more prudent in the short run? The PP would get some theoretical support if it would be socially efficient to be more prudent in economy $\tilde{y}$ with more scientific uncertainty. This would mean that scientific uncertainty gives support to develop more intensive risk-reduction activities in the short run. This is our interpretation of the idea of precaution.

This interpretation of the PP allows us to make a basic economic distinction between the words *prevention* and *precaution*. A preventive effort reduces the risk on $\tilde{\theta}$. It is a static concept that refers to the management of a risk at a given time and given a stable probability distribution. On the other hand precaution is tied to the notion of scientific uncertainty $\tilde{y}$. It is a dynamic concept that recognizes scientific progress over time. A precautionary measure is thus a temporary and flexible decision that is taken in face of the lack of current scientific evidence. In short, while prevention aims at managing risks, precaution aims at managing the wait for better scientific information.

4. An economic interpretation of the Precautionary Principle

In Section 3, we have introduced the notions of irreversibility and that of information value. We will now examine the interplay between these two notions leading us to propose our own interpretation of the PP based on the ‘irreversibility effect’. We proceed as follows. In our general model, we will focus on the effect of information on ex ante decision. In doing so, we examine how the structure of information about future risk is expected to affect the optimal timing of decisions. We then consider a specific model where the only link between period 1 and period 2 decisions is an irreversibility constraint. This yields an “irreversibility effect". We finally consider a broader model where the decision in period 1 also affects the risk born in period 2. This yields another effect, coined the "precautionary effect".

4.1. The comparative statics of more information

Consider model (4). Assume that the solutions to the first period problem in economy $\tilde{y}$ and $\tilde{y}'$, respectively denoted α_1^* and $\alpha_1^{*\prime}$, are the unique solutions to the respective equations

$$E_{\tilde{y}} j_1(\alpha_1^*, \pi_{\tilde{y}}) = 0 \quad \text{and} \quad E_{\tilde{y}'} j_1(\alpha_1^{*\prime}, \pi'_{\tilde{y}'}) = 0, \tag{12}$$

where j is the value function as defined in (10), and j_1 denotes its partial derivative with respect to α_1. It can then easily be checked that

$$\alpha_1^* \geq \alpha_1^{*\prime} \Leftrightarrow E_{\tilde{y}'} j_1(\alpha_1^*, \pi'_{\tilde{y}'}) \leq 0.$$

So using (12) it is obvious that a better information structure increases optimal α_1 when

$$E_{\tilde{y}} j_1(\alpha_1^*, \pi_{\tilde{y}}) \geq E_{\tilde{y}'} j_1(\alpha_1^*, \pi'_{\tilde{y}'}),$$

for every $\alpha_1^* \in D$. Inequality (11) gives then the following Lemma due to Epstein (1980). This Lemma is very general since it imposes no restriction on the decision problem nor on the random variables $\tilde{\theta}$ and $\tilde{y}$.

Lemma 1. *Consider the general problem* (4). *The optimal level of the ex ante decision* α_1 *is increased* (*resp. decreased*) *by any better information structure if and only if* $j_1(\alpha_1, \pi_y)$ *is convex* (*resp. concave*) *in* π_y.

This Lemma states that the convexity of slope of the value function with respect to α_1 is necessary and sufficient to control the comparative statics of more information. Sufficiency is obvious given the inequalities above. Necessity means that if the slope of the value function is neither concave nor convex in posterior probabilities, then it is always possible to find well-chosen information structures so that α_1 may both increase or decrease with a better information structure.[11]

However, despite its high degree of generality, this Lemma is difficult to understand and, in particular, it is hard to connect it to the primitives of the model (4). This is that connection that we are going to investigate now.

4.2. The 'irreversibility effect'

We will now use the previous Lemma to examine the interplay between information and irreversibility. Before, let us recall the example introduced in Section 3.1. Using Dixit and Pindyck (1994)'s parameters values, we showed a situation where no information led to investing in the first period $\alpha_1^{*\prime} = 1$ while perfect information led to delay the investment decision $\alpha_1^* = 0$. The basic insight is that the prospect to receive information in the future leads to adopt a more flexible position today. The intuitive reasoning is clear: choosing an inflexible position undermines the value of information. Hence, as the informativeness increases, the incentive to remain flexible and take advantage of it also increases.

Let us now generalize this example to derive a formal statement of this so-called "irreversibility effect", as it has been first formalized by Arrow and Fisher (1974) and Henry (1974a, 1974b). To keep the model simple, we assume that

$$D = [0, 1] \quad \text{and} \quad D(\alpha_1) = [0, 1 - \alpha_1]. \tag{13}$$

Unambiguously, lowering α_1 increases flexibility for the future. A simple application of this model is for a non-renewable resource of size 1 that can be consumed over two periods. Future profits associated to resource consumption are assumed to be uncertain in the future, due to the social cost it generates in terms of biodiversity for instance.

Importantly, although we will generalize the Dixit and Pindyck's model to introduce risk aversion and partial resolution of uncertainty, we still assume that future utility do not depend directly on previous actions (recall Eq. (6))

$$v(\alpha_1, \alpha_2, \theta) \equiv v(\alpha_2, \theta). \tag{14}$$

Yet, current actions may affect future utility indirectly through the impact on the future opportunity set.

Let us solve this problem. Let $\alpha_2^*(y)$ the solution when the constraint $\alpha_2 \leq 1 - \alpha_1$ is not binding, i.e.

$$E_{\tilde{\theta}/y} v_2(\alpha_2^*(y), \tilde{\theta}) = 0.$$

Hence, we have that

$$j(\alpha_1, \pi_y) = \begin{cases} E_{\tilde{\theta}/y} v(\alpha_2^*(y), \tilde{\theta}) & \text{if } E_{\tilde{\theta}/y} v_2(1 - \alpha_1, \tilde{\theta}) \leq 0 \\ E_{\tilde{\theta}/y} v(1 - \alpha_1, \tilde{\theta}) & \text{otherwise.} \end{cases}$$

From Definition 1, we know that this function is convex in π_y. Let us now differentiate with respect to α_1 so that we get

$$j_1(\alpha_1, \pi_y) = \begin{cases} 0 & \text{if } E_{\tilde{\theta}/y} v_2(1 - \alpha_1, \tilde{\theta}) \leq 0 \\ -E_{\tilde{\theta}/y} v_2(1 - \alpha_1, \tilde{\theta}) & \text{otherwise,} \end{cases}$$

or, equivalently,

$$j_1(\alpha_1, \pi_y) = -\max(0, E_{\tilde{\theta}/y} v_2(1 - \alpha_1, \tilde{\theta})).$$

Since $E_{\tilde{\theta}/y} v_2(1 - \alpha_1, \tilde{\theta})$ is linear in π_y and max is a convex operator, $j_1(\alpha_1, \pi_y)$ is concave in π_y. Lemma 1 implies that the optimal α_1 decreases with better information. Since decreasing α_1 leads to a larger opportunity set in the future $D(\alpha_1)$, an increase in the degree of informativeness biases ex ante decisions in favor of more flexibility. This is in the spirit of the PP. The prospect to receive information is an argument to reduce irreversibility. In the following Proposition, scientific uncertainty means a more informative structure.

Proposition 1. *In problem* (4) *with* (14) *and* (13), *scientific uncertainty leads to preserve more flexibility for the future.*

We conclude that the notion of option value that sustained the PP in the example of Section 3.1 can be generalized in several directions: partial resolution of uncertainty, relative flexibility, continuous decision variables and risk aversion. However, several authors have pointed out that the 'irreversibility effect' holds in rather special models (see e.g. Freixas and Laffont, 1984; Graham-Tomasi, 1995). For example models such as growth models do not satisfy restriction (14) since today's output realization affect directly future welfare. In most cases, future utility $v(\alpha_1, \alpha_2, \theta)$ does depend on α_1. The next section examines whether the 'irreversibility effect' may carry over to a broader class models. An important question is to determine the optimal timing of prevention efforts when current actions affect the risk borne by future generations. This is typically the case when there are stock externalities.

4.3. The 'precautionary effect'

There is an important literature since Keeler, Spence, and Zeckhauser (1971) on the optimal growth in the presence of environmental externalities, particularly stock externalities. Consumption accumulates in some medium (water, soil, air, body…) and may have harmful effects in the future. We now examine the effect of better information in a very simple model where there is a risk of consumption externality. We will exhibit the conditions so that the presence of scientific uncertainty about this risk leads to more precaution today.

The model work as follows. We assume that the only source of utility comes from the consumption α_t of a good in each period t. The good is free but its consumption may turn out to be toxic in the future. The damage representing this toxicity is measured in terms of final consumption and is supported only in the second period. This damage is proportional to the quantity of the good already consumed $C \equiv \delta\alpha_1 + \alpha_2$ so that we get

$$v(\alpha_1, \alpha_2, \theta) \equiv v(\alpha_2 - \theta(\delta\alpha_1 + \alpha_2)). \tag{15}$$

Parameter δ denotes the fraction of the good consumed in the first period which remains toxic in the second period. This parameter depicts the stock externality. When $\delta = 0$, restriction (14) applies.

The extent of the damage is unknown at the beginning of the first period. This is represented by the random variable $\tilde{\theta}$. Experiments $\tilde{y}$ will allow the consumer to revise the distribution of $\tilde{\theta}$ according to the Bayes' rule. The decision problem (4) may thus be written as

$$\max_{\alpha_1} u(\alpha_1) + E_{\tilde{y}} \left\{\max_{\alpha_2} E_{\tilde{\theta}|\tilde{y}}\, v(\alpha_2 - \tilde{\theta}(\delta\alpha_1 + \alpha_2))\right\}. \tag{16}$$

As before, our aim is to examine the effect of scientific uncertainty on the initial efficient decision. To keep this analysis simple, we assume that u is increasing and concave and that the v belongs to the well-known class of Hyperbolic Absolute Risk Aversion (HARA) functions such that

$$v(x) = \frac{\gamma}{1-\gamma}\left[\eta + \frac{x}{\gamma}\right]^{1-\gamma}. \tag{17}$$

Some restrictions on the parameters are required to make $v(\cdot)$ increasing and concave in its domain $\{x \in R \mid \eta + x/\gamma > 0\}$.[12]

Let us now solve this problem. It is easy to check that if $v(\cdot)$ is defined as in (17), then the optimal stock of consumption $C^* = \delta\alpha_1 + \alpha_2^*$ is proportional to $\eta - \delta\frac{\alpha_1}{\gamma}$. More precisely, we obtain $C^*(\alpha_1, \pi_y) = c^*(\pi_y)(\eta - \delta\frac{\alpha_1}{\gamma})$, with $c^*(\pi_y)$ defined by $E\tilde{z}(1 + \frac{c^*(\pi_y)\tilde{z}}{\gamma})^{-\gamma} = 0$. As a result future consumption is linear in $\eta - \delta\frac{\alpha_1}{\gamma}$. It yields

$$j(\alpha_1, \pi_y) = \frac{\gamma}{1-\gamma}\left(\eta - \delta\frac{\alpha_1}{\gamma}\right)^{1-\gamma} g(\pi_y) \tag{18}$$

with $g(\pi_y) = E(1 + \frac{c^*(\pi_y)\tilde{z}}{\gamma})^{1-\gamma}$. By Definition 1, we know that j is convex in π_y. Thus, g is convex in π_y if and only if γ is less than 1 and larger than 0. But we have also

$$j_1(\alpha_1, \pi_y) = -\frac{\delta}{\gamma}\left(\eta - \delta\frac{\alpha_1}{\gamma}\right)^{-\gamma} g(\pi_y). \tag{19}$$

We conclude that j_1 is concave in π_y if and only if γ is strictly positive and less than unity. Lemma 1 then concludes the comparative statics analysis. We thus derive the following proposition due to Gollier, Jullien, and Treich (2000) in which the level of precaution means the level of consumption of the polluting good in period 1.

Proposition 2. *Consider the decision problem* (16) *with* (17). *Scientific uncertainty increases the efficient level of precaution if and only if* $0 < \gamma < 1$. *In the case with* $\gamma \to 1$, *i.e.* $v(x) = \ln(\eta + x)$, *scientific uncertainty has no effect on the efficient level of precaution.*

This proposition describes the circumstances where the prospect to receive information in the future induces the consumer to reduce the consumption of the toxic product. This in turn gives a normative support to the PP in the presence of stock externalities.

Two opposite effects take place in this analysis. On the one hand, a better information structure leads the DM to behave in a more efficient way in the future because of the better knowledge of the risk. If we interpret an improvement in efficiency as a sure increase in future incomes, this implies that the agent will want to consume more today, as he wants to smooth consumption over time. This effect goes the opposite direction to the one suggested by the PP. However, on the other hand, better information leads to a mean-preserving spread of posterior beliefs (recall Definition 1). This makes future payoffs more variable since the future decision varies for every posterior belief. A prudent consumer may then reduce initial consumption for a precautionary motive. For the special case of HARA utility functions, we have shown that this last effect dominates when $0 < \gamma < 1$.[13]

This shows that the PP cannot be justified independently of the preferences of the DM when the important aspect of the question is a stock externality rather than an irreversibility constraint. This raises the issue of the choice of preferences and of the type of DM which is considered. This also leads to inquire about the importance of specification (15) in the previous analysis. Basically that specification meant that damages could be evaluated in monetary terms. Assume now instead that damages are intangible and take the following form

$$v(\alpha_1, \alpha_2, \theta) \equiv v(\alpha_2) - \theta S(\delta\alpha_1 + \alpha_2), \tag{20}$$

where $S(C)$ denotes the impact on future utility of previous consumption C. Using specification (20), Ulph and Ulph (1997) showed that the result is in general ambiguous. They so took quadratic functional forms for $v(\cdot)$ and $S(\cdot)$ and showed that the PP is never justified in this situation.

Another important specification in model (16) is that we have implicitly assumed $D = D(\alpha_1) = \Re$. There is no irreversibility constraint. What would happen if we extend model (16) by incorporating an irreversibility constraint? Ulph and Ulph (1997) and Gollier et al. (2000) examined the interplay between irreversibility and stock externalities. They considered a constraint of type $\alpha_2 \geq k\alpha_1$. E.g., in a model of global warming, when $k = 0$, this means that emissions in period 2 cannot be negative. It is not possible to remove greenhouse gases from the atmosphere. These two papers showed that such an irreversibility constraint always require lower current consumption. Gollier et al. (2000) also showed that the 'irreversibility effect' always combines with the 'precautionary effect' towards more precaution today when more precaution was already sustained in the model without the irreversibility constraint.

Interestingly Kolstad (1996) introduced the symmetrical constraint, i.e. a constraint of type $\alpha_2 \leq m\alpha_1$. In his model of global warming, this constraint means that next-period controlled emissions should be at least as large as current-period controlled emissions (up to a factor m). This represents irreversibility of capital investment in control measures: emissions cannot go too high because of previous investment in capital abatement. Kolstad (1996) showed that this type of constraint may make precautionary policies non-optimal. Irreversibility of capital may dominate environmental irreversibility.[14]

In summary, we have mentioned three sources of inertia in our model of pollution externality. First, stock externality, $\delta > 0$: pollution accumulates and it is not possible to reduce this stock more than the natural rate of decay δ. Second, environmental irreversibility, $\alpha_2 \geq k\alpha_1$: if one emits pollution one cannot retrieve the initial state of the environment. Third, capital irreversibility, $\alpha_2 \leq m\alpha_1$: if one invests in pollution control, one cannot immediately reduce the abatement capital stock.

An interesting problem is to determine the dominant effect. We have shown that the first effect, due to stock externality, may be broken down into two basic effects of opposite sign. Its global sign depends upon the specification of the DM's preferences. We have also said that the second and third ones have clear-cut but opposite directions. As a result, there is no theoretical consensus on which is the dominant effect. At least four different effects play in opposite directions. This ambiguity has also been demonstrated in empirical works on the effect of scientific uncertainty on the climate policy, as in Nordhaus (1994) and Ha-Duong (1998).

5. Decentralized decision-making under scientific uncertainty

In the previous section, we have analyzed the changes that scientific uncertainty brings to the optimal timing of prevention efforts. We have shown that it may support the adoption of the Precautionary Principle as a socially efficient guideline. Instrumental to the reasoning is that information has a positive value and that it increases the incentives to remain flexible (Proposition 1) and to reduce current risk-exposure (Proposition 2). To derive these results, we have considered a class of problems where there is one single DM. However, in market situations, there is not one single DM but multiple DMs who act in a decentralized way.

We will show in this section that market forces often do not sustain the implementation of precautionary policies. More precisely, we will show that, even when precautionary policies should be adopted in the global economy, these policies may not be selected at the equilibrium of the economy. The PP may then be viewed as an incentive or constraint for the DMs to select even so precautionary policies.

5.1. Competition and innovations

A typical difficulty of a decentralization process comes from the incentive of competitive firms to invest too early, as explained for example by Weeds (1999) for the market of innovations. The reason is that most innovations are non-proprietary investment opportunities. Not all markets are indeed such that legally enforceable property rights (like patents) confers a firm the right to possess the innovation. As a result, several firms may face in the same time a similar investment opportunity. There thus is a possibility for every firm that another firm introduces the same innovation earlier and takes most of the rent from it. This possibility of being preempted undermines the option value of waiting for introducing the innovation, as we will now show.

To keep the argument simple, let us use the simple two-period model presented in Section 3.1. We hereafter assume that n risk neutral firms compete for the introduction of an innovation whose expected value is P per period. Because of the fixed sunk cost I to initiate production, there is increasing return to scale and only one firm will invest at equilibrium. The natural monopoly extracts all the surplus at equilibrium.

As before, at the end of the first period, everybody will learn whether the value of the innovation is $0.5P$ or $1.5P$ for the future. We have seen in Section 3.1 that it is socially efficient to wait for this information to come before deciding whether to introduce the innovation or not if NPV_2 is larger than NPV_1. It is interesting to see whether competitive firms follow this rule or not.

To answer this question, let us solve this problem by backward induction. Suppose that all firms decide to delay the introduction of their investment up to the date where the scientific uncertainty is resolved. When a low value of the innovation is revealed by scientific progress, no firm is willing to introduce the innovation, under condition (2). Suppose alternatively that a high value of the innovation is revealed. In that case, the monopoly discounted profit $1.5P(1-\beta)^{-1} - I$ is positive, and each firm is willing to take the market before the other firms. Suppose that each firm has an equal probability to act first and to get the monopoly rent. This lottery can come from the uncertainty about which firm will get the information a bit earlier about the quality of the innovation. As seen from the first period, the net present expected profit for each firm is NPV_2/n. This is the value of a firm in the first period if they all decide to delay the introduction of the innovation.

Let us now look at the decision of the firms in the first period. Under which condition is it an equilibrium for the firms to postpone their investment? Because the net present expected value of the investment is NPV_1 for the firm which gets the market, the decision not to introduce the innovation in the initial period if no other firm did introduce it before is an optimal decision if NPV_1 is smaller than NPV_2/n. Thus, delaying the introduction of the innovation in the first period is an equilibrium only when NPV_1 is smaller than NPV_2/n, which tends to zero has n tends to infinity. This means that in a competitive economy, all innovations are introduced as soon as their net present expected value is nonnegative. Competitive firms do not use the option value to wait, because the risk would be too large to be preempted by other firms. This implies that innovations are introduced too early in competitive economies.

5.2. Time-inconsistencies

In the previous model, we have shown that competition could induce DMs to invest too early. We will now investigate another reason for why the timing of decisions might be sub-optimal. It is based on the conflict between the current DM and the future DMs, the so-called time-inconsistency problem.

Time-inconsistency is traditionally associated to the process of procrastination (Akerlof, 1991). This process is well-known: from my point of view it may be optimal to "smoke today" and to "stop smoking" tomorrow. But when tomorrow comes, the trade-off is the same as today and I decide to continue to "smoke today", delaying one day further the decision to "stop smoking".

With this daily life example in mind, it surely requires no algebra to understand why time-inconsistencies may affect the analysis developed above. Simply replace in the sentence above "smoke" by "invest". Then the sentence would mean that even if it is optimal to delay investment until tomorrow, the tomorrow's DM may also find optimal to delay it as well. As a result, each DM may decide to put off the project an additional day and the project is never undertaken. Time-inconsistencies may thus generate a process of inefficient procrastination. Current DMs wait when they should act. This effect is not compatible with the PP since our interpretation of the PP is based on an *efficient* procrastination process. Furthermore, time-inconsistency may lead conversely to a process of inefficient rush. Current DMs may act when they should wait.

To see that, consider again the two-period model presented in Section 3.1. Yet, imagine now a situation where the implementation of the project is left to the government in power. There is one government in each period, and of course the project can be approved only once.

In addition, assume that if one of the two governments approves the project, it receives an extra-gratification $g > 0$. This is prestige for government bodies for example. Importantly, g does not have any social value, nor any value for the government that has not adopted the project. As a result, there is a "bias for the present" (O'Donoghue and Rabin, 1999) in that economy since both governments prefer the project to be adopted when they are in power. This bias may generate a time-inconsistent decision rule, as we will now show.

For government-1, undertaking the project yields net present value $NPV_1 + g = P(1-\beta)^{-1} - I + g$. Assume that

$$1.5P(1-\beta)^{-1} - I + g \geq 0 \geq 0.5P(1-\beta)^{-1} - I + g, \tag{21}$$

so that, this is only when the good scientific theory is true that government-2 will approve the project. In that case, government-1's net present value of delaying the project until date 2 is the same as before $NPV_2 = 0.5\beta[1.5P(1-\beta)^{-1} - I]$. But it may be that

$$NPV_1 + g > NPV_2 > NPV_1, \tag{22}$$

so that, as in the previous section, the decentralized decision's rule is to invest in period 1, while the socially optimal decision's rule is to delay the adoption of the project until period 2 (since $NPV_2 > NPV_1$). More surprisingly, note that there exist some values of the parameters so that (21) and (22) hold together with $NPV_1 + g < 0$.[15] In that case, government-1 would even rush on a project with a negative net present value for itself.[16] This is because it anticipates that, if the good scientific theory turns out to be true, government-2 would adopt a project with a negative net present value (since in that case we have $1.5P(1-\beta)^{-1} - I < 0$).

5.3. Global pollution

Another typical problem is the global aspects of some externalities. When pollution is a public good, no one would want to pay the cost of reducing pollution alone. This raises the familiar free-riding problem. In this section, we show an example where this problem is getting worse in the presence of scientific progress.

Consider the general model (4). Interpret it as a model of global warming. Yet, assume that there are two DMs, say two countries $i = A, B$, and that the damages depend on the total emissions of *both* countries. As before, damages only occur in period 2.

Each country chooses the level of emission in each period, α_t^i. Assume that the utility of each country has a separable form (20), i.e. so that utility in period 2 may be written

$$u(\alpha_2^i) - \theta^i S(C),$$

where $C = \delta\alpha_1^A + \delta\alpha_1^B + \alpha_2^A + \alpha_2^B$ denote total emissions. Parameter θ^i indicates the extent of the damage in country i. Future damages are unknown in period 1. The structure of uncertainty is the following:

- With probability π, damages will occur in country A: $(\tilde{\theta}^A, \tilde{\theta}^B) = (\theta, 0)$ where $\theta > 0$.
- With probability $1 - \pi$, they will occur in country B: $(\tilde{\theta}^A, \tilde{\theta}^B) = (0, \theta)$.

The decision about α_2^i is taken before observing which country incurs the damage, but after observing some signal correlated to π.

To solve the model, we follow Ulph and Maddison (1997). They consider quadratic functional forms,

$$u(x) = -0.5(\eta - x)^2, \quad \text{and} \quad S(C) = 0.5C^2. \tag{23}$$

These assumptions enable us to get closed-form solutions for the Nash equilibrium of this game. Optimal level of emissions in period 2 as a function of π are

$$\alpha_2^A(\pi) = \frac{\eta(1 + \theta - 2\pi\theta) - \pi c\theta}{1 + \theta}$$
$$\alpha_2^B(\pi) = \frac{\eta(1 - \theta + 2\pi\theta) - (1 - \pi)c\theta}{1 + \theta},$$

where $c = \delta\alpha_1^A + \delta\alpha_1^B$. Using these solutions, it is straightforward to compute the value functions for both countries as a function of π. We obtain

$$j_A(\pi) = -\frac{\pi(2\eta + c)^2\theta(1 + \pi\theta)}{2(1 + \theta)^2}$$
$$j_B(\pi) = -\frac{(1 - \pi)(2\eta + c)^2\theta(1 + (1 - \pi)\theta)}{2(1 + \theta)^2}.$$

Observe that $j_A'(\pi) < 0$ and that $j_B'(\pi) > 0$. An increase in the probability to have its own country incurring the damage reduces one's own expected utility at the equilibrium.

We want to compare the welfare at the non-cooperative equilibrium of the economy

$$j_{nc}(\pi) = 0.5 j_A(\pi) + 0.5 j_B(\pi),$$

to the one reached at the cooperative equilibrium, denoted $j_c(\pi)$. In fact, since the damage $\theta S(C)$ will occur in one and only in one of the two countries, we simply have

$$j_c = \max_{\alpha_2^A, \alpha_2^B} 0.5u\left(\alpha_2^A\right) + 0.5u\left(\alpha_2^B\right) - \theta S(C),$$

which does not depend on π. Let us compute the cost due to non-cooperation $C(\pi)$ in that economy. It is simply given by $C(\pi) = j_c - j_{nc}(\pi)$, so that

$$C''(\pi) = \frac{(2\eta + c)^2\theta^2}{(1 + \theta)^2} > 0.$$

Hence, this cost is a convex function in posterior beliefs. According to Definition 1 in Section 3.2, this means that it increases with a better information structure. As a result, when scientific progress is expected over time, the cost of non-cooperating increases. This is because scientific progress reveals the asymmetric consequences of the game. This resembles an "Hirshleifer effect" (Hirshleifer and Riley, 1992). When one ignores which country will be affected, the two countries may find a mutual advantage in reducing emissions. Yet if information is revealed early, it may destroy risk-sharing opportunities. Note also, that, in the period 1 of this game, the *incentives to cooperate* for the two countries are thus stronger when scientific progress is expected over time.[17]

6. Discussion

Our objective in this section is to relate our economic interpretation of the PP to some policy-oriented issues.

First of all, it is important to recognize that other interpretations of the PP can be found, in particular the one based on ambiguity aversion in a static framework. In our approach, we have emphasized above all the role played by scientific progress within the process of decision-making. This is because we consider that the concept of precaution only refers to situations where the knowledge of the risk evolves over time. This idea related the presence of scientific uncertainty is really the novel idea that brought the Principle into risk regulatory decision-making. This is why we think that it is important, as a first step, to clearly separate the discussion on the effect of scientific uncertainty on risk management from extended topics on the regulation of externalities (Polluter-pays Principle) or on intergenerational equity (Sustainable Development Principle).

As an illustration of our interpretation of the PP, consider the Kyoto Protocol. In the global warming issue, uncertainty are pervasive and implicit in the problem about controlling emissions is how fast this uncertainty will resolve over time. In relation to that question, the response of the Kyoto Protocol has been to set near-term reduction objectives together with introducing a large degree of flexibility for the implementation of future commitments. The Protocol specifies limiting emission levels rather than specifying long-term concentration targets. This will permit to adapt the strength of abatement efforts to evolving scientific knowledge. In addition, the Protocol incorporates several dimensions of flexibility, e.g. the Protocol is defined in terms of a basket of several greenhouse gases and it allows several regulatory instruments: joint implementation, clean development mechanism and emission trading (see e.g. Grubb, 2000).

Yet, of course, there are many reasons for why the timing of the climate policy may not account appropriately for the dynamics of uncertainty resolution. Section 5 has presented two of these reasons. One is because the global warming issue is a global problem. Suppose that scientific information reveals that the risk of climate change is less important in some specific country than in other countries. Then there are incentives for this country to free-ride over other countries' reductions in emissions. Another reason is time-inconsistency. There are incentives for governments to refuse to abate emissions of CO_2 at a level announced by former governments. A natural response to these problems is to design institutions and policy architectures to help the enforcement of abatement policies (Shmalensee, 1998). The PP may be used to facilitate this process. In particular, the PP could be invoked when a government refuse to cooperate, acknowledging that the problem is "too uncertain" to set up important abatement efforts.

The implications of the PP are not limited to environmental protection policy. The PP is now getting a prominent role in health and safety debates. The 'mad cow' affair in Europe has been the first popular illustration of the idea of precaution. Current debates over transgenic food is another important illustration. What can say the economic approach about current health and safety policy debates? To start with, it may be useful to come back to model (16). Interpret it as a model of an individual consumer getting utility from eating a specific product. As before, there is a risk that this food will be toxic in the future. Yet improvements in scientific knowledge will reveal whether this is a case or not. In such a situation, Proposition 2 tells us that the existence of the "precautionary effect" in the short run critically depends on the shape of the preferences of the consumer. A straightforward conclusion is that this effect may exist for some consumers and not for others. Consequently, a precautionary measure such as banning the food is inefficient, as it gives no choice to consumers.[18] In the domain of food safety, the PP thus merely requires that consumers know, via product warnings or labellings, the risk they face. No direct public intervention is really necessary.

In fact, such a basic view in favor of no intervention is probably incorrect under conditions of high scientific uncertainty. A simple reason for that is that consumers often misperceive the risks they face (Viscusi, 1998). There is a very well documented in psychology on that issue. Individuals have problems with the mathematics of probability, they use rules of thumbs or heuristics that are useful but misleading. In addition, the presence of scientific uncertainty likely exacerbates consumers misperceptions, so that their consumption choices may deviate significantly from optimal ones. In the presence of high scientific uncertainty, there is likely a role for government intervention.[19]

A related point is the issue of risk ambiguity. Based on the Ellsberg paradox and related literature, there is a lot of empirical evidence showing that people are sensitive to the degree of risk ambiguity. For instance, in a situation where there are various equally likely scenarios, the population behave as if the worst-case scenario is more likely. However, there is no clear normative support to such an observed behavior. In particular, this behavior is inconsistent with the Bayesian updating of uncertain beliefs over time. It may thus lead to some bias in individuals sequential choices, like overreactions to highly publicized risks (Viscusi, 1997). Again, this may be in favor of some public intervention to correct the biases.

Also, there is the important issue of information aggregation and information communication. Needless to say, scientific uncertainty complicates risk assessment and risk communication procedures. How to compare different experts conclusions? How can policy-makers deliver the message to the public that two scientific theories are contradictory? In some complex situations, it may be better to develop simple command-and-control measures than displaying complex information to consumers. Furthermore, it is important to account that experts may be self-interested as well. They may be sensitive to some financing provided some lobby involved in the matter or to some reputation effects. Under conditions of large scientific uncertainty, experts may then provide more easily biased policy recommendations. Policy-makers may, in turn, rely more easily on the scientific theory that matches their objective.

This last remark gives rise to another issue, related to the effect of scientific uncertainty in risk politics. Scientific uncertainty may for example generate a typical phenomenon of political demagogy. Indeed, given the complexity of the underlying scientific problems, the public is in general less informed than politicians about some particular danger. Then, politicians with strong career concerns may prefer to select the risk policy that the public believes is good rather than the one which is actually good for the public. This is true in particular when long term risks, i.e., risks whose outcome will be observed in a distant future. As a result, the influence of politics together with imperfect knowledge of the risk by the public will cause the regulator to depart from social welfare maximization. Maskin and Tirole (2000) have a model describing such a source of political inefficiency.

How to reduce political opportunism? One may investigate ways to modify the Constitution in order to generate better incentives in risk regulatory decision-making. From this point of view, it is often said that the PP may change the rule of the game in risk politics. Indeed, it may help to make politicians aware of their responsibilities for decisions taken under large conditions of uncertainty. In France for instance, in April 1993, the Conseil d'Etat gave a warning of caution to politicians: *"In a situation of risk, one non-validated hypothesis should be taken as temporary true, even if it is not formally demonstrated."* A few years after this caution, several French ministers have been judged for their respective liabilities in the contaminated blood affair.

In the same vein, it makes sense to think that the PP will increase the liability of firms under conditions of scientific uncertainty. Think of the example presented in Section 5.1. In that example, firms introduce innovations too early, i.e. before learning whether introducing the risky innovation is socially desirable or not. In this situation, the question is to design the PP so that it introduces a constraint for firms to include the value of future information generated by scientific progress in their decision process. Using the PP, an entrepreneur may for instance be blamed because he has not sufficiently tested a product that turned out to be toxic. This may lead firms to better internalize for the damages they generate to society. But this may not be enough to guarantee that firms implement an efficient level of precaution. Indeed the damages may occur far in the future so that the firm may no longer exist at that date, as it was the case in the abestos industry for example. Also, it raises the issue of the potential bankruptcy of the firms, which gives rise to an ex post problem of victim compensation and to an ex ante problem of under prevention by injurers.

Finally, it is important to recognize that the discussions on the design of risk regulatory policies do not only concern experts, politicians or entrepreneurs. They must also account for the acceptability of the policies by the public. Increasingly, the public is aware of the limits of scientific knowledge. Policy-makers may have lost legitimacy in the eyes of lay people. In Europe, the failures of risk regulatory institutions in the past decades has drastically reduce citizens' trust in them. They have put into question the standard channels of decision-making, based on an elite which makes decision, without any real public consultation.

As a final word, let us recall that the PP may have many drawbacks as well. If it is interpreted in a too extreme way, the PP may inhibit economic development in our society (Gollier, 2001). It may lead to delay innovations that are safe and effective. It may be used to set up high safety domestic standards in order to develop protective measures. A broad discussion on the PP should also recognize that too much effort is spent on newly discovered risks compared with familiar risks (Viscusi, 1998). There is thus a need to re-think usual risk evaluation criteria in a broad cost-benefit analysis perspective.

7. Conclusion

The PP has defined a new standard of risk management when the very existence of the risk is subject to scientific controversies. It provides the foundations for building a new risk regulatory pattern under conditions of scientific uncertainty. However the common formulation of the Precautionary Principle (PP) has no practical content and offers little guidance for conceiving regulatory policies. It was said recently that "*no general agreement exists on what the PP means in different socioeconomic and cultural systems*" (Report of the Conference on Science and The Precautionary Principle, 2000).

In this paper, we have presented our economic interpretation of the PP. Let us sum up the main points of the analysis.

- Our framework for defining the optimal regulatory policy is based on a cost-benefit analysis. There is scientific uncertainty either on the costs or on the benefits of the policy. We assume that new scientific knowledge may arrive over time, thus resolving current uncertainties. As a result, the analysis should be different from standard cost-benefit analysis. Within an expected utility/Bayesian framework, we examine the following question: Under which conditions should the prospect of obtaining better scientific information in the future lead to a more precautionary policy today?
- One condition is that the policy leads reduce the degree of irreversibility for future choices. For instance, a policy that leads to preserve a wildland area is more valuable if one expects to obtain better information over time. Indeed, it leaves the option of reconsidering the development decision later on. More generally, the prospect of increasing information over time biases decisions in favor of more flexibility. This well-known "irreversibility effect" (Arrow and Fisher, 1974; Henry, 1974) justifies the PP when preserving the environment leaves more flexibility for future choices.
- However, the irreversible nature of our decisions is only one element entering the picture of risk policies. Generally, today's actions affect future welfare, not only through a reduction of the future set of choices, but also directly by changing the risk borne by future generations. Gollier, Jullien, and Treich (2000) consider a model where more consumption today increases the risk borne in the future. They show that scientific uncertainty leads to decrease current consumption. This "precautionary effect" takes place under a restrictive but plausible condition on the degree of risk-aversion of the consumer. Thus, together with the pure "irreversibility effect", the "precautionary effect" provides a strong normative basis to the PP.
- Another issue is that precautionary policies may not be selected at the equilibrium of the economy, even when it would be globally optimal to do so. This is typically the case in sectors where high profits are promised for the industries able to preempt the market. As a result, competitive firms may not use the option value to wait and may introduce innovations too early. The PP may then be viewed as an incentive or a constraint to include the value of information generated by future scientific progress on the optimal decision process of the firms. Other concerns such as free-riding or time-inconsistencies have also been discussed.
- Finally, the presence of scientific uncertainty may favor, through the multiple channels of decision-making, opportunistic behaviors. Indeed, scientific uncertainty opens

a considerable room for discretion and for self-interested biases. Several social actors (entrepreneurs, lobbies, experts, politicians...) may use the argument of the lack of scientific evidence to push the final decision toward their own interest. The problem then consists in determining the right mechanism to force the various social actors to participate efficiently to the process of regulatory decision-making. The PP, by increasing the liability of these actors, may be viewed as a safe-guard against opportunistic behaviors in situations of asymmetric information or imperfect monitoring. Yet, examining these questions needs a broader reflection on the channels and on the institutions of risk management. This was not the purpose of the present paper. This leaves open an interesting domain for future research in information economics and law and political economy.

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Notes

1. Sandin (1999) catalogues 19 different interpretations.
2. For various interpretations, see for example Cameron and O'Riordan (1994) or the Report of the Conference on Science and The Precautionary Principle (2000).
3. Related discussions on this approach may be found in Farrow (2001), Graham (2001) and Treich (2001). A growing number of theoretical papers has also been written recently on this topic. See for example a recent conference in Environmental Economics at Wageningen (Proceedings, 2002).
4. Equivalent definitions have been enacted in many international conventions such as recently for the Cartagena Protocol on Biosafety to the Convention on Biological Diversity adopted in january 2000 . In national law, similar definitions exist as well. For instance, in the French law, the PP is defined as a clause of the Loi Barnier in 1995 on the reinforcement of the protection of the environment. It states that "*the absence of certainty, given our current scientific knowledge, should not delay the use of measures preventing a risk of large and irreversible damages to the environment, at an acceptable cost.*"
5. We assume that the revelation of the true theory comes from pure scientific research, not from experimentation. This is due to the long delay occuring between consumption or development and the observation of the adverse effects. This may be unrealistic in some cases. For instance early phasing out of ozone depleting substances has certainly slow down the knowledge of the destructive effects of CFCs. It has also boosted chemical research. The reader may find in Fisher and Hanneman (1987), Orphanides and Zervos (1995) and Datta, Mirman, and Schlee (1998) some theoretical insights on this so-called experimentation effect. Note that there is no discussion either on the way the choice is made among various scientific experiments. In our model, information is free and we do not directly pay attention to the process that drives the production of information. As a consequence, our framework does not permit to explore the interplay between the PP and the economics of invention and research (see e.g. Hirshleifer and Riley, 1992).
6. See also more recently Bernanke (1983), McDonald and Siegel (1986) and Drazen and Sakellaris (1996).
7. Even if the utility functions u and v are concave in the choice variables, unicity of solutions is not guaranteed for any set $D(\alpha_1)$.
8. It is important to notice that definition (8) implies that the cost of moving from α_1 to α_2 inside the opportunity set $D(\alpha_1)$ is zero while the cost of moving outside the opportunity set is infinite. From this point of view, one could argue that irreversibility is not well defined economically. Jones and Ostroy (1984) relax these assumptions and refer to the broader notion of *adjustment cost*.

9. A careful examination of the different effect of upward and downward irreversibilities is developed in Viscusi (1984).
10. See e.g. Shannon (1948).
11. More on this point may be found in Fisher, Hanemann, and Narain (2002).
12. HARA utility functions corresponds to the set of functions whose absolute risk tolerance is linear in x. Indeed, we can easily verify that $-v'(x)/v''(x) = \eta + \frac{x}{\gamma}$. If $\eta = 0$, we get the standard Constant Relative Risk Aversion (CRRA) functions, with constant relative risk aversion γ. We get Constant Absolute Risk Aversion (CARA) functions if γ tends to infinity.
13. This result may sound strange at first since a lower risk aversion γ should rather lead to reduce risk-exposure. However Gollier et al. (2000) proved that the result depends in fact on an whether the coefficient of prudence (Kimball, 1990) is larger than twice the coefficient of risk-aversion. This is thus only for the special class of HARA utility functions that this condition implies that more risk-averse agents take more risk in the initial period.
14. The model of Dixit and Pindyck (1994) presented above could easily be adapted and reinterpreted as a model of investment in pollution control, leading to that conclusion.
15. Take for example $I = 2P(1-\beta)^{-1}$ and $g \in [(1-0.25\beta)P(1-\beta)^{-1}, P(1-\beta)^{-1}]$.
16. See Brocas and Carrillo (2001) for a thourough analysis.
17. Several working papers presented at a recent conference investigate this question (Proceedings, 2002). Moreover, it is noticeable that Ulph and Ulph (1996) examined numerically in this game the effect of learning on first period global emissions. They showed that this effect can go either way.
18. This problem has been recognized by R. Coleman in a recent communication on the PP (Coleman, 2002). *"My department is constantly faced with the challenge of balancing the freedom and rights of individuals, industry and organizations with the need to reduce the real and potential adverse effects of products and processes on human, animal or plant-health or the environment."*
19. Salanié and Treich (2002) examine the interaction between regulation and private consumption choices when consumers misperceive the risks they face.

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