Should we beware of the precautionary principle?

Christian Gollier[1]
University of Toulouse

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Abstract

There is a growing sensitivity of public opinions to the emergence of new risks, before scienti¯c research has been able to establish the problems. This paper addresses the problem of determining the e±cient dynamic management of these risks. We show that a few adaptations of the standard cost-bene¯t analysis provide the necessary operational instruments to deal with scienti¯c uncertainties in risk management. We discuss various arguments for and against the use of the precautionary principle to promote welfare-improving policies: aversion to ambiguity, ine±cient risk sharing, long-term e®ects, option values and irreversibilities, the cumulative e®ect of pollutants and learning. We also discuss the role of entrepreneurs, experts and politicians in the management of scienti¯c uncertainties. This paper promotes various interpretations of the precautionary principle that are compatible with social welfare. It is a ¯rst step towards making this principle operational. We also examine why and how we should adapt our procedures to manage risk in our society given the propensity of ¯rms, politicians and experts to behave in an ine±cient way.

1 Introduction

If some precaution may be useful, too much or too little precaution is certainly harmful. In the early ¯fteen century, China was by far above all other countries in terms of scienti¯c knowledge, technology and welfare. Along the east African coast, Chinese °otillas far surpassed in grandeur the small Portuguese °eets that came later. In 1405, one of these Chinese °eets consisted in 317 vessels and carried 28,000 men. But, as stated by Landes (1999, p. 96), "after some decade of tugging and hauling, [...] the decision was taken not only to cease from maritime exploration but to erase the very memory of what had gone before lest later generations be tempted to renew the folly. [...] In 1500, anyone who built a ship of more than two masts was liable of the death penalty. [...] The abandonment of the program of great voyages was part of a larger policy of closure, of retreat from the hazards [...]." This precautionary aversion to change struck generations of visitors of the Celestial Empire for long. On the contrary, Europeans accepted without precaution innovations from their exploration of the world. Some European plants and biomass disappeared but we got corn, tomatoes, turkey,.... Agricultural productivity steadily increased, thereby triggering the industrial revolution. As a consequence, Europe left China far behind. By an interesting reversal of History, the famous Club the Rome recommended in 1972 a cessation of economic growth on the basis of pollution hazards and uncertain reserves of natural resources.

In this paper, we want to address the di±cult question of how Society should manage hazards whose characteristics are not perfectly known. The precautionary principle (PP) is o®ering a guideline for risk management under these circumstances. This principle was enshrined at the 1992 Rio Conference in its principle 15, which states that: "where there are threats of serious or irreversible damage, lack of full scienti¯c certainty shall not be used as a reason for postponing cost-e®ective measures to prevent environmental degradation". The European Community o±cially endorsed the PP in Article 174 of the EC Treaty. It is clear that the applicability of the PP is not limited to environmental risks.[2]However, the PP does not stipulate how to perform a cost-e®ective analysis when full scienti¯c certainty is missing. Thus, the PP is subject to diverging interpretations.

Many experts and politicians, particularly in France after the infected blood scandal in the 90's, now favor a restrictive interpretation in which everything should be done to reduce the risk at its lowest possible level, whatever the cost.[1] Of course, this policy is not compatible with economic e±ciency, as it would virtually eliminate innovation in our society. The extraordinary innovation-driven growth rate of our economies over the last two centuries clearly calls for the rejection of this extremist approach. The extremely low variability of the growth rate over this period is an indication that the riskiness of the innovation process has been under control, at least at the macro level.[2] This does not mean that enough precaution has been obtained at the micro level, however. Some risks taken in our economies are socially undesirable. Detecting them is di±cult. In particular, it is unfair and logically false to rely on the observation that a loss has been incurred to claim ex-post that the risk was undesirable ex-ante. The zero-risk, even when technically attainable, is not necessarily socially e±cient.

For a risk to be socially desirable, the bene¯t for Society to undertake it must exceed its cost. The di±culty is to evaluate the bene¯ts and costs. In the simplest case, the risk is measurable and diversi¯able. From Arrow and Lind (1970), such a risk is desirable if its expected net present value is positive. This decision criterion is a standard rule used by public decision makers in a wide variety of ¯elds from road safety to long term investments in the energy sector. When there is some uncertainty about the distribution of costs and bene¯ts, this technique is obviously less mechanical. A central objective of this paper is to show that this technique can still be used in this environment, at the cost of some re¯nements. If scienti¯c progresses are made over time, and it may happen ex post that much money has been spent to ¯ght phantom risks, whereas not enough attention has been devoted to other risks that happened to be catastrophic.[3] These should be considered as

[1] See Godard (1997) for other interpretations of the precautionary principle. Godard (2000) compares the kind of economic approaches of the PP considered in this paper to an interpretation of the PP taken as a social norm.

[2] Lucas (1987) came to a similar conclusion. He showed that the observed variability of consumption per capita around a secular trend of 2% per year as the same e®ect on the well-being of risk-averse consumers than a reduction of less than 0:01 percent of the growth rate! Risk and risk aversion are a second order phenomenon.

[3] The history of innovation is full of stories. Abstesos after WWII is an example of the introduction of a new product that happened to have adverse health e®ects. On the contrary, many innovations of primary importance were delayed for some time because of insu±cient knowledge of the public. Parmentier in the XVIII century had to protect the ¯elds of potatoes imported from America because the common wisdom at that time

the consequence of a bad management of the risk ex ante only if the decisions that have been taken to prevent the risk did not maximize welfare conditional to all existing scienti¯c knowledge available at that time. The di±culty is to characterize the optimal prevention strategy when there is some scienti¯c uncertainty about the distribution of bene¯ts.

Any e±cient public policy should be based on the preferences of those who will bene¯t from this policy. It is thus useful to examine the e®ect of scienti¯c uncertainty and irreversibility on the acceptability of risk in the population. We will examine the following normative questions:

- does the introduction of uncertainty about probabilities make risk less acceptable?
- does the acceptability of the risk depend upon our ability to diversify it?
- does the acceptability of the risk depend upon which generation will incur the damages?
- is the risk more acceptable when future actions are more °exible to control it?
- should we postpone preventive e®orts to the time when enough information will establish the intensity of the risk (learn-then-act principle)?

This paper is organized as follows. The next section provides two illustrations of the kind of problem that we are considering in this paper. In section 3, we focus on the e®ect of scienti¯c uncertainty in a static framework. We discuss the notions of subjective probabilities and ambiguity aversion, and we show how they are linked to the PP. Section 4 is also devoted to scienti¯c uncertainty, but we introduce time in the model. We characterize the e®ect of scienti¯c progresses on the optimal timing of e®orts to prevent risk. Insurability problems and long term e®ects are examined in sections 5 and 6. Up to that point, we assume that there is no asymmetric scienti¯c information in the economy. Section 7 is devoted to an overview of various problems linked to asymmetric information: citizen's freedom, tracability, incentives for experts and politicians to reveal their information,...

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was that it was a poison. Similarly, a large fraction of the population was against the building of railroads, because it was believed that human beings could not survive to the high speed.

2 Illustrations

Examples abound of risks with an imprecise distribution for potential damages due to the lack of scientific knowledge: hazards from various wastes, species extinction, global warming, low doses of radiation, electromagnetic fields, cellular phones, genetically modified (GM) food, and the list could go on. In the following, we will focus on two cases: the bovine spongiform encephalopathy (BSE) and global warming. In this section, we just want to summarize the existing knowledge as they are useful for economists.

The mad cow crisis. The three mad cow crises of 1996, 1999 and 2000 raise the difficult question of imposing common European prevention rules in the face of BSE. Should we impose a complete ban of the use of recycled cattle bones to feed animals, given evidence of the transmission of the disease through animals proteins and the existence of frauds in countries allowing cattle to be fed to pigs and poultry? Should we, as in France, kill all the animals in a herd where a case of BSE has occurred, in spite of the evidence that among the thousands of animals of french massacred herds, only one extra cow was found to have BSE? Should we test for BSE all cows that enter into the food chain? These are among the several questions related to the risk management of the new variant Creutzfeld-Jakob disease (nvCJD).

Because of the scientific uncertainty prevailing on the transmission of the disease, the current best estimate of the cumulated number of victims in the U.K. over the next 20 years is 6,000, but with a minimum in the hundreds and a maximum at 250,000. For a population of British citizens at 60 millions, this puts the individual probability of getting nvCJD within the next 20 years in between $2\ 10^{-5}$ and $4\ 10^{-3}$, with a mean at 10^{-4}.[4] From the start of the BSE epidemic in 1988 to March 1996, the British government expenditure on fighting BSE had already reached 247 million pounds, just for compensating farmers, destroying cattles, administering controls and research. Due to measures taken in 1996 in the face of the first human cases of nvCJD, the cost of preventive action went up to around 700 million pounds per year, or around 0.1% of GDP. Whereas the costs of the preventive efforts are relatively easy to measure, the central question is to determine how to take into account of the ambiguity of the health risk to evaluate the benefit

[4] For the sake of comparison, the death toll per year for respectively car accidents and cancer are 3421 (in 1998) and 156,000 (in 1996). This puts the probability of death over the next 20 years at respectively 0.001 and 0.06 for these two hazards.

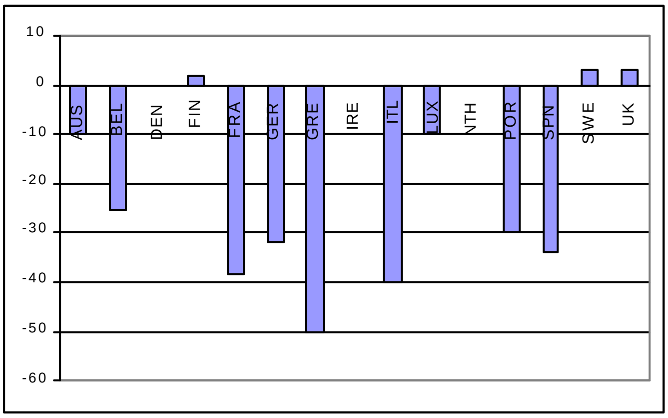

Figure 1: Percentage change in EU beef consumption, Oct 1 -Dec 31, 2000. (Source: European Union)

of these e®orts.

How did consumers react to the risk? In March 1996, french consumers reduced their purchase of beef by 35%, but the reduction was only 10% by the end of the year. The price went down by 20% during the crisis, and by 10% by the end of the year. The crisis was much stronger in November 2000 after potentially tainted meat was discovered on supermarket selves in France. During the last quarter of 2000, beef consumption slumped by 27 percent across the 15 countries of the European Union, whereas the wholesale price of beef in France went down by almost 25%. The e®ect of the crisis on the consumption is depicted in Figure 1 for each of the 15 countries.

Global warming. The risk linked to global warming is a®ected by the same degree of scienti¯c uncertainty. For example, the Intergovernemental Panel on Climate Change (IPCC, 1995) has published estimates range between $5 and $125 for the net present value of future damages generated per tonne of carbon emitted today. Because each liter of petrol consumed yields 2.36 kg of carbon dioxide, we should impose a pigouvian tax { or the equilibrium price of emission permits should be { somewhere between 1.2 and 30 cents per liter of petrol. The wide range of damage estimates does not re°ect some natural risks due exogenous random shocks to the biosphere. Rather, it comes from our limited scientific knowledge of the mechanisms linking the various stages of the process linking emissions to damages: imperfect knowledge of impacts of the concentration of greenhouse gases in the atmosphere on the climate, imperfect knowledge of the effect of the change in the climate on the environment (with possible feedback loops), and imperfect knowledge of the impacts of the change in the environment on welfare.

3 Dealing with a static scientific uncertainty

When the decision maker faces such a degree of ambiguity on the distribution of the risk, how should he behave? In the next two sections, we assume that the decision maker is benevolent and that he is in a situation to aggregate any relevant information to measure the risk.

3.1 Subjective expected utility

Suppose that you prefer a lottery $\tilde{x}_1$ to a lottery $\tilde{x}_2$. Now, rather than offering lottery $\tilde{x}_i$, you are confronted to compounded lottery $\tilde{x}_i^0$ which gives lottery $\tilde{x}_i$ with probability p and a specific gift a with probability p. Given the fact that you prefer $\tilde{x}_1$ to $\tilde{x}_2$, do you also prefer lottery $\tilde{x}_1^0$ to $\tilde{x}_2^0$? If this is true for any and $p \in [0,1[$, you satisfy the so-called "independence axiom introduced by von Neumann and Morgenstern (1944) and extended by Savage (1954). Under very general conditions, the independence axiom implies that the individual objective function is linear in probabilities. This leads to the (subjective) expected utility (SEU) theory.

What does this imply for risk management under ambiguous probabilities? To keep it simple, suppose that there are two possible states of nature, a high loss state and a low loss state. They are n mutually exclusive theories predicting the probability of the high loss state. Namely, if theory i is true, the probability of the high loss state is unambiguously equal to $p_i \geq 0$. There is a probability π_i that theory i is the true one, with $\sum_{i=1}^{n} \pi_i = 1$.[5] In such a situation, SEU decision makers behave as if the true probability of

[5] We suppose that there is an accepted meta-theory that determines these probabilities. One could imagine a more complex situation where experts disagree on the likelihood of the various theories because they use different meta-theories. This just introduces an additional dimension to the uncertainty without changing the nature of the problem.

the high loss state be the mean probability $\bar{p} = \pi_1 p_1 + ... + \pi_n p_n$ extracted from the competing theories. In a sense, SEU agents are neutral to scientific uncertainty.

To illustrate, consider the case of nvCJD in the U.K.. We assume that being a victim of the disease generates a damage that is equivalent to the financial loss of 50 times the GDP per capita.[6] We also assume that victims are fully compensated for the reduction of their life expectancy. This implies that the risk is well diversified ex-ante. In spite of the high uncertainty of being a victim of the disease, we know that, under the independence axiom, we can just focus on the average probability $\bar{p} = 10^{-4}$ (see section 2). Under this theory, the existence of this ambiguous risk for British citizens over the next 20 years is equivalent to a reduction in their wealth amounting to $50\bar{p} = 0.5\%$ of GDP/cap. In other words, if there would exist a method to eliminate the nvCJD risk for human beings in one shot, it would be efficient to implement it only if it costs less than 0.5% of GDP.

Using this method to deal with scientific uncertainties makes precaution not much different from measures of protection (where probabilities are objective): just take expected probabilities and apply the standard cost-benefit analysis with these probabilities to determine the optimal effort to limit the risk. The European Commission, in his communication paper (CEC, 2000) on the PP, says nothing else in the following statement: "If the absence of scientific data makes it impossible to characterize the risk, taking into account the uncertainties inherent to the evaluation, the measures taken under the PP should be comparable in nature and scope with measures already taken in equivalent areas in which all the scientific data are available". (page 19)

3.2 Aversion to ambiguity

Not everyone agrees with taking expected probability to deal with scientific uncertainties. For example, most environmental organizations like Greenpeace favor an alternative wording of the PP: " When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically". This is interpreted as requiring to behave as if the

[6] There would be much to say about the value of life. The debate about the PP can also be examined from the viewpoint of a crisis about the value of life and of environmental assets.

worst theory be true, even if not fully established scienti¯cally. This strong interpretation of the PP is even clearer in the conclusion of the French Conseil d'Etat about the infected blood a®air (1995): "In an uncertain situation, an hypothesis that cannot be rejected should be taken as temporarily valid, even if it cannot be formally proven". Can we justify such an alternative approach to the PP on an economically sounded basis?

Keynes (1921) distinguished between probabilities and the weight of evidence. Probabilities represent the balance of evidence in favor of a particular event, whereas the weight of evidence represents the quantity of evidence supporting that balance. He then raised the following question: "If two probabilities are equal in degree, ought we, in choosing our course of action, to prefer that one which is based on a greater body of knowledge?" As shown above, Savage (1954) argued that ambiguity in probabilities has no role in the decision process.

But Daniel Ellsberg (1961) showed in a well-known experiment that some people do not behave as SEU agents. They don't behave in the same way in the face of two uncertain environments with the same probabilities, but with di®erent weights of evidence. More precisely, they are ready to pay more to get rid of a more ambiguous risk. In the Keynes-Ellsberg's "two-color" problem, there are two urns each containing red and black balls. Urn 1 contains 50 red balls and 50 black balls, whereas urn 2 contains 100 red and black balls in an unknown proportion. A ball is drawn at random from an urn and one receives 100 euros or nothing depending on the color of the ball. The fact that people are indi®erent to bet on red or black if urn 2 is used indicates that their subjective probability for each color is 0.5, as in urn 1. If they would be SEU maximizers, they should thus be indi®erent to using urn 1 or urn 2 for gambling. However, most people prefer to gamble with the unambiguous urn 1, where the "weight of evidence" is larger.

Betting on urn 2 is like facing scienti¯c uncertainty. There are 101 possible "theories" about the actual risk taken by those who bet on urn 2, with theory i assigning a value i to the number of red balls in the urn, $i = 0, 1, ..., 100.$ In this example, there is some logic to assign the same probability to each theory, so that the probability to win with urn 2 is exactly equal to 1/2. The Ellsberg's paradox tells us that the public opinion does not work like that, in the sense that the weight of evidence about probabilities a®ects the attitude towards them. The Commission of EC (2000,p.4) says nothing else when it states that "decision-makers need to be aware of the degree of uncertainty attached to the results of the evaluation of the available scienti¯c information".

Gilboa and Schmeidler (1989) proposed a decision criterion alternative to SEU to explain the Ellsberg's paradox. Under Gilboa and Schmeidler 's criterion, individuals perform a sequence of two operations. First, for each possible theory, they compute the corresponding expected utility that they would get by assuming that this theory is the true one. Second, they behave as if the true theory be the one that yields the lowest expected utility. Notice that the advantage of this criterion is that we don't need to assign any probability to each possible theory. This maximin criterion obviously generates a strong aversion to ambiguity that can be assimilated to maximum pessimism.

In the nvCJD case, this would mean that one should do as if the unfavorable theory yielding a cumulated dead toll of 250,000 be the true one. Under Gilboa and Schmeidler criterion, the U.K. government should be ready to pay as much as 20% of GDP immediately to get rid of BSE.

The Gilboa and Schmeidler's criterion has its own problems, however. SEU decision makers can violate their neutrality to ambiguity for various reasons. Savage's own line of defense was based on bounded rationality: SEU agents can make mistakes, but they will change their mind after a more detailed evaluation of the situation. A second argument is based on the idea that the layperson does not trust experts for various reasons. Public decision makers and experts are believed to be captured by industrial and agricultural lobbies that tend to systematically underestimate the risk for the population. The population will then counterbalance this bias by biasing their estimate of the risk towards the worst case scenario, as a cheap-talk equilibrium (Crawford and Sobel (1982)). These two arguments favor a better and more independent information channeling to the public.

The extreme pessimism implied by Gilboa and Schmeidler's criterion is a third argument against it. People that would behave according to this criterion would simply never accept to enter into an uncertain scheme. We will always ¯nd some experts exhibiting an extreme catastrophic scenario. Even if it extremely unlikely to occur, ambiguity-averse agents will dislike the risk according to Gilboa and Schmeidler. They will never invest, and they will never innovate. This is not supported by economic history. Observe for example that ambiguity-averse consumers would just stop eating beef because of the ambiguity surrounding the risk of nvCJD. This is not what has been observed. Still on the empirical ground, Viscusi and Chesson (1999), using a sample of 266 business owners facing risks from climate change, show evidence of both ambiguity-seeking behavior and ambiguity-averse behavior. More precisely, people seem to exhibit fears effect of ambiguity for small probabilities of suffering a loss, and hope effects for large probabilities. Fox and Tversky (1995) also showed in a series of experimental studies that ambiguity aversion, present in comparative contexts in which a person is confronted to both clear and ambiguous prospects, seems to disappear in noncomparative contexts in which a person evaluates only one of these prospects in isolation.

Finally, the Gilboa and Schmeidler's criterion does not explain how to manage the update of uncertain beliefs. It implies that this criterion is not operational to deal with dynamic risks where a flow of new information is expected to reduce scientific uncertainty over time. For these reasons, we assume in the remaining of this paper that people are SEU maximizers.

4 Dealing with a dynamic scientific uncertainty

In the previous section, we did not take into account of the intrinsically dynamic nature of scientific uncertainty, which is expected to be resolved over time. In this respect, the PP is very clear by stating that scientific uncertainty should not be used to postpone preventive efforts. With a smooth resolution of the uncertainty over time, decision makers should use a prospective analysis (backward induction) to adapt their actions in the light of new scientific data. As stated in the second report of IPCC on climate change (1995), "the challenge is not to find today the best policy for the next 100 years, but to select a prudent strategy and to adjust it over time in the light of new information". This is quite apparent in the case of BSE, where the British government multiplied by 10 the preventive effort in 1996 when the possible human form of the disease became a reality.

4.1 The option value of flexible actions

The central concept of any dynamic risk analysis is flexibility. When our knowledge about the underlying long tail risk is expected to change over time, being able to adapt actions to information is valuable. In other words, information is valuable only because we can adjust our behavior to it. Thus, any immediate action that reduces our ability to be flexible in the future should be penalized. To do this, Arrow and Fischer (1974) and Henry (1974) proposed to introduce an option value in the measurement of the benefits of a more flexible, or less irreversible, action.

The concept of option value is best illustrated by the problem of genetically modified seeds in agriculture. It is usually considered that the introduction of GM seeds in agriculture is an irreversible decision. This means that the decision to introduce them today eliminates any degree of freedom for future actions. In particular, it will not be possible to remove GM seeds if some alarmist scientific information about the induced risk is revealed ex post. Suppose that using the GM product raises the added value v per period in comparison to the classical product, but it also generates a risk of damage $\tilde{x}$ at the end of the second period. In the absence of any scientific progress in this two-period economy, a risk-neutral society should decide to introduce the GM product if $NPV = -I + v + (v - E\tilde{x})/(1+r)$ is positive, where I is a sunk cost.

If we take into account of scientific progresses that could be made between periods 1 and 2, we must solve this problem by backward induction. If the GM is introduced in the first period, the scientific information is useless because the introduction is irreversible. The net present value of the innovation is NPV as before. Alternatively, if one decides to postpone the possible introduction to the second period, one may implement a flexible strategy by introducing GM only when the expected damage $E[\tilde{x} \mid s]$ conditional to scientific information s is larger than $v - I$. The net present value of this flexible strategy is thus $NPV' = (1+r)^{-1} E_s \max(0; -I + v - E[\tilde{x} \mid \tilde{s}])$: This is the option value of postponing the validation of GM. Taking into account of scientific progresses transforms the decision rule from $NPV \geq 0$ to $NPV \geq NPV'$ for the introduction of the GM seeds. This is compatible with the precautionary principle, where the preventive action consists in postponing the introduction of GM when the range of parameters values are such that NPV is positive but smaller than NPV'.[7]

Most risks presented in the introduction are subject to irreversible decisions. Reducing biodiversity is an irreversible phenomenon. Most of the

[7]Common wisdom suggests that introducing risk aversion should reinforce the option value of more flexible actions. This is not true in general, because more flexibility ends up with agents taking globally more risk in some circumstances. This is explained and discussed in more details in Gollier (2001, chapter 24).

carbon dioxide that we emit today cannot be removed from the atmosphere in the future, thereby reducing the ability of future generations to select the best level of concentration given their scientific knowledge. Nordhaus (1994) and Manne and Richels (1992) calibrated a model of global warming with scientific progress. They found that learning has little or no effect on decisions, mostly because the likelihood is small that future generations will ever want not only to eliminate their own emission, but also to reduce the concentration. In some cases, the different possible actions yield different irreversible effects. For example, slaugthering herds to fight BSE is an irreversible decision from the production viewpoint. But introducing potentially infected animals in the food chain is also an irreversible decision from the consumer viewpoint. Consumers may think that stopping eating beef today would be too late anyway, as they probably already ate infected beef in the past. It is important to measure the option values associated to these alternative strategies.

Calculating option values may be a difficult challenge. It requires the establishment of potential scenarios for the speed of scientific progresses and on their impact on the evaluation of the economic risk. The important progresses in computing technologies and stochastic modeling in operations research make it possible to determine optimal dynamic strategies with complex dynamic scenarios. This is exactly what Manne and Richels (1992), Nordhaus (1994) and Ha-Duong (1998) did for global warming. In some cases, the financial theory of option pricing may be useful as shown in McDonald and Siegel (1986) and Dixit and Pindyck (1994). Gollier (2000b) and Gollier and Devezeaux de Lavergne (2000) use this technique to evaluate the option value of organizing long-term accessibility to the nuclear wastes site, respectively from a safety point of view, or because future generations may want to recycle some of these products for their own benefits.

An interesting question is about whether competitive firms do integrate option values in their decision to invest. Competing firms may be tempted to introduce it immediately in order to preempt the market. To see this, consider a n competing firms that are examining the opportunity to produce a new good. Because of the large fixed cost I, only one firm can enter at equilibrium. Suppose that all firms restrained themselves from entering the market in the first period. Given the new scientific information s acquired during the first period, all firms will want to enter the market if $y(s) = -I + v - E[\tilde{x} \mid s]$ is positive. Suppose that all firms have the same probability to get the market, thereby extracting the monopoly rent y(s). Seen from period 1, each risk-neutral ¯rm has thus an expected net present value $NPV^0{=}n$ $<<$ NPV^0 for the project: This is the option value of delaying the innovation if all other ¯rms decide to postpone their entry. This option value that each ¯rm will optimally introduce in its cost-bene¯t analysis is smaller than the socially e±cient one. This implies that competing ¯rms will innovate too often and too early, even if they internalize all damages. At the limit, when there is a large number of ¯rms, all new products with a nonnegative expected net present value will be introduced, without taking into account of the value to wait due to the resolution of scienti¯c uncertainty over time. This point is made by Weeds (1999) for example. This argument provides a justi¯cation for public institutions with the power of authorizing new products on the market. However, these public institutions have there own ine±ciencies.

4.2 Accumulation of pollutants and the learn-then-act principle

The option value is not the only e®ect to be taken into account when the distribution of the risk is unknown but subject to Bayesian updates. In the previous section, we assumed that our actions today only a®ect our opportunity set of future actions. But our current decisions may also directly a®ect our future exposure to the risk. This is for example the case when the risk is an increasing function of the cumulated exposure to the pollutant in the past. To illustrate, it is not just the current emission of carbon dioxide that determines the current climate. Rather, it is the current concentration of this pollutant which determines it. It is also the accumulation of past exposures to nuclear radiation, cellular phones and smoking that seems to determine the health risk. When the risk depends upon the concentration of the pollutant, there is a tension between the desire to postpone the action to after learning in order to improve e±ciency (learn-the-act principle), and the desire to smooth the e®ort over time.

Consider a new good whose production generates some immediate added value v, but yields some future hazard. When the future health risk depends upon the sum of past consumptions (potentially weighted by a rate of natural decay in the accumulation process), we can analyze a reduction in current consumption as a precautionary saving, as it allows for a future extraction of surplus by increasing future consumption, leaving the future risk unchanged. The problem is thus to determine the effect of scientific progress on our willingness to postpone the extraction of surpluses from innovation. This question is examined in Ulph and Ulph (1997) and Gollier, Jullien and Treich (2000). As we will see, there is no general answer to this question, as the solution depends upon individual preferences.

Scientific progress reduces the risk ex-post, and it induces more efficient future consumption choices. This is the learn-then-act principle: the planner is in a position to select a better action with the better information. Because of the reduction in risk due to better information, consumers will be, in expectation, less reluctant to consume the new good. Ex ante, consumers will anticipate that and they will worry less about the future, thereby increasing their immediate consumption of the risky good. This wealth effect goes against the PP. But there is a second effect. Because the future exposure to the risk is depend upon the random scientific signal ex post, potential scientific progresses yield an increase in the uncertainty affecting the future consumption net of the damage, ex-ante. But, as observed by Leland (1968) and Kimball (1990) for example, an increase in future uncertainty raises the willingness to save for the future if consumers are prudent, i.e. if the marginal utility of their consumption is convex. This precautionary effect is an argument for the PP, as it means that people will want to postpone the extraction of the surplus of the innovation by consuming less today. Gollier, Jullien and Treich (2000) show that the precautionary effect dominates the wealth effect only the degree of prudence, $P(c) = -u'''(c)/u''(c)$; is larger than twice the degree of risk aversion $A(c) = -u''(c)/u'(c)$.[8] Notice that $P = 2A$ in the case of a logarithmic utility function, which implies that logarithmic consumers are neutral to scientific uncertainty, as long as there is no irreversibility problem. In the case of constant relative risk aversion, it can be checked that P is indeed larger than $2A$ if and only if relative risk aversion is smaller than unity. Most economists believe that relative risk aversion is larger than unity. Thus learning may have counter-intuitive effects on the optimal dynamic strategy.

To illustrate, let me consider the case of global warming. To keep the

[8]Gollier et al. assume a time-separable utility function, which implies that A measures at the same time aversionto risk ad to consumption fluctuations over time. We are not aware of any research on this problem when these two concepts are disantangled by using recursive utilities.

story simple, we consider two periods, "today" and "the future". Each liter of petrol consumed at any time yields a discounted damage θ to the environment in the future that is evaluated to be either 1 cents or 30 cents. This is compatible with the degree of uncertainty expressed in the second report of IPCC (1995). The probability p that θ be 0.30 is uncertain. Namely, p is either $0.5(1-k)$ or $0.5(1+k)$ with equal probabilities. Parameter k measures the speed of scientific progress. Using petrol is cheaper, and $v = 20$ cents is the immediate benefit of using this source of energy, per liter of petrol.[9] If relative risk aversion is constant and equal to 2, the optimal initial consumption of petrol is $c_1 = 0.310$ when $k = 0$ (no scientific progress). Suppose alternatively that some scientific information are expected to come over the next 10 years (k positive). If we fix $k = 0.2$, we can check that the optimal initial consumption of petrol goes up to $c_1 = 0.322$. This represents an increase in initial consumption by 3.9%. We can also check that the initial optimal emission is almost doubled by the potential scientific progress if $k = 0.8$, i.e. if 80% of the uncertainty is eliminated in the second period.[10]

4.3 Learning by observing trends

In the previous section, we assumed that the improvement of our knowledge comes from theoretical progresses. We could alternatively consider situations where progresses are made just because we observe early realizations of the risk. A large part of the recent alarm about global warming comes from observing a positive trend in the average temperature on the earth, more than from a better understanding of the physical determinants of the climate.[11] Similarly, a large part of the BSE psychosis comes from the sharp increase of nvCJD cases in the U.K..

[9] Technically, in the absence of more scientific progress between today and the future, the socially optimal consumption plan of fuel maximizes $u(vc_1) + \beta E u(vc_2 - (c_1 + c_2)\theta)$, where $\beta = 0.8$ is the discounting factor of the first period, which lasts for around 10 years. We consider a utility function $u(c) = (1+c)^{1-\gamma}/(1-\gamma)$.

[10] Notice however that we do not take into account of the irreversibility constraint $c_2 \geq 0$. For these values of the parameter ($k = 0.8$), this constraint would in fact be binding in case of a bad scientific information be revealed in the second period. From the previous section, we know that the introduction of this constraint would reduce the initial optimal emission. It can be shown that c_1 goes actually down by one-third due to the scientific progress when the irreversibility constraint is taken into account.

[11] Globally, the 1990s was the warmest decade on record and 1998 the hottest year.

When such a learning process goes on, the observation of an increase in the damages implies that a large initial loss is worsened by the prospect of larger losses in the future. On the contrary, the absence of damage today is a good information for the distribution of future losses. Thus, ex-ante, this learning process increases the risk, implying a larger efficient prevention effort. Thus learning by observing trends is compatible with the PP.

To illustrate, suppose that there has been a switch in the climate. This switch will generate new random natural catastrophes, but the probability of these events is unknown. In some countries, catastrophes will occur at a frequency p_1, whereas in some other countries, the frequency will be p_2 smaller than p_1. The difficulty is that we don't know which countries will be in the high risk group 1. There is no international risk sharing. The occurrence of a catastrophe reduces the GDP/cap by L. Take a specific country whose prior belief to belong to group 1 is π_0, so that the prior probability of a natural catastrophe is $\overline{p} = \pi_0 p_1 + (1 - \pi_0) p_2$. Obviously, by observing natural disasters years after years, one will learn the true probability through the process of Bayesian updating. The decision problem is the following. At each period, the government has to determine the amount to be devoted to protection. Each euro invested in protection reduces the damage by h euros in case of a catastrophe occurring in that period. Moreover, the level of capital investment is endogenously determined. There is a linear production technology that generates $1 + r$ euros in $t + 1$ for each euro invested in t. The existence of this storage technology implies that the country can self-insure the risk by reducing its capital investment to finance consumption when a catastrophe occurs. The problem is to jointly determine the dynamic protection and consumption strategy.

What is the effect of learning on the initial optimal protection level? This question is examined in details in Gollier (2000c). More precisely, we compare the optimal dynamic protection strategy in this economy with learning to the one that would be optimal when the country knows with certainty that the probability of catastrophe per period is $\overline{p}$.

To illustrate, consider the case where, with equal probabilities, the probability of loss is either $p_1 = 0.5$ or $p_2 = 0.01$. This illustrates a situation with a large degree of uncertainty. At each period, the planner revises the probability of loss by observing the state of nature that prevailed in that period. The numerical simulation in Gollier(2000c) indicates an important effect of learning on the initial level of protection which is increased by 90%

when relative risk aversion is equal to 2. Interestingly enough, the optimal initial decision is close to the one that would be optimal without learning, but using the largest possible probability p_1 of damage: learning make SEU agents behave as if they would be ambiguity-averse à la Gilboa-Schmeidler.

What is the intuition of this learning e®ect? The occurrence of a loss in the ¯rst period has two e®ects. First, it reduces wealth and it raises the marginal utility of this wealth. Second, it induces agents to revise upward the probability of the worst scenario. The intuition suggests that this shift in the expected distribution of the risk should raise the marginal value of wealth. If this is true, then learning raises the marginal value of wealth where it is large, and reciprocally, it reduces the marginal value of wealth where it is low. In consequence, the process of learning plays a role on the initial risk attitude that is equivalent to an increase in risk aversion. In other words, the uncertainty about the distribution of damages makes agents more averse to the risk, i.e., they will invest more in prevention. This is compatible with the precautionary principle. Notice that poorer countries will be more a®ected by this uncertainty in the sense that they will want to invest more in protection.

However, this result relies on the assumption that a bad news, i.e. an increase in the probability of the bad scenario, raises the marginal value of wealth. This is not true in general, however. Intuitively, an increase in the probability of damages has two e®ects on the marginal value of wealth. First, it makes agents poorer in expectation in the future. This wealth e®ect raises the marginal value of wealth. But there is a second e®ect that goes the opposite direction. The increase in the probability of loss induces agents to reduce their exposure to the risk in the future. That yields a negative precautionary e®ect, in the sense that the reduced future risk makes wealth accumulation less valuable for a precautionary saving motive. Thus, again, the index of prudence will enter into the picture, this time against the PP. Without entering into the details, it happens that when relative risk aversion is constant and larger than unity, the wealth e®ect dominates the precautionary e®ect, and the uncertainty should induce us to invest more in protection.

This result is related to a reviving literature of learning in dynamic portfolio management. Our problem is an example of a decision problem in which the future investment opportunity set is stochastic, to follow the terminology in ¯nance. Merton (1973) was the ¯rst to characterize rules for the optimal dynamic portfolio management. Detemple (1986), Gennotte (1986), Brennan (1998) and Brennan and Xia (1999) examined the speci¯c case where the opportunity set is stochastic due to the initial parameter uncertainty of the dynamic stochastic process. McCardle and Winkler (1992) examined a similar problem applied to gambling. In a casino, there is an urn of indistinguishable coins, half of which are "good" and half "bad". The good coins land heads with di®erent probabilities that are known a priori. A single coin is picked at random from the urn that is used for n plays of the game. At each play of the game, you choose how much you want to bet. What is the optimal dynamic strategy in this game against nature? McCardle and Winkler (1992) raised this question to over 200 students and obtained that most people prefer not to bet at ¯rst, in order to gather information about the coin. This literature on learning the distribution of asset returns shows that, when relative risk aversion is constant, the sign of the e®ect of learning on the initial optimal portfolio depends upon whether relative risk aversion is larger or smaller than unity. Gollier (2000d) relaxes the assumption of constant relative risk aversion. He shows that the sign of the e®ect of learning depends upon whether absolute prudence is smaller or larger than twice the absolute risk aversion.

5 Risk aversion, loss aversion and risk sharing

In public economics, there is a well-known result by Arrow and Lind (1970) which states that one should behave in a risk neutral way to deal with risks that are diversi¯ed away in a large population. Full diversi¯cation requires that the victims are fully indemni¯ed for their loss ex post in such a way that the risk be e±ciently shared ex ante. In most cases, this assumption is unrealistic. There are obvious reasons why these risks are di±cult to insure on competitive insurance markets. If, for any reason, insurance companies are more pessimistic than consumers, the latter could ¯nd it better not to insure the risk because of the expensive premium rate. Moreover, after the asbestosis crisis of the 80's, insurance companies discovered the legal risk associated to uncertain future interpretations of Tort laws that is inherent to long tail risks. They are now very reluctant to insure long tail risks. Finally, when risks are borne by future generations, as for global warming or waste hazard, it is technically not possible for earlier generations to participate to their sharing. Similarly, when facing a global risk like climate change, it would be useful to create financial instruments that would allow for an international diversification of country-specific risks. As of today, these financial instruments do not exist, or are not used. The provision of public insurance via implicit solidarity schemes is also imperfect due to the uncertainty of the benefit that will be paid to the victims.

When risk are not efficiently shared and diversified away, each consumer will bear some risk ex ante. This implies that a risk premium should be added to the benefit of any action that reduces this individual risk. In order to quantify it, let us consider again the case of nvCJD. Victims of nvCJD have their life expectancy reduced by a factor $k = 50\%$. The value of a healthy life is $V = 100$ times the GDP per capita, whereas the value of life is only $(1-k)V$ for a victim. There is no compensation for the disease. Let $\bar{p} = 10^{-4}$ be the expected cumulated frequency of the disease over the next 20 years. Ex ante, agents will be ready to pay the expected loss $\bar{p}kV$ plus a risk premium equaling a proportion Π of V to eliminate the risk of developing the disease for their entire life. When relative risk aversion is constant and equal to γ; Π must be such that

$$(1-\bar{p}k-\Pi)^{1-\gamma} = (1-\bar{p}) + \bar{p}(1-k)^{1-\gamma}.$$

A risk neutral agent ($\gamma = 0$) would be ready to pay up to $100\bar{p}k = 0.5\%$ of the GDP per capita to eliminate the nvCJD risk. But people with a reasonable degree of risk aversion $\gamma = 2$ will double this willingness to pay ($\Pi = 0.5\%$).[12] Thus, risk aversion double the evaluation of the cost of risk. This relatively small effect is an illustration of the fact that risk and risk aversion are of the second order under expected utility with a differentiable

[12] There is a consensus for a degree of relative risk aversion between 2 and 4, as most macroeconomists and researchers in finance use values of γ in this region for their calibration. The reader can verify by introspection that these estimates make sense: suppose that you face the risk of losing or gaining 10% of your wealth with equal probability. Which share of your wealth would you be ready to pay to escape this risk? If $\gamma = 2$; the answer would be 1%, which is a reasonable number. By comparison, $\gamma = 0.5$ would just generate 0.3%, and $\gamma = 40$ would imply 8.4%. However, the classical model of asset pricing in finance requires $\gamma = 40$ to explain the high level of the equity premium during the XX century, leading to the famous "equity premium puzzle".

utility function. This means that Π tends to zero as k^2. Tversky and Kahneman (1992) suggested an alternative model using their concept of "loss aversion". In a static framework, their prospect theory can be seen as a special case of expected utility where the utility function would have a kink at the reference point. From this reference point, a unit loss generates a disutility that is roughly equal to twice the utility of a unit gain. Because this utility function is not differentiable, risk and risk aversion generate first order effects. Let us assume that the reference point is the expected lifetime $1 - \overline{p}k$. After some computations, we obtain that $\Pi = 0.5\overline{p}(1 - \overline{p})kV$ which is indeed linear in k. With $\overline{p} = 10^{-4}$ and $k = 0.5$, this implies that $\Pi = 0.25\%$ of GDP. Because the size $k = 0.5$ of the risk is medium, the magnitude of the risk premium are similar for the two models. Of course, a change in the size would have very contrasted effects on Π in the two models. Risk aversion would stress the prevention of catastrophic risks, whereas loss aversion is more about the prevention of small risks.

Because Π is positive, an important conclusion of these analyses is that more preventive effort should be done in countries or sectors of the economy where risks are less efficiently shared. Prevention is a substitute to insurance.

We assumed up to now that the risk was homogenous in the population. Suppose alternatively that it is very unequally distributed among citizens, with some of them facing a damage ratio close to unity in case of an accident.[13] A simple illustration of this is provided by the health risk induced by nuclear waste disposals. In that case, the distribution of potential damages is very unequal, with the so-called "target population" living close to the site bearing a much larger damage. The acceptability of the risk to the public would be much reduced by the absence of a proper compensation scheme for these potential victims of the pollution.[14] A similar point can be made for global warming, where some countries may actually benefit from it, whereas others, like small island nations, will confront great vulnerability

[13] This would be a formal argument only if the risk premium Π would be convex in the damage ratio k. Function $\Pi(k)$ is clearly locally convex for low values of k, since we can apply the Arrow-Pratt approximation which makes Π proportional to k^2. But, because of a wealth effect, it may be possible for Π to be locally convex for larger sizes of the risk, as shown in Eeckhoudt and Gollier (1998).

[14] This is well understood by some french environnementalists, who strongly oppose the idea that areas accepting nuclear waste disposals should be compensated for the potential damages.

to the subsequent rise of sea level.

6 Future generations

For several potential applications of the PP as global warming, GM products, nuclear wastes and biodiversity, potential damages will expand long into the future. The classical technic to take into account of future damages is to discount them at some socially e±cient discount rate which may or may not be equal to the equilibrium risk free rate in the economy. The idea of using a positive discount rate is based mainly on the argument that future generations will be wealthier, so that the same marginal unit of damage is less damaging to their welfare than for the current generation, if the marginal utility of wealth is decreasing. But the consequence of discounting is that damages occurring long in the future, say in more than 100 years, are just valued peanuts today. This re°ects the expectation that, at the secular growth rate of GDP/cap at 2% per year, the level of consumption in 100 or 200 years will be multiplied by a factor equaling respectively 7.2 and 52.5. It implies that the current generations should not really care about these future risks. This is clearly against the PP and is inconsistent with the view of the CEC (2000) which recommends that "the potential long-term e®ects must be taken into account in evaluating the proportionality of measures in the form of rapid action to limit or eliminate a risk whose e®ects [...] will a®ect future generations".

In Gollier (2000a), we show that it may be socially e±cient to apply a smaller discount rate for longer time horizons, thereby reducing the exponential nature of discounting. This principle is sustained by the fact that a prudent society should invest more for the future when this future becomes more uncertain. We use the term "prudence" to refer to a concept introduced by Kimball (1990). Prudent persons are characterized by their reaction to increase precautionary savings due to the uncertainty of future earnings. Technically, an expected-utility maximizer is prudent if the third derivative of the utility function is positive. Therefore, prudence should not be confused with risk aversion which corresponds to the negativity of the second derivative. Prudence is necessary for the widely accepted assumption that absolute risk aversion is decreasing.

The possibility that the socially e±cient discount rate be decreasing with time horizon comes from the increasing uncertainty about the GDP per capita that accumulates for these longer horizons. Assuming a growth of the economy similar in trend and volatility to what we observed during the XX century, Gollier (2000a) suggests to take a 5% discount rate per year over the first 100 years, and then to reduce it to around 2% per year for much longer time horizons.

It is noteworthy that there is a mutually aggravating effect of the natural risk, due for example to global warming, and the background economic risk expressed by the uncertainty on the growth rate. Gollier and Pratt (1996) show that the presence of the background economic risk should induce us to raise the risk premium associated to the natural risk, even when the two sources of risks are independent. In other words, in the cost-benefit analysis, we cannot dissociate the selection of the discount rate to the measurement of the certainty equivalent loss of the risk. The uncertainty about the growth rate of the economy will affect both of them in a direction which is compatible with the PP. However, for short horizons, the uncertainty on the future GDP/cap is too small to really affect the risk premium of the natural risk.

7 Asymmetric scientific information

Up to now, we assumed that everyone in this economy was endowed with the same information at each date. But the PP is also about the difficult problem of producing and aggregating information from various sources, some of them being sometimes contradictory. In the following, we address a few issues related to asymmetric information and incentives.

7.1 Citizen's freedom, cost of information and tracability

Existing scientific information has the nature of a public good, but it is costly to acquire for consumers. If the cost is high enough, it may be socially efficient for a subgroup of independent citizens to pay this cost in order to formulate guidelines for other consumers. This calls for the organization of popular juries to determine public policies. However, there is a risk that this subgroup be captured by lobbies. We examine this problem in section 7.4. Another problem with a centralized decision rule is that it does not take into account of the diversity of tastes in the population of risk-bearers. The heterogeneity of risk aversion, ambiguity aversion, prudence and values calls for o®ering some degrees of freedom to citizen's risk management.

When the central authority has no more scienti¯c knowledge than the population, it should restrain from imposing choice to the population. In the absence of any asymmetric information, heterogeneous agents should be allowed to make their own decision freely. Public intervention can be potentially Pareto-improving only in case of the presence of externalities, or when insider information cannot easily be transmitted to consumers. However, in order to allow for the e±cient consumers' exercise of freedom, the State should guarantee the tracability of products.

When existing scienti¯c information is not costly to acquire for the public, the objective of the public authority should be to provide an e±cient mechanism to produce and to di®use scienti¯c knowledge. The responsibility to consume the good should be left to the consumer in that case. Insurers should be allowed to cover the associated risk on competitive insurance markets.

7.2 Product liability

An interpretation of the PP is that ¯rms should not be freed from their liability for de¯ciencies of their product because they were not aware of any scienti¯c uncertainty at the time of the production. Imposing a no-fault liability system is an incentive for ¯rms to acquire the scienti¯c knowledge before delivering a new product to the market. But this may not be enough to guarantee that ¯rms implement an e±cient level of precaution. A ¯rst argument for this has been developed at the end of section 4.1: ¯rms will compete to preempt new markets. Therefore, they will innovate too early.

In the light of the case of asbestos and other "long-tailed" risks, another obvious argument is that it may be impossible to induce ¯rms to internalize all potential damages when some of these potential damages may occur in a far-distant future, simply because most of them will not exist anymore. Another related argument is limited liability. This can be partially cured by organizing "deep pockets" for industrial ¯rms. A possible policy recommendation is to make banks jointly liable for damages caused by borrowers, but this may generate an adverse selection problem on the credit market, as shown for example by Boyer and La®ont (1997). Another possible solution is to organize a market for product liability insurance, but this generates a moral hazard problem to be controlled by insurance companies.

7.3 Imposing the precautionary principle to the politician

In the face of asymmetric scienti¯c information between the State and its citizens, politicians may face con°icting interests to determine the best course of action to ¯ght against a public peril. This is particularly true when the resolution of uncertainty is slow. Suppose, as in Maskin and Tirole (2000), that the population does not know which action is socially e±cient in the face of a global health hazard. Consider a political body that owns some information about the intensity of the risk. Transmitting this information is made very di±cult because of its technical sophistication. Suppose however that, with some probability, the public will learn this information during the term of the political mandate. This can be due to some scienti¯c progress that are more accessible to the public, or to the observation of the trend of the damages. Finally, suppose that the only way to punish a politician convicted of not selecting the socially e±cient policy given her information is not to reappoint her for a second mandate. The interesting case is when the scienti¯c information owned by the politician refutes the uninformed public opinion. If the politician has a strong career concern for his reelection, and if the probability is low that the public will be informed within the term of her ¯rst mandate, it may be optimal for her to ignore the information and to take an ine±cient action that is compatible with the public opinion. This can be done for example by engaging in "bolstering", attending to much to expert sources that share the politician's own predispositions. Imposing the PP to the politicians will ¯ght against this pandering.

The regulatory capture by industrial and agricultural lobbies is another reason why self-interested politicians can select ine±cient policies. This calls for the organization of referendums to determine public policies, but only for less technical a®airs. However, referendums may induce politicians to shirk their responsibilities. Also, the public opinion may be subject to herd behaviors (Banerjee (1992)). Maskin and Tirole (2000) examine the relative advantages of direct democracy, representative democracy and judicial power.

7.4 Second-best expert procedures

Experts aggregate scienti¯c information and transform it into simpler policy recommendations. Information gathering and processing represents an important aspect of production in our economies. Financial markets for example have long been seen as a good aggregator of private information about the ability of ¯rms to produce wealth in the future. But knowledge, contrary to property rights on ¯rms, is seldom considered as a tradable good. If experts cannot establish property rights on knowledge, they may have less incentives to aggregate it e±ciently, and to transfer it truthfully.

Rational experts that are benevolent would all aggregate new scienti¯c information in the same way. In consequence, juries of benevolent experts would systematically be unanimous in favor of the most e±cient policy recommendation. But in the real world, there is no reason to believe that experts are benevolent. They pursue private goals. For example, they may extract private bene¯ts from promoting their peers' view of the world. They may also be reluctant to produce e®orts to extract information. Or they may be sensitive to ¯nancial incentives from parties involved in the matter. Because most good experts are, almost by de¯nition, in contact with at least some of them, there is no doubt that a risk of collusion exists.

When we recognize that experts may provide biased recommendations, we must solve the di±cult problem of determining at the same time the socially e±cient attitude towards these recommendations and the incentive scheme for experts. The risk of collusion of experts is not always a source of ine±ciency. If risks are e±ciently shared in the economy, risk bearers have no con°ict of interest, and experts will not be under pressure to bias their advice. Alternatively, if risks are not e±ciently shared, some parties may loose and others may win from experts' policy recommendations, and the risk of collusion exists. But if all stakeholders have an equal access to the experts, the latter will have the good incentive to reveal the best policy, as this recommendation will win the competition for bribes. But in the real world, consumers are much less organized than the industry to in°uence experts, as documented by Cropper et al. (1992) for the use of pesticide in the United States.

If experts are biased towards the industry, a possible strategy for the decision maker is to follow a bureaucratic behavior by not using decentralized information in the decision process. This may be socially e±cient if the cost of collusion is small. Alternatively, for larger private costs of collusion, it may become e±cient for the decision maker to use experts, conditional to the existence of an incentive-compatible scheme for them. Whether to use experts depends upon the value of information relative to the rent that must be given to experts to tell the truth (Tirole (1992)). In most cases related to the precautionary principle, it is likely that the ¯rst dominates the second, therefore providing some discretion to experts that must be organized through incentive-compatible rewards.

The existence of heterogenous biases among experts implies that the absence of unanimity is not synonymous of scienti¯c uncertainty. This is in contradiction with the WTO Appellate Body report on hormones which states that "in some cases, the very existence of divergent views presented by quali¯ed scientists who have investigated the particular issue at hand, may indicate a state of scienti¯c uncertainty". The cost of collusion within scienti¯c juries would be greatly limited if one would require that their scienti¯c reports be accepted in a scienti¯c journal with a standardized refereeing procedure, in the spirit of Nature, Journal of Economic Perspectives, or Economic Policy. More generally, scienti¯c information presented by experts, before being considered by the policy maker, should be subject to peer reviews through their presentation in seminars and conferences.

Rewarding experts may be a crucial point for the credibility of the system even when there is no risk of collusion. In particular, recent events show that experts may be much penalized, at least in term of reputation, when they did not recommend a strong preventive action towards a risk that happened ex-post to be catastrophic. If this penalty is not compensated by a positive reward for those experts that did not recommended an expensive preventive action towards risks that happened ex-post to be innocuous, this will not be incentive-compatible. Under these circumstances, experts would systematically prefer to recommend maximum prevention, and the credibility of the system would be lost. Organizing an e±cient rewarding system would require keeping track of individual expert's recommendations.

8 Concluding remarks

We have shown that the scienti¯c uncertainty a®ecting the distribution of a risk of damage should be taken into account to determine the socially e±cient level of prevention. To sum up, the precautionary principle is sustained by

1. our inability to organize the e±cient sharing of these risks. This problem is magni¯ed by globalization, which limits diversi¯cation. A risk premium should be added to the cost of the risk. This premium is increasing with the degree of the heterogeneity of the individual exposure to the risk.

2. the uncertainty prevailing for the economic environment enjoyed by the future generations that will have to bear the risk. This calls for a smaller discount rate for damages occurring in longer time horizons, together with an increase in the risk premium associated to the natural risk.

3. the aversion to ambiguity of the population. However, recent researches question this dimension of risk attitude. The population bias towards the worst case scenario may be due to the absence of con¯dence on the potentially lobby-controlled experts.

4. the option value of postponing an irreversible action. Public institutions in charge of authorizing new products should force competing ¯rms to include this option value in their decision to introduce an innovation.

5. the learning e®ect. When the long-term distribution of the risk is estimated by observing the trends of damages over time, it is optimal to be more prudent at the initial stage of the learning process.

We also discussed a counter-argument to the precautionary principle: when scienti¯c progresses are expected to be made over time, it may be optimal to postpone the preventive e®ort to after getting the better information, in accordance to a learn-then-act principle. This improves the e±ciency of the decision, at the cost of an unequal distribution of the e®ort over time. We showed that this counter-argument is relevant when the degree of aversion to risk is su±ciently large. However, its size is probably small at realistic levels of the speed of scienti¯c progress.

We have shown that the economic concepts and the techniques exist to produce a quantitative analysis of the impact of scienti¯c uncertainty on the traditional cost-bene¯t analysis. Di®erent uncertain environments require the use of different modern economic concepts and operational methods. Do we really have the willingness to implement these methods to improve efficiency? The position of the Commission of EC (2000) about the precautionary principle is quite ambiguous on this. On pages 3 and 19 of this document, it is stated that "finding the correct balance so that the proportionate, non-discriminatory, transparent and coherent actions can be taken requires a structured decision-making process with detailed scientific and other objective information". However, the document also recurrently stresses the fact that "judging what is an "acceptable" level of risk for society is an eminently political responsibility".[15] But society's risk is eventually borne by citizens, who have their preferences towards risk to determine whether they find it acceptable or not. This paper provided the elements to determine the acceptability of risk from the citizen's point of view. Politicians may have a different viewpoint.

[15] It is clear that the European Commission did not ask economists to help them to shape their position with respect to the PP. In CEC (2000), there a lot of bizarre statements for an economist, like "the decision-maker may, in some circumstances, be guided by non-economic considerations such as the protection of health".

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APPENDIX: A general decision problem under risk and scientific progress

All models that are examined in section 4 can be seen as a special case of the following general model, which generalizes Epstein (1980)'s formulation:

$$\max_{c_1 \in K_1} \; E_1 h_1(c_1; \tilde{x}_1) + E_s \max_{c_2 \in K_2(c_1)} \; E_2 h_2(c_1; c_2; \tilde{x}_2 \mid \tilde{s}) \qquad (1)$$

The timing of the decision problem is as follows: First, the decision-maker (DM) selects $c_1 \in K_1$. The realization of $\tilde{x}_1$ is observed afterwards, which affects the first period welfare $h_1(c_1; x_1)$. At the beginning of the second period, the DM observes a signal $\tilde{s}$ that can be correlated to $\tilde{x}_1$ and $\tilde{x}_2$. This signal represents the (scientific) information produced during the first period about the risk $\tilde{x}_2$ borne during the second period. After observing this message, the DM selects c_2 under the condition that it belongs to some set $K_2(c_1)$. The realization of $\tilde{x}_2$, together with $(c_1; c_2)$ affect the second period welfare h_2. Usually, we compare the optimal c_1 of this problem to the one that would be optimal when $\tilde{s}$ is uninformative, i.e. when $\tilde{s}$ is uncorrelated to $\tilde{x}_2$. Some authors examine the more general problem of an improvement of the information structure in the sense of Blackwell.

The option value examined in section 4.1 can be seen as a special case of (1) where $K_1 = \{0; 1\}$; $K_2(0) = \{0; 1\}$; $K_2(1) = \{1\}$; $h_1(0; x) = h_2(0; 0; x) = 0$; $h_1(1; x) = -I + v$; $h_2(0; 1; x) = (1 + r)^{-1}(-I + v - x)$; and $h_2(1; 1; x) = (1 + r)^{-1}(v - x)$. Because K_2 depends upon the first period choice, there is some form of irreversibility.

The accumulation model in section 4.2 corresponds to: $K_1 = K_2(.) = R$; $h_1(c_1; x) = u_1(vc_1)$ and $h_2(c_1; c_2; x) = u(vc_2 - x(c_1 + c_2))$.

Finally, the learning problem is such that $c_1 = (\alpha_1; s)$ is bidimensional. There is no constraint: $K_1 = R^2$ and $K_2(.) = R$. The first period welfare is $h_1(\alpha_1; s; x) = u(w_0 - s - x(L - h\alpha_1) - \alpha_1)$, where w_0 is a parameter representing initial wealth, s is savings, and α_1 is some investment to reduce the loss in case of a accident ($x = 1$). The seond period welfare is similar with $h_2(s; \alpha_2; x) = \beta u((1+r)s - x(L - h\alpha_2) - \alpha_2)$. Finally, we assume that $\tilde{x}_1$ and $\tilde{s}$ are perfectly correlated (improvement in knowledge comes only from observing $\tilde{x}_1$). More specifically, we have $\tilde{x}_1 \sim (1; \bar{p}; 0; 1 - \bar{p})$, and $\tilde{x}_2 \mid x_1$ is obtained by using Bayes rule.