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Formalization and Applications of the Precautionary Principles

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Abstract:

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A formalization of the Precautionary Principle is given here: We formalize scientific knowledge on the likelihood of events in the state space and the concepts of scientifically unambiguous events and acts. We give a definition of a non-precautionary social planner as a Savage Expected Utility maximizer who evaluates acts relative to a baseline, called "business as usual," and who disregards scientifically ambiguous acts, and we show that, for a wide class of preferences for the representative agent, non-precautionary decision making is sub-optimal. A discussion of this formalization is given in the context of national and international debates on Precaution, in the fields of Climate Change, of WTO arbitrages, and of the safety regulations of chemical products.

Keywords: Ambiguity, objectively unambiguous events, precaution.

JEL Classification: D81, K32

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1 Introduction

The origins of the Precautionary Principle can be traced back to the German Vorsorgeprinzip introducing a distinction between human activity with "dangers" of catastrophic consequences (nuclear apocalypse was then high on the list) and which must be prevented at all costs (*Gefahrenvorsorge*) and human activity with potentially harmful consequences (*Risikovorsorge*), in which case preventive measures should be investigated and taken in case of sufficiently high risk of sufficient harm.

This principle implied a reversal of the burden of proof from the proponents of the hypothesis of a causal link between a particular activity and harmful effects, to the promoters of the said activity (from the Cassandras to the Agamemnons as it were).

Some hold the extreme view that this reversal of the burden of proof must be taken to mean that before engaging in (or indeed maintaining) an economic activity, proof must be supplied of its harmlessness. At the level of political decision making, such a view rests on an ill defined set of possible acts (in the case of Climate Change, for instance, the decision not to invest in renewable energy sources is an act which does not correspond to an economic activity as intended above) and is excessive in requesting a full reversal of the burden of proof. However, the (concept of) reversal of the burden of proof was clearly at the heart of that prevention principle through the relation between scientific knowledge and investment.

The formulations evolved in the international arena through a series of conferences on the protection of the North Sea At Bremen (1984) it was concluded that "damage to the environment can be irreversible, or remediable only at a considerable cost and over long periods of time, and that, therefore, coastal states and the EEC must not wait for proof of harmful effect for taking action." At the second conference in London (1987), the term 'precautionary approach' appeared as a decision approach that may require action to control inputs of the "most harmful substances (...) even before a causal link has been established by absolutely clear scientific evidence." By 1990 at the Hague, this same approach was referred to as the "Precautionary Principle."

Its main avatar appeared in the 1992 United Nations Conference on Environment and Development held in Rio de Janeiro, where a central topic was the potential causal link between the burning of fossil fuels and the "greenhouse effect."

Principle 15 of the Rio Declaration issued at that conference is a compromise between the Hague formulation of the precautionary principle and the US view that the lack of clear scientific evidence for a causal relationship between human behaviour and the greenhouse effect meant that taking expensive measures was not acceptable. As a result, there is no question of "principle," but of mere "approach," and the scope of the declaration is limited to damage which is either "serious" or "irreversible" and the measures are to be "cost-effective[2]."

[2]Principle 15 of the Rio Declaration: "In order to protect the environment, the precautionary approach shall be widely applied by states according to their capabilities. Where there

Partly because of the insistence on cost-effectiveness of preventive measures and on the issue of irreversibility, the principle was given an interpretation, within a framework suited to the debate on Climate Change, by Gollier, Jullien, and Treich (2000), purely in terms of traditional cost-benefit analysis under risk, thereby avoiding reference to the Knightian distinction[3] between risk (where a single additive probability measure represents the likelihood of all relevant events on the state space) and uncertainty -or ambiguity, as we shall call it throughout- (in all other cases). Gollier, Jullien, and Treich (2000) identify a "precautionary effect," which, along with the "irreversibilibility effect" of Arrow and Fischer (1974) and Henry (1974), refers to a lower optimal level of investment (in activities that are harmful to the environment) when the decision maker anticipates a (partial) "resolution of uncertainty" concerning the costs and benefits of the investment.[4]

Both effects concern optimal behaviour under risk in the Savage Expected Utility framework and both rely crucially on a dynamic framework and the resolution of uncertainty (i.e. the conditioning on realized events or the outcome of exogenous experiments). Although it is clear, on the one hand, that the notion of irreversibility is tied to the dynamic framework, when defined as the contraction of the set of possible acts at a future period, precaution and the precautionary principle, on the other hand, can be given a formulation in a static framework without prejudging of its dynamic extensions.

Moreover, it appears that the crucial concept underlying the principle is not the "resolution of uncertainty" but "uncertainty" itself, clearly referred to in the historic formulations as a departure from "sufficient scientific knowledge" or "conclusive scientific evidence" and therefore inconsistent with a representation of beliefs as a single additive probability measure on the relevant events in the state space.

The precautionary principle is therefore tied to an assumption of epistemological indeterminacy, especially in Timothy O'Riordan's definition (in O'Riordan and Jordan (1995) for example) which we adopt here as a reference: "the principle of precaution in environmental management implies committing human activity to investments where the benefits of action cannot, at the time of expenditure, be justified by conclusive scientific evidence."

The notions of "cost-effectiveness" (Rio Declaration) and "justified expenditure" (O'Riordan Definition) can be taken to mean optimal in a Savage Expected Maximization framework, and we therefore formalize epistemological indeterminacy (situation in which "expenditure cannot be justified") as the lack of a class

are threats of serious or irreversible damage, lack of full scientific certainty shall not be used a reason for postponing cost-effective measures to prevent environmental degradation."

[3]A similar distinction appears in Knight (1921) and Keynes (1921).

[4]There may be a countervailing "wealth effect" due to the possibility of making more accurate decisions on the basis of better information. This effect was first recognized by Epstein (1980), and is evaluated with respect to the precautionary and irreversibility effects in Gollier, Jullien, and Treich (2000). On the relative magnitude of these effects, see Chichilnisky and Heal (1993) and Ulph and Ulph (1997). On irreversibility in the dynamics of investment, see also Pindyck (1991) and Dixit and Pindyck (1994). Godard (2001) discusses the relationship between the Precautionary Principle and the results in Gollier, Jullien, and Treich (2000).

of relevant events on the state space, together with a single additive probability measure on those events, which accurately summarize scientific knowledge[5].

We place ourselves in the Savage decision framework where Ω is the state space, or set of elementary events, $\mathcal{H}$ is the space of consequences, and Φ is a family of possible actions (Savage acts) which map Ω into $\mathcal{H}$. We are considering a social planner, with set of possible acts Φ, who is maximizing the utility of a representative agent with preference relation over acts denoted by $\leq$, and we suppose that utility of outcomes and beliefs on the likelihood of events (subsets of Ω) are biseparable in the sense of Ghirardato and Marinacci (2001) (so that, in particular preferences are state independent). Outcome sensitivity is represented by a utility function on $\mathcal{H}$ and beliefs over the likelihood of events are represented by a set function on events. Savage expected utility provides such a separation, in which $\leq$ is fully represented by the expectation of the utility of acts taken with respect to a single subjective probability measure over events.

Such a separation is a crucial assumption since we identify the agent's beliefs over the likelihood of events with the social planner's, the latter being derived from "scientific knowledge." Whether this implies perfect extraction of subjective beliefs of agents by the planner, or that agents are perfectly informed of objective scientific knowledge, or a combination of both, is irrelevant in the formalization of the decision making principle we attempt. However, in the context of environmental preservation, the objective interpretation is the more attractive one. One may think, say, of the conclusions of the IPCC 2001 Report[6] as summarized by the knowledge of the relevant class of subsets of Ω ("scientifically determined events") and of a set function operating on this class. Because most of the physical models used in the report's predictions are deterministic and the uncertainty is introduced through different calibrations of relevant parameters, there is no reason to assume that the ranges of likelihood between upper and lower probabilities are degenerate, i.e. that beliefs can be accurately described by an additive measure on events.

However, from the scientific information suitably summarized by a non additive set function, one can define a subclass of events $\mathcal{A}$ on which the set function characterizing likelihood is indeed additive. This subclass will be called the class of scientifically unambiguous events (which may be empty), and acts which operate only on unambiguous events (i.e. are measurable with respect to $\mathcal{A}$) will be termed unambiguous acts. Φ^{ua} will denote the subfamily of unambiguous acts which have a simple interpretation as the acts the consequences of which there is "sufficient scientific knowledge" to evaluate in a traditional cost-benefit analysis under risk: in other words, such that the restriction of $\leq$ to Φ^{ua} can be realistically represented by Savage Expected Utility.

We see now that the formulations of the Precautionary Principle in international arenas yield a natural formalization of non-precautionary decision making

[5] To fix ideas, it is useful to take the philosophical stance that the system is ontologically determinate, meaning that all events occur according to a single -unknown- probability measure on the state space endowed with its power set.

[6] Any one of the series of three reports issued by the Intergovernmental Panel on Climate Change.

in this framework, namely maximization of expected utility on the set of acts which are scientifically unambiguous according to our definition. A simple formulation of the Precautionary Principle then becomes: "in all decision settings, non-precautionary decision making is sub optimal."

The rest of the paper is organized as follows; the next section introduces the model of scientific knowledge on the state space and the definition of scientifically unambiguous acts, and presents the main formalization of the Precautionary Principle as Theorem 1. Section 3 shows the equivalence between scientifically unambiguous acts as defined here and subjectively unambiguous acts as defined by Epstein and Zhang (2001) in a large class of state-independent preference relations for the representative agents. Section 4 discusses the formalization in the context of controversies on the Principle. Section 5 concludes.

2 Precautionary Principle

We begin this section with an objective definition of scientific knowledge and its induced beliefs over the state space, general enough to avoid precluding a subjective interpretation of the latter. We model scientific knowledge over the state space as a family of onto mappings from a standard Borel set Y ($[0,1]$ for instance), into Ω.

$$\text{Scientific Knowledge:} \quad \mathcal{F} = \{f \in \mathcal{F} : Y \to \Omega, \text{onto}\}.$$

This can be interpreted as the result of experimentation carried within the framework of a set of "scientific theories," and a special case of $\mathcal{F}$ is the family of measurable selections of a random correspondence $F\colon Y \to \mathcal{P}(\Omega)$ (see Castaldo and Marinacci (2001) for details). As in Amarante (2001), we define the induced representation of beliefs on Ω as the push-forward of the usual exterior measure on Y, denoted μ^*: for each f in $\mathcal{F}$, we define an induced set function μ^*_f on all subsets of Ω as

$$\mu^*_f(A) = \mu^*(f^{-1}(A)), \quad \text{all } A \in \mathcal{P}(\Omega), \tag{1}$$

and we call Σ_f the largest σ-algebra on which μ^*_f is a probability measure, and finally we denote by P_f the restriction of μ^*_f to Σ_f. Therefore, for each f, we define a probability space (Ω, Σ_f, P_f), and if we consider the measurable space $(\Omega, \Sigma_{\mathcal{F}})$, where $\Sigma_{\mathcal{F}}$ is the largest σ-algebra contained in $\cap_{f\in\mathcal{F}}\Sigma_f$, $\{P_f, f \in \mathcal{F}\}$ can be interpreted as a set of priors on the scientifically determined class of relevant events. If $\Sigma_{\mathcal{F}} = \{\emptyset, \Omega\}$, we call the scientific knowledge $\mathcal{F}$ irrelevant to the state space.

Finally, we summarize the belief representation on Ω with the definition of $\mu^*_{\mathcal{F}}$ such that, for all $A \in \mathcal{P}(\Omega)$,

$$\mu^*_{\mathcal{F}}(A) = \inf_{f\in\mathcal{F}} \mu^*_f(A). \tag{2}$$

We immediately see that $\mu^*_{\mathcal{F}}$ is a non additive probability on $\mathcal{P}(\Omega)$ satisfying

$$\mu^*_{\mathcal{F}}(\emptyset) = 0, \quad \mu^*_{\mathcal{F}}(\Omega) = 1, \tag{3}$$
$$A \subset B \implies \mu^*_{\mathcal{F}}(A) \leq \mu^*_{\mathcal{F}}(B). \tag{4}$$

Call $\mu_{\mathcal{F}}$ the restriction of $\mu^*_{\mathcal{F}}$ to $\Sigma_{\mathcal{F}}$. By construction, $\mu_{\mathcal{F}}$ is the lower envelope[7] of the set of priors $\{P_f, f \in \mathcal{F}\}$, and therefore $\{P_f, f \in \mathcal{F}\} \subset \text{Core}(\mu_{\mathcal{F}})$, where the core of the non additive probability $\mu_{\mathcal{F}}$, denoted $\text{Core}(\mu_{\mathcal{F}})$, is the set of probability measures on $(\Omega, \Sigma_{\mathcal{F}})$ which dominate $\mu_{\mathcal{F}}$ setwise:

$$\text{Core}(\mu_{\mathcal{F}}) = \{p \in \mathcal{M},\ p(A) \geq \mu_{\mathcal{F}}(A),\ \text{all } A \in \Sigma_{\mathcal{F}}\} \tag{5}$$

where $\mathcal{M}$ is the set of all countably additive probability measures on $(\Omega, \Sigma_{\mathcal{F}})$. In the special case mentioned above, where $\mathcal{F}$ is defined as the family of measurable selections of a random correspondence F, $\mu_{\mathcal{F}}$ is actually the belief function[8] induced on Ω by F as defined in Dempster (1967) (i.e. for all $A \in \mathcal{P}(\Omega)$, $\mu_{\mathcal{F}}(A) = \mu^*(F^{-1}(A))$). In addition, as shown by Castaldo and Marinacci (2001), when Ω is a Polish space (complete, separable and metrizable topological space), and F is compact valued, the core of $\mu_{\mathcal{F}}$ is equal to the weak*-closed convex hull of $\{P_f, f \in \mathcal{F}\}$.

To formalize the idea of epistemological indeterminacy as a departure from a single additive probability on relevant events, we call "scientifically unambiguous" all the events on which $\mu_{\mathcal{F}}$ and all the measures in $\{P_f, f \in \mathcal{F}\}$ coincide[9]. We call $\mathcal{A}$ the class of scientifically unambiguous events and we observe the following properties of $\mathcal{A}$, proved in Amarante (2001):

Lemma 1: $\mathcal{A}$ is a λ-system (i.e. stable with respect to complementation and countable disjoint union), it contains all the $\mu_{\mathcal{F}}$-null events, and for all $A \in \mathcal{A}$, $\mu_{\mathcal{F}}(A^c) = 1 - \mu_{\mathcal{F}}(A)$.

An immediate corollary of Lemma 1 is that all measures in the Core also coincide on $\mathcal{A}$.

It is important to note that $\mathcal{A}$ is not necessary closed with respect to finite intersections. To illustrate the definitions above, consider a state space with four states of nature $\Omega = \{C, B, G, W\}$, where elementary states C, G, B and W stand for Catastrophic, Good, Bad and Windfall respectively. Consider scientific knowledge over states as described by $\mathcal{F} = \{f, g\}$ on $Y = [0, 1]$,

[7] The fact that the set function representing beliefs is a lower probability by construction does not constitute a restriction from a subjective point of view, as shown in Jaffray and Philippe (2001). The restriction to lower envelopes, on the other hand, can be improved upon, in particular by considering events outside $\Sigma_{\mathcal{F}}$.

[8] An objective interpretation of belief functions is sketched in Henry (2001). Note that here, "belief function" is a well defined object and should not be confused with "beliefs" used above as a general term for the agent's representation of the likelihood of events in the state space.

[9] This is by no means a new definition (see Epstein and Zhang (2001) and references therein). It is the most natural definition of unambiguous events in our objective framework.

$$f(s) = \begin{cases} C & s \in [0, 0.01) \\ B & s \in [0.01, 0.5) \\ G & s \in [0.5, 0.95) \\ W & s \in [0.95, 1] \end{cases} \qquad \text{g(s)=} \begin{cases} C & s \in [0, 0.05) \\ B & s \in [0.05, 0.5) \\ G & s \in [0.5, 0.99) \\ W & s \in [0.99, 1]. \end{cases}$$

This is a summary of the interval-valued probability statements of the form "the probability of windfall gains ranges between one and five percent." Notice that, in this setting, $\Sigma_f = \Sigma_g = \Sigma_{\mathcal{F}} = \mathcal{P}(\Omega)$, and the set of scientifically unambiguous events,

$$\mathcal{A} = \{\emptyset, \{C, B\}, \{B, G\}, \{G, W\}, \{C, W\}\},$$

is not closed with respect to finite intersection ($\{C, B\} \cap \{B, G\} = \{B\}$ is ambiguous)[10].

Returning to the general setting, we define the set of scientifically unambiguous acts, denoted Φ^{ua}, as the set of acts which are measurable with respect to $\mathcal{A}$, i.e.

$$\Phi^{\text{ua}} = \{\phi \in \Phi, \phi^{-1}(X) \in \mathcal{A}, \text{ all } X \in \mathcal{P}(\mathcal{H})\}.$$

They are the acts which operate only on unambiguous events. In terms of the historic formulations of he Precautionary Principle, they are the investments which can be "justified by conclusive scientific evidence."

In the example above, consider two acts I and T, so that $\Phi = \{I, T\}$, defined by the following table of outcomes (or pay-offs):

	C	B	G	W
I	-110	-10	+10	+110
T	-20	-20	+11	+11

We see that $\Phi^{\text{ua}} = \{T\}$ because I, which we call "investment without insurance," is an ambiguous act, as $I^{-1}(\{-10\}) = \{B\}$, say, is an ambiguous event; whereas T, or "trading of uncertainty on the basis of the minimum belief in the windfall outcome and the maximum plausibility of the catastrophic outcome," is an unambiguous act, because $T^{-1}(\{-20\}) = \{C, B\}$ and $T^{-1}(\{-11\}) = \{G, W\}$ are both unambiguous events.

In such a simplified portfolio example, it would seem that of the two possible acts, the one that is intuitively "precautionary" in the sense that it hedges uncertainty, is also -and naturally so- the unambiguous act: indeed naturally so, since we have constructed our T act in order to remove Knightian uncertainty (assuming arbitrarily that it was feasible). So it appears that the decision maker is confronted with a static portfolio choice with two available acts, a scientifically ambiguous investment, the "intuitively non-precautionary" act, and

[10] This is a slight variant from the numerical example in Amarante (2001).

a scientifically unambiguous investment with hedged Knightian uncertainty, the intuitively "Precautionary" act.

It should be noted at this point, however, that we have not considered investment in a riskless asset or any kind of baseline act relative to which other acts would be considered. Now social planning does not occur in a void, and can be more easily apprehended in a static framework, with reference to a baseline act which can be rationalized as the path of least political effort, and which we will call "business as usual."

Consider the example of a local authority confronted with uncertain scientific information on the health hazards of a construction material in a school building. The baseline act, in the absence of opinion pressure mechanisms creating opposite incentives, would naturally be to disregard the information and avoid spending public money with uncertain rewards. In the case of the diffusion of genetically modified crops, the baseline act from the point of view of the social planner is naturally to avoid interfering through restrictive regulation in the agricultural development process. If introducing a genetically modified strand of a crop unambiguously increases yield, the decision to halt through regulations it is considered as an alternative to non intervention, with unambiguous costs and ambiguous rewards.

The case of Climate Change can be apprehended in a similar way, and we shall consider a stylized representation of the problem. The state of the industry and the state of the technology are paramount in the identification of the baseline act. If we consider the regulation of electricity production with respect to carbon dioxide (hereafter CO_2) emissions in a country which produces all its electricity in coal plants, the state of the industry is then defined by all-coal generation of electricity. Suppose further that the state of the technology is defined by the availability of an alternative generation method using natural gas and producing less CO_2 emissions. Finally, CO_2 free generation methods are considered, but more costly research is needed to develop them and to find out whether or not they are economically viable. So the acts available to the planner are the following: The social planner may keep producing energy with coal plants (act BU for "business as usual"), shift all generation to gas which produces less CO_2 emissions (act Gas) at a cost C_g, or combine either of the previous acts with R&D into an alternative energy generating technology that produces no CO_2 emissions at an extra cost C_r (acts R for "Research" and RG for "Research and Gas"). Both the outcome of research into the alternative technology and the effects of CO_2 emissions are supposed uncertain. Let the relevant events be classified in the table below:

S: Successful Alternative Technology

F: Failure of Alternative Technology

C: No Significant Effect of CO_2 emissions on Climate

H: Significant Effect of CO_2 emissions on Climate.

Elementary events (elements of Ω) are therefore $W{=}S\&C$, $G{=}F\&C$, $B{=}S\&H$

and C=$F\&H$. Scientific knowledge on the likelihood of events is summarized by $\mathcal{F} = \{f, g\}$ on $Y = [0,1]$,

$$f(s) = \begin{array}{ll} C & s \in [0, p_f^1) \\ B & s \in [p_f^1, p_f^2) \\ G & s \in [p_f^2, p_f^3) \\ W & s \in [p_f^3, 1] \end{array} \qquad \text{g(s)=} \begin{array}{ll} C & s \in [0, p_g^1) \\ B & s \in [p_g^1, p_g^2) \\ G & s \in [p_g^2, p_g^3) \\ W & s \in [p_g^3, 1], \end{array}$$

with p_i^j's strictly increasing in j. Finally the acts are defined by the following outcome table:

	W or G	B	C
Gas	$-C_g$	$D_c - D_g - C_g$	$D_c - D_g - C_g$
R	$-C_r$	$D_c - C_r$	$-C_r$
RG	$-(C_g + C_r)$	$D_c - (C_g + C_r)$	$D_c - D_g - (C_g + C_r)$,

where D_c and D_g are the costs of potential damages caused by coal emissions and gas emissions respectively. Note that the acts are normalized with respect to the baseline act BU, so that the costs of environmental degradation due to CO_2 emissions from coal plants appear as benefits of CO_2 emissions reducing technologies.

So far, we have not specified the values of the p_j^i, so that we can make no statement about the ambiguous nature of the acts defined in the table above. If all $p_i^j \in (0,1)$ are distinct, none of the three acts above is unambiguous. Suppose now that $p_f^2 = p_g^2$, but $p_f^1 < p_g^1$. In that case, $\{B, C\}$ and $\{W, G\}$ are unambiguous events, so that Gas is an unambiguous act. However, $\{B\}$ is an ambiguous event, so that both R and RG are ambiguous acts. In terms of the historical formulations of the Precautionary Principle, investing in research for the development of CO_2 free electricity generation methods has a cost which "cannot be justified by conclusive scientific evidence:" indeed, the expected utility of R and RG cannot be evaluated.

There emerges therefore from this example a notion of "non-precautionary" social planner, as one who considers the set of acts as normalized with respect to a baseline act (in this case, maintaining coal powered generation) and who is prepared to engage in an alternative act if and only if its expected utility is positive. Such a social planner would therefore consider the expected utility of Gas, i.e. $p_f^2[D_c - D_g] - C_g$, and decide to shift to gas if and only if $p_f^2[D_c - D_g] > C_g$, thereby totally disregarding acts R and RG. It is clear, however, that even if say $p_f^2[D_c - D_g] = C_g$, so that the social planer is indifferent between B and Gas, there exists reasonable conditions under which the Choquet expectation of R and RG, with respect to capacity $\mu_{\mathcal{F}}$, is positive. For example, the Choquet expectation of RG is[11]

$$\int_{\mathrm{Ch}} u(RG(\omega))\mu_{\mathcal{F}}(d\omega) = -(C_g + C_r) + (D_c - D_g)\mu_{\mathcal{F}}(C \cup B) + D_g \mu_{\mathcal{F}}(B)$$
$$= -(C_g + C_r) + (D_c - D_g)\min(p_f^2, p_g^2) + D_g \min(p_f^2 - p_f^1, p_g^2 - p_g^1)$$
$$= -C_r + D_g(p_g^2 - p_g^1),$$

under the conditions $p_f^2 = p_g^2$, $p_f^1 < p_g^1$ and $p_f^2[D_c - D_g] = C_g$ above, so that the Choquet expectation of RG is positive if and only if

$$C_r < D_g(p_g^2 - p_g^1).$$

We see, therefore, that under the condition above, for a social planner acting on behalf of a representative agent with Choquet Expected Utility preferences (defined precisely in the next section), disregarding act RG leads to a suboptimal decision. This shows that the Precautionary Principle does not systematically lead to conservative action, contrary to a largely held belief[12].

We now give our main definition and state our formalization of the Precautionary Principle as Theorem 1.

Definition 1: Given scientific knowledge $\mathcal{F}$, a utility function on the space of consequences, and a set of acts Φ, measurable with respect to $\Sigma_{\mathcal{F}}$ and normalized in such a way that and act ϕ_0, called "Business as Usual" is a null act, a non precautionary social planner is a Savage Expected Utility Maximizer with set of acts restricted to Φ^{ua}.

We can now state the main theorem.

Theorem 1: If $\leq$ is a separable preference relation on acts in Φ such that the restriction of $\leq$ to Φ^{au} is SEU, then non precautionary social planning is sub optimal.

It is easy to see that the "theorem" trivially follows from the contraction of the set of possible acts which, in the case of state independent preferences, unambiguously reduces welfare. As with the Coase Theorem for example, the problem is not in the proof but in the relevance of the assumptions, which will be examined in the next section.

3 Scientific and subjective ambiguity

To examine the scope of the validity of Theorem 1, we need to consider conditions on the representative agent's preference relation under which the condi-

[11] See, for instance, Cohen and Tallon (2000)

[12] For example, Nunn (2001), page 101: "The Precautionary Principle has been defined in various ways but may be simply seen as the principle of adopting a conservative approach when the relevant information needed to make an informed decision is limited -the greater the uncertainty, the more conservative the decision".

tions of Theorem 1 are satisfied. To this end, we shall consider two axiomatizations of preferences, Choquet Expected Utility (hereafter CEU) and Multiple Priors (hereafter MEU), and use recent results in Epstein and Zhang (2001) and Amarante (2001) to show that they both satisfy the conditions of Theorem 1 under mild additional conditions. We shall then be able to summarize this section by the following claim: *When the representative agent has CEU or MEU preferences compatible with scientific knowledge $\mathcal{F}$, then Theorem 1 applies, so that non-precautionary social planning is sub-optimal.*

This rests essentially on the identification between scientifically unambiguous events as defined above, and subjectively unambiguous events from the point of view of a CEU or a MEU preference relation as defined in Epstein and Zhang (2001). We shall therefore recall the general result of the Ellsberg experiments which show that an agent presented with objectively ambiguous information on the state space does not in general transform this information into an additive probability measure, so that the notion of subjectively unambiguous events is relevant. We shall then recall the definition of Epstein and Zhang (2001), and give conditions under which the thus defined subjectively unambiguous events coincide with scientifically unambiguous events as defined above. Corrolary 7.3 part c) of Epstein and Zhang (2001) and corrolary 13 of Amarante (2001) will then allow us to conclude that the conditions of Theorem 1 are satisfied.

Elsberg's experiments have shown (in Ellsberg (1961)) that when decision makers are presented with objectively ambiguous information about the state space, their preferences are not supported by a single additive subjective probability over events. The stylized experiment whose results support this claim is the following. The decision makers are presented with an urn in which they are told there are 30 red balls and 60 either green or blue. This objective information is of ambiguous nature, so that the situation is one of epistemological indeterminacy as formalized above. The decision makers are asked to choose between acts ϕ_1 and ϕ_2 on the one hand, and between acts ϕ_3 and ϕ_4 on the other hand, where all four acts are simple bets defined by the outcome table below.

		R red is drawn	B blue is drawn	$Green$ green is drawn
ϕ_1	bet on R	100	0	0
ϕ_2	bet on B	0	100	0
ϕ_3	bet on R or $Green$	100	0	100
ϕ_4	bet on B or $Green$	0	100	100

Preferences uncovered in the experiment are the following: ϕ_1 is in most cases strictly preferred to ϕ_2, while ϕ_4 is in most cases strictly preferred to ϕ_3. Such preferences cannot be supported through expected utility maximization by a single additive probability measure P over events in the state space, since that would imply $P(R) > P(B)$ and $P(R) + P(Green) < P(B) + P(Green)$ which are incompatible. Intuitively, these preferences can be explained by the fact that some events in the state space are considered as subjectively ambiguous, and that they are shunned by the decision maker. This yields a distinction between subjectively ambiguous events (such as $\{R, B\}$ in this case) and subjectively unambiguous events (such as $\{B, Green\}$)[13].

In the example of section 2, we may presume that the representative agent, informed of "scientific knowledge" on the state space, would also consider $\{G, B\}$ ("Good or Bad," not "Green or Blue"!) as subjectively unambiguous and $\{C\}$, say, as subjectively ambiguous.

Epstein and Zhang (2001) give a subjective definition of unambiguous events relying purely on the given preference relation $\leq$. Under their definition, an event T is unambiguous if for all disjoint sub events A, B of T, acts ϕ and outcomes y^*, y, z, z',

$$(y^*, A; y, B; \phi(\omega), T - (A \cup B); z, T^c) \geq (y, A; y^*, B; \phi(\omega), T - (A \cup B); z, T^c)$$

implies

$$(y^*, A; y, B; \phi(\omega), T - (A \cup B); z', T^c) \geq (y, A; y^*, B; \phi(\omega), T - (A \cup B); z', T^c),$$

and the condition above is also satisfied when T is everywhere replaced by T^c.[14]

To investigate the relation between objectively and subjectively unambiguous events, we need to consider separable preference relations which generalize Savage Expected Utility in the sense that beliefs over the likelihood of events in the state space are represented by $\mathcal{F}$.

Two main axiomatizations of preferences exist in the literature which satisfy these criteria: Choquet Expected Utility (hereafter CEU) in Schmeidler (1989) and α Maxmin Expected Utility (hereafter α-MEU) generalized from Gilboa and Schmeidler (1989).

- We call a preference relation $\leq$ a CEU ordering if there exist a utility function $u : \mathcal{H} \to I\!R$ and a monotone set function ν on a measurable space (Ω, Σ), Σ a σ-algebra of subsets of Ω, such that $\nu(\Omega) = 1$ and $\nu(\emptyset) = 0$ and $\leq$ can be represented by the functional $V : \Phi \to I\!R$ defined by

  $$V(\phi) = \int_\Omega u(\phi(s))\nu(\mathrm{ds}),$$

  where the integral is taken in the sense of Choquet. Axiomatizations of such preferences in the Savage domain are given in Gilboa (1987) and Wakker (1989) among others.

- We call a preference relation an α-MEU ordering, if there exists a utility function u and a unique nonempty, weak*-compact and convex set $\mathcal{C}$ of

[13] For real life examples of the influence of ambiguity on behaviour -mergers of forms that otherwise seem inexplicable for instance- see Mukerji (1998).

[14] The notation $(\phi(\omega), A; \psi(\omega), B)$ naturally indicates the act equal to $\phi(\omega)$ for all $\omega \in A$ and $\psi(\omega)$ for all $\omega \in B$.

countably additive probabilities on (Ω, Σ) as above, such that $\leq$ can be represented by the functional

$$V(\phi) = \alpha \inf_{P \in \mathcal{C}} \int_{\Omega} u(\phi(s)) P(\mathrm{ds}) + (1-\alpha) \sup_{P \in \mathcal{C}} \int_{\Omega} u(\phi(s)) P(\mathrm{ds}),$$

for $\alpha \in [0,1]$. An axiomatization of such preferences in the Savage domain is given in Casadesus-Masanell, Klibanoff, and Ozdenoren (2000) (for $\alpha = 1$).

The two models coincide in case the non additive probability ν is a convex capacity (i.e. $\nu(A \cup B) + \nu(A \cap B) \geq \nu(A) + \nu(B)$ for all A and B in Σ). In that case, the CEU preference is identical to an α-MEU with $\alpha = 1$ and $\mathcal{C} = \mathrm{Core}(\nu)$.

The multiple prior principle is often criticized when applied to collective decision on the grounds that it evaluates acts according to the "worst case scenario," thus emulating the proponents of a total reversal of the burden of proof. It is clear, first of all, that this criticism can only apply to the α-MEU with $\alpha = 1$ (or the special case of CEU with a convex capacity), and, second, that in our setting, inasmuch as beliefs and outcome sensitivity are separable, and as beliefs are perfectly extracted and objectively represented by $\mathcal{F}$, considerations of ambiguity aversion are irrelevant to the general formulation of the Precautionary Principle given above.

In both cases described above, we show that the set $\mathcal{A}$ of scientifically unambiguous events coincides with the set $\mathcal{A}'$ of EZ-subjectively unambiguous events, and that preferences are SEU on $\mathcal{A}$, so that Theorem 1 applies.

Theorem 2: If $\leq$ is CEU with $\nu = \mu_{\mathcal{F}}$ defined in Section 2, and if $\mu_{\mathcal{F}}$ satisfies in addition

(i) $\mu_{\mathcal{F}}$ is exact on $\Sigma_{\mathcal{F}}$, i.e.

$$\inf_{f \in \mathcal{F}} \{P_f(A)\} = \min_{f \in \mathcal{F}} \{P_f(A)\}, \quad \text{all } A \in \Sigma_{\mathcal{F}}, \tag{6}$$

and satisfies

$$A \cap B = \emptyset \implies (\, \mu_{\mathcal{F}}(A \cup B) = \mu_{\mathcal{F}}(B) = 0 \implies \mu_{\mathcal{F}}(A)\,). \tag{7}$$

(ii) $\mu_{\mathcal{F}}$ is continuous from above on $\mathcal{A}'$, i.e. for all decreasing sequence (A_i) of subjectively unambiguous events,

$$\mu_{\mathcal{F}}\left(\cap_{i=1}^{\infty} A_i\right) = \lim_{n \to \infty} \mu_{\mathcal{F}}(A_n), \tag{8}$$

(iii) $\mu_{\mathcal{F}}$ is convex-ranged on $\mathcal{A}'$, i.e. for all $A \in \mathcal{A}'$,

$$[0, \mu_{\mathcal{F}}(A)] = \{\mu_{\mathcal{F}}(B), B \in \mathcal{A}', B \subset A\}, \tag{9}$$

Then the set of scientifically unambiguous events coincides with the set of EZ-subjectively unambiguous events, and $\leq$ is SEU on Φ^{ua} (so the Theorem 1 applies).

If $\leq$ is monotone continuous and α-MEU with $\mathcal{C} = \{P_f, f \in \mathcal{F}\}$, then the conclusions above still hold.

Proof of Theorem 2: First of all, recall that, by construction, $\mu_{\mathcal{F}}$ is the lower envelope of a non empty set of additive probability measures on $\Sigma_{\mathcal{F}}$. So, as a Choquet capacity, $\mu_{\mathcal{F}}$ is continuous from below along all sets in $\Sigma_{\mathcal{F}}$. Moreover, as a lower probability, it satisfies

$$A \cap B = \emptyset \implies \mu_{\mathcal{F}}(A \cup B) \geq \mu_{\mathcal{F}}(A) + \mu_{\mathcal{F}}(B), \tag{10}$$

$$\mu_{\mathcal{F}}(A) + \bar{\mu}_{\mathcal{F}}(A^c) = 1, \tag{11}$$

where $\bar{\mu}_{\mathcal{F}}$ is the conjugate upper probability. From 10, it is easy to see that

$$A \cap B = \emptyset \implies (\,\mu_{\mathcal{F}}(A \cup B) = \mu_{\mathcal{F}}(A) \implies \mu_{\mathcal{F}}(B) = 0\,)\,. \tag{12}$$

The conditions of Corrolary 7.3 part c) of Epstein and Zhang (2001) are satisfied, which proves the CEU part of the result above. In the α-MEU case, the result follows from Corrolary 13 of Amarante (2001). Note that the assumptions implicitly impose convexity and weak*-compacity of $\{P_f, f \in \mathcal{F}\}$.

4 Applications of the precautionary principle

In this section, we want to investigate the nature of scientific knowledge, represented in the model by functions in $\mathcal{F}$, in actual cases where the Precautionary Principle is invoked. We will see that the functions f in these cases are science-based, in a sense that is not in general the traditional one, but is nevertheless logical and supported by facts. We shall first consider the Intergovernmental Panel on Climate Change (IPCC) approach of the perspectives of climate change. The expected effects of climate change are warmer temperatures, a more intense and chaotic hydrological cycle, rising sea levels, and possible "surprises" like a weakening of thermohaline circulation (e.g. a weakening of heat carrying to Europe by the Gulf Stream). In order to estimate these effects, the IPCC used six greenhouse gases emissions scenarios in various climate models. The results, as presented in the third IPCC report (2001), are that

- Carbon dioxides concentrations in 2100 would range between 540 and 970 ppm, i.e. between 1.5 and 2.7 times the present level.
- Global average temperatures over the 1990 to 2100 period would increase by 1.4^oC to 5.8^oC.
- Global average sea level would rise by 0.09 to 0.88 meters over this century.

These changes would be larger than anything experienced in the past 10 000 years, and would be even larger locally (where exactly is still too uncertain to be mapped). Why such ranges? Because of the uncertainty associated with such critical parameters as:

- Greenhouse gas emissions (that, for example, have been larger than expected between 1990 and 2000).
- Impacts of clouds and aerosols (paradoxically, the current emissions of $S0_2$ and $N0_x$ are to be regretted in this respect, as the concentrations of these gases in the atmosphere tend to reduce warming).
- Feedback effects from oceans (as regards both temperatures and storage of CO_2).
- Natural climate variability.

No probability measure can be put on the magnitudes of these phenomena, hence on the ranges of the effects previously mentioned. It is thus clear that the science of climate change is ambiguous. But the ambiguity is firmly kept within bounds, that may be seen as bounds on the $\mathcal{F}$-set of scientific knowledge. These bounds are not provided by the canonical form of scientific investigation as conducted in controlled laboratory conditions, but they are nevertheless the result of a highly methodical, systematic, and systematically scrutinized production process, that leaves no room for maverick prophecies. Indeed, the IPCC, as an international and intergovernmental group of experts, established by the United Nations and the World Meteorological Organization, is in charge of collecting relevant scientific data, and of having them produced when they are lacking. The group uses these data and its members' scientific expertise (in physics, chemistry, biology, economics, etc.) to asses the physico-chemical, ecological, and socio-economic consequences of climate change. The experts in the group are chosen by their scientific peers, and the choice is confirmed by their respective governments. Their work is organized as a continuous process, in subgroups gathered by field of investigation. They produce interim reports that are discussed with governments and NGOs. But they retain sole responsibility for the contents of their periodic official reports (1990, 1995, 2001). By contrast, the executive summary of each official report is examined line by line with representatives of governments. All this shows that the IPCC process contributes to the $\mathcal{F}$-set of scientific knowledge in a systematically organized, controlled and rigorous way. It is all the more remarkable that the US government rejects this contribution as scientifically unfounded.

We shall now more briefly consider the beef meat conflict between the USA and the EU before the World Trade Organization (WTO), and the ways the investigation processes in the possible dangers of chemical products accept or reject the precautionary principle.

The decision by the EU to block the imports of American beef - because, in raising beef, American farmers use various hormones that are forbidden in

Europe - has been challenged before the WTO as a trade impediment devoid of scientific justification.[15]

The case has been decided according to the rules of the WTO Agreement on the Application of Sanitary and Phytosanitary Measures (SPM). These rules are traditional in terms of what constitutes an acceptable proof of a sanitary danger (laboratory experiments according to standard protocols, epidemiological studies, bias towards avoiding Type I errors, i.e. accepting the existence of a danger when there is none, rather than Type II errors, i.e. rejecting the existence of a danger when there is one, etc.). The European representatives were unable to meet such requirements and their reference to the Precautionary Principle was rejected; accordingly, they lost the case.

However, it is interesting to observe in the minutes of the case, as did Noiville (2000), that the WTO Appellate Body in charge didn't rigidly adhere to the SPM spirit, and hinted that the actual cause of the rebuttal of the European defence was not a rejection of the Precautionary Principle per se, but of the insufficient and poorly organized evidence provided, that didn't permit to legitimately invoke the Precautionary Principle. Indeed the European defence concentrated on rather doubtful carcinogen effects and ignored more compelling factors, like immunological and neurobiological ones, favouring obesity for example.

As far as chemical products sold on the American market are concerned, their dealing with respect to the precautionary principle is contradictory, both in regulatory and judicial arenas. As recollected by Cranor (1999), "the regulation on carcinogens, for example, is in large part by means of post-market regulatory laws [...]. In a few cases, premarket regulatory statutes also address carcinogens (aspects of the Food, Drug and Cosmetic Act-notably the Delaney clause - the Toxic Substance Control Act, and aspects of the Federal Insecticide, Fungicide and Rodenticide Act). Where the regulation of toxic substances is by means of post-market regulatory statutes, standards of proof reinforce the scientific burdens" put on the victims[16].

The rulings of Courts are no less contrasted in their interpretation of what constitutes a scientific proof and what is the relevance of the precautionary principle. For example, while the Washington DC Circuit ruled, as early as 1976, that "The statutes - and common sense - demand regulatory action to prevent harm, even if the regulator is less than certain that the harm is otherwise inevitable [...] awaiting certainty will often allow for only reactive, not preventive, regulation" (Ethyl Corp. v. EPA), the Supreme Court, in 1993, ruled that "In order to qualify as 'scientific knowledge', an inference or assertion must be derived by a scientific method. Proposed expert testimony must be supported by appropriate validation -i.e., good grounds based on what is known" (Daubert

[15] On EC measures concerning meat and meat products (hormones), see Maruyama (1998) and Wilson and Gascoine (2001).

[16] For a detailed list of "post-market" (i.e. the product goes to the market without any legal requirement of testing its dangerousness; after the manifestation of a danger or the realization of a damage, proof must be delivered according to traditional scientific criteria) and "pre-market" (i.e. the product must be tested before going to the market) regulations, see Congress (1987).

v. Merrell Dow Pharmaceuticals, Inc.)[17].

The 1993 judgement was confirmed and reinforced in 1997 by General Electric v. Joiner. Obviously, what constitutes scientific proof, in cases where public health issues are at stake, needs clarification, all the more as "toxicology is not an exact science and there can be disagreements over data interpretation among toxicologists" in the words of one of them[18]. The Precautionary Principle, properly formulated and rigorously implemented, may provide such clarification, as suggested from a medical point of view by Graham (2001): "Waiting for scientific certainty of harm prior to taking protective action is a prescription for new epidemics as well as continued declines in public trust in government, industry and technology".

5 Conclusion

The precautionary principle is about the nature of scientific deduction and inference which is appropriate in choices under Knightian uncertainty (or ambiguity). It is not about "cost-effective" choices, that are anyway required by the principle of Paretian efficiency. Nor is it about "cost-benefit analysis" or "proportionality", that are embedded in the optimal choice of an act in the set Φ of possible acts with respect to the preference ordering $\leq$ of the representative agent. Trivially, it is all the more necessary to correctly apply the precautionary principle as the issues at stake are more "serious" and more "irreversible". But irreversibility, or VOI (Value of information) as the risk managers say (see Graham 2001) is a dynamic concept, that requires a dynamic version of our model. This is left for future research, as is the issue of who bears the burden of the proof, which is meaningless here and would require a game-theoretic setting.

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[17] The dissenting opinion, as expressed by Justice Rehnquist, concurred that scientific testimony must be relevant but argued the majority had gone too far in arguing for the "reliability" of evidence as part of Rule 702.

[18] Pugh (1998) page 16.

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