On Precautionary Policies

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In the United States and most industrialized countries, regulatory policies pertaining to food safety, occupational health and environmental protection are (according to laws and statutes) science-based. The complexity of some eco-systems and new technologies, however, make it increasingly necessary to deal with situations where scientists cannot yet provide a definite picture. In this context, a widely invoked (but debated) rule, known as the *Precautionary Principle*, says to address potential hazards right away with preventive measures. We develop an intuitive formalization of this rule, which allows to infer what an appropriate precautionary policy should do. Implications for resource conservation and the regulation of technological risks are then explored.

Key words: Environmental and health risks; science-based regulation; scientific uncertainty; Precautionary Principle; robust policies

FORTHCOMING IN **Management Science**

"Primum non nocere." - *Galen*[1]

1. Introduction

Science-based risk analysis is a fundamental input of regulations and public policies intended to protect human health and the environment. With the acceleration of technological innovation, however, governments are increasingly being called upon to address new or emerging risks and to manage issues where current scientific evidence is inconclusive. In such circumstances, a somewhat natural way to proceed - now referred to as the *Precautionary Principle* - is to 'err on the side of caution' until scientists can provide a clearer picture.[2]

As a formal rule for public policy and decision-making, the Precautionary Principle first appeared as the *Vorsorgeprinzip* (literally, the "forecaring" principle) introduced into German environmental law in the early 1970s.[3] It has since been embedded in several laws and regulations of the European Union, such as the Ministerial Declaration on the Protection of the North Sea and the Maastricht Treaty. In international agreements and rulings, it can now be found in the United Nations Framework Convention on Climate Change, the Bamako Convention on Transboundary Hazardous Waste, the 1992 Rio Declaration,

[1] This sentence, which translates as "First, do no harm.", is often attributed to Claudius Galenus of Pergamum (131-201 AD), better known as Galen, the ancient Greek physician whose views of medecine based on Hippocrates's work prevailed in Europe until the Renaissance.

[2] Some, particularly in the common law tradition, may prefer the term "precautionary approach." This paper uses these expressions interchangeably. Our goal is not to discuss the legal distinctions associated with various wordings, but to investigate precautionary actions.

[3] Precautionary measures to deal with danger have of course been applied for a long time. An oftentimes mentioned early example is the removal of the handle of the Broad Street water pump in London in 1854, an action that stopped an epidemic of cholera (see, e.g., Rosenberg 1962). This measure followed documented (but unconfirmed) suspicions by John Snow, a physician and much revered early epidemiologist, that the cause of the disease originated in the pump. (Afterwards, a detailed investigation determined that, more than 20 feet underground, a sewer pipe passed within a few feet of the well.)

the Energy Charter Treaty, the Code of Conduct of Responsible Fisheries, and the recent Cartagena Protocol on Biosafety. In a statement illustrative of what the Principle can mean in practice, the International Joint Commission appointed under the U.S.-Canada Great Lakes Water Quality Agreement issued, in 1992, the following call to phase out all persistent toxic substances in the Great Lakes ecosystem:

> Such a strategy should recognize that all persistent toxic substances are dangerous to the environment, deleterious to the human condition, and can no longer be tolerated in the ecosystem, *whether or not unassailable scientific proof of acute or chronic damage is universally accepted.* [Emphasis added]

In the United States, many laws, regulations and statutes, such as the National Environmental Policy Act, the Clean Water Act, the Occupational Safety and Health Act, and the Federal Food, Drug, and Cosmetic Act, have a similar precautionary nature. The State of Massachussetts enacted a Precautionary Principle Act in 1997. The Federal Aviation Administration took a precautionary action when it banned the use of cell phones and electronic devices at takeoff and landing, based on a single study that suggested these devices might interfere with a plane's electronic systems.[4] And the U.S. Food Safety System stipulates that "conservative" risk management decisions be implemented when safety information on a hazard in a food is "substantial but incomplete," a recommendation that was recently upheld by the prohibition of certain food or color additives, drugs and ruminant feeds in the aftermath of the bovine spongiform encephalopathy (or "mad-cow" disease) outbreak in Europe.[5]

[4] At the time, according to Myers and Raffensperger (2001), scientists had not been able to duplicate the results of that study.

[5] Contrary to a common belief holding that "Precaution is for Europeans" (*New York Times*, May 18,

Despite this widespread use, however, the Precautionary Principle remains controversial and is often the subject of acrimonious debates. Advocates argue that it provides potential victims with a safeguard against biases or manipulation in science-based regulation; but critics say that it gives undue veto powers to "environmental extremists" to block technological progress and opens the door to lobby groups to foster trade protectionism. Admittedly, in its present form the Precautionary Principle is a rather vague rule exposed to discordant interpretations.[6] The potentially high stakes involved would make a clarification of its meaning and use quite timely. Yet, aside from a few notable exceptions, management science and economics have so far devoted relatively little attention to this task.

Depending on which feature of the Precautionary Principle one seeks to investigate, formal analyses have so far built on three main streams. The first one is the literature on the irreversibility effect, learning and "real options" pioneered by Arrow and Fisher (1974) and Henry (1974). In a two-period model balancing the economic risk of immediate prevention versus that of possibly having to incur much harsher measures once scientific uncertainty dissipates, for instance, Gollier et al. (2000) and Gollier and Treich (2003)

2003), a closer look reveals that neither the U.S. nor the Europeans can claim to be systematically more precautionary. In fact, key differences in political systems, legal traditions and risk perceptions render the real pattern quite complex and risk-specific (see Wiener and Rogers 2002).

[6] Many books and articles discussing the interpretation and implementation of the Precautionary Principle have already been published. The following works constitute a representative sample: Appell (2001), Bodansky (1991), Ewald et al. (2001), Foster et al. (2000), Freestone and Hey (1996), Gee et al. (2001), Godard (1997), Goklany (2001), Gollier (2001), Gray and Bewers (1996), Myers and Raffensperger (2001), O'Riordan and Cameron (1994), Raffensperger and Tickner (1999), Sandin (1999), Scott et al. (1999), Sterling and Gee (2002), Sunstein (2005), and Wiener (2002).

exhibit formal conditions on the regulator's utility function - namely, that the coefficient of absolute prudence be larger than twice the coefficient of absolute risk aversion - that would make her adopt the former strategy. To deal explicitly with the fact that there are conflicting representations of risk, however, other contributions would rather feed on the literature on ambiguity (e.g., Ghirardato and Marinacci 2002; Gilboa and Schmeidler 1989). For example, Henry and Henry (2002) and Traeger (2005) provide conditions on social beliefs and preferences that would render non-intervention suboptimal, while Chevé and Congar (2002) argue that invoking the Precautionary Principle amounts to using a social decision rule which corresponds to the maximum of the minimum expected utility criterion proposed earlier (for individual decisions) by Gilboa and Schmeidler. A third stream that has proved useful, finally, is the one initiated by Ehrlich and Becker (1972) on the tradeoff between self-protection and self-insurance. Working along this line, Immordino (2001) concludes that interpreting the Precautionary Principle as requiring early self-protection (or the reduction in the probability of damages) may be hard to support on Pareto-efficiency grounds.

This paper would somewhat fit the latter stream in seeking to further characterize precautionary decisions. We begin by noticing that all statements of the principle bear three basic ingredients: (1) some disagreement among scientists giving way to a range of undismissable scenarios, (2) collective preferences and beliefs that identify at least one of these scenarios as raising a plausible danger, and (3) a candidate 'precautionary' policy which, if carried out, will modify one or more scenarios. An intuitive formal representation of these items is developed in the following section. Within this framework, the third section establishes that (3) shall be adopted whenever (1) and (2) occur - which is what all versions of the Precautionary Principle essentially say - only if a 'price' can be put on alleviating the weakest current threat, which covers the overall impact on all the scenarios. This formula turns out to embed some frequent, but apparently ad hoc and arbitrary, desiderata concerning precaution, such as cost-effectiveness and proportionality. Section 4 discusses briefly some applications to resource conservation (e.g., fisheries) and technological risk (e.g., nanotechnology). Section 5 concludes the paper.

2. Axioms and Definitions

A representative statement of the Precautionary Principle would be the following one:[7]

> 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.

As already noted by several people (e.g., Raffensperger and Ticker 1999), this rule rests essentially upon three components: *scientific uncertainty*, a *threat of harm*, and a set of possible *precautionary actions*. We will now give each of these items a direct formal representation. The first two are the *raison d'être* of the Precautionary Principle - without

[7] This statement comes from a conference involving ecologists, policy makers, scientists and lawyers that took place in January 1998 at Wingspread, Wisconsin (Raffensperger and Ticker 1999's book is a collection of the articles that were presented then). There exist many versions of the Precautionary Principle, however (Sandin 1999 and VanderZwaag 1999 respectively numbered nineteen and fourteen different ones!). The weaker statements say that uncertainty is no reason for inaction, while the strongest ones call for prohibiting any potentially dangerous activity until it is proven that it poses no 'unacceptable' threat. Sitting somewhat in the middle are the above statement and the ones figuring in the Maastricht Treaty or the Loi Barnier in France. The latter also allow cost-benefit analysis, endorsing precautionary measures only when the expense is deemed 'reasonable' given the stakes and the achieved protection. As we will show in Section 3, this qualification (and others) is actually implicit in the Wingspread statement.

some perceived potential harm there would be no rationale for precaution, and without scientific uncertainty standard risk management (as described, for instance, by Pollak 1995) would suffice - and they will be treated as axioms.[8] The third one will be given a precise definition, which extends to the present context the familiar distinction between self-protection and self-insurance.

2.1. Scientific Uncertainty

A common truism is that 'good' scientists can recognize 'good' science when they see it. This does not mean, however, that they would always endorse the same scientific conclusions. First, the systems investigated by health and environmental scientists are large and complex, often chaotic, and frequently not amenable to modelling or experimental manipulation. Hence, scientists have so far been unable to agree on the timing and regional impact of global warming, the assimilative capacity of the North Sea or the Great Lakes ecosystems, and the likelihood that genetically modified organisms (GMO) entail genetic mutations affecting humans. Second, sufficient data may also not be obtainable within a sensible time frame, if at all. The dioxin risk assessment initiated a decade ago by the U. S. Environmental Protection Agency, for example, has not yet succeeded in portraying accurately the impact of this chemical. Dioxin has been associated with cancer, chloracne, endometriosis, and other diseases, but contrary to the usual dose-response

[8] Improper - yet popular - usage of the Precautionary Principle often obscures these premisses. The Precautionary Principle has sometimes been invoked, for instance, to justify closing a restaurant because of several salmonella cases or invading a foreign country for fear of terrorism. But the former is a classical risk management situation involving no uncertainty about probabilities and consequences, and the latter is definitely out of the scope of the natural sciences.

patterns it is both acutely and chronically toxic at very low doses. This raises the possibility that similar effects would occur at even lower, still unmeasurable, exposure levels. Were extensive data available, finally, substantial gaps and disagreements might remain. The possible health effects of radio frequency fields, for instance, have been studied since World War II, and there is an abundant literature on the subject. Yet, no scientific consensus has emerged that would alleviate public concerns that living near a power line or other electrical utility increases the risk of cancer.[9]

In a formal sense, different, yet valid, scientific assessments can therefore produce different probability distributions. Discrepancies may arise when assessing the support of a distribution (as in the dioxin case) or the odds of a given outcome (as in the GMO example), or both (as in global warming). Such a situation is captured by the next axiom.

AXIOM 1. [No scientific agreement] *Scientific assessments form a set of* $n \geq 2$ *Bernoulli distributions* $[\omega_0, \omega_1; q_1], [\omega_0, \omega_2; q_2], ..., [\omega_0, \omega_n; q_n]$, *where* ω_0 *represents some reference state of the world,* ω_i $(i = 1, ..., n)$ *denotes the alternative state that may happen if a given activity is pursued, and* q_i *is the corresponding probability that* ω_i *materializes (so* $1 - q_i$ *is the probability of remaining in state* ω_0*). These distributions are distinct in the sense that, for at least one pair* (i, j), *we have that* $\omega_i \neq \omega_j$ *or* $q_i \neq q_j$.

Hereafter, these distributions will be referred to as *scenarios*. Note that the ω_i's $(i = 0, 1, ..., n)$ could themselves be probability distributions, dynamic trajectories or

[9] Other areas of scientific debates include the impact on human health or the environment of low radiations, water fluoridation, MTBE (a substitute for lead) in petrol, atmospheric halocarbons, antifoulants, DES, and PCBs. Facts and details about these cases and examples can be found in Mazur (2004) and Gee et al. (2001).

stochastic processes, so there is little loss of generality in focusing specifically on Bernoulli distributions.[10] In the context of global warming, the axiom would say that the n scientists consulted by the regulator agree on what the earth's climate (ω_0) will be over the next century if the current emissions of greenhouse gases in the atmosphere were to get back to the level they reached in 1990, but that at least two of them hold different assessments of the extent (ω_i) or the odds (q_i) of climatic changes associated with the continued or accelerating atmospheric accumulation of such gases.[11]

For policy planning, the provided scenarios now need to be weighed and ranked. This step is considered in the next section.

2.2. Threat of Harm

In order to choose an appropriate course of action, the regulator first has to compare the various states of the world in a consistent way. There is a potential hazard if at least one of the foreseen states, say ω_i ($i = 1, ..., n$), then appears to be worse than the reference state ω_0, though this finding must also be weighed by the credibility of scenario i. Our second axiom highlights these elements of decision making.

AXIOM 2. *The regulator's appraisal of scenarios and policies is such that*:

(i) [Ordinal scores] *Her evaluation of the various states of the world can be represented by a real-valued function* $u(\cdot)$ *where* $u(\omega_1) \leq u(\omega_2) \leq ... \leq u(\omega_n)$;

[10] Kurz (1994) has provided a compelling rationale for the persistence of disagreements among experts. According to this paper, furthermore, rational beliefs (i.e., beliefs which cannot be contradicted by the data) can be expressed as a convex combination of two probability measures.

[11] It is hard to figure out what 'erring on the side of caution' would mean without having a consensus on the representation of some safer state. Some scholars (e.g., Godard 1997) actually refer to a situation where scientists disagree about the reference state as one of *ignorance*, locating it out of the scope of the Precautionary Principle.

(ii) [Potential threat] *For at least one scenario i, she deems that* $u(\omega_i) < u(\omega_0)$;

(iii) [Scenario weighing] *She attributes relative weights* $\alpha_i \geq 0$, $\sum_{i=1}^{n} \alpha_i = 1$, *to each scenario*;

(iv) [Weighted average criterion] *She prefers scenarios and policies that increase the weighted average* $\sum_{i=1}^{n} \alpha_i (q_i u(\omega_i) + (1 - q_i) u(\omega_0)).$

While being compatible with expected utility, this axiom does not demand that the regulator's evaluation suits the Von Neumann-Morgenstern or Savage frameworks. First, the weights α_i do not need to be probabilities: they may be weighted probabilities (as in Kahneman and Tversky (1979)'s Prospect Theory), for instance, express the reliability of a scientific approach (according, perhaps, to the scientists themselves), or be the outcome of public debates and represent the proportion of stakeholders who believe that scenario i is the most realistic one. The grading function $u(\cdot)$, moreover, is rather arbitrary, as long as it indicates a potential threat and satisfies the inequalities in (a) and (b); it may not be concave, monotone, continuous, or even defined on some range (because of social controversies, notably, as it often happens when trying to rank some far-away consequences of global warming).

2.3. Precautionary actions

The Precautionary Principle points decidedly towards altering the available scenarios to make the occurrence of harm less likely or less severe. Interventions which amend some probabilities of losses can be viewed as *self-protection*. Examples would be a partial phase-out of industrial chlorine chemistry in the Great Lakes region (as the International Joint Commission recommended), the enforcement of limitations on neighboring radio frequencies (as Italy and Switzerland respectively did in 1998 and 1999), a ban on beef imports from countries that have experienced a few cases of bovine spongiform encephalopathy, or the prohibition of chrlorinated pesticides and polyvinyl chloride plastics (the largest sources of dioxine). Strategies that rather have an impact on the anticipated magnitudes of potential losses, on the other hand, are akin to *self-insurance*. Illustrations would be to encourage a lower rate of greenhouse gases emissions (in order to slow down global warming), to invest in buildings and infrastructure adapted to warmer and dryer weather, or to favor technologies that decrease a community's dependence upon its local habitat. In the present context, these two types of precautionary measures can be brought in as follows.

DEFINITION 1 [Precautionary policies]. *A precautionary policy is a measure that modifies the probabilities or the alternative states in some scenarios and that, for at least one scenario i where $u(\omega_i) < u(\omega_0)$, qualifies as self-protection or self-insurance.*

(a) *It is self-protecting if it increases the probability of remaining in the reference state of the world so that scenario i is transformed into $[\omega_0, \omega_i; p_i]$ with $p_i < q_i$.*

(b) *It is self-insuring if it fosters an alternative state that exhibits a higher score, so scenario i becomes $[\omega_0, \bar{\omega}_i; q_i]$ with $u(\bar{\omega}_i) - u(\omega_0) = \theta_i(u(\omega_i) - u(\omega_0))$ and $\theta_i < 1$.*

This definition presupposes that there is a one-to-one correspondance between the sets of scientific assessments before and after a precautionary action is undertaken, so that any modified scenario can be identified with the same index $i = 1, ..., n$ as an initial one. In practice, this amounts to assuming, for instance, that scientific assessments are always made using the same group of experts or methodologies (as in the examples of Section 4).

Note that the definition allows a policy to be self-protecting and self-insuring at the same time. In this case, two scenarios $i \neq j$ where $u(\omega_i) < u(\omega_0)$ and $u(\omega_j) < u(\omega_0)$ would be simultaneously transformed into $[\omega_0, \omega_i; p_i]$ and $[\omega_0, \bar{\omega}_j; q_j]$, with $p_i < q_i$, $u(\bar{\omega}_j) - u(\omega_0) = \theta_j(u(\omega_j) - u(\omega_0))$ and $\theta_j < 1$, or a scenario i such that $u(\omega_i) < u(\omega_0)$ would become $[\omega_0, \bar{\omega}_i; p_i]$ with $p_i < q_i$, $u(\bar{\omega}_i) - u(\omega_0) = \theta_i(u(\omega_i) - u(\omega_0))$ and $\theta_i < 1$.

In addition to bringing self-protection or self-insurance, an intervention is also characterized by its *impact*. The next definition introduces this notion in the actual setting.

DEFINITION 2 [Policy impact]. *The impact of a measure (be it self-protecting, self-insuring, or both) is the vector* $d = (d_1, ..., d_n)$ *of weighted differences* $d_i = \alpha_i(q_i - \theta_i p_i)$.[12]

This completes our formalization of the main components of the Precautionary Principle. In the upcoming section, we turn to the logical relationship between these items which is set by the principle itself and study its ramifications for precautionary policies.

3. Main Result

The previous section began with a generic version of the Precautionary Principle that can now be expressed as follows: the verification of Axioms 1 and 2 must trigger a precautionary strategy.

This formulation provides yet little guidance into how costly or drastic such a strategy should be. In most applications of the principle, regulators have therefore deemed it necessary to put more or less stringent qualifications on precautionary policies. The Rio

[12] In particular, if only the alternative state is modified in a given scenario i, then $p_i = q_i$ so $d_i = \alpha_i q_i(1 - \theta_i)$; if only the probabilities are affected, then $\theta_i = 1$ so $d_i = \alpha_i(q_i - p_i)$; and if this scenario is left unchanged, then $d_i = 0$.

Declaration and Maastricht Treaty, for instance, endorse precaution only when the expense seems reasonable given the stakes and the level of protection that would be achieved. Other statements demand that the regulator's action resembles the measures that were previously taken under similar circumstances; others that there be more flexibility when scientific uncertainty is greater. As we will now see, these arbitrary-looking and sometimes controversial desiderata can actually be inferred from the principle's own logic. This is a consequence of the following proposition.

PROPOSITION: *The rule that "the regulator must adopt a precautionary policy whenever Axioms 1 and 2 are verified" is logically equivalent to having:*

(i) $d_1 \geq 0$,

(ii) if scenario j *is such that* $u(\omega_j) \not< u(\omega_0)$, *then* $d_j + \dots + d_n \leq 0$,

(iii) $d_1 + \dots + d_n = s$, *for some* $s \geq 0$.

Part (i) agrees with the chief understanding of the Precautionary Principle (previously emphasized by the maximin interpretation of the principle): self-insuring or self-protecting actions must first target the *worst* potential danger, implying that $p_1 < q_1$ or $\theta_1 < 1$. Of course, some non-threatening scenario j might thereby be adversely affected, so that $d_j \geq 0$; but the second part of the proposition says that the overall impact on similar or better scenarios (which is given by the sum $d_j + \dots + d_n$) should not be unfavorable to their respective alternative states (that is, $d_j + \dots + d_n \leq 0$). This suggests that some tradeoff must be made between alleviating the most serious threats, on the one hand, and not putting off all potential benefits, on the other hand.[13] Part (iii) now regulates this tradeoff, in favor of conservative actions (since the total impact of the measure, $d_1 + \ldots +$ d_n, must be non-negative) but up to some ceiling (i.e., $d_1 + \ldots + d_n = s$).

For concreteness, the result can be illustrated with a numerical example. In the present notation, let $n = 2$, $u(\omega_0) = 10$, $u(\omega_1) = 3$, $u(\omega_2) = 11$, $\alpha_1 = \alpha_2 = 0.5$, and $q_1 = q_2 = 0.5$. A self-insurance policy that changes the latter probabilities into $p_1 = 0.2$ and $p_2 = 0.4$ respectively would not be acceptable according to the proposition, for although it satisfies part (i) with $d_1 = 0.15 \geq 0$ and part (iii) with $s = 0.2 = d_1 + d_2$, it violates part (ii) since $d_2 = 0.05 \nleq 0$. A different strategy that sets $p_1 = 0.2$ and $p_2 = 0.6$ would work, however. (As would actually the first policy, if there were an additional scenario carrying the same weight so $\alpha_1 = \alpha_2 = \alpha_3 = \frac{1}{3}$, say, and where $u(\omega_3) = 15$, $q_3 = 0.5$, and $p_3 = 0.6$.)

PROOF OF THE PROPOSITION: First, let $\delta_i = u(\omega_i) - u(\omega_0)$ for $i = 1, \ldots, n$, and $\delta^t = (\delta_1, \delta_2, \ldots, \delta_n)$.[14] Using this notation, Axiom 2 means that $A\delta \leq 0$, where A is the $n \times n$ matrix

$$A = \begin{pmatrix} 0 & \ldots & \ldots & 1 & \ldots & 0 \\ 1 & -1 & 0 & \ldots & 0 & 0 \\ 0 & 1 & -1 & \ldots & 0 & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & 0 & \ldots & 1 & -1 \end{pmatrix}$$

[13] A tradeoff that reminds the well-known one between type I (rejecting a 'good') and type II (endorsing a 'bad') errors in statistics.

[14] Here, δ is taken to be a column vector, so δ^t denotes its transposed.

whose top row corresponds to part (b) of the axiom (the number 1 sitting in the i^{th} column) and rows 2 to n represent part (a). Let finally a_{1j} refer to the number in the first row and j^{th} column of this matrix.

Now, suppose that, whenever Axioms 1 and 2 are valid, the regulator also finds that $d\delta \leq 0$ for some precautionary measure, so she should implement this measure. By Farkas's lemma, there must exist a row vector of nonnegative real numbers $k = (k_1, k_2, ..., k_n)$ such that $d = kA$, that is:[15]

$$d_1 = k_2 + a_{11}k_1, \quad d_2 = k_3 - k_2 + a_{12}k_1, \ \dots , \quad d_n = -k_n + a_{1n}k_1 \quad . \tag{1}$$

Clearly, this entails that $d_1 \geq 0$, which proves assertion (i) of the proposition. This also implies that $d_j + \dots + d_n = -k_j \leq 0$ for all $j > r$ when $a_{1r} = 1$, which supports part (ii). Finally, writing $k_1 = s$ and summing through the equations in (1) gives $d_1 + \dots + d_n = s$, as claimed in (iii).

Conversely, suppose that parts (i), (ii) and (iii) of the proposition are true. The d_i's can then take the form displayed in (1), with $a_{1i} = 0$ or 1, $\sum_{i=1}^{n} a_{1i} = 1$, and $k_i \geq 0$ for all i. If Axioms 1 and 2 hold, then we have $A\delta \leq 0$ and the d_i's can be decomposed and interpreted to fit Definition 2. The statement $(A\delta \leq 0 \Longrightarrow d{\cdot}\delta \leq 0)$ now comes from applying Farkas's lemma. **Q.E.D.**

[15] The version of Farkas's lemma we are using is the following one: *let x, y and b be (column) vectors in $\Re^m$, $\Re^n$ and $\Re^n$ respectively, then* $(\forall y, \ y^t A \leq 0 \Longrightarrow y^t b \leq 0)$ *holds if and only if* $(\exists x \geq 0, \ Ax = b)$. Various generalizations of this proposition now exist (for extensions to real vector spaces of arbitrary dimension, for instance, see Craven, B. D. and J. J. Koliha 1977), which may confer some robustness on our framework and results.

The demonstration contributes what could be called a 'dual formulation' of the Precautionary Principle. Accordingly, the nonnegative real number s is the shadow price associated with the threat-of-harm inequality $u(\omega_i) \leq u(\omega_0)$, and it can be viewed as the marginal benefit the regulator foresees from relaxing this constraint.[16]

This interpretation now suggests a practical way to exercise precaution. When there are several scientifically valid representations of a given context (the upcoming evolution of the earth's climate, say), and at least one of the possible scenarios raises a threat to human health or the environment, the regulator should first seek what 'price' society would pay to reduce the weakest threat.[17] Once such a price $s \geq 0$ is set, then an appropriate precautionary policy could be formulated using conditions (i), (ii) and (iii).

To be sure, when $s > 0$ this policy will run contrary to a rule asking that:

> When an activity raises potential *benefits* for human beings or the environment, *forward actions* should be taken even if some cause-and-effect relationships are not fully established scientifically.

For in the present context, such a tenet - which exemplifies what could be called a 'Boldness Principle' - would foster departure from the reference state and require instead that $d_1 + ... + d_n = -z$ for some $z \geq 0$.[18]

[16] In a similar fashion, each 'multiplier' k_i, $i > 1$, which is associated with the inequality $u(\omega_{i-1}) \leq u(\omega_i)$, can be seen as the value the regulator puts on closing the gap between $u(\omega_i)$ and $u(\omega_{i-1})$.

[17] A complete discussion of how to elicit and compute such a price is beyond the scope of this paper. The matter is analogous to that of putting a monetary value on human life or ecosystem services. For a summary of the availables means to achieve the latter, we refer the interested reader to Viscusi (1993) and Howarth and Farber (2002) respectively.

[18] To see this, note that the above axioms can accommodate this Boldness Principle, provided part (ii) of Axiom 2 is replaced by the following sentence:

Condition (ii) of the proposition ensures, however, that the achieved policy will never go as far as to undermine *all* non-threatening scenarios. This excludes some interventions which a common understanding might associate with an application of the Precautionary Principle.[19] On the other hand, a policy fulfilling the proposition's conditions will meet some frequently-requested qualifications of precautionary measures (see, e.g., Godard 1997; O' Riordan and Cameron 1994; or Raffensberger and Ticker 1999). It will be *cost-effective*, in the sense that its marginal benefit s is not allowed to be negative. Its harshness will be *proportional* to the importance of danger, since part (iii) of the proposition demands that the total impact of the current policy, which is given by the sum $d_1 + \ldots + d_n$, be equal to the value s of removing the current threat - the higher (lower) this value, the larger (lower) the d_i's must then be on average. It will also be *consistent* with measures taken in similar circumstances, where 'similar' means here that the shadow price s is the same. And greater scientific uncertainty will grant it more *flexibility*, if more disagreement between scientists means that the number n of distinct scenarios is larger, so the regulator has then more degrees of freedom to satisfy condition (iii).

The policy construction which is being outlined finally conveys a notion of *robustness*:

[Potential benefit] *For at least one scenario i, the regulator deems that $u(\omega_i) > u(\omega_0)$.*

The argument underlying the proposition holds again, with the positive digit in the top row of matrix A being replaced by -1. A measure's impact must now be such that: $(\bar{i})$ $d_n \leq 0$; $(\overline{ii})$ if $u(\omega_j) \not> u(\omega_0)$ at a scenario j, then $d_1 + \ldots + d_j \geq 0$; and $(\overline{iii})$ $d_1 + \ldots + d_n = -z$ for some $z \geq 0$.

[19] For instance, a strategy which alleviates the only dangerous scenario (making $d_1 \geq 0$) while adversely affecting the remaining potentially-good forecasts (so $d_2 > 0, \ldots, d_{n-1} > 0$) will not be an appropriate precautionary policy according to the proposition, nor will a measure that mitigates all the bad scenarios (so $d_1 \geq 0, \ldots, d_{n-1} \geq 0$) while undercutting the only non-threatening prediction (i.e. $d_n > 0$). (We thank a referee for pointing this out.) Note, however, that this simply acknowledges the regulator's willingness to consider and put a positive weight (respectively $\alpha_1 > 0$ and $\alpha_n > 0$) on dissenting views.

it certainly errs on the side of caution, but without relying exclusively on a single account. This is further illustrated by the use of the shadow price s. This price is not specifically linked to the worst case $u(\omega_1) < u(\omega_0)$ but to the least unfavorable one $u(\omega_i) < u(\omega_0)$.[20] Hence, while an appropriate precautionary policy will chiefly address the most severe potential danger (making $d_1 \geq 0$), its overall impact and the strength of its bias towards the reference state (which must satisfy condition (iii): $d_1 + ... + d_n = s$) will in turn adjust to the value of alleviating the weakest threat.

The upcoming section will now apply the proposition to some concrete policy settings.

4. Policy Applications

In practice, the Precautionary Principle is invoked mostly to deal with two distinct sets of issues: to preserve some living species and their habitat, or to regulate the production, distribution and use of new technologies. For scientific uncertainty is particularly present when assessing the resilience of some ecosystems or the dangers inherent to complex new artefacts. This section now applies the above framework and results to address some considerations in these respective areas. First, we investigate the choice between self-protection and self-insurance in marine fisheries management. Then we look at nanotechnologies, and discuss the implementation of the principle in this context.

4.1 Fisheries conservation

The earliest explicit applications of the Precautionary Principle were motivated by the conservation of aquatic species. The importance of fishery for the economy of entire re-

[20] The matter of which scenario to base policy discussions on is also common in risk management, where the issue is instead whether to rely on either the worst or the most likely assessment.

gions, together with the chaotic patterns of ocean dynamics (see, e.g., Rosser 2001), lead indeed naturally to 'err on the side of caution' if survival of a valuable marine variety (such as the Atlantic cod, the southern bluelin tuna, and the Atlantic halibut) was at stake. In 1992, the International Conference on Responsible Fishing launched the "Code of Conduct for Responsible Fisheries," which was endorsed three years later by the Food and Agriculture Organization (FAO). Article 7.5 of this document contains a standard (albeit weak) statement of the Precautionary Principle: "The absence of adequate scientific information should not be used as a reason for postponing or failing to take conservation and management measures."

Examples of self-protecting actions that have been adopted so far in fishery management include catch and effort limits, restrictions on the physical characteristics of gears (such as mesh or hook sizes), fishing schedules and seasons, and marine protected areas. These measures were set and are essentially being enforced by governement bodies. The market, on the other hand, is rapidly developing, notably through aquaculture, the means for self-insurance.[21] An interesting question nowadays is whether the regulator should rely more on the latter, thereby lowering the administrative and often political costs of precaution. In the present framework, this matter can be taken up as follows.

According to the scientists themselves, there are various methods of assessing extinction risks in marine fishes, and divergent, yet valid, conclusions may simultaneously

[21] According to the FAO, aquaculture is currently providing about one third of total fisheries supply, compared to 15% in 1989. A quarter of the fish eaten in the world now comes from aquaculture.

occur.[22] Using the present framework, let then n represent the number of distinct scenarios resulting from these assessment methods. These scenarios $i = 1, ..., n$ exhibit the same alternative state $\omega_1 = ... = \omega_n = \varnothing$, which refer to extinction, while their common reference state ω_0 represents the opposite situation with sustainable (but possibly fluctuating) marine fish stocks; their respective probabilities of extinction $q_1, ..., q_n$, however, are all different. Self-insurance would therefore modify every scenario according to the same parameter θ, where $u(\bar{\omega}) - u(\omega_0) = \theta(u(\varnothing) - u(\omega_0))$ and $\bar{\omega}$ stands for a situation where aquaculture, for example, can provide (at least partial) replacement for the extinct marine species; clearly, $0 \leq \theta < 1$ since $u(\varnothing) < u(\omega_0)$. Self-protecting measures, on the other hand, would make the probability of extinction become $p_i \leq q_i$ in each scenario i. The impact of a given policy is now given by $d = (d_1, ..., d_n)$ where $d_i = \alpha_i(q_i - \theta p_i)$ and α_i represents the relative reliability of the underlying method (possibly based on the scientists' own appraisal). Suppose that society puts a price $s \geq 0$ on alleviating the threat of extinction.[23] By the above proposition, holding the Precautionary Principle means that a policy involving self-insurance and self-protection must satisfy the equation

$$\sum_{i=1}^{n} \alpha_i(q_i - \theta p_i) = s \ . \tag{2}$$

Since $\theta \geq 0$, this condition is met only if $\sum_{i=1}^{n} \alpha_i q_i \geq s$. Direct algebra from (2) now gives

$$\theta = \frac{\sum_{i=1}^{n} \alpha_i q_i - s}{\sum_{i=1}^{n} \alpha_i p_i} \ . \tag{3}$$

[22] For a recent survey and an appraisal of the available approaches, see Dulvy et al. (2004).

[23] Note that this 'price' can be net of the implementation cost of the measure, and can altogether reflect economic, social, and political concerns.

This entails that $\frac{\partial\theta}{\partial p_i} = (-\alpha_i/\sum_{i=1}^{n}\alpha_i p_i)\theta < 0$, so self-insurance is indeed a substitute for self-protection (i.e., a decrease in the latter, making the p_i's larger, demands greater self-insurance effort, hence a smaller θ). However, the level of self-insurance necessary to compensate a decrease in self-protection is bigger (i.e., requires a further decrease in θ) the larger θ already is, the more significant the overall current self-protection (i.e., the smaller $\sum_{i=1}^{n}\alpha_i p_i$ is), and the more credible the targeted scenarios (i.e. the larger the α_i's associated with the scenarios where p_i increases).

4.2 Nanotechnologies

By contrast with the conservation of marine species, the regulation of the potential dangers linked to the production and use of nanotechnologies is perhaps the latest area where a precautionary approach is called for.

Nanotechnologies are the result of manipulations and designs performed at atomic, molecular or macromolecular scales (that is, between one and one hundred billionth of a meter). The obtained substances and devices thereby present at least two valuable features. First, they have a relatively larger surface area in comparison with the same mass of unmodified materials, which makes them more chemically reactive, quicker to ignite or melt, absorbing much faster, and affects their strength and electrical properties. Second, quantum effects that can dominate the behavior of matter at this scale may give rise to remarkable optical, electrical, and magnetic properties. Promising applications are therefore numerous and range from new materials (e.g., coatings, cosmetics, and ceramics) to electronics (e.g., miniaturization, sensors, and data storage), to health care (e.g., imaging and monitoring, drug delivery, and imaging tissue engineering).[24]

These valuable features of nano substances and devices, on the other hand, are precisely what makes them potentially harmful. One can reasonably suspect, for instance, that high surface reactivity and the ability to cross cell membranes might have negative health and environmental impacts. Despite a few alarming findings (for example, brain damages in fish and respiratory problems in laboratory rats), however, no scientific consensus currently exists on this issue.[25] In a recent study that considers the regulator's options in this context (Dowling et al. 2004), a group of experts commissioned by The Royal Society and The Royal Academy of Engineering of the United Kingdom thus recommended that *moderate* precautionary steps be taken, that is:

> Until more is known about their environmental impact we are keen that the release of nanoparticles and nanotubes to the environment is avoided as far as possible. Specifically, we recommend as a precautionary measure that factories and research laboratories treat manufactured nanoparticles and nanotubes as if they were hazardous and reduce them from waste streams (...). Overall [however], given appropriate regulation and research along the lines just indicated, we see no case for the moratorium which some have advocated on the laboratory or commercial production of manufactured nanomaterials.

This position can find a straightforward rationale in our framework. To be sure, society is putting a positive price s on reducing the potential threats of nanotechnologies. But

[24] This information is drawn from Dowling et al. (2004) and Baker and Aston (2005). According to the latter, "the questions around nano are no longer whether it's coming or if it's real but just how big it will be." Currently, some 1200 nano startups have emerged around the world, venture capital invested in such companies is up to \$1 billion, and government funding amounts to \$4.7 billion annually (nearly equally divided among Asia, Europe and North America). Despite all the hype in the media, however, many investors remain reluctant, in the aftermath of the internet bubble and due to persisting uncertainties about the impacts on human health and the environment.

[25] Some authors, like Posner (2004), also warn about possible laboratory accidents involving self-replicating nanomachines. Such tiny entities may be necessary to economically assemble materials at the nanoscale. Like viruses, however, they might some day find the means to proliferate uncontrollably.

the overall impact of a radical measure like a moratorium or a complete ban, which is given by $\sum_{i=1}^{n} \alpha_i q_i$ since such an action means that $\theta_i = 1$ and $p_i = 0$ (so $d_i = \alpha_i q_i$) in all the scenarios $i = 1, ..., n$, is apparently bigger than s.[26] What is prescribed, therefore, is some intermediate precaution, whereby $0 < \theta_j < 1$ or $p_j > 0$ (hence $0 < d_j < q_j$) in at least one bad scenario j and $\sum_{i=1}^{n} d_i = s$.

Such a fine-tuned measure, however, may not be available at this point; for the state of the art in metrology - the technology of measurement (appraised by Dowling et al. 2004) which parallels the development of nanoscience itself - allows the achievable impacts $d = (d_1, ..., d_n)$ to only form a coarse discrete set.[27] This may explain why the Precautionary Principle has so far found relatively few concrete applications to nanotechnologies.

5. Concluding Remarks

Science-based regulation must increasingly cope with situations where the input of science concerning the extent or likelihood of some potential danger remains ambiguous. In this context, a widely adopted approach - known as the Precautionary Principle - stipulates that one should take preventive measures right away, before and until scientific information becomes clearer. This paper contributes a straightforward formalization of this rule, which yields a practical characterization of what a proper precautionary policy should do.[28] In a nutchell, we show that once the 'price' society puts on reducing the weakest potential

[26] In this case the scenarios could be drawn by n experts the regulator wishes to get an advice from.

[27] The coarsest such set would be the one including only the two elements $(q_1, ..., q_n)$ and $(0, ..., 0)$, which correspond to a moratorium and to *laisser faire* respectively.

[28] Our representation, furthermore, does not rely on a peculiar interpretation of the Precautionary Principle. By contrast, the real options approach builds on the viewpoint that "(...) while prevention aims at managing risks, precaution aims at managing the wait for better scientific information." (see Gollier and Treich 2003, p. 86)

danger is elicited, the implemented measure must alleviate the worst forecast while keeping its total impact on all possible scenarios equal to that price. The upshot is a procedure to craft precautionary policies while managing the oftentimes conflictual trade off between abating the bad scenarios and conserving the unthreatening ones. In concrete settings such as fishery conservation (where the Precautionary Principle has been used for several years), moreover, this framework helps to clarify the relationship between self-protection and self-insurance.

The approach to policy making that is put forward in this paper could also be seen as one that fosters 'robust' policies, i.e. policies that may not be optimal according to a given model but whose impact would remain acceptable were the right model be a different one. In this sense, the above axioms and proposition may prove useful to other areas of public policy. For example, consider the following excerpt from a speech delivered by U.S. Federal Reserve Chairman Alan Greenspan at the 2004 annual meeting of the American Economic Association:

> (...) policy A might be judged as best advancing the policymakers' objectives, conditional on a particular model of the economy, but might also be seen as having relatively severe adverse consequences if the true structure of the economy turns out to be other than the one assumed. On the other hand, policy B might be somewhat less effective in advancing the policy objectives under the assumed baseline model but might be relatively benign in the event that the structure of the economy turns out to differ from the baseline. A year ago, these considerations inclined Federal Reserve policymakers toward an easier stance at policy aimed at limiting the risk of deflation even though baseline forecasts from most conventional models at that time did not project deflation; that is, we chose a policy that, in a world of perfect certainty, would have been judged to be too loose. (quoted in Walsh 2004)

In this paper's language, this quote could be interpreted as saying that in 2003 the Federal

Reserve was contemplating a number of scenarios $i = 1, ..., n$ predicting that the economy would deviate with respective probabilities p_i from a policy objective ω_0 (price stability, say) to some states ω_i. All $\omega_2, ..., \omega_n$ emphasized higher inflation, while ω_1 meant deflation. For the Fed, clearly, $u(\omega_1) < u(\omega_2) \leq ... \leq u(\omega_n) < u(\omega_0)$. In this situation, the above proposition would have indeed recommended to first address scenario 1 and the threat of deflation (adding, furthermore, that the strength of the intervention be set according to the value s of alleviating the least unfavorable case ω_n).

Despite its applied intent, however, the actual framework has left out many important issues, such as the management of expertise (notably the independence of scientists and the conflicting incentives they get from various stakeholders), the evolution of scientific knowledge (e.g., at a given time, what is to be kept in as an 'acceptable' scientific scenario), the political economy of environmental and safety regulation, the division of labor in selecting and implementing precautionary strategies, and the involved parties' respective legal liability. Dealing with these issues is now an essential complementary step to complete the analytical apparatus that public policymaking urgently needs.

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