The Precautionary Principle and Pareto Optimality in an Uncertain World

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The last decade has witnessed a significant increase in the utilization of the Precautionary Principle (PP) to manage environmental and public-health risks. The PP is typically invoked for hazards that are characterized by considerable scientific uncertainty. According to a Communication from the Commission of the European Communities (2000a), recourse to the PP is justified if "...potentially negative effects resulting from a phenomenon, product or process..." have been identified, and if "...scientific evaluation does not allow the risk to be determined with sufficient certainty...". Climate change, various foodborne hazards, genetically modified organisms (GMOs), loss of biodiversity, and toxins in the environment are often offered as hazards where these two pre-conditions of the PP hold.

Acceptance of the PP varies considerably. The European Union (EU) has been and continues to be very favorable to the PP. It has been implementing the PP as part of its environmental and public health policy since at least 1994. A recent milestone was the European Commission's publication of its White Paper on Food Safety in 2000, outlining policy orientations on risk analysis and the PP in relation to food safety (Commission of the European Communities (2000b), Byrne (2000)).

The United States (US) government, on the other hand, has been reluctant to implement the PP domestically and has vigorously opposed precautionary actions by foreign governments. Examples here include genetically engineered foods, beef hormones, and phthalates in children's PVC toys. Because of its relatively heavy reliance on GMOs, the US agricultural sector appears to be particularly vulnerable to PP actions on the part of foreign governments. Despite resistance to the PP, the US has participated in a few treaties on the PP and has demonstrated an occasional support of precautionary policies.[1] Still, most support for the PP in the US has been from non-governmental organizations and private individuals.

The World Trade Organization (WTO) articles do not contain a definition and an explicit reference to the PP. Nevertheless, the PP continues to be the center of many WTO disputes

[1] For instance, in 1998 Vice President Gore sent a letter to the US trade representatives stating that the US should not interfere with European countries taking precautionary actions to protect children's health hazards associated with phthalates (SEHN (2003)).

and negotiations. A recent example is the EU-US dispute over the EU ban of hormone-treated beef imports from the US. The dispute, which was the first commercial case settled under the WTO's Sanitary and Phytosanitary Agreement (SPA), was resolved in favor of the US. However, the recent Biosafety Protocol, originally negotiated in Cartagena (February 1999) and in Montreal (January 2000) weakens the SPA in the WTO by endorsing the right of importing countries to ban imports of living modified organisms on "precautionary" grounds, without having to produce any scientific evidence of risk.

The definition of the PP is ambiguous.[2] In particular, its pre-conditions are the subject of controversy. For example, some argue that an activity is "potentially dangerous" unless it has been proven to be safe. This places the burden of proof on parties interested in carrying out that activity. Opponents of such a radical interpretation counter by pointing out that almost all innovative activities entail some degree of risk and that adopting such an extreme stance would stunt innovation and growth. Some opponents of the PP further argue that unless there is "sufficient" scientific evidence that an economic activity entails certain hazards, that activity should not be categorized as satisfying the first pre-condition of the PP.

Controversy also surrounds the concept of "sufficient scientific uncertainty". Scientific uncertainty characterizes situations when risks associated with activity are imperfectly known. And, undoubtedly, for many economic activities this condition is satisfied. Consider, for example, the toxicity of industrial chemicals. In 1984, the National Academy of Sciences reported that 78 percent of the chemicals in the highest-volume commercial use did not have minimal toxicity testing (NRC (1984)). The Environmental Defense Fund (1997) and the Environmental Protection Agency (1998) much later reported that for the 3,000 highest production-volume chemicals (those with over one million pounds in commerce), 93 percent lack some basic chemical screening data, 43 percent only have basic toxicity data, 51 percent of chemicals on the Toxic Release Inventory lack basic toxicity information, and a large

[2] Difficulties of interpreting the PP are recognized not only by the opponents of the Principle but also by its proponents. For example, the Communication of the European Commission on the PP states: "The issue of when and how to use the Precautionary Principle, both within the European Union and internationally, is giving rise to much debate, and to mixed, and sometimes contradictory views."

percentage of available information is based only on acute toxicity (EPA (1998)).

Yet another example comes from the highly-publicized outbreak of the "mad cow" disease in the United Kingdom. It remains unknown how cows became infected with the disease. The exact contamination mechanism of humans is also unknown. In particular, how the probability of being infected is related to the past consumption of beef (Adda (2003)) is unknown. Estimates of the disease's incubation period in humans vary greatly. As a result, current estimates of human victims in the United Kingdom over the next two decades vary from 100 to more than 100,000 (Blakeslee (2001), Treich (2001)).

The foregoing suggests that scientific uncertainty and the PP inherently involve situations of Knightian uncertainty (ambiguity), when odds of different states of nature are not perfectly known. Since at least the time of Ellsberg (1961), it has been well-known that individuals facing such a choice scenario can make choices that violate the axioms underlying the expected-utility model. Moreover, a growing body of empirical evidence verifies the type of behavior postulated in the Ellsberg paradox.

Thus, it seems that an important key to the economic analysis of the PP will be the ranking of policies in the presence of (Knightian) uncertainty. To us, this implies that economic analysis of the PP should encompass an explicit specification of the economic agents' attitudes toward uncertainty or ambiguity. Because attitudes towards ambiguity can, in principle, vary widely, it should not be surprising that even in the absence of monopsonisitic or protectionist motivations, one decisionmaker might invoke the PP when another would not.

Even if different individuals have *identical* risk preferences and agree on the degree of scientific uncertainty, they need not have the same ranking of different actions. The following hypothetical example may help to clarify this point. Suppose that eating raw oysters during the spring season entails a risk of contracting a certain foodborne disease, but that there is scientific uncertainty about the probability of contracting the disease. In particular, suppose that there is only common agreement that the risk of contracting the disease lies somewhere in the range [0.001,0.002]. Consider two decision-makers: one is a pessimist who always bases decisions on the largest probability in the range, 0.002, the worst-case scenario. The other decision-maker is an optimist for whom the relevant probability is 0.001. Their willingnesses to pay for an oyster will differ.

This paper examines the trade implications of the PP in an uncertain world where different decisionmakers have different attitudes towards ambiguity. For concreteness sake, we represent these attitudes towards ambiguity in terms of the Gilboa and Schmeidler (1989) maximin expected-utility (MMEU) specification. The MMEU model axiomatizes the intuitive proposition that Ellsberg behavior can be explained by individuals having too little information to form an exact prior. (We would argue that the empirical evidence alluded to above strongly suggests that this is the case for many situations in which the PP has been applied.) When faced with such a situation, individuals view a set of priors as being possible, and aversion to uncertainty or ambiguity is manifested by them using their minimal expected utility over that set of priors to evaluate an uncertain outcome. Our central result is that in a simple two-country, general-equilibrium setting with both trading partners being ambigutiy averse in this sense Pareto optimality requires that the less ambiguity averse partner (if the partners can be strictly ranked in such terms) absorb all the uncertainty in th economy and that the more ambiguity averse partner absorb none. An immediate corollary of this finding is that autarky can be Pareto optimal if the more ambiguity averse trading partner is also endowed with a degenerately uncertain technology. Thus, in such a setting, the most extreme prescription of the PP, no trade in uncertain products, can be Pareto optimal.

In what follows, we first construct a simple general equilibrium model of trade between two countries (or two individuals) with different attitudes towards uncertainty, but common attitudes towards risk. The countries have access to uncertain technologies, which transform their current period inputs into uncertain quantities, and the countries are allowed to freely trade these uncertain quantities *ex ante.* After developing our results, we briefly compare our analysis with other economic analyses of the PP, and the paper then concludes.

1 The Model

We use a simple general equilibrium model to examine trade in the presence of Knightian uncertainty. There are two periods. The first, 0, is certain, and the second, 1, is uncertain.

The uncertainty concerns the quality of the single consumption good in the economy and is represented by a neutral player ('Nature') making a draw from $\Omega = \{1, 2\}$ in between period 0 and period 1.[3] Each element of Ω is referred to as a state of Nature.

There are two potential trading partners, each representing the representative agents from two countries, which are mnemonically referred as the European Union (EU) and the rest-of-the-world (ROW). Because our interest is in Pareto optimal outcomes, and because it is well-known that incomplete markets typically generate non-Pareto-optimal outcomes, we confine attention to complete markets.[4] Each country is endowed with an uncertain production technology which transforms its period 0 endowment of a certain input vector, $\mathbf{x} \in \Re_{+}^{N}$, into uncertain period 1 output of the consumption good. For simplicity and concreteness sake, we assume that these uncertain production relations in each country can be modelled by an increasing production function mapping input committed, $\mathbf{x}$, in period 0 and the realized state of nature, s, into an uncertain output according to

$$z_s = f(\mathbf{x}, s) \quad s = 1, 2.$$

We specifically allow input endowments and technologies to vary across countries. We denote these differences notationally by superscript E for the EU and R for ROW.

Trading arrangements between EU and ROW cover two periods. All contracts are completely enforceable. In period 0, the trading partners agree on the level of trade of the consumption good for both realizations of Ω in period 1, and in period 1, these contracts are executed after Nature has made its choice. There is no trade in period 0 inputs.

The *ex ante* (period 0) attitudes of the representative consumer in both the EU and the ROW over period 1 consumption are described by linear *ex post* (period 1) utility functions. This assumption is made for two purposes. First, it rules out indeterminancies associated with wealth (endowment) effects, and by eliminating wealth effects, it also eliminates risk considerations from each representative consumer's decision. This serves to focus our analysis on the role that ambiguity or uncertainty aversion plays in the analysis without confounding

[3]Nothing of substance changes by moving to the general $S-$state space case.

[4]By the theory of the second best, it would not be surprising if restrictions on trade could be welfare improving in an incomplete markets setting.

it with risk aversion.[5]

Each representative agent, however, faces ambiguity regarding the prior probability measures which actually characterize random variables defined on $\Re^\Omega$. The beliefs of the EU representative agent are captured by closed interval $P^E \subset [0,1]$ and the beliefs of the ROW representative agent are captured by closed interval $P^R \subset [0,1]$. Representative agent $i's$ *ex ante* evaluation of period 1 state-contingent consumption (c_1, c_2) is given by the MMEU model of Gilboa and Schmeidler (1989) for linear ex post utilities.[6] That is,

$$\begin{aligned} W^i(c_1, c_2) &= \min_{\pi \in P^i} \{c_1 + \pi(c_2 - c_1)\} \quad i = E, R, \\ &= c_1 + \min_{\pi \in P^i} \{\pi(c_2 - c_1)\}. \end{aligned}$$

For simplicity, we have assumed a common discount factor across countries and have normalized it to equal one.

A complete-markets equilibrium, therefore, is characterized by the material-balance conditions

$$\begin{aligned} c_2^R + c_2^E &= f^R\left(\mathbf{x}^R, 2\right) + f^E\left(\mathbf{x}^E, 2\right) \\ c_1^R + c_1^E &= f^R\left(\mathbf{x}^R, 1\right) + f^E\left(\mathbf{x}^E, 2\right). \end{aligned} \tag{1}$$

2 Pareto-optimality

We first prove the following theorem that characterizes an important class of Pareto optimal consumption vectors for the economy characterized in the previous section.

Theorem 1 *If $P^R \subset P^E$, then for any Pareto optimal consumption vector $((c_1^E, e_2^E), (c_1^R, e_2^R))$, $c_1^E = e_2^E$.*

[5] As the recent axiomatic literature on ambiguity aversion has clarified, there is always some degree of arbitrariness in distinguishing between the effects of ambiguity aversion and risk aversion (Epstein (1999); Ghiradato and Marinacci (2002)) in any decision environment.

[6] The MMEU preferences are equivalent to Choquet expected utility preferences with convex core P^i (see Schmeidler (1986)).

Proof. Let $a \equiv c_1^E = c_2^E$. If $((a,a),(c_1^R,c_2^R))$ does not represent a Pareto equilibrium, there must exist $\left(\widetilde{c}_1^R, \widetilde{c}_2^R, \widetilde{c}_1^E, \widetilde{c}_2^E\right)$ satisfying (1) such that

$$\begin{aligned}
\widetilde{c}_1^R + \min_{\pi \in P^R} \left\{ \pi \left(\widetilde{c}_2^R - \widetilde{c}_1^R \right) \right\} &> c_1^R + \min_{\pi \in P^R} \left\{ \pi \left(c_2^R - c_1^R \right) \right\}, \\
\widetilde{c}_1^E + \min_{\pi \in P^E} \left\{ \pi \left(\widetilde{c}_2^E - \widetilde{c}_1^E \right) \right\} &\geq a,
\end{aligned}$$

The first two inequalities and (1) require

$$\min_{\pi \in P^E} \left\{ \pi \left(\widetilde{c}_2^E - \widetilde{c}_1^E \right) \right\} + \min_{\pi \in P^R} \left\{ \pi \left(\widetilde{c}_2^R - \widetilde{c}_1^R \right) \right\} > \min_{\pi \in P^R} \left\{ \pi \left(c_2^R - c_1^R \right) \right\}.$$

Substituting (1) into the minimand on the right-hand side allows us to rewrite this necessary condition as

$$\min_{\pi \in P^E} \left\{ \pi \left(\widetilde{c}_2^E - \widetilde{c}_1^E \right) \right\} + \min_{\pi \in P^R} \left\{ \pi \left(\widetilde{c}_2^R - \widetilde{c}_1^R \right) \right\} > \min_{\pi \in P^R} \left\{ \pi \left(\left(\widetilde{c}_2^E - \widetilde{c}_1^E \right) + \left(\widetilde{c}_2^R - \widetilde{c}_1^R \right) \right) \right\}. \quad (2)$$

Expression (2) cannot be satisfied if $P^R \subset P^E$. ■

Theorem 1, which is the central result of the paper, manifests a general result on ambiguity or uncertainty sharing that is analogous to familiar results on risk sharing. Under the assumptions of the Theorem, the EU is more ambiguity averse than the ROW. This can be seen by noting that for any (c_1, c_2) if $P^R \subset P^E$

$$\begin{aligned}
W^R(c_1, c_2) &= c_1 + \min_{\pi \in P^R} \left\{ \pi \left(c_2 - c_1 \right) \right\} \\
&\geq c_1 + \min_{\pi \in P^E} \left\{ \pi \left(c_2 - c_1 \right) \right\} \\
&= W^E(c_1, c_2).
\end{aligned}$$

Intuitively, this happens because decisionmakers with MMEU preferences always evaluate stochastic outcomes in the most conservative or most pessimistic light. When $P^R \subset P^E$, therefore, the EU never evaluates any uncertain consumption bundle at more favorable odds than ROW. It is, of course, trivially true that if $P^E \subset P^R$, then the reverse implications holds

Given the linear nature of the *ex post* utility structures and the assumption that the EU is more ambiguity averse than the ROW, any *ex ante* ambiguity, therefore, should be borne by ROW and not by the EU. Because $P^R \subset P^E$, the ROW evaluates any uncertain consumption bundle at least as favorably as the EU. Because $W^R(c_1, c_2) \geq W^E(c_1, c_2)$, ROW does not lose by agreeing to exchange the consumption bundle $\left(W^R(c_1,c_2), W^R(c_1,c_2)\right)$ for (c_1,c_2). The EU, on the other hand, gains (at least weakly) from such an exchange. Hence, it is always at least weakly optimal to transfer any residual uncertainty from EU to ROW.

We illustrate the content of Theorem 1 visually in Figure 1 with a familiar Edgeworth box diagram for the case of an endowment economy. The dimensions of the Edgeworth box are given by the sum of the period 1 endowments of the uncertain output $\left(e_1^R + e_1^E, e_2^R + e_2^E\right)$, which is represented as the point E in the figure. EU preferences are measured relative to the southwest corner of the Edgeworth box, and ROW preferences are measured relative to the northeast corner of the box.

The indifference curve of the EU (the ROW) is kinked at the 45^0 degree line if and only if P^E $\left(P^R\right)$ is not a singleton set. In Figure 1, we have depicted the case where both $P^{i\prime}s$ are not singleton sets. ROW preferences, as represented, are more ambiguity averse. This is visually represented by the indifference curve for ROW being 'more nearly flat' than the indifference curve for the EU. For clarity's sake, we depict the case where the endowment is along the certainty line for the EU, that is, $e_1^E = e_2^E = a$. As drawn, it is obvious that there are no Pareto improving trades from the endowment point. Moreover, it is easy for the reader to verify that since ROW's indifference curve always supports the EU's indifference curve at the kink that occurs along its certainty line, the contract curve will coincide with that certainty line.

An immediate corollary of Theorem 1 follows trivially:

Corollary 2 *If $P^R \subset P^E$ and*

$$f^E(\mathbf{x},1) = f^E(\mathbf{x},2),$$

then autarky is Pareto optimal.

For the technology in Corollary 2, the EU is exposed to no uncertainty in autarky. The only thing that could induce it to trade, therefore, would be if the ROW were prepared to offer it terms of trade that improved this situation. The condition $P^R \subset P^E$ by Theorem 1, however, implies that such trade is Pareto optimal only if it keeps the EU's consumption nonstochastic. Thus, the EU would only be strictly willing to trade only if it received a higher nonstochastic consumption. This necessarily entails a transfer of real income from the ROW to the EU, and thus trade is Pareto inferior.

Corollary 2 is closely related to results obtained in other contexts in the presence of ambiguity aversion. For example, Dow and Werlang (1992) demonstrated that Choquet expected utility (CEU) preferences can lead to the presence of nondegenerate, zero-trade price intervals in the standard portfolio problem.[7] The reason is that in the CEU (as well as in the MMEU) model an individual's marginal willingness to buy and his marginal willing to sell an asset can diverge. If the market price of the asset falls in the interval defined by this divergence, then the individual will neither short or long that asset. A similar phenomenon occurs here. As a consequence of their indifference curves being kinked in the neighborhood of certainty, each country's offer curve possesses a range of no-trade prices defined by P^i. Because $P^R \subset P^E$, the ROW's no-trade price zone is smaller than that of the EU.[8]

Theorem 1 and Corollary 2 do not imply that trade is always Pareto inferior so long as one country is more pessimistic or ambiguity averse than the other. In fact, just the opposite can be true as our next corollary demonstrates:

Corollary 3 *If $P^R \subset P^E$ and*

$$f^E(\mathbf{x},1) \neq f^E(\mathbf{x},2),$$

then trade is Pareto optimal.

When the more pessimistic country produces uncertainly, then it finds it optimal to trade in order to eliminate its uncertainty in consumption. Here the precautionary principle would seem to work in reverse because now the more pessimistic country wants to offload any uncertainty that arises in its production to its trading partner.

[7] Mukerji (1998), Mukerji and Tallon (2001), and Chateauneuf et al. (2000) obtain similar no-trade results in different contexts.

[8] Pareto optimality of the autarky allocation is not predicated upon linearity of *ex post* utilities. Chateaneuf et al. (2000) demonstrate that no trading equilibria can be optimal in the presence of strictly convex preferences.

3 Relation to Previous Work

The PP is often called an "act-then-learn" strategy. This is in contrast to a "learn-then-act" strategy, which requires conducting scientific investigation and then acting based on the results of research. An "act-then-learn" strategy reverses the order. PP advocates often argue that the current state of science is too ambiguous to prescribe an optimal course of action with adequate precision. Under these circumstances, costs of inaction (where inaction now means no government intervention) before risks are learned with sufficient certainty can be very high. Inaction may lead to *irreversible* outcomes that are very costly or impossible to correct.

The PP stipulates that even though these scientific uncertainties are expected to be resolved in the future, precautionary actions to prevent adverse human, animal and plant health effects and environmental degradation should not be postponed. Precautionary actions taken before the resolution of scientific uncertainty may vary from weak (mandating an intensive scientific analysis of the problem) to very strong (phasing out or prohibiting an activity).

Gollier et al. (2000) analyze optimality of "act-then-learn" versus "learn-then-act" strategies in an expected-utility framework. Three effects are considered. First, future actions may be restricted due to physical constraints. This "irreversibility effect" of Arrow and Fisher (1974) and Henry (1974), favors an "act-then-learn" strategy.[9] Second, the "learn-then-act" strategy has the advantage of making a more informed decision. On the other hand, waiting for the resolution of uncertainty before acting induces a larger variation of *ex post* actions which, in turn, amounts to more risk faced by the decision-maker. This third factor, called by authors a "precautionary effect", may dominate the second effect even in the absence of "irreversibility effect". Gollier et al. (2000) identify conditions on third-order derivatives of the Bernoulli utility function of the decision-maker, measuring his or her prudence, that guarantee optimality of the precautionary strategy. They conclude that this provides a justification for the PP.

[9] An example of the "irreversibility effect" is the disappearance of Aral Sea, one of the largest bodies of water in Central Asia, as a result of an environmental catastrophe caused by irresponsible policies during the Soviet era.

Further support of the PP has been offered by Gollier (2001) and Treich (2001). In addition to discussing results in Gollier et al. (2001), the two papers provide an interesting discussion of advantages and disadvantages of the PP. Treich (2001) calls for the enforcement of the PP at the international level to encourage stronger cooperation between countries and avoid problems associated with the inability of governments to precommit to desired policies.

Immordino (2000) considers a framework similar to Gollier et al. (2001) with the exception that actions in his model affect *probabilities* of different outcomes ("self-protection") while in Gollier et al. (2001) actions affect *payoffs* in different states of nature ("self-insurance"). Immordino (2000) finds that improvements in future information have an ambiguous effect on self-protection. Thus, according to the author's interpretation, it is not warranted that implementation of the PP is welfare-improving.

Corollary 2 offers an alternative explanation for the PP in certain contexts, and thus, in a sense agrees with those of Gollier et al., Gollier (2001) and Treich (2001). However, its motivation differs substantially from that used in any of these models because we depart from the expected-utility framework. Specifically, our results emerge from a different evaluation of uncertainty by trading partners and technical differences across trading partners. These differences crudely approximate, for example, differences popularly ascribed to the EU and the US. The former is often perceived as more "Green" than the latter, and partly as a consequence it has been more reluctant to introduce technologies which increase uncertainty. Thus, our results emerge from distinctly different effects than those isolated by Gollier et al., Gollier, and Treich.

We should also note that Gollier (2001) expresses doubts about ambiguity aversion saying that "...there is good reason to doubt just how averse to ambiguity people really are". Ambiguity aversion is relatively well documented in the experimental literature on the Ellsberg paradox, but because we are aware of no firm evidence on just how ambiguity averse people actually are, we find it prudent at this time to neither agree nor disagree with Gollier on this point.

In a similiar sense, our results are not directly comparable to Immordino (2000) because our model, which implicitly assumes a state-space and act setting, does not permit self-protecting activities. But at this juncture, we should point out that our Corollary 3 describes a situation that can be interpreted as buttressing Immordino's (2000) position. Corollary 3, therefore, presents a rationalization of the practice (of which many developed countries are accused) of exporting environmentally and public-health damaging products to the apparently less environmentally sensitive developing world under the presumption that the developing world is less ambiguity averse than their more developed trading partners.

More recently, Henry and Henry (2002) have taken an approach much closer to ours and provide a formalization of the PP where decision-maker's prefererences can exhibit (positive or negative) preference for ambiguity. However, they equate non-precautionary decision-making to choosing from the set of unambiguous acts which are acts that are measurable with respect to unambiguous events. Given this assumption, Henry and Henry (2002) demonstrate that non-precautionary policies are in general non-optimal.

4 Conclusion

This paper has considered trade and the PP in an uncertain world where trading partners have divergent attitudes towards uncertainty (ambiguity). We have shown that in such a world, in the absence of risk concerns, Pareto optimality requires that the less ambiguity averse country absorb all of the uncertainty in its consumption pattern. The more ambiguity-averse country, on the other hand, optimally absorbs no ambiguity. An immediate corollary of this result is that a common prescription of the PP, no trade in uncertain products, can be Pareto optimal.

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