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Pollution control with uncertain stock dynamics: When, and how, to be precautious

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ABSTRACT

The precautionary principle (PP) applied to environmental policy stipulates that, in the presence of uncertainty, society must take robust preventive action to guard against worst-case outcomes. It follows that the higher the degree of uncertainty, the more aggressive this preventive action should be. This normative maxim is explored in the case of a stylized dynamic model of pollution control with uncertain (in the Knightian sense) stock dynamics, using the robust control framework of Hansen and Sargent [12]. Optimal investment in damage control is found to be increasing in the degree of uncertainty, thus confirming the conventional PP wisdom. Optimal mitigation decisions, however, need not always comport with the PP. In particular, when damage-control investment is both sufficiently cheap and sensitive to changes in uncertainty, damage-control investment and mitigation may act as substitutes and a PP with respect to the latter can be unambiguously irrational. The theoretical results are applied to a calibrated linear-quadratic model of climate change. The analysis suggests that a reversal of the PP with respect to mitigation, while theoretically possible, is very unlikely.

1. Introduction

A common thread running through much of environmental economics is a reliance on expected utility as a means of performing cost-benefit analysis and, more broadly, as a normative criterion. There are many compelling reasons for its primacy: expected utility theory has solid theoretical underpinnings, going back to the work of von Neumann and Morgenstern [27] and Savage [30], is conceptually intuitive, and leads to tractable optimization problems. However, in the case of environmental economics, its attractive qualities often come at a price, primarily due to two basic factors: (a) the high structural uncertainty over the physics of environmental phenomena which makes the assignment of precise probabilistic model structure untenable [35] and (b) the high sensitivity of model outputs to controversial modeling assumptions (for instance, the functional form of the chosen damage function [32,36] and the value of the social discount rate). As a result, separate models may arrive at dramatically different policy recommendations, generating significant uncertainty over the magnitude and timing of desirable policy.[1]

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[1] William Nordhaus' DICE model [28] and the Stern Report [31] are the canonical examples of this deep divergence within the context of climate change economics.

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A general guide for crafting policy under such uncertain conditions can be found in the formulation of a *precautionary principle* (PP). Simply put, the PP embodies the age-old mantra "better safe than sorry". Here is the way it was expressed as Principle 15 of the Rio Declaration, in the context of the 1992 United Nations Earth Summit:

> In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.[2]

The Wingspread Statement, formulated at the 1998 Wingspread Conference on the Precautionary Principle, goes even further:

> 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.[3]

In our work we focus on another variation, which involves the adaptation of policy to *changing* levels of uncertainty. In particular, we consider an extension of the PP that prescribes an increase in the stringency of precautionary policy as the degree of uncertainty grows. While this statement does not necessarily follow from either of the above formulations of the PP, we believe it to be a defensible extension of its overarching logic.

To ground our study on a rigorous quantitative basis, we take the broad term of "uncertainty" to mean an inability to posit precise probabilistic structure to physical and economic models. This derives from the concept of uncertainty as introduced by Knight [24] to represent a situation where a decisionmaker lacks adequate information to assign probabilities to events. Knight argued that this deeper kind of uncertainty is quite common in economic decisionmaking, and thus deserving of systematic study. Knightian uncertainty is contrasted to risk (measurable or probabilistic uncertainty) where probabilistic structure can be fully captured by a *single* Bayesian prior. There is considerable evidence that it may provide a more appropriate modeling framework for many applications in environmental economics, and especially climate change [35,26].

Inspired by the work of Knight and subsequently by Ellsberg [4], economic theorists have questioned the classical expected utility framework and attempted to formally model preferences when probabilistic beliefs are not of sufficiently high quality to generate prior distributions.[4] Klibanoff et al. [22,23] developed an axiomatic framework, the "smooth ambiguity" model, in which different degrees of aversion for uncertainty are explicitly parameterized in agents' preferences. In their model an act f is preferred to an act g if and only if $\mathbf{E}_p\phi(\mathbf{E}_\pi u \circ f) > \mathbf{E}_p\phi(\mathbf{E}_\pi u \circ g)$, where u is a von Neumann–Morgenstern utility function, ϕ an increasing function, and p a subjective second order probability over a set Π of probability measures π that the decisionmaker is willing to consider ($\mathbf{E}$ denotes the expectation operator). When ϕ is concave the decisionmaker is said to be *ambiguity averse*. A compelling feature of the smooth ambiguity model is that it allows for a separation between ambiguity (the set Π and the second-order distribution p) and a decisionmaker's attitude (i.e., aversion) towards it, nesting in a smooth fashion the entire continuum between simple aggregation of the prior π's (ambiguity neutrality) to absolute focus on the worst-case (absolute ambiguity aversion). Comparative statics exercises involving the above are relatively easy to perform (at least in the static version of the model) and generate rich and insightful results.

In recent years the smooth ambiguity framework has been applied to a number of issues in environmental economics [9,33,26,25]. However, despite its prominent role in the recent literature, the smooth ambiguity model seems (at least to us) to have more of a positive instead of a normative focus, and questions about how to calibrate agents' ambiguity aversion in environmental settings appear difficult to address. As an example, consider global climate-change policy: it is unclear to us how one could, or even should, use Ellsberg-type thought experiments to calibrate ambiguity aversion parameters on whose ultimate basis optimal emissions trajectories will be determined. An additional, potential, shortcoming of the general approach is that it relies on knowledge of second-order probabilities (the distribution p) when in some instances such knowledge may not be possible or justified. Finally, the dynamic version of the smooth ambiguity model [23] poses nontrivial tractability challenges, so that (at times) only the utility of very simple, exogenously given policies can be computed [26].

Our focus is on robust control in this setting. In a seminal contribution, Gilboa and Schmeidler [8] developed the axiomatic foundations of *maxmin* expected utility, an alternative to classical expected utility for economic environments featuring unknown risk. They argued that when the underlying uncertainty of an economic system is not well understood, it is sensible, and axiomatically compelling, to optimize over the worst-case outcome (i.e., the worst-case *prior*) that may conceivably come to pass. Doing so guards against potentially devastating losses in any possible state of the world, and thus adds an element of robustness to the decision-making process.

Motivated by the possibility of model misspecification in macroeconomics, Hansen and Sargent [12] and Hansen et al. [15] extended Gilboa and Schmeidler's insight to continuous-time dynamic optimization problems, introducing the concept of robust control to economic environments. They showed how standard dynamic programming techniques can be modified to yield robust solutions to problems in which the underlying stochastic nature of the model is not perfectly known. In their work, the degree of misspecification is a model input, so that decisionmakers can test the sensitivity of a

[2] http://www.unep.org/Documents.multilingual/Default.asp?DocumentID=78&ArticleID=1163

[3] http://www.sehn.org/state.html#w

[4] The related decision-theoretic literature is both vast and deep so the following remarks are by no means meant to be exhaustive. We purely focus on the few contributions that are directly relevant for our purposes.