Johnson, A. R. 2012. Avoiding environmental catastrophes: varieties of principled precaution. *Ecology and Society* 17(3): 9.
http://dx.doi.org/10.5751/ES-04827-170309

Synthesis

Avoiding Environmental Catastrophes: Varieties of Principled Precaution

Alan R. Johnson [1]

ABSTRACT. The precautionary principle is often proposed as a guide to action in environmental management or risk assessment, and has been incorporated in various legal and regulatory contexts. For many, it reflects the common sense notion of being safe rather than sorry, but it has attracted numerous critics. At times, proponents and critics talk at cross purposes, due to the multiplicity of ways the precautionary principle has been formulated. The approach taken here is to examine four general varieties of precaution, relating each to arguments made in various contexts by others. First, I examine the parallel between the precautionary principle and an argument referred to as Pascal's wager. Critics are right to dismiss versions of the precautionary principle that follow the logic of Pascal's wager, because that argument requires assumption of an infinite catastrophe, which is seldom the case in environmental decisions. Second, I explore precaution viewed as an instance of the phenomenon of ambiguity aversion as described by Daniel Ellsberg. Third, I evaluate precautionary perspectives on our duties to future generations, drawing inspiration from the views of Gifford Pinchot. Fourth, I consider the precautionary principle as an instance of Aldo Leopold's notion of intelligent tinkering. Although controversy persists, I find that a legitimate theoretical foundation exists to implement Ellsbergian, Pinchotian and Leopoldean varieties of precaution in environmental decision making. Additionally, I remark on the role of adaptive management and maintaining resilience in ecological and social systems as an approach to implementing the precautionary principle.

Key Words: *adaptive management, Aldo Leopold, ambiguity, Blaise Pascal, Daniel Ellsberg, decision theory, future generations, Gifford Pinchot, intelligent tinkering, precautionary principle, resilience, risk, uncertainty*

INTRODUCTION

The precautionary principle is notoriously difficult to pin down. It reflects the traditional wisdom, "better safe than sorry", but as a guide to action is severely limited. All things being equal, of course, one would rather be safe than be sorry. But, all things are seldom equal. Choosing the safest course of action may entail foregoing potential benefits afforded by riskier actions. Avoiding risk may lead to regret over missed opportunities, raising the prospect of being both safe and sorry.

Sandin (1999) and Manson (2002) summarize the key components of the precautionary principle. Manson (2002) presents a framework consisting of three elements: a damage condition, a knowledge condition, and a remedy statement. Manson (2002) lists seven damage conditions, seven knowledge conditions, and six remedies, each of which have been suggested in some statement of the precautionary principle. Sandin's (1999) framework is similar, consisting of four dimensions: threat, uncertainty, action, and command. Sandin (1999) lists nine threat phrases, ten uncertainty phrases, nine action phrases, and ten command phrases. These frameworks demonstrate the multiplicity of possible precautionary principles (294 combinations in Manson's framework, 8100 in Sandin's). Not all are equally defensible, but the frameworks assist comparative analysis of formulations that have been advocated.

Consider two frequently cited statements of the precautionary principle. The first comes from Principle 15 of the United Nations Rio Declaration from the 1992 United Nations Earth Summit (United Nations Conference on the Environment and Development 1993):

> *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.*

In this formulation, the damage condition is "threats of serious or irreversible damage", the knowledge condition is "lack of full scientific certainty", and the remedy is rejection of arguments for postponing preventative measures. As Sandin et al. (2002) point out, this formulation does not really mandate specific action, but rather nullifies a particular sort of argument against taking action.

Another frequently cited version comes from a conference in the Wingspread Conference Center, in Racine, Wisconsin in 1998 (http://www.sehn.org/state.html):

> *Therefore it is necessary to implement the Precautionary Principle: Where an activity raises threats of harm to the environment or human health, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically.*
>
> *In this context the proponent of an activity, rather than the public bears the burden of proof.*

[1]Clemson University

> *The process of applying the Precautionary Principle must be open, informed and democratic, and must include potentially affected parties. It must also involve an examination of the full range of alternatives, including no action.*

Analyzing this statement within Manson's framework, the damage condition is "threat of harm to the environment or human health", the uncertainty condition is "some cause and effect relationships not fully established scientifically" and the remedy is vaguely worded as "precautionary measures" that, based on the rest of the statement, would seem to include a full examination of alternatives with the burden of proof resting on the proponents of the potentially harmful activity. This shift in the burden of proof, from the need to demonstrate risk to a requirement to demonstrate safety, is often noted as an implication of the precautionary principle by advocates and detractors alike.

The precautionary principle has many proponents, and has been incorporated in legal and regulatory contexts (Freestone and Hey 1996, Raffensperger and Tickner 1999). It also has numerous critics. Various formulations of the principle have been criticized for being ill-defined (Bodansky 1991), incoherent (Peterson 2006), or absolutist (McKinney 1996, Nollkaemper 1996), for leading to increased risk (Nollkaemper 1996), for stifling innovation (Holm and Harris 1999), or for being unscientific (Gray and Bewers 1996). It is beyond the scope of this paper to evaluate each of these criticisms with respect to the many possible formulations of the precautionary principle. The approach taken here will be to examine four general varieties of precaution, relating each to arguments made in various contexts by others. First, I examine the parallel between the precautionary principle and an argument referred to as Pascal's wager. Second, I will explore precaution viewed as an instance of the phenomenon known as ambiguity aversion. Third, I evaluate precautionary perspectives on our duties to future generations, drawing inspiration from the views of Gifford Pinchot. Fourth, I consider the precautionary principle as an instance of Aldo Leopold's notion of intelligent tinkering. Additionally, I remark on the role of adaptive management and maintaining resilience in ecological and social systems as an approach to implementing the precautionary principle.

PASCALIAN PRECAUTION: AVOIDING INFINITE CATASTROPHES

Blaise Pascal (1623 - 1662) made substantial contributions to physics, mathematics, and religious philosophy. Of particular relevance here is an argument, known as Pascal's wager, concerning the existence of God. The wager is not strictly an argument for the existence of God, but rather a prudential argument regarding rational behavior in the face of uncertainty about God's existence.

Pascal's wager has been presented in many variant forms, not all of which are directly attributable to Pascal (Hájek 2003, Jordan 2006). In his posthumously published work, *Penseés*, Pascal poses the following dilemma (Pascal and Krailsheimer 1966:149-153):

> *'Either God is or he is not.' But to which view shall we be inclined? Reason cannot decide this question. Infinite chaos separates us. At the far end of this infinite distance a coin is spun which will come down heads or tails. How will you wager?*

It is fitting that Pascal, who contributed much to the developing mathematics of probability through his analysis of gambling, frames the argument as a wager. In modern discussions, the decision is analyzed using a payoff matrix as employed in game theory. There are two mutually exclusive and exhaustive possible states of reality: either God exists or not. The individual must decide between two courses of action: to wager for or against the existence of God. Wagering for God's existence is not exactly equivalent to believing in God: a close reading of Pascal's writing indicates that the wager is better described as acting in a manner consistent with belief in God. For Pascal, belief is a matter of the heart rather than rational choice, but behaving as if God exists (attending mass, etc.) can lead one toward genuine belief. In the payoff matrix (Fig. 1), some payoffs are infinite and others are finite.

Fig. 1. Payoff matrix for Pascal's wager. There are two possible states of reality (God exists or not), and two possible actions (wager for or against God). Each element of the matrix reflects the payoff, or utility, corresponding to a possible situation. A wager for God yields an infinitely positive utility, if God exists. In all other cases, the utility is either finite, or possibly negative infinity for a wager against an existent God.

	God exists	God does not exist
Wager for God	$u_1 = +\infty$	u_2 = finite
Wager against	$u_3 = -\infty$ or finite	u_4 = finite

It is crucial to Pascal's argument that, if God exists, those who wager for God will be rewarded with "an eternity of life and happiness" (Pascal and Krailsheimer 1966: 151). The payoff is infinitely positive. Pascal leaves unspecified the fate of those who wager against God if God exists. One could assume the payoff is either finite or negative infinity. If God does not exist, the payoffs are realized during a human lifespan, and therefore finite (u_2 and u_4). Pascal argues that "wherever there is infinity, and where there are not infinite chances of losing against that of winning, there is no room for hesitation, you must give everything." In short, the possibility of an infinite reward swamps all other considerations, compelling the individual to wager for God (see Appendix 1 for details).

The logic of the precautionary principle, in some formulations, bears an analogy to Pascal's wager. This can be seen from a payoff matrix (Fig. 2) which assumes the possibility of a negatively infinite payoff (the catastrophe) if precautionary steps are not taken to avoid it. The situation involves uncertainty: it is possible the catastrophe will not arise, even if no precautionary action is taken. However, in a kind of reverse application of Pascal's logic, whenever a negative infinity is involved, we must do everything to avoid it (Haller 2000). Manson (2002) calls this the "catastrophe principle" (see Appendix 1 for details).

Fig. 2. Payoff matrix for an environmental analogue of Pascal's wager. It is assumed that an ecological catastrophe, should it occur, would have an infinite negative utility. However, precautionary action would avert this catastrophic outcome, leading to a finite payoff.

	Catastrophe would occur	Catastrophe would not occur
Wager for catastrophe (precautionary action)	u_1 = finite	u_2 = finite
Wager against (no precautionary action)	$u_3 = -\infty$	u_4 = finite

Pascal's argument, based on infinite expected utility for those who wager for God, has provoked many critical responses. Most philosophers find Pascal's reasoning is valid, in the sense that the conclusions follow logically from the stated premises (e.g., Hacking 1972, Jordan 2006), but they question the premises. The "many gods" objection criticizes Pascal for framing the decision problem too simplistically. In a world where multiple religions worship different gods, one must consider the consequences of worshiping the "wrong" god. Assume God_1 is Pascal's deity, and God_2 is some other deity that rewards his/her own believers, but eternally punishes followers of God_1. The payoffs for any wager for God_1 now includes both positive infinity (if God_1 exists) and negative infinity (if God_2 exists), so it is no longer clear how to compute the expected utility.

The environmental "catastrophe principle" has similarly been attacked as being oversimplified (Manson 2002, van den Belt 2003). A "many catastrophes" objection would argue that the precautionary action may itself lead to a catastrophe, albeit a different one. For instance, van den Belt (2003) presents a scenario (attributed to Comstock, but the cited web page is no longer available) in which the use of genetically modified (GM) crops carries a nonzero probability of leading to ecological catastrophe. However, it is also assumed that the precautionary measure of banning GM crops implies a small probability of catastrophic food shortages. As long as these catastrophes are treated as infinite disutilities, Pascal's logic provides no guidance for action, since the expected utility is the same whether precautionary action is taken or not.

Some philosophers (e.g., Duff 1986, Hájek 2003), challenge the logical validity of Pascal's argument. The gist of their objection is this: in game theory, it is usual to consider not only pure strategies (i.e., wager for or wager against God), but also mixed strategies. One mixed strategy would be to flip a coin; if it comes up heads, wager for God, if it comes up tails, wager against. Now, it might seem absurd to make a potentially fateful decision using a random process, but it turns out that such a process has the same expected utility (positive infinity) as a pure wager for God. In fact, any mixed strategy that has a nonzero probability of wagering for God is as good as Pascal's pure wager. So, I could buy a lottery ticket, resolving that if I win the jackpot I will wager for God, otherwise I will wager against God. This strategy, too, has infinite expected utility.

In the ecological analogue of Pascal's wager, precautionary action is the preferred strategy. But what if mixed strategies are considered? As long as the mixed strategy has any nonzero probability of avoiding precautionary action, its expected utility is $-\infty$, which we will seek to avoid. Thus, in contrast to Pascal's original formulation, a pure precautionary strategy is always the dominant choice.

However, the use of infinite disutility to characterize ecological catastrophe requires scrutiny. What environmental consequences would constitute an infinite disutility? The answer depends upon the perspective from which values are assessed. Arguably, an individual might assign an infinite disutility to the loss of a single human life, if the life to be lost is one's own. However, from the perspective of society at large, the loss of a single human life, although regrettable, can hardly be regarded as an infinite catastrophe. What constitutes an infinite catastrophe for society? Extinction of the human race? Some environmental catastrophes might rise to that level, but these are not the circumstances to which the precautionary principle is usually applied. More typically, precaution is urged in circumstances in which there is a possibility of a catastrophe with large, but finite, disutility. This can be represented in a payoff matrix (Fig. 3) where $-k$ is the cost associated with precautionary action, $-c$ is the cost of the catastrophe, and b is the payoff if precautionary action is not taken and a catastrophe does not occur. Since precautionary action often translates into avoiding some risky but potentially beneficial alternative, b might be assumed to be positive. Unlike Pascal's wager, the expected utilities are always finite, and the expected utility of not taking precautionary action decreases linearly with p. There will always be some value of p below which the expected value of not taking precautionary action will exceed the expected value of precaution (Appendix 1). Typically this will only be true when *p* is quite small; however, the value of *p* is no longer irrelevant when catastrophes have finite disutility. We do not live in a world where precaution *always* trumps other courses of action, but surely there are many cases in which precaution is warranted, even when dealing with less than infinite catastrophes.

Fig. 3. Payoff matrix assuming that an ecological catastrophe would result in a large, but finite, negative cost (-c). The cost associated with taking precautionary action is –k. The payoff if no precautionary action is taken and no catastrophe occurs is b, which could be positive or negative, but is often assumed to be a positive benefit.

	Catastrophe would occur	Catastrophe would not occur
Wager for catastrophe (precautionary action)	$u_1 = -k$	$u_2 = -k$
Wager against (no precautionary action)	$u_3 = -c$	$u_4 = b$

ELLSBERGIAN PRECAUTION: AVOIDING AMBIGUITY

Daniel Ellsberg (born 1931) is best known for leaking classified documents (the Pentagon Papers), which detailed the history of decisions made regarding the involvement of the United States in Vietnam. Before his involvement in this political drama, Ellsberg studied economics. The ideas relevant to this research were presented in a seminal publication (Ellsberg 1961) and expanded in his thesis (recently published as Ellsberg 2001). Ellsberg is concerned with decisions under uncertainty, following the distinction drawn by Knight (1921) between measurable uncertainty (which Ellsberg calls risk) and unmeasurable uncertainty (which Ellsberg calls ambiguity). Similarly, John Maynard Keynes (1921) distinguishes between probabilities that can be assigned definite numerical values versus noncomparable probabilities for which the weight of evidence does not support numeric estimates (Feduzi 2007). Like Keynes, Ellsberg believes that in situations characterized by high ambiguity, rational actors may make decisions that cannot be explained by any assignment of numerical probabilities reflecting degrees of belief associated with events. Their behavior implies a systematic violation of certain axioms that have been taken as foundational in decision theory (Ramsey 1931 or Savage 1954). Many people persist in their choices, even upon reflection and with full knowledge that they are violating axioms often viewed as normative for rational decisions. Often, the inconsistency takes the form of ambiguity aversion: a systematic preference for gambles in which probabilities are precisely known or restricted to tighter bounds (Ellsberg 1961, 2001).

Gilboa et al. (2008) illustrate ambiguity aversion by the hypothetical deliberations of Ann, an admissions officer for a graduate program. Ann is reviewing the files of two applicants: X, who comes from a college that is well known to Ann, and Y, who comes from a foreign country and unfamiliar college. Based on her experience with similar students in the program, she estimates that X has a probability of 0.6 of successfully graduating from the program. For applicant Y, lacking any basis for a more informed estimate, she assumes a probability of success equal to the success rate for all students, which happens to also be 0.6. The probabilities assigned to each candidate are equal, so by standard decision theory, Ann should be indifferent to choosing one applicant or the other. However, the two probabilities do not “feel” the same. They differ in the ambiguity associated with the numerical value, and it would not be surprising if Ann were to bet on X in preference to Y.

Various alternatives to the standard approach have been suggested (Appendix 2). Ellsberg (2001: 190-199) suggests the use of the restricted Bayes/Hurwicz criterion. Gilboa and Schmeidler (1989) have developed an approach based on Maxmin Expected Utility (MEU), which seeks to avoid worst-case outcomes. The more general α-MEU decision criterion weighs both worst-case and best-case outcomes (Ghirardato et al. 2004, Basili and Zappia 2010). Schmeidler (1989) developed an alternative called Choquet Expected Utility (CEU), in which probabilities are treated as nonadditive. This approach has been further elaborated by Basili (2006) and Basili et al. (2008).

Empirical studies of decisions in the face of ambiguity reveal a complicated pattern (Viscusi and Chesson 1999, Di Mauro and Maffioletti 2004). Decision makers tend to be ambiguity-adverse with respect to low probability losses, which can be viewed as a kind of pessimism motivated by fear of worst-case scenarios. Conversely, with respect to low probability gains, decision makers often exhibit ambiguity-seeking behavior, reflecting optimism triggered by hope for best-case scenarios. However, with respect to (presumably familiar) high probability events, rather than being ambiguity-neutral, in many cases decision makers demonstrate a crossover to reverse ambiguity attitude displayed for low probability events. In other words, they display ambiguity seeking for high probability losses and ambiguity aversion for high probability gains. Viscusi and Chesson (1999) document a reversal in ambiguity attitude by coastal business owners and managers asked to decide where to locate a new business, based on hypothetical information about the risks of storm damage. In cases in which the mean risk of damage is low, respondents prefer locations where experts agree about the degree of risk (ambiguity aversion), whereas when the mean risk is high, they preferred locations where experts disagreed (ambiguity seeking), perhaps reflecting a hope that the more favorable risk estimates would prevail.

It has been well documented that attitudes toward ambiguity lead decision makers to violate the predictions of expected utility theory (von Neumann and Morgenstern 1944) or subjective expected utility (Savage 1954). From a descriptive standpoint, behaviors such as the Ellsberg paradox, or precautionary measures taken to avoid catastrophes with low but ambiguous probabilities, are a common phenomenon. More controversial is the normative value of ambiguity attitudes in setting rational public policy.

Statistician and Bayesian decision theorist Dennis Lindley (2006) denies any normative role for precaution based on ambiguity attitudes. According to Lindley, ambiguity-adverse choices made by subjects in the Ellsberg paradox are "ridiculous" because they are incoherent, that is, they lead to violations of sensible axioms of expected utility or subjective expected utility theory (Lindley 2006:157). For Lindley, those axioms characterize rational decisions, and their violation simply indicates that such ambiguity avoidance must be an error in decision making, however intuitively appealing it might be. A number of economists and risk analysts agree (for example, Peterson 2006).

Ellsberg (2001) does not view ambiguity-induced violations of decision-theoretic axioms as irrational. Rather, he traces the disagreement to a difference in opinion about the relevance of certain kinds of information. He suggests that those who ignore their own perceptions of ambiguity in order to act consistently with an axiomatic framework are, in fact, behaving irrationally because they fail to distinguish situations in which the consequences of one's actions are well known from those in which they are not (Ellsberg 2001).

Similarly, Hansson (2009) criticizes the misapplication of probabilistic risk analysis, which proceeds on the assumption that reliable probabilities can be specified for all outcomes, to situations with ambiguous outcomes. This misuse of probabilistic decision logic in situations in which it does not apply he terms the *tuxedo fallacy*. The name comes from casino games, such as roulette, where probabilities are well known, and probabilistic reasoning can be applied. Much of real life, Hansson argues, is more like an expedition into an unknown jungle, where hazards are known to exist, but their nature and probabilities cannot be reliably quantified. Some of these uncertainties may extend beyond the ambiguity considered by Ellsberg, and include areas of complete ignorance, or unknown unknowns.

Various alternatives to probabilistic risk analysis could be suggested in the face of ambiguity and unknown hazards. One practical suggestion offered by Costanza and Cornwell (1992) is the "precautionary polluter pays principle", dubbed the 4P approach. Rather than expecting science to yield precise predictions, the role of science should be seen as defining an envelope of possible outcomes, and policy should be set with special reference to the worst-case edge of the envelope.

Thus, although controversy exists, a strong case can be made for precautionary decision making under ambiguity when catastrophic outcomes are possible. We turn now to a consideration of the precautionary principle as means of pursuing the utilitarian goal of producing the greatest good for the greatest number, and particularly to the question of the time scale appropriate to such considerations.

PINCHOTIAN PRECAUTION: LOOKING TO THE FUTURE

Gifford Pinchot (1865 – 1946) helped shape the American conservation movement of the early twentieth century as Chief of the newly created United States Forest Service under President Theodore Roosevelt. Pinchot viewed the natural world as a repository of resources to be used for human benefit, while preventing waste and inequitable distribution. As Pinchot (1910:79) wrote in *The Fight for Conservation*, his book defending the goals of the conservation movement to the American public:

> *The central thing for which Conservation stands is to make this country the best possible place to live in, both for us and for our descendants. It stands against the waste of the natural resources which cannot be renewed, such as coal and iron; it stands for the perpetuation of the resources which can be renewed, such as the food-producing soils and forests; and most of all it stands for an equal opportunity for every American citizen to get his fair share of benefit from these resources, both now and hereafter.*

The approach adopted by Pinchot and other Progressive Era conservationists has been characterized as a "gospel of efficiency" (Hays 1969:266). But, arguably, considerations of equity were at least as important (Koppes 1987, Miller 1992). Pinchot's orientation toward the environment was utilitarian, emphasizing the instrumental value of nature, that is to say, the practical uses of nature as resource. However, the equitable distribution of the benefits of natural resource use was also paramount. Of particular importance for us is the question of intergenerational equity. His concern for the needs of future generations is evident (Pinchot 1910:48):

> *Conservation means the greatest good to the greatest number for the longest time. One of its greatest contributions is just this, that it has added to the worn and well-known phrase, "the greatest good to the greatest number," the additional words "for the longest time," thus recognizing that this nation of ours must be made to endure as the best possible home for all its people.*

This concern for future generations can justify a form of precaution regarding current consumption of natural resources, which is at the heart of Pinchot's vision of conservation.

Public policy must often take into account not only present costs and benefits, but future consequences as well, perhaps extending many generations hence. The traditional economic approach is to apply a discount rate, converting costs and benefits that accrue in the future to a net present value (Heal 2007; Appendix 3). A high discount rate results in less weight being given to consequences for future generations.

Justification of discounting in evaluation of public policy has tended to focus on either the time preference of individuals (assuming preferences of current consumers should prevail), or on opportunity costs (requiring public expenditures to compare favorably with other possible investments) (Robinson 1990). Although deference to consumer time preferences is often taken for granted now, the early utilitarians Jeremy Bentham and David Hume were highly suspicious of time preference in matters of public policy. In his 1739 *A Treatise of Human Nature*, Hume writes (Norton and Norton 2007:345):

> *There is no quality in human nature, which causes more fatal errors in our conduct, than that which leads us to prefer whatever is present to the distant and remote...*

Hume concludes that it is a proper role of government to guard against such errors.

Determining a discount rate based on opportunity costs is independent of individual time preference, and might seem objective. However, determining the proper numerical value for the discount rate is highly controversial. Some argue that market interest rates should be used (Montgomery 1999). However, the application of even a modest discount rate, when applied over an intergenerational time span reduces the value of far future benefits dramatically, leading others to question the use of any fixed discount rate (Kysar 2007). Furthermore, the premise of continued economic growth into the indefinite future, which undergirds an opportunity cost calculation, could itself be questioned.

Considerable controversy has emerged over the treatment of discounting in the Stern Review, which presents an economic analysis of long-term costs and benefits of global climate change and strategies for mitigation or adaption (Stern 2007). This review, published by the UK Treasury, is not the first cost-benefit analysis of the impacts of climate change, but is the first to carry the imprimatur of a major government (Cole 2008). A key assumption is the use of a low value ($\delta = 0.001$ yr^{-1}) for the pure rate of time preference. In justification of this value, the Stern Review argues that there is no sound ethical justification to value the utility of future generations less than our own, and the only reason to apply a nonzero value of δ is to reflect uncertainty about the existence of future generations. Thus, $e^{-\delta t}$ can be interpreted as the probability that the world (or at least the human race) will exist *t* years in the future, assuming extinction is a Poisson process (Stern 2007). Even $\delta = 0.001$ might seem high if literal world destruction were the only possibility considered, but the Stern Review also intends for δ to account for eventualities such as nuclear war or global pandemics that would represent catastrophic shocks to the global economy without total human extinction (Stern 2007).

Nordhaus (2008:176) questions the ethical justification for a low value of δ, remarking that “it stems from the British utilitarian tradition, with all the controversies and baggage that accompany that philosophical stance”. He briefly discusses ethical frameworks that might allow very different rates of time preference. Perhaps each generation should leave as much total capital (tangible, natural, human, and technological) as it inherited. Although not mentioned by Nordhaus, this clearly assumes the substitutability of various kinds of capital. Thus, a decline in natural capital could be justified as long as it is made up for by gains in, say, tangible and technological capital. Alternatively, a Rawlsian perspective would suggest that we should maximize the well-being of the poorest generation. This, Nordhaus concludes, would tilt the scales toward increasing current consumption. Finally, he suggests a “precautionary (minimax) principle” (Nordhaus 2008:176) to maximize the minimum consumption along the riskiest path, which might entail stockpiling vaccines, food, energy supplies, etc. Although Nordhaus does not say so, such a precautionary approach might also justify substantial current expenditures to avert the risk of devastating and irreversible effects from climate change, in concordance with the recommendations of the Stern Review.

Nordhaus’ primary objection is that the discounting applied in the Stern Review is at variance with observed dynamics of existing markets. Nordhaus, using the Stern Review’s values for δ, η and g, calculates the overall discount rate (ρ) as 1.4%, which he maintains should reflect the real interest rate on investments. Since economic data point to considerably higher rates of return (typically 3 – 6%), Nordhaus rejects the Stern Review as unrealistic. Although Nordhaus (2007) notes the distinction between “descriptive” versus “prescriptive” discussions of discounting, he clearly favors a descriptive approach. The Stern Review, in contrast, makes a prescriptive claim about how society ought to value future costs and benefits, without regard to current practice.

Weitzman (2007:723) is also critical of the choice to use a near-zero value for δ, but ultimately concludes that the Stern Review may be “getting it right for the wrong reasons.” According to Weitzman (2007), climate change challenges the standard economic approach to discounting, and a low discount rate may be justified given the large uncertainty associated with potentially catastrophic long-term consequences. In this case, a low discount rate serves as insurance against potential catastrophe (a form of Ellsbergian precaution, rather than a Pinchotian concern for future generations).

Beyond debating the appropriate numerical value for the discount rate, one can challenge the approach more fundamentally. Instead of the standard discounting procedure, one could apply a nonconstant discount rate, particularly one that declines over time (Groom et al. 2005). The most widely suggested form of a declining discount rate is proportional to the logarithm of time (Appendix 3).

One might abandon the use of any form of discounting in evaluating temporal choices. Heal (1998, 2007), following von Weizäcker (1967), discusses the overtaking criterion, where one economic path is said to be preferable (i.e., to overtake) another if at some point the cumulative utility along the preferred path exceeds the cumulative utility along the other path, and remains higher for all future times. Unfortunately, there is no guarantee that an overtaking path exists, or, there may be multiple paths that cannot be ranked by this criterion alone. Another approach is the safe minimum standard (Ciriacy-Wantrup 1968), proposed for the conservation of renewable resources with a critical zone, that is, a threshold beyond which the effects of depletion are technologically or economically irreversible. This definition could apply to many resources, but has found particular application in endangered species management. The minimum viable population defines the critical zone, and the safe minimum standard approach would guard against reducing the population below this threshold. According to Bishop (1978), the safe minimum standard approach implies preventing extinction unless the social costs of doing so are unacceptably large. It recognizes an imperative to protect species, but does not always trump economic considerations (Berrens et al. 1998). Norton (2001) notes two sources of vagueness in this formulation: (1) uncertainties in quantifying the threshold or critical zone, and (2) the unresolved question of what level of social costs are unacceptable. These require resolution in any practical application.

The precautionary approaches that have been discussed are all concerned with sustaining resources for use by future generations of humans. As such, they are compatible with Gifford Pinchot's utilitarian vision of the goal of conservation. They are also compatible with most of the modern rhetoric on environmental sustainability. However, as Newton and Freyfogle (2005) discuss, a fundamentally different vision of the goal of conservation was offered by Aldo Leopold.

LEOPOLDEAN PRECAUTION: THE ART OF INTELLIGENT TINKERING

Aldo Leopold (1887 - 1948) was trained as a forester, established the field of game management, and has been highly influential in environmental philosophy. Based on his experience in New Mexico and Arizona, he questioned Pinchot's principle of highest use, at least as it was being applied to land use decisions in the American Southwest. He was instrumental in the creation of the first officially designated wilderness area in the United States, surrounding the headwaters of the Gila River. His book of collected essays, *A Sand County Almanac*, published after his death, remains influential. It provides a philosophical foundation for what Leopold calls a "land ethic", a set of moral obligations regarding our treatment of the environment (Callicott 1987, Rolston 2000).

In his essay, *The Round River*, Leopold (1966:190), writes:

> *The last word in ignorance is the man who says of an animal or plant: 'What good is it?' If the land mechanism as a whole is good, then every part is good, whether we understand it or not. If the biota, in the course of aeons, has built something we like but do not understand, then who but a fool would discard seemingly useless parts? To keep every cog and wheel is the first precaution of intelligent tinkering.*

Leopold repeatedly uses the image of a clock as a metaphor for the complicated structure of interacting parts that characterize the land or the biotic community. He implies that as one learns more about complex ecological relationships, one comes to greater appreciation of how much is still unknown:

> *The ordinary citizen today assumes that science knows what makes the community clock tick; the scientist is equally sure that he does not. He knows that the biotic mechanism is so complex that its workings may never be fully understood.* (Leopold 1966:240-241)

> *To sum up: a system of conservation based solely on economic self-interest is hopelessly lopsided. It tends to ignore, and thus eventually eliminate, many elements in the land community that lack commercial value, but that are (as far as we know) essential to its healthy functioning. It assumes, falsely, I think, that the economic parts of the biotic clock will function without the uneconomic parts.* (Leopold 1966:251)

In contrast to Pinchot's emphasis on the instrumental value of nature, Leopold is often interpreted as supporting an intrinsic value of nature. In the watch metaphor, however, the values at stake are difficult to classify. Components of a watch derive their value from their function in the integrated whole. This is a sort of instrumental value: the parts are valuable because they are useful to the whole. The whole itself can be viewed as valuable on either instrumental or intrinsic grounds. Leopold's rule of intelligent tinkering is therefore a precautionary principle designed to prevent unintended damage to the whole by destruction of poorly understood parts. It is a hedge against ignorance.

It should be noted that although Leopold expresses caution with regard to the management of ecological systems, he clearly does not object to some level of use and manipulation of those systems for human purposes. A prerequisite for developing a philosophy of “intelligent tinkering” is the concession that tinkering should be allowed, with appropriate precautions. This contrasts with the decision strategy recommended by Hansson (1996) for dealing with situations characterized by uncertainty in the consequences of human actions. Hansson advocates a policy of “noninterference”, essentially refraining from any action if the consequences are unclear but potentially catastrophic. Such a hands-off approach may be feasible in some cases, but in cases in which ecosystems are utilized to satisfy human resource demands, noninterference is not an option. However, Leopold insists on a respect for the land, including its uneconomic parts, which dictates a cautious approach.

The idea of “intelligent tinkering” is similar to that of adaptive management, in which management interventions or policies are implemented as experiments and results are monitored, allowing for subsequent changes in management, leading to an improvement over time (Holling 1978, Walters 1986). Clearly, adaptive management requires willingness to experiment, or tinker, with the system being managed. The value of tinkering is that it allows the manager to learn about the dynamics of the ecosystem, hopefully leading to more effective and efficient management strategies in the long run.

Doyen and Pereau (2009) illustrate how an adaptive approach to decision making can result in precautionary, cost-effective management. They frame their discussion as a robust control problem in which the decision maker’s goal is to reach a safe target condition at minimal cost. They distinguish strong precaution, which requires the decision maker to reach the target without any learning to reduce uncertainty, versus adaptive precaution, which assumes learning and decreasing uncertainty over time. Their analysis quantifies the value of information when adaptive precaution is employed, and they demonstrate that the safe target may be reachable following adaptive precaution, even in cases where no strongly precautionary solution exists.

Hauser and Possingham (2008) consider adaptive management in terms of optimal harvesting of a natural resource which, at each time step, has a known probability of collapse, and an unknown probability of recovery. They conclude that management for long time horizons favors experimentation because accumulated observations allow the uncertainty in recovery probability to be reduced. A short management horizon favors a more precautionary approach because known benefits are preferred to possibly higher but uncertain benefits. When the time horizon for management is short, there may be insufficient opportunity for information gained by experimentation to actually improve the management outcome. The way Hauser and Possingham present experimentation and precaution as opposing strategies seems at odds with the notion of intelligent tinkering. However, experimentation in their model simply drives the system to different states in order to observe the dynamics. It does not alter the system in a way that fundamentally alters its behavior. Specifically, they assume the system will recover from a collapsed state with a fixed (but unknown) probability, and experimentation does not change the recovery rate. Since this experimentation maintains the integrity or resilience of the system, it is compatible with Leopold’s precautionary notion of intelligent tinkering.

There is a natural tension between adaptive management and the precautionary principle. Adaptive management requires a degree of risk taking as policies are implemented as experiments with uncertain outcomes, and advocates of precaution are wary of actions that may entail unforeseen results. However, in the face of great uncertainty about the dynamics of the system under management, it may be impossible to know which (if any) management option will attain the desired goal, as argued by Doyen and Pereau 2009. In that situation, the risk of experimentation (or learning by doing) may be justified as a strategy to reduce the longer term risk of undesired consequences arising from unknowingly applying maladapted policies. Leopold’s metaphor of intelligent tinkering provides guidance to the adaptive manager: experiment with the system to better understand its dynamics (“what makes the community clock tick”), but avoid irreversible structural alterations (“keep every cog and wheel”).

Many versions of the precautionary principle advocate the avoidance of irreversibility, but leave the term undefined. Manson (2007) explores the concept of irreversibility, identifying three fundamentally different usages: thermodynamic, medical, and economic. Irreversible thermodynamic processes are ubiquitous, and not the issue of concern for advocates of precaution. The precautionary principle seems to employ an analogy to medical usage, which characterizes some disease states as irreversible, in the sense that medical intervention cannot bring about recovery to a healthy state. This is a functional concept, claiming that the biological functions associated with health are irreversibly lost. Finally, the precautionary principle may relate to the concept of economic irreversibility, which focuses on the degree to which decisions can or cannot be reversed.

Of these, Leopold’s caution to keep all the parts seems most closely allied with an extended notion of medical irreversibility. It may be that some of those cogs and wheels are necessary for the proper, healthy functioning of the ecosystem. Even if they are not currently essential for ecosystem function, they may be needed in other contexts. For instance, native thistles (*Cirsium* species) are relatively minor components of North American grasslands and often viewed as undesirable. However, it has been argued that they serve to maintain a reservoir of native insects that promote resistance to invasion by alien species, which would be ecologically and economically disruptive (Louda and Rand 2003). Such functional considerations undoubtedly factor into Leopold's admonition, but I do not think they capture the whole of his sentiment.

Martin (1979) analyzed the concept of irreplaceability as applied to environmental management decisions, formulating the argument based on a utilitarian ethical framework. He argues that utilitarianism can support most appeals to preserve irreplaceable objects, including heirlooms and original works of art, which are valued for their origins or for sentimental reasons, because attitudes toward an object count in the calculation of utility. Even so, Martin (1979) expresses some reservation as to whether a utilitarian framework can always capture the argument for preservation of nature based on irreplaceability. Katz (1979) is more critical, finding the utilitarian approach fundamentally incompatible with the preservationist argument. He would ground such arguments on a basis that was not dependent upon fickle human attitudes toward nature. I think that Leopold would agree. Although the urge to maintain the parts is partially motivated by functional considerations, and these can often be given utilitarian value, Leopold is simultaneously critical of those who would base the argument for preservation on purely economic considerations. Perhaps species and ecosystems have unique value analogous to that which some philosophers invoke to argue for the irreplaceability of individual human beings (Grau 2006).

Norton (2005:88-92) argues that Leopold anticipated the core ideas of adaptive management. I have argued that his notion of intelligent tinkering mandates a precautionary approach. Leopold's injunction to keep all the parts is motivated by a concern for maintaining the functioning of ecosystems, even, or especially, if we do not completely understand how they function. Today we might say that experimentation on managed ecosystems should be conducted in a way that does not threaten the resilience of the ecosystem. Maintaining resilience seems to reflect the essence of Leopold's precautionary sentiment, and since resilient ecosystems are arguably more likely provide ecological goods and services over the long term, it may be precautionary from a Pinchotian perspective as well.

SUMMARY

There are many varieties of precaution, variously expressed as principles to guide action in environmental management or risk assessment. Critics are right to dismiss versions that follow a logic analogous to Pascal's wager, because that argument requires the assumption of an infinite catastrophe, which is seldom, if ever, the case in environmental decisions. However, there are few advocates for a truly Pascalian precautionary principle. There are, on the other hand, more plausible versions of the precautionary principle, of which I have examined three types.

Perhaps the relevance of these varieties of precaution are best articulated by reference to an actual environmental policy debate. Consider the case of oil versus wilderness in the Arctic National Wildlife Refuge (ANWR) in Alaska (Standlea 2006, Layzer 2012). Created by the U.S. Congress in 1980 under the Alaska National Interest Lands Conservation Act (ANILCA), ANWR encompasses over 78,000 km^2 of remote and diverse landscape. Controversy over the best use of this land was evident before the passage of ANILCA, and continues to the present. While much of ANWR has been designated as wilderness, section 1002 of ANILCA instructed the Department of Interior to study the suitability of the Coastal Plain portion for oil and gas development. However, in an unusual provision, actual leasing, exploration, and production were prohibited unless authorized by Congress. For three decades now there has been vigorous debate, but the American public and their representatives have thus far chosen to forego oil and gas development. This outcome may be viewed as a precautionary approach.

Ellsbergian precaution applies when probabilities associated with catastrophic outcomes cannot be reliably estimated, whether due to lack of information, conflicting evidence, or divergent expert opinion. In the case of ANWR, both estimates of recoverable oil and gas reserves and of the risks associated with oil and gas development vary widely. The ambiguity in probabilities associated with possible outcomes make it difficult to place confidence in decisions based on calculations of expected utility. Various decision criteria have been developed, which take ambiguity into account as alternatives to the standard formulation of decision theory. Though controversial, they do offer tools that might be more broadly applied to environmental decision making in circumstances warranting Ellsbergian precaution.

Pinchotian precaution is motivated by a concern for environmental benefits and costs to future generations, reflecting Pinchot's concern for "the greatest good to the greatest number for the longest time" (Pinchot 1910:48). A common theme in the debate over ANWR is the trade-off between relatively short-term and temporary benefits of oil and gas production versus the possible long-term impacts that would be apparent for generations. Economists view such issues in terms of the discount rate to be applied to future benefits and costs. Again, the topic is controversial, but advocates of a Pinchotian precautionary principle can find support for choosing a low constant discount rate, or a discount rate that declines over time, or employing criteria that do not use a discount rate.

Leopoldean precaution is based on Aldo Leopold's notion of intelligent tinkering. Experimentation in the management of natural resources (tinkering) should always be conducted in a manner that preserves the integrity of the ecosystem. Leopoldean precaution is motivated by the humble recognition that scientists or ecosystem managers do not really understand the complex dynamics of the systems they study and manage. Ecosystems are always capable of surprise. In ANWR, there is concern over the impact of oil and gas development on particular species or wildlife populations, such as polar bears or the Porcupine caribou herd. There is also concern that oil and gas development will pave the way for future land and resource uses, eroding the wilderness character of the area. I have interpreted Leopold's perspective as being equivalent to the goal of maintaining resilience in ecological systems, and compatible with adaptive management. Thus, theoretical tools developed for characterizing ecological resilience and adaptive management of social-ecological systems are applicable.

The precautionary principle, in various formulations, has been the subject of much discussion at a conceptual level, especially from philosophical, policy, legal, and economic perspectives. Much of what I have highlighted so far has been at a conceptual level. This was necessary to lay the groundwork on which to build. In addition, I have pointed to a number of formal or quantitative approaches that offer legitimate approaches for applying the precautionary principle to environmental decision making. Some of these approaches have been explored, particularly in economic analyses, but much remains to be done. This research offers a guidepost to promising paths for future work.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol17/iss3/art9/responses/

Acknowledgments:

I gratefully acknowledge Dr. Sandra Turner for valuable comments on the manuscript. This material is based upon work supported by the NIFA/USDA, under project number SC-1700406, and by the USGS through the South Carolina Water Resources Center. Technical Contribution No. 6039 of the Clemson University Experiment Station.

LITERATURE CITED

Ainslie, G., and N. Haslam. 1992. Hyperbolic discounting. Pages 57-92 *in* G. Lowenstein, and J. Elster, editors. *Choice over time.* Russell Sage Foundation, New York, NY, USA.

Basili, M. 2006. A rational decision rule with extreme events. *Risk Analysis* 26:1721-1728. http://dx.doi.org/10.1111/j.1539-6924.2006.00826.x

Basili, M., A. Chateauneuf, and F. Fontini. 2008. Precautionary principle as a rule of choice with optimism on windfall gains and pessimism on catastrophic losses. *Ecological Economics* 67:485-491. http://dx.doi.org/10.1016/j.ecolecon.2007.12.030

Basili, M., and C. Zappia. 2010. Ambiguity and uncertainty in Ellsberg and Shackle. *Cambridge Journal of Economics* 34:449-474. http://dx.doi.org/10.1093/cje/bep008

Berrens R. P., D. S. Brookshire, M. McKee, and C. Schmidt. 1998. Implementing the safe minimum standard approach. *Land Economics* 74:147-161. http://dx.doi.org/10.2307/3147047

Bishop, R. C. 1978. Endangered species and uncertainty: the economics of a safe minimum standard. *American Journal of Agricultural Economics* 60:10-18. http://dx.doi.org/10.2307/1240156

Bodansky, D. 1991. Scientific uncertainty and the precautionary principle. *Environment* 33(7):4-5, 43-44. http://dx.doi.org/10.1080/00139157.1991.9929978

Callicott, J. B. 1987. The conceptual foundations of the land ethic. Pages 186-217 *in* J. B. Callicott, editor. *Companion to a Sand County almanac: interpretive and critical essays.* University of Wisconsin Press, Madison, WI, USA.

Ciriacy-Wantrup, S. V. 1968. *Resouce conservation: economics and policies.* Third edition. University of California, Division of Agricultural Sciences, Berkeley, CA, USA.

Cole, D. R. 2008. The Stern review and its critics: implications for the theory and practice of benefit-cost analysis. *Natural Resources Journal* 48:53-90.

Costanza, R. E., and L. Cornwell. 1992. The 4P approach to dealing with scientific uncertainty. *Environment* 34:12-20, 42.

Cowen, T. 2007. Caring about the distant future: why it matters and what it means. *The University of Chicago Law Review* 74:5-40.

Di Mauro, C, and A. Maffioletti. 2004. Attitudes to risk and attitudes to uncertainty: experimental evidence. *Applied Economics* 36:357-372. http://dx.doi.org/10.1080/00036840410001674286

Doyen, L., and J.-C. Pereau. 2009. The precautionary principle as a robust cost-effectiveness problem. *Environmental Modeling and Assessment* 14:127-133. http://dx.doi.org/10.1007/s10666-008-9153-7

Duff, A. 1986. Pascal's wager and infinite utilities. *Analysis* 46:107-109. http://dx.doi.org/10.2307/3328185

Ellsberg, D. 1961. Risk, ambiguity, and the Savage axioms. *Quarterly Journal of Economics* 75:643-669. http://dx.doi.org/10.2307/1884324

Ellsberg, D. 2001. *Risk, ambiguity and decision.* Garland, New York, NY, USA.

Feduzi, A. 2007. On the relationship between Keynes's conception of evidential weight and the Ellsberg paradox. *Journal of Economic Psychology* 28:545-565. http://dx.doi.org/10.1016/j.joep.2007.01.005

Freestone, D., and E. Hey. 1996. Origins and development of the precautionary principle, Pages 3-15 *in* D. Freestone, and E. Hey, editors. *The precautionary principle and international law*. Kluwer Law International, Dordrecht, The Netherlands.

Ghirardato, P., F. Maccheroni, and M. Marinacci. 2004. Differentiating ambiguity and ambiguity attitude. *Journal of Economic Theory* 118:133-173. http://dx.doi.org/10.1016/j.jet.2003.12.004

Gilboa, I., A. W. Postlewaite, and D. Schmeidler. 2008. Probability and uncertainty in economic modeling. *Journal of Economic Perspectives* 22:173-188. http://dx.doi.org/10.1257/jep.22.3.173

Gilboa, I., and D. Schmeidler. 1989. Maxmin expected utility with non-unique prior. *Journal of Mathematical Economics* 18:141-153. http://dx.doi.org/10.1016/0304-4068(89)90018-9

Gollier, C. 2001. Should we beware of the precautionary principle? *Economic Policy* 33:301-327. http://dx.doi.org/10.1111/1468-0327.00077

Grau, C. 2006. Irreplaceability and unique value. *Philosophical Topics* 32:111-129.

Gray, J. S., and M. Bewers. 1996. Towards a scientific definition of the precautionary principle. *Marine Pollution Bulletin* 32:768-771.

Groom, B., C. Hepburn, P. Koundouri, and D. Pearce. 2005. Declining discount rates: the long and the short of it. *Environmental and Resource Economics* 32:445-493. http://dx.doi.org/10.1007/s10640-005-4681-y

Hacking, I. 1972. The logic of Pascal's wager. *American Philosophical Quarterly* 9:186-192.

Hájek, A. 2003. Waging war on Pascal's wager. *The Philosophical Review* 112:27-56.

Haller, S. 2000. A prudential argument for precaution under uncertainty and high risk. *Ethics and the Environment* 5:175-189. http://dx.doi.org/10.1016/S1085-6633(00)00026-7

Hansson, S. O. 1996. Decision making under great uncertainty. *Philosophy of the Social Sciences* 26:369-386. http://dx.doi.org/10.1177/004839319602600304

Hansson, S. O. 2009. From the casino to the jungle: dealing with uncertainty in technological risk management. *Synthese* 168:423-432. http://dx.doi.org/10.1007/s11229-008-9444-1

Hauser, C. E., and H. P. Possingham. 2008. Experimental or precautionary? Adaptive management over a range of time horizons. *Journal of Applied Ecology* 45:72-81. http://dx.doi.org/10.1111/j.1365-2664.2007.01395.x

Hays, S. P. 1969. *Conservation and the gospel of efficiency: the progressive conservation movement 1890-1920.* Harvard University Press, Princeton, NJ, USA.

Heal, G. 1998. *Valuing the future: economic theory and sustainability.* Columbia University Press, New York, NY, USA.

Heal, G. 2007. Discounting: a review of the basic economics. *The University of Chicago Law Review* 74:59-77.

Holling, C. S., editor. 1978. *Adaptive environmental assessment and management*. Wiley, Chichester, UK.

Holm, S., and J. Harris. 1999. The precautionary principle stifles discovery. *Nature* 400:398. http://dx.doi.org/10.1038/22626

Jordan, J. 2006. *Pascal's wager: pragmatic arguments and belief in God.* Clarendon Press, Oxford, UK.

Katz, E. 1979. Utilitarianism and preservation. *Environmental Ethics* 1:357-364.

Keynes, J. M. 1921. *A treatise on probability.* MacMillan, New York, NY, USA.

Knight, F. H. 1921. *Risk, uncertainty and profit.* Houghton Mifflin, Boston, MA, USA.

Koppes, C. R. 1987. Efficiency/equity/esthetics: towards a reinterpretation of American conservation. *Environmental Review* 11:127-146. http://dx.doi.org/10.2307/3984024

Kysar, D. A. 2007. Discounting ... on stilts. *The University of Chicago Law Review* 74:119-138.

Layzer, J. A. 2012. *The environmental case: translating values into policy.* Third edition. CQ Press, Washington, DC, USA.

Leopold, A. 1966. *A Sand County almanac, with essays on conservation from Round River.* Ballantine Books, New York, NY, USA.

Lindley, D. V. 2006. *Understanding uncertainty.* Wiley, Hoboken, NJ, USA. http://dx.doi.org/10.1002/0470055480

Louda, S. A., and T. A. Rand. 2003. Native thistles: expendable or integral to ecosystem resistance to invasion? Pages 5-15 *in* P. Kareiva, and S. Levin, editors. *The importance of species: perspectives on expendability and triage.* Princeton University Press, Princeton, NJ, USA.

Manson, N. A. 2002. Formulating the precautionary principle. *Environmental Ethics* 24:263-274.

Manson, N. A. 2007. The concept of irreversibility: its use in the sustainable development and precautionary principle literatures. *The Electronic Journal of Sustainable Development* 1:3-15.

Martin, J. N. 1979. The concept of the irreplaceable. *Environmental Ethics* 1:31-48.

McKinney, W. J. 1996. Prediction and Rolston's environmental ethics: lessons from the philosophy of science. *Science and Engineering Ethics* 2:429-440. http://dx.doi.org/10.1007/BF02583929

Miller, C. 1992. *Gifford Pinchot: the evolution of an American conservationist.* Grey Towers Press, Milford, PA, USA.

Montgomery, W. D. 1999. A market-based discount rate: comments on Bradford. Pages 45-49 *in* P. R. Portney, and J. P. Weyant, editors. *Discounting and intergenerational equity.* Resources for the Future, Washington, DC, USA.

Newton, J. L., and E. T. Freyfogle. 2005. Sustainability: a dissent. *Conservation Biology* 19:23-32.

Nollkaemper, A. 1996. 'What you risk reveals what you value', and other dilemmas encountered in the legal assaults on risks. Pages 73-94 *in* D. Freestone, and E. Hey, editors. *The precautionary principle and international law*. Kluwer Law International, Dordrecht, The Netherlands.

Nordhaus, W. 2007. Critical assumptions in the Stern review on climate change. *Science* 317:201-202.

Nordhaus, W. 2008. *A question of balance: weighing the options on global warming policies.* Yale University Press, New Haven, USA.

Norton, B. G. 2001. What do we owe the future? How should we decide? Pages 213-231 *in* V. A. Sharpe, B. G. Norton, and S. Donnelley, editors. *Wolves and human communities: biology, politics, and ethics.* Island Press, Covelo, CA, USA.

Norton, B. G. 2005. *Sustainability: a philosophy of adaptive management.* University of Chicago Press, Chicago, IL, USA.

Norton, D. F., and M. J. Norton, editors. 2007. *David Hume: a treatise of human nature.* Volume 1: Texts. Oxford University Press, Oxford, UK.

Pascal, B. Translated by A. J. Krailsheimer. 1966. *Pensées*. Penguin Books, Baltimore, MD, USA.

Peterson, M. 2006. The precautionary principle is incoherent. *Risk Analysis* 26:595-601. http://dx.doi.org/10.1111/j.1539-6924.2006.00781.x

Pinchot, G. 1910. *The fight for conservation.* Doubleday, Page & Company, New York, NY, USA.

Raffensperger, C., and J. Tickner, editors. 1999. *Protecting public health and the environment: implementing the precautionary principle.* Island Press, Washington, DC, USA.

Ramsey, F. P. 1931. Truth and probability. Pages 156-198 *in* R. B. Braithwaite, editor. *The foundations of mathematics*. Routledge & Kegan Paul, London, UK.

Robinson, J. C. 1990. Philosophical origins of the social rate of discount in cost-benefit analysis. *The Millbank Quarterly* 68:245-265. http://dx.doi.org/10.2307/3350098

Rolston III, H. 2000. The land ethic at the turn of the millennium. *Biodiversity and Conservation* 9:1045-1058. http://dx.doi.org/10.1023/A:1008918517655

Sandin, P. 1999. Dimensions of the precautionary principle. *Human and Ecological Risk Assessment* 5(5):889-907. http://dx.doi.org/10.1080/10807039991289185

Sandin, P., M. Peterson, S. O. Hansson, C. Rudén, and A. Juthe. 2002. Five charges against the precautionary principle. *Journal of Risk Research* 5(4):287-299. http://dx.doi.org/10.1080/13669870110073729

Savage, L. J. 1954. *The foundations of statistics.* John Wiley & Sons, New York, NY, USA.

Schmeidler, D. 1989. Subjective probability and expected utility without additivity. *Econometrica* 57:571-587. http://dx.doi.org/10.2307/1911053

Standlea, D. M. 2006. *Oil, globalization, and the war for the Arctic refuge*. State University of New York Press, Albany, NY, USA.

Stern, N. 2007. *The economics of climate change: the Stern review.* Cambridge University Press, Cambridge, UK.

Summers, L., and R. Zeckhauser. 2008. Policymaking for posterity. *Journal of Risk and Uncertainty* 37:115-140. http://dx.doi.org/10.1007/s11166-008-9052-y

United Nations Conference on Environment and Development. 1993. *The Earth Summit: the United Nations Conference on Environment and Development.* Graham & Trotman/Martinus Nijhoff, London, UK.

van den Belt, H. 2003. Debating the precautionary principle: "guilty until proven innocent" or "innocent until proven guilty"? *Plant Physiology* 132:1122-1126. http://dx.doi.org/10.1104/pp.103.023531

Viscusi, W. K. 2007. Rational discounting for regulatory analysis. *University of Chicago Law Review* 74:209-246.

Viscusi, W. K., and H. Chesson. 1999. Hopes and fears: the conflicting effects of risk ambiguity. *Theory and Decision* 47:153-178. http://dx.doi.org/10.1023/A:1005173013606 von Neumann, J., and O. Morgenstern. 1944. *Theory of games and economic behavior.* Princeton University Press, Princeton, NJ, USA.

von Weizäcker, C. C. 1967. Lemmas for a theory of approximately optimal growth. *Review of Economic Studies* 34:143-151.

Walters, C. 1986. *Adaptive management of renewable resources*. Macmillan, New York, NY, USA.

Weitzman, M. L. 2001. Gamma discounting. *American Economic Review* 91:260-271. http://dx.doi.org/10.1257/aer.91.1.260

Weitzman, M. L. 2007. A review of *the Stern review on the economics of climate change*. *Journal of Economic Literature* 45:703-724. http://dx.doi.org/10.1257/jel.45.3.703

Pascal's wager

Hacking (1972) distinguishes three separate logical arguments in the passage from *Pensées* discussing the wager. The discussion is based on a game-theoretic analysis, and can be understood by assuming the following payoff matrix:

	God exists	God does not exist
Wager for God	$u_1 = +\infty$	$u_2 =$ finite
Wager against	$u_3 = -\infty$ or finite	$u_4 =$ finite

The first argument Hacking (1972) describes he calls the "argument from dominance." In game theory, one strategy is said to dominate if its payoff is better than alternative strategies in at least one case, and is never less than the payoff for alternative strategies. For Pascal's wager, it is clear that, if God exists, $+\infty > u_3$, and Pascal goes on to argue that nothing is lost by wagering for God if God does not exist, and there are gains to reaped in this life, implying $u_2 \geq u_4$. For the environmental analogue, clearly $u_1 > -\infty$. However, for the argument from dominance to succeed, we must also show that $u_2 \geq u_4$. This latter condition is likely to be at least as contentious in the environmental sphere as it is in theological discussions, so an argument from dominance will not generally be persuasive in urging precautionary action.

The second logical argument is called the "argument from expectation" (Hacking 1972). Here Pascal develops an argument based on the probabilities associated with various outcomes in a manner akin to the modern concept of expected utility. Pascal at first assumes that there is an equal chance that God that exists or not. The assumption of equiprobability is reminiscent of the "principle of indifference" used in assigning probabilities to random events such as a coin toss or roll of dice (Jordan 2006, p.22). Pascal proceeds to consider the case where probability that God exists is assigned any non-zero value, *p*, which Hacking calls the "argument from dominating expectation." Based on this assumption the expected utility (EU) of each of the wagers can be calculated:

EU(Wager for God) = $p \cdot (+\infty) + (1 - p) \cdot (u_2) = +\infty$

EU(Wager against God) = $p \cdot (u_3) + (1 - p) \cdot (u_4) =$ finite

Thus, a wager for God yields a higher (i.e., infinite) expected value. Pascal concludes one should wager for God, even if one thinks it is very unlikely that God exists.

An environmental analogue of Pascal's wager

These arguments can be adapted to an environmental analogue of Pascal's wager (Haller 2000). We assume the following payoff matrix:

	Catastrophe would occur	Catastrophe would not occur
Wager for catastrophe (precautionary action)	u_1 = finite	u_2 = finite
Wager against (no precautionary action)	$u_3 = -\infty$	u_4 = finite

We can calculate expected utilities in the environmental catastrophe wager as:

EU(Precautionary Action) = $p \cdot (u_1) + (1 - p) \cdot (u_2) = \text{finite}$

EU(No Precautionary Action) = $p \cdot (-\infty) + (1 - p) \cdot (u_4) = -\infty$

Since any finite payoff is always better than $-\infty$, it follows by the argument of dominating expectation that we should take precautionary action. Note that this is true no matter what the relative values of u_2 and u_4 (unlike the argument from dominance), and even in cases where the probability of catastrophe (p) is very small.

If we relax the assumption of an infinite negative payoff if the catastrophe occurs, and make all the payoffs finite, the payoff matrix can be represented as:

	Catastrophe would occur	Catastrophe would not occur
Wager for catastrophe (precautionary action)	$u_1 = -k$	$u_2 = -k$
Wager against (no precautionary action)	$u_3 = -c$	$u_4 = b$

where $-k$ is the cost associated with precautionary action, $-c$ is the cost of the catastrophe, and b is the payoff if precautionary action is not taken and a catastrophe does not occur. Since precautionary action often translates into avoiding some risky but potentially beneficial alternative, b might be assumed to be positive. In accordance with the notion that $-c$ represents a catastrophic disutility, assume that $|c| >> |k|$ and $|c| >> |b|$. Let p represent the probability that catastrophe would occur in the absence of precautionary action. The expected utility of each (pure) strategy can be calculated as:

$$\text{EU(Precautionary Action)} = \quad p\cdot(-k) + (1 - p)\cdot(-k) = -k$$

$$\text{EU(No Precautionary Action)} = \quad p\cdot(-c) + (1 - p)\cdot(b) = b - (b+c)p$$

Unlike Pascal's wager, the expected utilities are always finite, and the expected utility of not taking precautionary action decreases linearly with p. There will always be some value of p (specifically, $p = (k+b)/(c+b)$), below which the expected value of not taking precautionary action will exceed the expected value of precaution. Presumably this will only be true when p is quite small; however, the value of p is no longer irrelevant when catastrophes have finite disutility.

LITERATURE CITED

Hacking, I. 1972. The logic of Pascal's wager. *American Philosophical Quarterly* 9:186-192.

Haller, S. 2000. A prudential argument for precaution under uncertainty and high risk. *Ethics and the Environment* 5:175-189.

Jordan, J. 2006. *Pascal's Wager: Pragmatic Arguments and Belief in God.* Clarendon Press, Oxford, UK.

Alternatives to standard decision theory for decisions under ambiguity

As an alternative to the standard approach, Ellsberg (2001, pp.190-199) suggests the use the restricted Bayes/Hurwicz criterion. Its essential features can be summarized as follows. Decisions are based on maximization over possible acts of an index containing a parameter, ρ, which varies between 0 and 1, depending upon the degree of ambiguity. If $\rho = 1$, the decision-maker maximizes expected utility. If $\rho = 0$, corresponding to the highest level of ambiguity (complete ignorance of relevant probabilities), the decision-maker acts to maximize a weighted average of the maximum and minimum expected utilities for each act. The standard Bayesian decision model assumes that *a priori* uncertainty is represented by a single probability distribution, whereas this approach allows for multiple prior probability distributions. The relative weight given to maximum versus minimum utilities is determined by a parameter α, which also varies between 0 and 1. When $\alpha = 0$ and $\rho = 0$, it reduces to Wald's criterion (Ellsberg 2001, p.159), also known as the minimax principle, in which the decisionmaker acts to maximize the minimum payoff – in other words, choosing the least disadvantageous of the worst case scenarios.

Gilboa and Schmeidler (1989) developed an axiomatic foundation for decision based on maxmin expected utility (MEU), encompassing application of Wald's or related criteria. This approach differs substantially from the standard approach to maximizing expected utility (e.g., von Neumann and Morgenstern 1944), which assumes an unambiguous assignment of probabilities to possible states of the world (i.e., a unique prior distribution). The MEU approach encompasses ambiguity by allowing multiple prior distributions. Gollier (2001) criticizes this approach as pathologically risk-adverse, leading to the stifling of innovation. It can be viewed as an extremely pessimistic approach to ambiguity which decisions only considers the worst plausible outcomes. However, ambiguous gambles can have favorable outcomes as well, which may also influence the decision-maker (Ellsberg 2001, p.206). This can be accounted for by use of the more general α-MEU decision criterion, which weighs both worst-case and best-case outcomes (Ghirardato et al. 2004, Basili and Zappia 2010).

Schmeidler (1989) developed an alternative formulation, called Choquet expected utility (CEU), in which a single prior distribution is assumed, but probabilities are treated as non-additive. In standard probability calculus, an event, X, and its complement, X^c, are assumed to be mutually exclusive and exhaustive of all possibilities, so $p(X) + p(X^c) = 1$. In situations characterized by ambiguity regarding the assignment of probabilities to states of the world, a decision-maker may act as if the probabilities are sub-additive, $p(X) + p(X^c) < 1$. Based on the CEU approach, Basilli (2006) proposed a decision rule that takes account of both familiar events (for which probabilities can be unambiguously assigned) and unfamiliar, extreme events (which are characterized by ambiguity). The decision maker is assumed to exhibit optimism with regard to low-probability windfall gains, pessimism with respect to low-probability catastrophic losses, and to be ambiguity-neutral with respect to familiar events (Basili 2006, Basili et al. 2008).

LITERATURE CITED

Basili, M. 2006. A rational decision rule with extreme events. *Risk Analysis* 26:1721-1728.

Basili, M., A. Chateauneuf and F. Fontini. 2008. Precautionary principle as a rule of choice with optimism on windfall gains and pessimism on catastrophic losses. *Ecological Economics* 67:485-491.

Basili, M. and C. Zappia. 2010. Ambiguity and uncertainty in Ellsberg and Shackle. *Cambridge Journal of Economics* 34:449-474.

Ellsberg, D. 2001. *Risk, Ambiguity and Decision.* Garland Publishing, New York, NY, USA.

Ghirardato, P., F. Maccheroni and M. Marinacci**.** 2004. Differentiating ambiguity and ambiguity attitude. *Journal of Economic Theory* 118:133-173.

Gilboa, I. and D. Schmeidler**.** 1989. Maxmin expected utility with non-unique prior. *Journal of Mathematical Economics* 18:141-153.

Gollier, C. 2001. Should we beware of the Precautionary Principle? *Economic Policy* 33:301-327.

Schmeidler, D. 1989. Subjective probability and expected utility without additivity. *Econometrica* 57:571-587.

von Neumann, J. and O. Morgenstern. 1944. *Theory of Games and Economic Behavior.* Princeton University Press, Princeton, NJ, USA.

Discounting over time in economic theory

Consider the problem of the optimal consumption of a natural resource. Let *s* represent the stock of resource (e.g., biomass of timber, abundance of fish, volume of ore, etc.), and let *c* represent consumption of the resource, which for simplicity, is assumed constant. The dynamics of the resource under exploitation can be represented as:

$$\frac{ds}{dt} = f(s) - c \quad \textbf{[1]}$$

where *f*(*s*) is a function representing the natural dynamics of the resource stock. From a utilitarian perspective, we assume that the goal of resource utilization should be to maximize the utility derived from consumption. Representing the utility of present consumption by *u*(*c*) and discounting exponentially in the future, the objective is to find:

$$\max \int_0^\infty u(c) e^{-\delta t} dt \quad \textbf{[2]}$$

where δ is the rate at which utility is discounted, also know as the pure rate of time preference (Heal 2007). Applied to individuals, δ reflects the preference for immediate rather than delayed enjoyment, which may be seen as a rational attitude toward an uncertain future (Viscusi 2007), or less flatteringly as impatience (Kysar 2007). Whatever the merits of a pure rate of time preference for individuals, its application in an intergenerational context is problematic (Cowen 2007, Heal 2007). It is not clear why the enjoyments of future generations should count for less simply because they occur in the future.

Discounting of utility is not the only motivation for discounting in economic analyses. Economists typically discount consumption based on the equation:

$$\rho = \delta + g\eta \quad \textbf{[3]}$$

where ρ is the discount rate applied to future per-capita consumption, δ is the pure rate of time preference, *g* is the rate of growth of per capita income, and η is minus the elasticity of marginal utility with respect to consumption (Summers and Zeckhauser 2008). The rate at which consumption is discounted, ρ, is sometimes called the social discount rate (Heal 2007). The second term of the equation implies that, in a growing economy, even if no discount is applied for pure time preference, an increment of consumption will be valued less in the future because of its lesser marginal utility as income rises. In this equation, per capita income is used as a surrogate for per capita resource consumption, implying:

$$g = \frac{1}{N}\frac{dI}{dt} \propto \frac{1}{c}\frac{dc}{dt} \qquad \textbf{[4]}$$

$$\eta = -c\frac{\partial^2 u / \partial c^2}{\partial u / \partial c} \qquad \textbf{[5]}$$

where I is total income, N is the number of consumers, and the other variables retain their previously stated meanings.

Instead of the standard discounting procedure, one could apply a non-constant discount rate, particularly one that declines over time (Groom et al. 2005). The most widely suggested form of a declining discount rate is one where the discount is proportional to the logarithm of time. In that case, we could re-write equation [2] as follows:

$$\max \int_0^\infty u(c)e^{-\delta \log t} dt = \max \int_0^\infty u(c)t^{-\delta} dt \qquad \textbf{[6]}$$

This form of discounting is variously referred to as hyperbolic discounting (Ainslie and Haslam 1992), logarithmic discounting (Heal 1998) or gamma discounting (Weitzman 2001). Heal (1998, pp.62-63) justifies this form of discounting as an expression of the Weber-Fechner law, an empirical generalization that human response many stimuli (e.g., sound or light) is proportional to the logarithm of the stimulus intensity. Weitzman (2001) presents an entirely different justification, arguing that if there is substantial disagreement among individuals about the proper exponential discount rate to apply, the effective social discount rate will decline over time. Weitzman (2001) conducted a survey of over 2000 professional economists, asking them to provide their best estimate of the discount rate that should be applied in evaluating projects to mitigate global climate change. The distribution of estimates was well approximated by a gamma distribution, which fit a model with a declining discount rate (approximately 4% for time horizons less than 5 years, declining to near zero for horizons greater than 300 years).

LITERATURE CITED

Ainslie, G. and N. Haslam. 1992. Hyperbolic discounting. Pages 57-92 in G. Lowenstein and J. Elster, editors. *Choice Over Time.* Russell Sage Foundation, New York, NY, USA.

Cowen, T. 2007. Caring about the distant future: why it matters and what it means. *The University of Chicago Law Review* 74:5-40.

Groom, B., C. Hepburn, P. Koundouri and D. Pearce. 2005. Declining discount rates: the long and the short of it. *Environmental and Resource Economics* 32:445-493.

Heal, G. 1998. *Valuing the Future: Economic Theory and Sustainability.* Columbia Univ. Press, New York, NY, USA.

Heal, G. 2007. Discounting: a review of the basic economics. *The University of Chicago Law Review* 74:59-77.

Kysar, D. A. 2007. Discounting ... on stilts. *The University of Chicago Law Review* 74:119-138.

Summers, L. and R. Zeckhauser. 2008. Policymaking for posterity. *Journal of Risk and Uncertainty* 37:115-140.

Viscusi, W.K. 2007. Rational discounting for regulatory analysis. *The University of Chicago Law Review* 74:209-246.

Weitzman, M. L. 2001. Gamma discounting. *American Economic Review* 91:260-271.