ENVIRONMENTAL POLICY AND RISK*

Kathleen Segerson**

Introduction

All economic activities, including agricultural production, involve risk or uncertainties. For example, agricultural production can involve uncertainty about what output prices will be at the time of harvest, uncertainty about the yields that will result from given input levels, and uncertainty about the effect that production will have on water quality. Some of these risks, such as price and output uncertainty (or more generally financial risks relating to revenues and costs), are internal to the firm, while the risks associated with environmental quality are often external.

This paper discusses a number of issues that arise when analyzing risks relating to environmental quality, with particular emphasis on the characteristics of those risks that make them different from financial risks and their implications for the design of public policy. The goal is not to provide a comprehensive review of the literature on environmental risk, but rather to provide an overview of the questions and considerations that arise in this context. The hope is that this will provide risk researchers who have focused on the impacts of uncertainty regarding costs and revenues with a sense of how environmental economists approach risk analysis and thereby pave the way for some cross-fertilization between researchers.

Examples of Environmental Risks

Nearly all environmental problems involve risk of some kind. Thus, the term "environmental risk" is very broad and relates to a wide range of environmental problems. The following is a partial list of environmental problems for which risk has been an important issue.

(1) Air pollution

- (a) Traditional (local) air pollutants (e.g., SO_2,NOx)
- (b) Global air pollutants (e.g., global warming)
- (c) Chemical releases into the air

(2) Water pollution

- (a) Surface water pollution from runoff or discharges
- (b) Groundwater contamination from leaching
- (c) Spills (e.g., oil spills)

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**Associate Professor, Department of Economics, University of Connecticut, Storrs, CT.

(3) Waste disposal

   (a) Hazardous waste disposal
   (b) Nuclear waste disposal

(4) Occupational health and safety (e.g., worker exposure)

(5) Food safety (e.g., pesticide residues in food)

(6) Ecological damages (e.g., biodiversity)

While a discussion of the specifics of these problems is beyond the scope of this paper, the list suggests that there are a number of different environmental contexts in which risk is an important element. Despite the differences in the details of each problem, there are some similarities across these problems that allow us to construct a general framework for discussing and analyzing environmental risks. Thus, rather than discuss any specific problem in detail, we instead present below some principles that relate to environmental risks in general.

Sources of Risk

As noted above, there are often many sources of risk involved in a particular production process. Figure 1 provides a summary of some of these sources. It indicates that a firm's actions are influenced by both input and output prices and government policies of various types. For example, both government price support programs and environmental policies relating to pesticides can influence a farmer's decisions about what to produce as well as how to produce it.[1] Price uncertainty can arise because of fluctuations in demand and supply conditions. Likewise, the impact of policies can be uncertain. For example, when a uniform policy is applied to a set of heterogeneous firms, the overall impact of the policy will depend on the unknown distribution of firms.[2]

The firm's decisions in turn combine with the physical characteristics of the production site to determine both the output of the firm (as well as the cost of producing that output and the profits resulting from its sale) and the level of pollution or environmental quality at or near the site. For example, agricultural output levels can be affected by soil characteristics and weather, which can also influence the extent to which chemicals applied at the surface leach to the groundwater or run off to nearby bodies of surface water. Again, however, there is uncertainty in these effects. Clearly, randomness related to weather creates risk regarding the actual output levels that will result from a given level of inputs. This randomness also creates uncertainty about leaching and runoff. Even in the absence of weather effects, the impact of a firm's actions on environmental quality can be uncertain because of imperfect information about the fate and transport coefficients that govern the movement of pollutants.

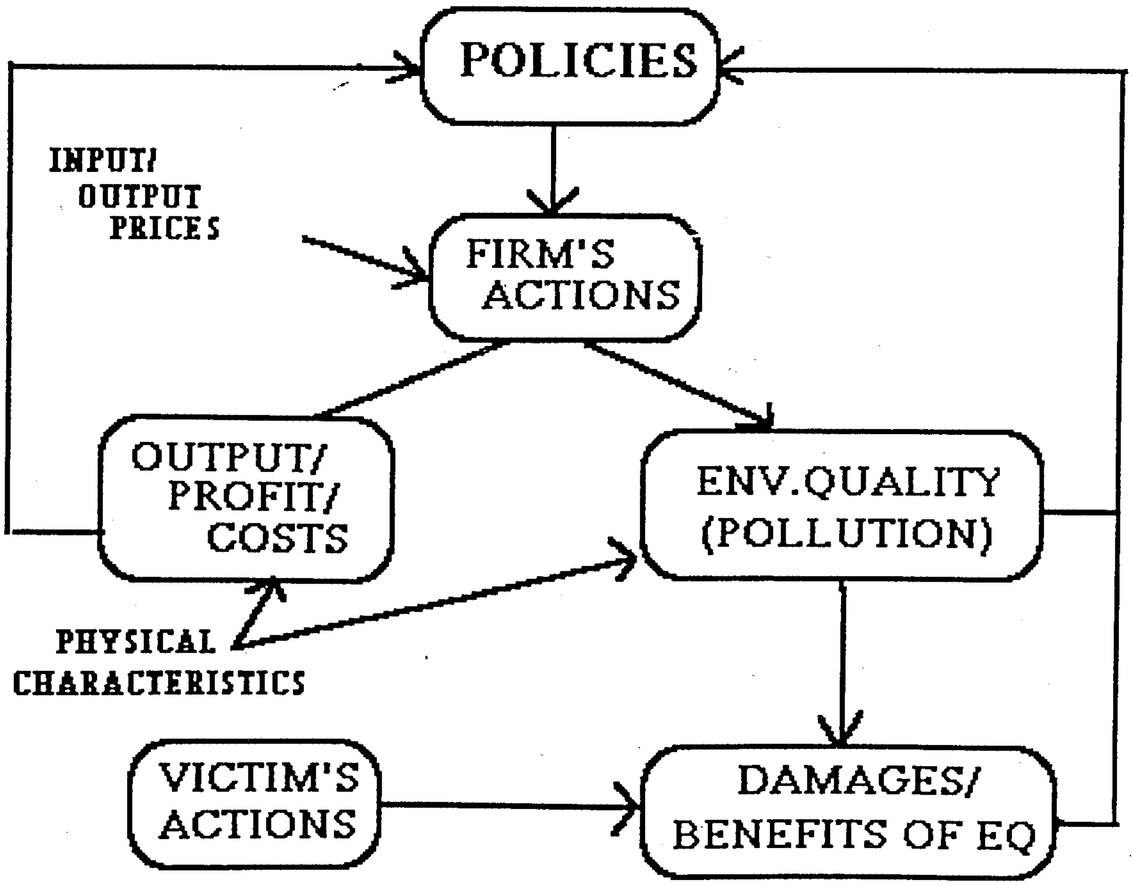
POLICIES
INPUT/
OUTPUT
PRICES
FIRM'S
ACTIONS
OUTPUT/
PROFIT/
COSTS
ENV.QUALITY
(POLLUTION)
PHYSICAL
CHARACTERISTICS
VICTIM'S
ACTIONS
DAMAGES/
BENEFITS OF EQ

FIGURE 1

The damages that result from any given level of pollution depend not only on that level but also on any actions taken by potential victims to reduce their exposure or reduce the damages associated with a given level of exposure. For example, the damages resulting from a given concentration of contaminants in groundwater can be reduced by installing filters or purchasing bottled water. While such actions are costly, they can be effective in reducing the damages that result from a given pollution level. The costs of these actions, together with the resulting physical damages, then determine the benefits from improvements in environmental quality, or the amount that individuals are willing to pay for a reduction in pollution. This willingness-to-pay can be interpreted as the demand for environmental quality.

In general, however, the damages that result from a given level of pollution will be uncertain. For example, pollutants combine with a number of other factors to determine overall health risks (e.g., the risk of getting cancer). Thus, increased exposure to a pollutant can increase the risk of contracting a particular illness but the amount by which that risk increases cannot generally be predicted with certainty. Even if it could be, the increased risk still implies that the effects are probabilistic rather than certain. Thus, in determining the demand for reductions in pollution, individuals are often required to value an effect that is uncertain. They are effectively expressing a perceived benefit from or willingness to pay for a reduction in a given health risk.

When setting environmental policies, legislators and regulators consider the improvement in environmental quality that is expected to result and the benefits associated with that improvement.[3] In some cases they then weigh these benefits against the cost of achieving the reduction as reflected in increased costs or reduced profits for firms.[4] Thus, policies can be responsive to both costs and benefits. However, in most cases neither the costs nor the benefits of achieving a given reduction will be known with certainty by the policymaker. For example, cost uncertainty can arise from the inability of the policymaker to know the technology of each firm, particularly when firms are heterogeneous. Likewise, uncertainties about the benefits of environmental quality can stem from imperfections in the valuation process used to estimate those benefits.

An Introduction to the Literature

Risk analysis by farm management and production economists has generally focused on the uncertainty relating to the firm's costs and revenues. Specifically, much work has been done on the implications of uncertainty regarding input and output prices and the existence of random variables (such as weather) in the production function. In contrast, risk analysis by environmental economists has generally focused on uncertainty relating to the other links in Figure 1.[5] A brief discussion of some of the relevant literature provides an indication of the types of questions that have been addressed in this context.

A number of studies have analyzed the role of uncertainty in the relationship between firm-level decisions and environmental quality in the context of agricultural nonpoint source pollution.[6] For example, Segerson (1988) considered whether a policy can be designed to induce efficient pollution abatement decisions by farms when those decisions cannot be easily monitored nor directly inferred from observation of ambient pollution concentrations due to the stochastic relationship between abatement decisions and pollution concentrations. She shows that an incentive mechanism based on an ambient pollution tax for concentration levels above a given threshold can induce efficient farmer decisions in the presence of uncertainty.

The literature on the valuation of non-market goods has also recognized the importance of uncertainty.[7] For example, in many contexts, a reduction in pollution concentrations will reduce the risk of morbidity (sickness) or mortality (death), and some measure of the amount individuals are willing to pay for reductions in these risks is sought. The standard valuation techniques, such as hedonic pricing models and contingent valuation, have been extended to incorporate uncertainty of this type. This can be done by defining expected utility to be a function of certain probabilities or risks and then interpreting a reduction in risk as the "good" that is to be valued.

Uncertainty can also arise from imperfect information about future demand for or benefits from an environmental resource. For example, the benefits from a dam that provides increased flood control will depend upon whether it is a wet year or a dry year. Similarly, the benefits that an individual derives from preservation of an environmental resource such as the Grand Canyon will depend upon whether that individual will ever visit the site, which may be uncertain at the time that the benefits are being measured. In such cases, Weisbrod (1964) suggested that, in addition to expected benefits based on the probability of a future visit and the benefits if such a visit occurred, an individual might also be willing to pay an "option value" to preserve the option of visiting the site in the future.

Weisbrod's suggestion spurred a large body of literature on the measurement of benefits (and the appropriate design of cost-benefit analysis) under uncertainty. The work that followed from his seminal paper can be divided into two categories. The first focuses on the difference between benefit estimates based on the expected values of consumer surplus and true (i.e., theoretically correct) measures of willingness to pay for a project or policy change. Some have argued that the true measure is the fixed amount an individual would be willing to pay for the change in all future states of the world, given the uncertainty about what the future state of the world will actually be. This measure has been termed "option price", and the difference between it and expected surplus has been termed "option value". Unlike the expected consumer surplus measure, option price reflects the individual's risk preferences. However, in an influential article Graham (1981) has shown that expected surplus and option price are just two possible measures of benefits. He defines an entire "willingness-to-pay locus" that represents all possible state-contingent price combinations that would make an individual just as well off with the change as without it. This has, in turn, led to an extended debate about which point on the willingness-to-pay locus is, in fact, the appropriate measure of benefits in the context of uncertainty and risk aversion. Since the measures differ in terms of their allocations of risk, the appropriateness of the measures hinges on the ability of individuals to insure against risks and the potential for reallocation of risk through state-contingent payments and compensation.[8]

The second strand of work that grew out of Weisbrod's paper relates to uncertainty about future benefits and the ability to gain additional information about those benefits over time. For example, Arrow and Fisher (1974) show that, when it is possible to learn about the future demand for a natural site, there is an additional benefit from preserving the site, i.e., delaying irreversible development in the current period, until better information becomes available.[9] This benefit has been termed "quasi-option value". It equals the conditional value of the information that would become available if the development were delayed. Unlike option value, quasi-option value exists even under risk neutrality.

Uncertainty about the benefits of improvements in environmental quality or natural resources raises questions about the appropriate "test" to use in the implementation of cost-benefit analysis. In particular, the standard compensation or potential pareto improvement test must be modified to reflect uncertainty. Alternative modifications are possible. For example, Freeman (1991) suggests that a change be deemed a potential pareto improvement if there is at least one set of state-dependent payments from the gainers that will finance a set of state-dependent compensations to the losers in such a way that no one is any worse off (in expected utility terms) and at least one person is strictly better off. This test is a generalization of some of the tests that have been proposed by others (Freeman 1993).

In addition to uncertainty about the benefits of environmental improvements, there can also be uncertainty about the costs of achieving those improvements, which can have implications for policy choice as well. If the uncertainty stems from uncertainty about what the state of the world will be, then cost uncertainty can be incorporated into a cost-benefit analysis in much the same way as benefit uncertainty. In fact, Freeman's (1991) potential pareto improvement test under uncertainty assumes that the cost of the project are uncertain as well.

Other forms of cost uncertainty may exist as well. For example, in some contexts pollution abatement costs might be known to the firms but unknown to the regulator who sets environmental policy. Weitzman (1974) considered the choice between price and quantity instruments in such a context.[10] Specifically, in setting the level of the policy (i.e., the level of the tax or the allowable level of emissions), the regulator is assumed to be uncertain about the marginal cost of abatement.[11] However, actual abatement decisions are made with perfect information about those costs. Weitzman compared the sizes of the resulting welfare losses under the two policy approaches and identified the conditions under which each would be preferred to the other. His seminal paper led to subsequent work on the implications of cost uncertainty for the choice of environmental policy instruments.[12]

Policy Responses

The brief introduction to the literature on environmental aspects of risk analysis given above suggests that most analyses are heavily policy-oriented. Specifically, researchers have in most cases been motivated by an interest in the implications of risk for the design of environmental policy. There are a number of different approaches to the design of risk-related environmental policy. A brief overview of these provides an indication of the range of policy instruments usually considered as possible risk management tools.[13]

One possible approach is to rely heavily on private actions to reduce environmental risks. In such cases, the role of the government can be primarily to provide information about the level of risk that individuals face.[14] For example, the government can provide information about the risks from certain substances such as pesticide residues in food or nitrates in groundwater. It can also provide information about the effectiveness of alternative means of reducing risks, and in some cases subsidize risk reduction (through, for example, well replacements or installation of filters). Under this approach, the government takes a passive role in risk management, leaving the primary role to private individuals and firms.

Alternatively, the government can take a more active role in risk management and institute policies designed specifically to ensure or induce certain types of behavior. For example, the government can use ex ante economic incentives (such as taxes or deposits) to induce firms to cut back on risk-generating activities.[15] Taxes on pesticides encourage farmers to cut back on pesticide use and therefore reduce their associated risks.

An alternative to the use of economic incentives is the direct use of regulation to control behavior. Most risky activities are subject to some sort of regulation. Those regulations generally take the form of safety standards or environmental quality goals. For example, regulations exist that govern the use of pesticides and the allowable time between application and worker re-entry into the field.[16] These regulations are designed to ensure "safe" use of the product. Environmental quality goals, on the other hand, are used to identify targets that must be met by some approach (unspecified in the goal). Examples include maximum contamination levels and the "fishable-swimmable" goal of the Federal Water Pollution Control Act (Freeman 1990).

Both tax-based policies and regulations are examples of ex ante policy approaches that are operative before any environmental damages occur. In contrast, legal liability is an ex post policy tool. It becomes operative only after damages have occurred, at which time the responsible party becomes liable for those damages. The two main approaches to legal liability are strict liability (under which a responsible party is held liable regardless of the amount of care he exercised in his activities) and negligence-based rules (under which the responsible party is liable only if he conducted his activities in a "negligent" way).

Finally, the government can establish victim compensation funds or otherwise help in the provision of insurance as a risk management approach. Victim compensation funds can be either narrowly or broadly based.[17] For example, a fund can be designed to provide compensation for victims of a specific type of environmental risk, such as Black Lung disease. This requires that a victim be able to establish the connection between his illness and an environmental exposure. While this is relatively easy in some cases (such as Black Lung disease), it can be difficult to establish causation for more broadly-based diseases such as cancer. While the causation problem can be solved by using a broad-based compensation fund (such as Workers' Compensation) that does not require proof of causation, such funds effectively become public insurance mechanisms.

This overview of alternative policy responses suggests that there are a wide range of policy approaches that can be used to manage environmental risks. The appropriateness of any given approach will in general depend on both the goal(s) of policy makers in designing risk management policies and the nature of the risks involved. Some policy approaches are effective in achieving one goal but not another. Likewise, some are more effective for certain types of risks than for others. We turn to a brief discussion of these issues next.

Goals of Risk Management Policies

Risk management policies can have three possible goals. The first is to reduce risks, where such a reduction can come about either through a reduction in the probability of a given event (e.g. a chemical spill) occurring or a reduction in the magnitude of the damages given the event has occurred (e.g., a reduction in exposure given a spill). Thus, policies can be designed to provide parties with incentives to reduce risks or to control directly the actions that create risks. Incentives for risk reduction can be targeted either toward the "injurer" or the "victim" when both can affect the risks involved. For example, the government should consider the impacts of the policy on both the incentive of the injurer to take care and the incentives of the victim to take steps to mitigate damages.

Some policies involve a tradeoff between injurer and victim incentives. For example, using a strict liability rule for damages creates efficient incentives for injurers to take care but does not provide an efficient incentive for victims to undertake mitigation (Shavell 1980). Alternatively, under a simple negligence rule, victims are induced to take efficient mitigation steps and, while injurers take efficient care, they do not produce an efficient amount of the risk-generating product. A similar conclusion holds for regulation of risk-generating activities. In contrast, under a Pigouvian tax, both victims and injurers can in theory be induced to act efficiently.[18]

A second goal of risk management policies is risk-sharing. When parties are risk averse, the allocation of risk has welfare impacts. An efficient allocation of risk spreads risks according to the risk aversion of the parties involved. For example, if one party is risk neutral while the other is risk averse, an efficient allocation of risk would place all of the risk on the risk neutral party.[19] If injurers are firms and victims are individuals, it might be appropriate to view injurers as risk neutral and victims as risk averse. In this case, efficient risk sharing would place the risk on injurers and require victim compensation to eliminate any risks borne by the victim. Of course, the ability of the parties to bear risk will be affected not only by their own risk preferences but also by the ability to purchase insurance to cover environmental risks. Thus, whether victim compensation is necessary to ensure efficient risk sharing will depend on the availability of insurance.

Policies can involve a tradeoff between risk reduction incentives and risk sharing as well. For example, policies that ensure efficient victim incentives (such as a Pigouvian tax or a simple negligence rule) do not provide victim compensation. In fact, any form of victim compensation that is tied to the level of damages (rather than lump sum) will create inefficient victim incentives because of the moral hazard problem associated with any form of insurance, including compensation for damages.

A third goal of risk management policies relates to the allocation of the costs associated with risk reduction and residual damages. This is mainly a distributional issue regarding the fairness of alternative cost allocations. For example, some have argued that the parties who are responsible for creating risks should bear the costs of reducing those risks as well as the costs associated with any damages that still result even under the lower level of risk — a version of the "polluter-pays-principle" advocated by OECD and others. On the other hand, for activities that are socially valuable but inherently risky, some have argued that, as long as parties comply with existing safety regulations, they should not bear the costs of the residual damages. Clearly, different policies imply different cost allocations, and any given policy can be evaluated on the basis of how well it achieves a given distributional goal.

Categorization of Risks

The appropriateness of any given risk management approach depends not only on the policy goal(s) but also on the type of risk involved. Environmental risks can be categorized in a number of ways. One possible categorization is based on the nature of the releases of the pollutants into the environment. Some environmental risks stem from continuous (intentional) releases of pollutants. Examples include continuous releases of traditional air and water pollutants as a by-product of production. Others involve discrete events that are unintentional "accidents". These include spills and accidental releases of chemicals into the air, as well as leaching of pollutants from landfills. Some policy approaches (such as Pigouvian taxation) are better suited to continuous releases, while others (such as legal liability) are more appropriate for pollution "accidents".[20]

A second possible categorization of environmental risks is based on the degree of internalization of the risk.[21] Some risks are fully internalized in that the person whose activities generate the risk is also the person who bears that risk. In such cases, in the absence of any subsidization, a single individual (or firm) bears both the costs associated with risk reduction and the benefits, i.e., the injurer is also the victim. Examples include the risks from indoor radon, the risks generated by certain types of electromagnetic fields, and the risks to a farmer from handling pesticides.

Other risks are not directly internalized in that the injurer is not the victim, but still some internalization occurs through the market. This occurs when the injurer and the victim have a contractual relationship and the price paid by one to the other can adjust to the level of risk. For example, in the context of pesticide residues on food, the injurer (farmer) has a contractual relationship with the victim (consumer) since the consumer buys the product from the farmer.[22] Any (known)[23] increased risk associated with food consumption due to pesticide residues can translate into a lower price that consumers are willing to pay for the product. Thus, the farmer indirectly bears (through a lower price received) the costs associated with residue-related risks and he would benefit (through an increase in price) from a reduction in those risks. Similarly, the risks that farm workers face from exposure to agricultural chemicals can in theory be internalized through the wage rate.[24]

When there is no contractual relationship between the injurer and the victim, there is no mechanism for internalizing risks. In such cases, the victim is a "third party" and the risk is external to the injurer. Traditional air and water pollutants as well as contamination resulting from off-site waste disposal or spills are typically of this type. The external risks can be either unilateral (i.e., affected only by the actions of the injurer) or bilateral (i.e., affected by the actions of both the injurer and the victim). In bilateral cases, a certain portion of the risk — namely, that part that is influenced by the victim's actions — can be viewed as internalized since the victim would both bear the cost and receive the benefit of any mitigation he undertakes. However, the external effects generated by the injurer's actions are not internalized and thus, in the absence of a policy response, the injurer will not face an incentive to reduce those risks.

The appropriateness of any given policy response depends on the extent to which the risk is internalized. For example, an approach that relies primarily on voluntary reductions, with the role of the government limited to providing information or possibly subsidizing those reductions, may be appropriate for risks that are internalized either directly or through market transactions. However, in cases of external risks where the damages are borne by third parties, such an approach is likely to be ineffective in inducing efficient risk reduction. For cases of external risks, a more active role for the government (such as regulating risk-generating activities or using economic incentives to affect those activities) will generally be required.

Characteristics of Environmental Risks

Regardless of the categorization used to classify environmental risks, these risks in general share a number of characteristics that make public policymaking in this context particularly challenging. The following is a list of some of those characteristics.[25]

(1) Non-monetary nature of risks. Most environmental risks are non-monetary in that the risk involves loss of something other than money, such as health, life, or an ecological environment. In addition, in general there are no close substitutes for the "good" that could be lost. This has implications for the determination of the benefits from a reduction in the risk. For example, the non-monetary nature of the risks implies that putting a dollar value on the risk reduction may be difficult. In addition, the lack of close substitutes implies that large differences between willingness-to-pay and willingness-to-accept measures of benefits may exist (Hanemann 1991). Thus, it may be difficult to come up with a single, meaningful measure of benefits that can be compared to the cost of achieving the reduction in risk.

(2) Long latency periods. Many environmental risks also involve long latency periods, i.e., there is a considerable lag between the time that the risk-generating activity is undertaken and the time that the environmental effect is realized. For example, waste disposal undertaken decades ago is now causing environmental problems in places where the substances have leached or migrated through the soil or water. Similarly, exposure to a given toxic substance today may cause cancer in an individual 20 or 30 years later. These long time lags imply that it is often difficult to prove the exact cause of a given outcome (i.e., whether the cancer case was caused by exposure to the toxic substance or something else) or to identify the party who was responsible (i.e., which firms disposed of which substances in a given landfill). In addition, even if the responsible party can be identified and causation proven, that party may now be judgment-proof. For example, the firm may no longer be in operation and thus can no longer be held responsible for the damages resulting from its actions. Long time lags also imply that discounting of future damages may have important consequences for the evaluation of current policies, although the non-monetary nature of environmental risks suggests that discounting in this context is likely to be controversial.

(3) Irreversibility and learning. Environmental risks often involve effects that are irreversible, such as contraction of a disease, death of an individual, destruction of a unique habitat, or loss of a species. If the future benefits associated with environmental improvements are uncertain, there is the possibility of learning more about those benefits over time. However, the irreversibility of the current effect may foreclose the opportunity to respond to that new information when it becomes available. Thus, in designing policies to manage environmental

risks, care must be taken to avoid "mistakes" now that cannot be undone in the future if the benefits from environmental quality in the future are found to be larger than expected.

(4) Composite nature of risks. Most environmental risks also involve a sequence of events, each of which has its own conditional probability distribution (Crouch and Wilson 1981). For example, the risk from consumption of groundwater contaminated by pesticides involves the probability that the pesticide applied to the surface will leach to the groundwater, the probability that the pesticide plume in the groundwater will migrate to the point of withdrawal, the probability that the contaminated water withdrawn will be consumed, and the probability that consumption of the water will lead to disease. The overall "risk" then is a combination of these individual "risks". This implies that any safety margin built into estimation of the individual risks will be compounded in the estimation of the overall risk. In addition, it implies that there are multiple points at which to intervene to reduce the overall risk. For example, steps can be taken to prevent leaching of a pesticide, prevent migration of a plume, or prevent consumption of contaminated water. Any one of these steps will reduce the overall risk of damages from consumption of contaminated water. Thus, while the composite nature of many environmental risks makes them difficult to measure, it also provide a broader range of opportunities for risk management.

(5) Definition of risk/damages. Related to the composite nature of environmental risks is the question of how to define the risk and how to determine when damages have occurred. For example, in the example above, one could define damages to have occurred at the time of ingestion when there is now a positive probability of contracting the disease (time of exposure) or at the time that the exposed individual actually gets the disease (time of contraction). This distinction has important implications for the design of compensation mechanisms. While traditionally compensation is based on contraction of the disease, some have argued that those who are exposed but never ultimately contract the disease have still suffered damages and should thus be compensated (Robinson 1985). Compensating on the basis of exposure rather than contraction would also alleviate some of the problems posed by long latency periods, such as the difficulty of proving causation and the possibility that the responsible party will be judgment-proof.

(6) Role of risk perceptions. Because of the complex nature of most environmental risks, the perceptions of those risks can play an important role in both individual choice and policy formation. In such cases, the standard expected utility theory may be an inappropriate model of how choices are and should be made.[26] For example, individuals can have subjective probabilities and use reference points in evaluating changes, implying possible framing effects. Such factors suggest that some of the non-expected utility theories of decision making under uncertainty (such as prospect theory (Kahneman and Tversky 1979) or regret theory (Loomes and Sugden 1982)) may provide better predictions of actual choices than the expected utility model. However, the implications for normative analysis are unclear (Weinstein and Quinn 1983).

Conclusion

The purpose of this paper is to provide an introduction to the analysis of risk in the context of environmental policy. Environmental economists interested in risk analysis typically focus on sources of risk that are very different from those considered by farm management and production economists, who typically deal mainly with financial and output risks. Specifically, environmental risk analysis focuses on the impact that the firm's production processes have on environmental quality and the related sources of risk. In addition, it is inherently policy-oriented, since many environmental risks (particularly those that are not fully internalized) require a public policy response. Most environmental risk analysis is ultimately motivated by an interest in the implications for policy choice.

The types of policy responses that might be used are varied and the appropriateness of any one depends on both the goals of the policy and the nature of the environmental risk it addresses. Most policies involve tradeoffs in meeting goals. For example, those that are effective in providing risk reduction incentives may not be satisfactory in terms of cost allocation or risk sharing. Similarly, approaches that are effective in controlling continuous sources of pollution may not be effective in controlling discrete environmental accidents, just as those that are appropriate for internalized risks will not generally work for externalized risks. Thus, no single policy approach emerges as the preferred approach for all risks and all goals.

Finally, many environmental risks have characteristics that make policy design in this context particularly difficult. Unlike financial risks, which are typically one-dimensional, environmental risks have many dimensions (e.g., many components) and can involve long time lags. In addition, the non-monetary nature of these risks can make their evaluation more difficult. Because of these and other characteristics, environmental risk analysis requires more than simply taking a deterministic model of firm behavior and making one or more of the variables random. While it uses the standard tools of risk analysis such as the expected utility model and measures of risk aversion, the overview provided here suggests that the analysis has had to go well beyond simple application of these tools to define new concepts and issues. The challenge has then been to use economic theory to formalize these concepts or ideas and then make use of the knowledge that has been gained to inform the public policy debate.

Endnotes

1. For the effect of government programs on production decisions, see, for example, Chavas and Holt (1990). An example of the impact of environmental policy on firm-level decisions is discussed in Lichtenberg, Spear, and Zilberman (1993).

2. Note that in this context the impact of the policy on the firm's decision may be fully known to the firm, implying that from the firm's perspective there is no uncertainty regarding that impact.

3. These benefits are not always measured in dollar terms. In some cases, a measure of the physical benefits (such as health improvements) is used.

4. Some statutes allow for a weighing of costs and benefits, while others explicitly prohibit this (Portney 1990). In his Executive Order No. 12291, President Reagan ordered that all environmental regulations be subjected to a benefit-cost test. For a discussion of the impact of this on environmental policy, see Smith (1984).

5. The field of environmental economics in general emphasizes the other links in Figure 1, even when risk is not the central focus of the analysis. For an overview of the field, see Cropper and Oates (1992).

6. See Tomasi, Segerson, and Braden (forthcoming) for a review of this literature.

7. For a useful survey of related literature, see Freeman (1993).

8. See Freeman (1993) for a summary of these and related issues.

9. If information is gained only by allowing some development, then the conclusions regarding the additional benefit of preservation do not necessarily hold. See Miller and Lad (1984).

10. Cost uncertainty on the part of regulators has also been modeled as an adverse selection problem. See Spulber (1989).

11. Uncertainty about the marginal benefit of abatement is also included, but the choice between the two policy approaches is independent of any uncertainty about the benefits of abatement.

12. See, for example, Adar and Griffin (1976) and Fishelson (1976).

13. A more detailed discussion of these approaches can be found in Segerson (1992).

14. See Viscusi, Magat, and Huber (1986) for an analysis of the effectiveness of this approach.

15. See Stewart (1988) for a discussion of the use of economic incentives in this context.

16. See Grossman (forthcoming) for a general discussion of pesticide regulation in the U.S. and Lichtenberg, Spear, and Zilberman (1993) for an analysis of re-entry regulations.

17. See Trauberman (1981) for a discussion of the use of victim compensation funds.

18. See Baumol and Oates (1988) for a discussion of the uniqueness of the Pigouvian tax in this regard.

19. See Borch (1962) for an early discussion of efficient risk sharing.

20. See Shavell (1984) for a discussion of the conditions under which alternative approaches are appropriate.

21. For a more detailed discussion of this categorization of environmental risks, see Segerson (1992).

22. Technically, the consumer has a contractual relationship with the retail establishment at which they bought the food, which in turn has a contractual relationship with the wholesaler, etc. However, this chain of relationships effectively creates a contractual relationship between the consumer and the original producer (farmer).

23. Clearly, if risks are not known, then prices will not adjust appropriately to reflect these risks. This is true even if consumers correctly perceive average risks but have no way of knowing the risks associated with any given firm's output.

24. In practice, of course, there are a number of reasons why wages might not fully reflect risk differentials. For a related discussion, see Ehrenberg (1988).

25. For a more detailed discussion of some of these characteristics, see Segerson (1992).

26. For overviews of some of the criticisms of the expected utility model, see Schoemaker (1982) and Machina (1987).

References

Adar, Z., and J. M. Griffin. 1976. "Uncertainty and the Choice of Pollution Control Instruments." *Journal of Environmental Economics and Management* 3(3): 178-188.

Arrow, Kenneth J., and Anthony C. Fisher. 1974. "Environmental Preservation, Uncertainty, and Irreversibility." *Quarterly Journal of Economics* 88(1): 312-319.

Baumol, William J., and Wallace E. Oates. 1988. *The Theory of Environmental Policy,* 2nd, Cambridge: Cambridge University Press.

Borch, K. 1962. "Equilibrium in a Reinsurance Market." *Econometrica* 30(3): 424-444.

Chavas, Jean-Paul, and Matthew Holt. 1990. "Acreage Decisions Under Risk: The Case of Corn and Soybeans." *American Journal of Agricultural Economics* 72(3): 529-538.

Cropper, Maureen, and Wallace E. Oates. 1992. "Environmental Economics: A Survey." *Journal of Economic Literature* 30(2): 675-740.

Crouch, E., and R. Wilson. 1981. "Regulation of Carcinogens." *Risk Analysis* 1: 47-57.

Ehrenberg, Ronald G. 1988. "Workers' Compensation, Wages, and the Risk of Injury," in Burton, John F., Jr. (ed.), *New Perspectives in Workers' Compensation.* Ithaca, New York: ILR Press, Cornell University.

Fishelson, Gideon. 1976. "Emission Control Policies under Uncertainty." *Journal of Environmental Economics and Management* 3(3): 189-197.

Freeman, A. Myrick III. 1990. "Water Pollution Policy," in Portney, Paul R., (ed.), *Public Policies for Environmental Protection.* Washington, DC: Resources for the Future.

Freeman, A. Myrick III. 1991. "Welfare Measurement and the Benefit-Cost Analysis of Projects Affecting Risk." *Southern Economic Journal* 58(1): 65-76.

Freeman, A. Myrick III. 1993. *The Measurement of Environmental and Resource Values: Theory and Methods.* Washington, DC: Resources for the Future.

Graham, Daniel A. 1981. "Cost-Benefit Analysis Under Uncertainty." *American Economic Review* 71(4): 715-725.

Grossman, Margaret R. (Forthcoming). "Environmental Federalism in Agriculture: The Case of Pesticide Regulation in the United States," in Braden, John B., Charles Kolstad, and Thomas S. Ulen (eds.), *Environmental Policy with Economic and Political Integration: The European Community and the United States.*

Hanemann, W. Michael. 1991. "Willingness to Pay and Willingness to Accept: How Much Can They Differ?" *American Economic Review* 81(3): 635-647.

Kahneman, Daniel, and Amos Tversky. 1979. "Prospect Theory: An Analysis of Decisions Under Risk." *Econometrica* 47(2): 263-291.

Lichtenberg, Erik, Robert C. Spear, and David Zilberman. 1993. "The Economics of Reentry Regulation of Pesticides." *American Journal of Agricultural Economics* 75(4): 946-958.

Loomis, Graham, and Robert Sugden. 1982. "Regret Theory: An Alternative Theory of Rational Choice Under Uncertainty." *Economic Journal* 92: 805-824.

Machina, Mark J. 1987. "Choice Under Uncertainty: Problems Solved and Unsolved." *Journal of Economic Perspectives* 1(1): 121-154.

Miller, Jon R., and Frank Lad. 1984. "Flexibility, Learning and Irreversibility in Environmental Decisions: A Bayesian Approach." *Journal of Environmental Economics and Management* 11: 161-172.

Portney, Paul R. (ed.) 1990. *Public Policies For Environmental Protection*. Washington, DC: Resources for the Future.

Robinson, Glen O. 1985. "Probabilistic Causation and Compensation for Tortious Risk." *Journal of Legal Studies* 14: 779-805.

Schoemaker, Paul J. H. 1982. "The Expected Utility Model: Its Variants, Purposes, Evidence and Limitations." *Journal of Economic Literature* 20: 529-563.

Segerson, Kathleen. 1988. "Uncertainty and Incentives for Nonpoint Pollution Control." *Journal of Environmental Economics and Management* 15: 87-98.

Segerson, Kathleen. 1992. "The Policy Response to Risk and Risk Perceptions," in Bromley, Daniel W., and Kathleen Segerson (eds.), *The Social Response to Environmental Risk: Policy Formation in an Age of Uncertainty*. Boston: Kluwer Academic Press.

Shavell, Steven. 1980. "Strict Liability Versus Negligence." *Journal of Legal Studies* 9(1): 1-25.

Shavell, Steven. 1984. "Liability for Harm vs. Regulation of Safety." *Journal of Legal Studies* 13: 357-374.

Smith, V. Kerry, (ed.). 1984. *Environmental Policy Under Reagan's Executive Order*. Chapel Hill and London: The University of North Carolina Press.

Spulber, Daniel. 1989. "Optimal Environmental Regulation Under Asymmetric Information." *Journal of Public Economics* 35: 163-181.

Stewart, Richard B. 1988. "Controlling Environmental Risks Through Economic Incentives." *Columbia Journal of Environmental Law* 13(2): 153-169.

Tomasi, Theodore, Kathleen Segerson, and John B. Braden. (Forthcoming). "Issues in the Design of Incentive Schemes for Nonpoint Source Pollution Control," in Dosi, Cesare, and

Theodore Tomasi (eds.). *Nonpoint Source Pollution Regulation: Issues in Analysis.* Kluwer Academic Publishers.

Trauberman, Jeffrey. 1981. "Compensating Victims of Toxic Substances Pollution: An Analysis of Existing Federal Statutes." *Harvard Environmental Law Review* 5(1): 1-29.

Viscusi, W. Kip, W. A. Magat, and J. Huber. 1986. "Informational Regulation of Consumer Health Risks: An Empirical Evaluation of Hazard Warnings." *Rand Journal of Economics* 17: 351-365.

Weinstein, Milton C., and Robert J. Quinn. 1983. "Psychological Considerations in Valuing Health Risk Reductions." *Natural Resources Journal* 23(3): 659-673.

Weisbrod, Burton A. 1964. "Collective Consumption Services of Individual Consumption Goods." *Quarterly Journal of Economics* 77(3): 71-77.

Weitzman, Martin L. 1974. "Prices vs. Quantities." *Review of Economic Studies* 41(4): 477-491.