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DETERMINATION OF REGIONAL ENVIRONMENTAL POLICY UNDER UNCERTAINTY: THEORY AND CASE STUDIES

by

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Determination of Regional Environmental Policy Under Uncertainty: Theory and Applications

Summary

Uncertainty about environmental effects is a key factor shaping environmental policy decisions. We review alternative approaches to taking uncertainty into account in formal decision methodologies, such as using "conservative" environmental impact estimates, expected utility using multiattribute decision analysis or revealed preference estimation, and the safety rules. Safety rules are more appealing in an empirical context and also correspond to the legal framework guiding environmental regulation. We then present three cases studies involving agricultural drainage and runoff that use the safety rule approach, focusing on the impact of incorporating uncertainty, modeling behavioral responses to policy, the role of heterogeneity in production and the relative importance of long run versus short run distributional effects.

DETERMINATION OF REGIONAL ENVIRONMENTAL POLICY UNDER UNCERTAINTY: THEORY AND CASE STUDIES

I. Introduction

Uncertainty is ubiquitous in environmental policy problems. One reason is simply the complexity typical of environmental problems. Adverse environmental effects typically have multiple causes and are mediated by a multitude of factors. Some of these factors are observable, others are not; thus, science can account for part of observed variations in environmental outcomes. In addition, scientific knowledge is usually limited: There are many things about adverse environmental effects we do not understand fully in a theoretical or empirical sense. For example, little is known about the long term effects of synthetic organic chemicals on human beings and other animal species of interest. The aim of policy is to prevent avoidable damage. At the same time, many adverse environmental effects are quite subtle and are therefore detectable in a reliable way only in cases of extreme damage. Thus, policy makers must generally rely on estimates of these adverse effects derived from indirect evidence that are heavily dependent on the assumptions made in simulation modeling, adding an extra layer of uncertainty. This preventive posture constrains policy makers to issue decisions in a timely manner as well, so that data collection is often not as thorough as might be desired.

The evidence suggests that the public is quite sensitive to these uncertainties. The work of psychologists indicates that the public perceives as more hazardous effects that have greater uncertainty associated with them (for a summary see Slovic, Fischoff and Lichtenstein [1980]). The recent furor over pesticide residues on foods (e.g., Alar on apples) bears this notion out. The best data available suggest that roughly 85 percent of fresh produce in the marketplace have no detectable residues and that almost all of the remaining cases involve residue levels that are extremely small and well below what the U.S. Environmental Protection Agency considers the maximum safe levels. Yet much of the U.S. public believes that pesticide residues on foods pose a serious threat to public health.

Policy makers appear to be quite sensitive to these uncertainties as well, in part because of public demands for taking uncertainty into account in making regulatory decisions, in part (perhaps) because mistakes are the most visible indicator of poor performance. Moreover, much of the legislative governing policy formulation directs decision makers to take uncertainty into account, in that they require policies to safeguard environmental quality with an adequate margin of safety.

To be truly useful in aiding policy determination, then, quantitative decision methodologies should take uncertainty into account explicitly. Cost-benefit or risk-benefit analyses based on expected values are inadequate in this regard, since they make no adjustment for uncertainty. This paper discusses the applicability of several approaches to uncertainty adjustments in quantitative decision methodologies, notably (1) cost-benefit analysis using "conservative" environmental damage estimates, as practiced by the U.S. Environmental Protection Agency and other state and federal regulatory agencies, (2) expected utility analyses, specifically multiattribute decision analysis, and (3) cost-benefit, risk-benefit or cost-efficiency analysis using safety rules. The safety rule approach is illustrated in the final section using problems of agricultural drainage and runoff management, specifically, river discharge of heavy-metal rich drainage water, groundwater contamination by agricultural pesticide use and shellfish contamination by livestock waste runoff.

II. Alternative Approaches to Uncertainty Adjustment

Consider a region in which a productive activity creates spillovers that are believed to have detrimental side effects. Irrigated agriculture in areas with perched water table problems, for example, generates drainage flows that are highly saline and may contain naturally occurring toxic elements such as selenium, arsenic and boron as well as residues of applied chemicals such as pesticides. Surface runoff typically contains fertilizer and pesticide residues as well. Disposal of surface and subsurface runoff into rivers, lakes or artificially created receiving waters may have adverse effects on vegetation, wildlife and human health. The degree to which these adverse effects occur will depend on random factors such as weather that govern the amount of receiving water, breakdown or immobilization of toxic chemicals, uptake of toxic chemicals by vegetation, wildlife population sizes and chemical uptake, and so on. Estimates of the causal linkages between disposal of runoff and these adverse effects will be influenced by errors in model specification and estimation due to incomplete knowledge about the causal processes and incomplete data on causal factors and will thus exhibit greater randomness than the effects themselves.

A decision methodology that takes uncertainty into account must thus begin with an environmental impact assessment that incorporates randomness explicitly. Two different approaches have been taken: (1) adjusting the estimates used to ensure that they contain a suitable margin for error and (2) building an explicitly probabilistic model of environmental impacts. The former has been standard operating procedure for the U.S. Environmental Protection Agency, the Food and Drug Administration, the Fish and Wildlife Service and other federal and state agencies. Its attraction is practicality: Margins for error can be taken from existing engineering rules of thumb. This advantage is its main weakness: Margins for error are derived in an arbitrary way, with no reference to the randomness appearing in the case at hand. These margins for error have no statistical basis and therefore no real meaning. Standardization of protocols for making estimates in this way does note ensure that the resulting estimates provide the same margin for error, because level of error (and inherent randomness) varies from case to case. In addition, margins for error derived in this way cannot be compared in different cases -- or even for different policies designed to address a single environmental impact -- in a rigorous way, making it difficult to evaluate policy alternatives. The latter approach is more difficult to implement. It is more subject to specification error, in the sense that omission of relevant factors can bias the estimates obtained. It does make it possible to ascribe statistical meaning to any adjustments for error, however, and thus makes alternative policy options comparable. It has been growing in popularity - at least for estimating human health risks -- for precisely this reason.

One implication of using probabilistic environmental impact assessments in decision making is that the separation of economic from environmental impact analysis cannot be maintained. It becomes important to incorporate the effects of alternative policy options into ecological models in a complex manner, since effects on estimated outcomes and on the randomness of these estimates are both important. Thus, a policy modeling process that is organically interdisciplinary is a necessity for implementing a more sophisticated approach to policy analysis.

A. *Cost-Benefit Analysis with "Conservative" Damage Estimates*

The approach taken by the U.S. Environmental Protection Agency and other regulatory agencies to adjusting for uncertainty about environmental damage is to make "conservative" estimates of potential damage under alternative policy scenarios that incorporate margins for error using engineering rules of thumb. These estimates are then provided as a rough form of "certainty-equivalent" data for cost-benefit or risk-benefit assessments. As I have argued elsewhere [Lichtenberg, 1990], this procedure does more than bias policy toward more stringent standards, as is intended. It may also bias the type of policy chosen in favor of setting stricter standards and against increased monitoring and enforcement, as the following example indicates.

Consider the case of a rice growing region located upstream of an urban area that uses river water for drinking. Suppose that rice growers use an herbicide believed to pose a human health risk. To control temperature, rice growers find it necessary to lower water levels in their fields. On infrequent occasions (say, a small fraction of the time α) this occurs shortly after applying the herbicide. For convenience, assume that all rice growers discharge simultaneously, so that exposure to the herbicide in drinking water, when it does occur, is always the same. Let the risk from exposure to the herbicide be R, expressed as the number of cases occurring in the population, so that urban residents face an expected health risk αR from exposure to the herbicide in their drinking water. One possible policy is to ban use of the herbicide. Let the social cost of banning this pesticide be C_B. An alternative policy is an enhanced monitoring program that detects the herbicide in time for the city water department to shut off intake until the contaminated water has passed downstream. Suppose that the monitoring program has a cost C_M. If only expected values matter, the pesticide should be banned as long as $C_B < C_M$. A "conservative" risk estimate of the type used by EPA treats the exceptionally high residue levels as normal occurrences and inflates the estimated risk to R. The cost per case avoided under a ban will be C_B/R, while the cost per case avoided under the monitoring program will remain $C_M/\alpha R$, so that the ban will be preferred as long as $C_B < C_M/\alpha$. Thus, whenever $C_M < C_B < C_M/\alpha$, the use of a "conservative" risk estimate will erroneously indicate the superiority of the ban.

B. Expected Utility and Multiattribute Decision Analysis

Expected utility has long been the preferred paradigm in economics for treating issues of choice under uncertainty. Recent criticisms of this approach have focused on its inability to capture some common aspects of individuals' actual choice behavior, that is, its performance as a descriptive model [Machina, 1987]. It remains attractive as a normative model, although some argue that it sets too strict a standard for rationality.

Empirical applications of expected utility depend on estimation of multiattribute utility functions describing preferences over relevant outcomes, to be combined with estimated outcome probabilities. Multiattribute utility functions can be estimated in two ways. The first involves elicitation of utility function parameters by questioning a crucial decision maker, the second utilizes the revealed preference approach to estimate the parameters from past decisions.

Elicitation of the preferences of a key decision maker has been used successfully in a number of business applications (see for example Keeney and Raiffa, 1976). Such an approach is problematic in a public policy context because it is not at all clear that any single decision maker can or should speak for the body politic.

An alternative is to derive information on public preferences by analyzing past decisions. Several studies have employed such a revealed preference approach to estimate the relative social welfare weights on producer welfare, consumer welfare and similar outcomes in cases involving agricultural policies, trade policies and highway construction (for a survey see Rausser, Lichtenberg and Lattimore [1983]).

A number of difficulties arise in connection with the use of this approach, especially for environmental policies. First, information on key variables involved in environmental policy decisions may not be available. Second, public preferences regarding policy outcomes such as environmental quality and agricultural income may change over time, so that past decisions are poor indicators of current welfare weights. For example, policy decisions in California have historically favored agriculture over urban income in cases such as water subsidies. More recent decisions appear to have reversed the situation, as evidenced by the defeat of the Peripheral Canal, the imposition of stringent standards for water quality from agricultural drainage and the imposition of strict pesticide use reporting requirements. Third, public preferences regarding policy outcomes may also vary from case to case, so that decisions from one situation will give erroneous information about preferences in another. Decisions about development of a Yosemite Valley or a Glen Canyon may have little bearing on situations involving agricultural drainage. Finally, theory and empirical evidences suggest that past decisions are in large measure determined by the relative political clout exercised by different sets of agents active in political markets. Revealed preference approaches thus tend to conflate public preferences and past relative political power. It is by no means clear that the parameters estimated in this way can or should be interpreted as expressions of true social preferences.

In sum, it appears that practical difficulties in deriving estimates of parameters expressing social preferences make application of the expected utility framework to public policy issues quite questionable.

C. Safety Rules

A third alternative is to assess tradeoffs between productivity losses and environmental quality using safety rules to adjust for uncertainty, as proposed by Lichtenberg and Zilberman [1988a]. Such an approach has several advantages. First, it is essentially a way of deriving a "conservative" estimate of risk that has formal statistical meaning. As a result, it is likely to be appealing to regulators and scientists accustomed to dealing with "conservative" estimates while bringing some rigor to the definition of "conservative", so that the criticisms raised above do not apply. Second, the safety rule approach conforms closely to the stricture contained in much environmental legislation that posits a goal of providing adequate protection of public health and/or the environment with a sufficient margin of safety, as well as corresponding to a "disaster avoidance" approach that is often felt to characterize bureaucratic decision making. In other words, it corresponds to public preference structures codified in law and in regulatory practice. Third, it can be thought of as an extension of the Baumol and Oates [1971] standards-and-charges approach to cases involving uncertainty. Finally, safety rules have been used in a variety of economic applications; they are well understood and have been shown to give good approximations of expected utility decisions in several empirical contexts [Thomson and Hazell, 1972].

This approach views the government as having two objectives: maximizing net market benefits and minimizing environmental damage. Net market benefits refers to the real incomes of producers and consumers derived from production and consumption of items affected by regulation, less government expenditures. To account for uncertainty about environmental damage estimates, the environmental quality objective is defined as an upper bound that is not exceeded with a certain degree of confidence, for example, the level below which environmental damage is estimated to fall, say, 95 percent of the time. This corresponds to the use of confidence intervals from classical statistics to adjust for uncertainty and addresses the need for allowing a margin for error raised in the legislation.

The tradeoffs between these two objectives can be estimated by solving a constrained optimization problem of maximizing net market benefits subject to the constraint on the environmental quality objective. Solving the problem while varying the constraint repeatedly yields a set of tradeoffs between market welfare and environmental quality and an associated set of policies.

Formally, let X be a vector indicating the extent of use of the policies to be considered. For example, X_1 may be the level of a tax on emissions of toxic elements into a body of water, X_2 may indicate the severity of restrictions on pesticide use, etc. Net market benefits are a function of these policies B(X). Environmental quality is similarly a function of these policies R(X) and is a random variable. Let R_0 be the desired environmental quality level and P be the desired margin for error. The optimization problem is

$$\max_{X} B(X)$$

$$\text{s.t. } \Pr\{R(X) < R_0\} > P.$$

The solution is an optimal policy vector $X^*(R_0,P)$ that is a function of the environmental quality target and the desired confidence level, which measures the margin for error. Substituting into the net market benefits function gives the maximum net market welfare attainable given the environmental quality objective and confidence level $B(X^*) = B^*(R_0,P)$. By varying R_0, one obtains the set of tradeoffs with a given confidence level P. Varying the confidence level as well gives a complete set of tradeoffs between market welfare, environmental quality and the reliability of attaining the acceptable risk level.

A key measure derived from is the uncertainty premium, the absolute value of dB^*/dP, the reduction in net market benefits associated with a small increase in the confidence level. It indicates the additional cost required to increase reliability in meeting the environmental quality standard, and can be considered as similar to the risk premium derived from expected utility theory.

The information generated by this methodology can be used to determine policy using a variety of decision criteria, including cost-benefit and risk-benefit criteria. In cost-benefit analysis, the optimal policy equates the marginal cost of risk reduction dB^*/dR_0 with the monetary value of improved environmental quality.

III. Applications of the Safety Rule Approach

The preceding discussion stressed that decision methodologies for addressing agricultural drainage and runoff problems should: (1) incorporate uncertainty and (2) correspond to the legal and regulatory framework that governs policy. It was argued that the safety rule approach fits these needs better than other available alternatives. This section reviews some recent applications of the safety rule approach to problems of agricultural drainage and runoff to illustrate its use and insights that can be gained from explicit consideration of uncertainty.

The discussion of these empirical applications also highlights the importance of three additional features (1) modeling behavioral responses of economic agents, (2) providing distributional information and (3) modeling heterogeneity. First, as many economists have noted, economic agents seldom remain passive in the face of an altered regulatory landscape. In fact, changes in regulation typically bring forth changes in producer and consumer behavior that, if not taken into account in formulating a policy, may in large measure negate its intended effects. Thus, decision methodologies should incorporate behavioral models of producer and consumer responses. Second, the existence of political activity around proposed regulation and many notions of justice or fairness indicate that the distribution of costs and benefits matters a great deal in policy formulation. Thus, decision methodologies should provide this kind of information. Third, heterogeneity among agents is often critical in determining the actual effects of policies as well as shaping the distribution of gains and losses. This suggests the importance of modeling quantitatively key dimensions of heterogeneity.

A. *River Discharge of Agricultural Drainage*

The first case study involved river discharge of agricultural drainage water [Hanemann et al., 1987]. In 1983, it was established that selenium in agricultural drainage water was responsible for a variety of reproductive problems in waterfowl and other aquatic fauna in the Kesterson Reservoir, a repository for agricultural drainage flows emanating from the Westlands Water District on the west side of the San Joaquin Valley, California. In 1985, the California State Water Resources Control Board initiated a process of setting standards for selenium and other heavy metals (boron, molybdenum) in the San Joaquin River, affecting growers cultivating 94,000 acres in four water districts to the north of Westlands that had been discharging drainage water into the San Joaquin River.

Farms in the affected area differed in terms of land quality (and therefore cropping patterns and percolation coefficients) and water charges (which varied according to irrigation district). Estimates of acreages and yields of crops on different soil types were obtained from soil surveys and combined with estimates of production costs and variable and fixed (per acre) water charges for each irrigation district to form distributions of quasirents for all possible production patterns.

Furrow irrigation with half-mile runs was the standard irrigation technique presently used with all crops in the area. Subsurface drainage per acre per month under this technology was estimated by combining estimates derived from data on annual drainage per acre from all districts with an estimate of the monthly distribution of drainage patterns for the one district for which monthly data were available. Surface runoff was estimated by subtracting estimated subsurface drainage discharges from total flows recorded in the drains of each irrigation district. Water application rates under furrow irrigation were set equal to the average values reported in the literature.

Crop rotations, rather than individual crops, were the unit of analysis. Rotation frequencies were determined by combining expert opinion on standard operating practices in the area with data on crop acreages in each district. Because the area provides a small fraction of output of all crops considered, price effects were assumed to be negligible and prices were assumed to remain constant at the average prices received in the previous year. The profitability of each rotation under furrow irrigation on each quality of land in each district was then calculated as the weighted average of these crop profitabilities, with weights derived from the rotation frequencies. The distribution of current per acre quasirents under furrow irrigation in each district was then estimated via linear programming by selecting land allocations to maximize quasirents in each district subject to the constraints that (1) total land allocated to each crop equaled the average level in the most recent year and (2) total land of each quality allocated to all crops equaled the estimated amount. Differences in rotational profitabilities were sufficiently large and differences in crop water requirements were sufficiently small to rule out shifts in cropping patterns in response to technology changes or cost increases.

Two possible approaches to meeting selenium standards were considered: source reduction via installation of water conserving irrigation technologies and selenium removal via water treatment. Four alternative irrigation technologies were selected for analysis: furrow irrigation with runs shortened to one quarter-mile, installation of tailwater recovery systems, sprinkler irrigation and drip irrigation. The parameters describing irrigation efficiency, deep percolation and surface runoff were chosen to be broadly representative of the estimates in the literature. They were used to estimate reductions in water application, deep percolation and surface runoff and increases in per acre production costs relative to the baseline estimates. The cost function for selenium removal consisted of three components: a cost of selenium removal, a cost of removing suspended solids (applicable when combined surface and subsurface drainage flows were treated) and a cost of storing drain water to smooth monthly treatment requirements. In addition, the minimum cost strategy always involved delivering drainage water into the San Joaquin River at a point upstream of the Merced River, to take advantage of the additional dilution capacity of the Merced. This approach required construction of a canal.

Four year types were used to characterize precipitation, and therefore riverflow, patterns. The years 1978/1979 and 1983/1984 were chosen as representative of normal years, 1984/1985 was selected as representative of a dry year and 1980/1981 was selected as representative of a critical year. The confidence level associated with setting standards designed to hold in each year was estimated using the historical distribution of river flows reported by the California Department of Water Resources. By this criterion, 1978/79 corresponded to a 43.9 percent confidence level, 1983/84 to a 53.7 percent confidence level, 1984/85 to a 76.8 percent confidence level and 1980/81 to an 81.7 percent confidence level. For each year, the optimal treatment capacity under each technological alternative was chosen by minimizing total treatment cost subject to the constraint of meeting selenium concentration standards of 2, 5 and 10 parts per billion (ppb) in the San Joaquin River during every month. The total cost of treatment plus investment in irrigation technology was then calculated for each technological alternative.

The analysis indicated that the choice of a control strategy depended critically on the confidence level selected, that is, the choice of policy instrument depended on the adjustment made for uncertainty. Source reduction via water conservation appeared increasingly important for more stringent selenium standards and for greater margins for error. In normal years, a standard of 10 ppb could be met entirely through dilution under the existing irrigation technology. A 76.8 percent confidence level made it optimal to construct a small treatment plant for the combined surface and subsurface flows, but implied no change in irrigation technologies. Shortened runs combined with small storage and treatment facilities became the optimal way to meet a 10 ppb standard with an 81.7 percent confidence level or to meet a 5 ppb standard under any of the safety margins considered here, while drip irrigation was optimal for meeting a standard of 2 ppb under any of these safety margins. In each of these cases the adoption of the water conserving irrigation technology reduces drainage flows sufficiently to afford substantial savings in storage and treatment costs.

The adjustment made for uncertainty had a substantial effect on the total cost of meeting most of these selenium standards. The average uncertainty premium per 1 percent increase in the confidence level ranged from zero to 1.13 percent for a standard of 10 ppb, from 0.74 to 5.83 percent for a standard of 5 ppb and from 1.32 to 3.45 percent for a standard of 2 ppb. It increased as the selenium standard became more stringent and as the confidence level increased in almost every case.

Growers were assumed to have two sorts of behavioral responses to the imposition of selenium standards: long run land retirement and short run financial distress. It was assumed that land would be retired permanently whenever the cost of meeting selenium standards, spread equally among all acreage remaining in production, exceeded current quasirents. Short run financial distress was assumed to occur when the per acre costs of meeting selenium standards exceeded the debt carrying capacity of the land, which was estimated by combining estimates of the distribution of debt/asset ratios of California farmers with the estimated distribution of land values derived from the estimates of quasirents.

The long run effects of any of these standards were quite small. Meeting a standard of 2 ppb under any confidence level would force retirement of only about 3.5 percent of the crop land in the area, all of which was of low productivity. With any other standard, production would remain profitable on all land currently cropped. The short run financial effects of imposing selenium standards are quite substantial. Meeting a standard of 10 ppb would induce financial distress on 1 to 2 percent of the crop land in the area, meeting a standard of 5 ppb would induce financial distress on 5 to 7 percent and meeting a standard of 2 ppb would cause financial distress on 17 to 28 percent. In other words, short run financial difficulties outweighed long run productivity effects and were likely to constitute the main incentive for political opposition to the proposed standards. This suggests that directed credit programs may often be of critical importance in making environmental quality enhancement programs both equitable and politically feasible.

B. Groundwater Contamination by a Pesticide

The second case study involved residues of the nematicide 1,2-dibromo-3-chloropropane (DBCP) found in drinking water wells in Fresno County, California [Lichtenberg, Zilberman and Bogen, 1989]. DBCP had been used as a soil fumigant for orchard crops, but was banned for all agricultural uses by the U.S. Environmental Protection Agency in 1979 after having been implicated in adverse reproductive effects in chemical plant operators and oncogenesis in mice and rats. Because DBCP was no longer in use, the study focused on tradeoffs between excess gastric cancer risk and the cost of developing clean drinking water supplies.

Monte Carlo simulation was used to construct probabilistic quantitative risk assessment of the excess cancer risk faced by an individual drawn at random from the population of the county as a multiplicative combination of the concentration of DBCP in drinking water, error in measuring that concentration, lifetime consumption of water, an interspecies dose equivalence factor and a carcinogenic potency parameter. The distribution of DBCP concentrations in well-based water systems and the error in measuring DBCP concentrations were constructed from California State Department of Health Services data. The data presented by the International Commission of Radiological Protection were used to estimate a distribution of lifetime water consumption. The distribution of the dose-equivalence factor was estimated under the assumption that the two main hypotheses (calibrating dose on the basis of surface area versus body weight) were equally likely to be correct. The distribution of the carcinogenic potency parameter was estimated using maximum likelihood estimation of a multistage dose-response model using data from a feeding study of mice.

An element of heterogeneity was introduced by the fact that costs of developing new water supplies differed between rural and urban areas. Drilling new wells was less costly for large systems, while installing filtration devices was cheaper for individual wells. Residential areas within the county thus differed in two ways: average DBCP concentrations in drinking water and cost of remediation. Least-cost strategies for meeting a risk standard for an individual drawn at random from the county population were derived for the entire feasible range of standards using an algorithm derived from the methodology described above. For ease of analysis, the relationship between risk standards and remediation costs were smoothed using a second-order polynomial regression of cost on the natural logarithms of the risk standard and confidence level.

Increasing the confidence level entailed substantial increases in cost. A 1 percentage point increase in the confidence level raised the total cost of meeting any given risk standard by $3-4 million, or 2-10 percent. Making allowance for uncertainty in this way thus had notable effects on risk-benefit tradeoffs.

Urban and rural areas differed significantly in terms of the costs of remediation, as the cost of providing clean water from individual wells in rural areas was about 2.5 times as great as the cost for community water systems in urban areas. Because of these differences, the cost-efficient strategy involved more stringent standards in urban areas and more lax ones in rural areas. In other words, heterogeneity in the population at risk implied the desirability of heterogeneity in regulation.

The marginal cost of reducing risk on average was 21 to 26 percent higher than the marginal cost with a 95 percent confidence level and 23 to 29 percent higher than the marginal cost with a 99 percent confidence level. Making allowance for uncertainty thus reduces the marginal cost, or slope of the tradeoff curve, substantially. Economists evaluating existing health and safety regulation using cost-benefit analysis applied to estimates of average risk have typically found that marginal costs exceed marginal benefits by significant amounts, suggesting that these policies are excessively stringent. When allowance is made for uncertainty, however, marginal costs and benefits will be closer. The results obtained here indicate that the adjustment will be significant, suggesting that allowances for uncertainty account for a significant share of the observed discrepancies.

C. Shellfish Contamination by Livestock Wastes

The third case study involved a shellfishery located in an estuary affected by dairy runoff [Lichtenberg and Zilberman, 1988b]. During rainstorms, wastes from dairies were washed into the estuary, resulting in microbial contamination of the oysters growing there and a concomitant risk of severe gastroenteritis for anyone consuming them. The analysis centered on source reduction because open access to the fishery ruled out fishery closure as an effective means of risk reduction.

Rainfall was assumed to be the only random element affecting the risk of acute gastroenteritis, which was modeled as a multiplicative combination of parameters describing microbial contamination in runoff per cow, microbial uptake in oyster population, the probability of contracting acute gastroenteritis upon consumption of contaminated oysters and the number of cows contributing to runoff. Microbial contamination in runoff per cow was estimated from maximum fecal coliform counts observed around oyster beds in the estuary. The fraction of oysters contaminated was estimated by applying regression analysis to data in a study examining the usefulness of fecal coliform counts as an indicator of bacterial contamination of oysters. The probability of contracting acute gastroenteritis after consuming contaminated oysters was derived from epidemiological studies. The number of cows contributing to runoff in any size rainfall event equalled the number of cows at dairies with runoff control facilities with insufficient capacity of the amount of rainfall. The probability distribution of rainfall events was derived from data on local rainfall.

The dairies in the watershed differed in terms of topography and therefore in terms of the cost of constructing runoff control facilities adequate for any given size rainfall event. Data on these costs for each dairy in the region were obtained from a detailed engineering study. Least-cost patterns of runoff control facility construction and tradeoffs between gastroenteritis risk and source reduction expenditures were estimated using an algorithm derived from the methodology described above.

The optimal policy involved building holding ponds only at dairies with the lowest marginal costs. The optimal capacity at each dairy was determined by the confidence level required, and the total number of dairies subject to undertaking source reduction measures was determined by the risk standard. Because topography, and therefore cost, differed markedly at different sites, different dairies received markedly different treatment under this policy. Runoff control facilities were required at only a few sites to meet lax risk standards. As the risk standard became more stringent, the number of sites investing in source reduction grew. The optimal set of standards thus implied marked inequities among dairies, with some dairies required to undertake substantial investments in source reduction while others continued with unregulated emissions.

Economists have long argued that taxes can be used to achieve pollution control aims instead of imposing standards. In the case at hand, the per-cow tax required to meet any desired risk standard with a given confidence level equalled the marginal cost of installing runoff control facilities of the requisite capacity at the most expensive site needed. Holding pond construction patterns remained the same, but dairies not needing to invest in source reduction had to pay taxes on runoff generated. The result was a much more equitable set of losses. When the risk target was lax, very few dairies found it less costly to build runoff control facilities than pay the tax, so tax payments accounted for almost all runoff control expenditures. As the risk target became more stringent and the optimal tax increased, more and more dairies found it less costly to build.

IV. Conclusion

Decision methodologies for addressing regional environmental policy issues should incorporate several key features characterizing these issues. The first is uncertainty, which is prevalent in ecological problems because of their complexity, because of limits on fundamental scientific knowledge and because data collection is often necessarily limited in the interests of timeliness. Existing legislation and regulatory practices have mandated that uncertainty be addressed in formulating policy; specifically, they typically require that decision makers provide an adequate margin for error. Second, political sense as well as most notions of fairness dictate that policy makers care about the distribution of the costs and benefits of alternative policies as much as efficiency effects, i.e., net benefits. Heterogeneity is often important in determining both the actual effects of proposed policies and the distribution of these effects across groups of economic agents and should thus also be taken into account. Finally, decision models must recognize that economic agents typically react to new policy environments, so that producer and consumer behavioral responses must be incorporated into policy models.

This paper has argued that the safety rule approach proposed by Lichtenberg and Zilberman [1988a] allows policy analysts to make adjustments for uncertainty in a way that corresponds to existing legislative and regulatory frameworks. Three recent case studies employing this approach were discussed to examine the effects of adjusting for uncertainty and to demonstrate how heterogeneity, behavioral responses and distributional concerns can be addressed at the same time. The case studies show that adjustment for uncertainty is feasible and that it can have significant effects on several aspects of policy, including (1) the total cost of meeting a given environmental quality goal, (2) optimal environmental quality goals implied by any given level of marginal benefits, (3) the cost efficient choice of policy instruments and (4) the distribution of costs among producers in the short and long run. Short run distributional effects were shown to be substantially greater than long run efficiency effects in some cases;

in others, the distributional effects of different policy approaches differed markedly. In both sorts of cases, the analysis was able to pinpoint factors likely to determine political responses among groups of growers to proposed environmental quality goals. The results underscore the notion that failure to address these key features will result in policy analyses that fail to meet the real needs of policy makers.

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