ASSESSING THE ADEQUACY OF NATURAL SCIENCE INFORMATION: A BAYESIAN APPROACH

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Abstract—We apply a Bayesian framework in which the adequacy of natural science information used in setting environmental regulations may be assessed. Informational adequacy is defined as the extent to which the variability in agricultural yield response information affects the probabilities of overestimating ultimately realized economic surplus and thereby failing to plan for a more lax ambient pollution standard, or by underestimating the realized surplus and thereby failing to plan for a stricter ambient standard. For linear and for quadratic yield response functions, the framework is applied to four major U.S. field crops having dissimilar growing requirements and diverse market relations.

I. Introduction

CONSIDERABLE Federal research resources have been expended to quantify the biological and economic effects of air pollutants, including the effects of ozone and other photochemical oxidants on agriculture. The acquisition of such information is motivated by the U.S. Environmental Protection Agency's legislative mandate to establish secondary national ambient air quality standards for these pollutants. Nevertheless, uncertainty still exists with respect to crop yield responses to various levels of ambient ozone control (Jacobson and Millen (1982)). Limited research budgets and the need to comply with mandated revisions of ambient standards force regulators to ask how much this uncertainty might be reduced prior to control decisions. If economic considerations have a role to play in control decisions, knowledge of the extent to which improved yield response information will affect estimates of

control benefits takes on interest.¹ Our purpose in this paper is to show how this knowledge might be provided and to present an example application for the responses of U.S. corn, cotton, soybean, and wheat yields to ambient ozone.

Uncertainties in yield response research arise from three sources: (1) natural uncertainty, or uncertainty about a physical process such as the exact manner in which a plant metabolizes each molecule of a toxin; (2) statistical uncertainty, or the doubts due to limited data, about the parameter values for a model of a physiological process; and (3) model uncertainty, or the misgivings about whether a model of a biological process is the "true" model. The discussion of this paper is limited to statistical uncertainty and model uncertainty, where the former refers to imprecision in biological estimates of yield response and the latter to the effects of alternative functional forms on these same estimates.

The analytical framework that we employ is set forth in the next section. An empirical application to the above-mentioned four crops follows. The application uses biological yield response data drawn from USEPA's National Crop Loss Assessment Network (NCLAN).² A concluding section summarizes our findings and offers suggestions for future research.

II. The Framework

Incomplete yield response information is assumed to be the source of the regulator's uncertainty about the net benefits of alternative ozone control policies. For each plausible form of the yield response function, his basic problem, then, is to decide how many yield response observations to

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¹ The importance of economic information in this setting was recently enhanced by President Reagan's Executive Order 12291, which specifically requires the application of benefit-cost procedures to any regulation a Federal agency wishes to promulgate.

² NCLAN is a coordinated, multiple site program of research experiments explicitly aimed at providing estimates of biological yield responses for use in economic assessments of air pollution control (Heck et al. (1982)).

acquire. To capture the regulator's problem, we adopt a Bayesian approach, thereby allowing him to revise his probability distribution of net benefits whenever he acquires additional yield response information.

Consider a finite number, say I , of feasible regulatory actions, a_i , $i = 0, 1, \dots, I - 1$. Action a_0 maintains the current ambient standard, in which case the mean ambient ozone is $X_{(0)}$. Action a_i , $i \geq 1$, results in a new standard, causing mean ozone to be $X_{(i)}$, where $X_{(i)} \neq X_{(0)}$. The expected payoff, $E[R(i)]$, from a_i is

$$E[R(i)] = E[W(i)] - c(i), \quad (1)$$

where E is the expectations operator, the random variable $W(i)$, $i \geq 1$, is the gross economic benefit to society, and $c(i)$ is costs. Because $c(i)$ is assumed known, knowledge of $E[R(i)]$ requires the derivation of an explicit expression for $E[W(i)]$.

Let Q_{ij} be the quantity of the j^{th} commodity ($j = 1, 2, \dots, J$) produced under ozone level $X_{(i)}$. Then,

$$Q_{ij} = \gamma_{ij} Q_{0j} \quad (2)$$

where the random variable γ_{ij} denotes the yield of the j^{th} commodity under ozone level $X_{(i)}$ as a fraction of its yield under the current standard. Relative rather than absolute yield adjustments are used because homogeneity tests of the data employed in the example application of section III indicated that proportionate yield responses for each crop were similar across experiment sites but that absolute yield responses differed. The use of relative adjustments also served to standardize the units in which responses were measured.

Now consider the following inverse demand and supply functions:

$$P_j^D = r_j - b_j g, \quad (3)$$

$$P_j^S = d_j + e_j g, \quad (4)$$

where P_j^D and P_j^S are, respectively, the demand and supply prices for quantity g of the j^{th} commodity, and r_j and d_j are constants incorporating the effects of other variables in the demand and supply structure. While assuming that all markets clear, let the social benefit, $w(Q)$, obtained from the agricultural system when quantity Q is produced be measured in terms of the Marshallian surplus of the mean level of realized consumption. The economic benefits when Q of the j^{th} commod-

ity is produced can then be expressed as

$$w_j(Q) = \frac{1}{2}(b_j + e_j)Q^2, \quad (5)$$

where b_j is the *absolute* slope of (3) and e_j is the slope of (4). Applying (2) and (5), the total expected economic benefit for all J commodities when action a_i is taken is given by

$$E[W(i)] = \frac{1}{2} \sum_{j=1}^J (b_j + e_j) Q_{0j}^2 E(\gamma_{ij}^2). \quad (6)$$

To obtain the distribution of the total economic benefit, $W(i)$, including its expected value, $E[W(i)]$, in (6), one must derive the distribution of γ_{ij} . Assume that the yield response experiments are generated by a "simple normal linear" regression model (Zellner (1971)); that is,

$$Y_{kj} = \alpha_j + \beta_j X_{kj} + \epsilon_{kj}, \quad (7)$$

$k = 1, 2, \dots, n_j$, with the errors, ϵ_{kj} , being independently normally distributed with zero mean and variance σ_j^2 . Here X_{kj} denotes the pollutant level applied to the k^{th} plot of the experiment, and Y_{kj} is the corresponding observed yield for the j^{th} crop. If no prior information is available on the parameters, then α_j , β_j , and σ_j have the prior joint probability density function:

$$p(\alpha_j, \beta_j, \sigma_j) \propto \sigma_j^{-1} \\ -\infty < \alpha_j < \infty, -\infty < \beta_j < \infty, 0 < \sigma_j < \infty. \quad (8)$$

The yield ratio, γ_{ij} , can be expressed as

$$\gamma_{ij} = 1 + \beta_j (X_{(i)} - X_{(0)}) / E(Y_{0j}). \quad (9)$$

In (9), the current mean yield, $E(Y_{0j})$ is assumed known, so that γ_{ij} is simply a linear transformation of the slope β_j of the yield response function. Since the posterior distribution of β_j is of the Student t form with $n_j - 2$ degrees of freedom, it follows that

$$\gamma_{ij}^* = (\gamma_{ij} - \hat{\gamma}_{ij}) / s(\hat{\gamma}_{ij}) \quad (10)$$

is a random variable having the Student t distribution with $n_j - 2$ degrees of freedom. Here

$$\hat{\gamma}_{ij} = 1 + \hat{\beta}_j (X_{(i)} - X_{(0)}) / E(Y_{0j}) \quad (11)$$

$$s(\hat{\gamma}_{ij}) = s(\hat{\beta}_j) |X_{(i)} - X_{(0)}| / E(Y_{0j}) \quad (12)$$

where $\hat{\beta}_j$ is the estimated slope of the regression line, and $s(\hat{\beta}_j)$ is the standard error of $\hat{\beta}_j$. This assumes that the yield response function is linear. However, if the mean pollution level $X_{(i)}$ is re-

placed by its square, then all these expressions also hold for a quadratic yield response function.

As in Lindgren (1968, p. 381), the substitution into (6) of the expression for the second moment of a Student t distribution with $n_j - 2$ degrees of freedom produces

$$\begin{aligned} E[W(i)] &= \frac{1}{2} \sum_{j=1}^J (b_j + e_j)(\hat{\gamma}_{ij}Q_{0j})^2 \\ &+ \frac{1}{2} \sum_{j=1}^J (b_j + e_j)Q_{0j}^2 \\ &\times \left[(n_j - 2)/(n_j - 4) \right] s^2(\hat{\gamma}_{ij}), \end{aligned} \quad (13)$$

where by convention, $\hat{\gamma}_{ij} = 1$, and $s^2(\hat{\gamma}_{0j}) = 0$. Note, as is well known, that the naive approach of substituting $\hat{\gamma}_{ij}$ for γ_{ij} in (6) yields only the first term on the right-hand-side of (13) and would result in a negatively biased benefit value.

The above expression is based only on maximization of expected benefits. As Klein et al. (1978) demonstrate, other criteria may be more appropriate for some decision problems. It is therefore of interest to obtain the entire posterior probability distribution of the benefits, $W(i)$, when action a_i is taken, not just the expected benefits $E[W(i)]$. The imprecision in the benefits estimates for which imperfect information about the parameters of the yield response function is responsible is then made explicit. In order to show this, first derive an expression for the posterior probability density function (p.d.f.) of the benefits, $W(i, j)$, for the j^{th} commodity attributable to action i . Let

$$W(i, j) = \frac{1}{2}(b_j + e_j)(\gamma_{ij}Q_{0j})^2, \quad (14)$$

$i = 1, 2, \dots, I - 1$. Using change of variable techniques set forth in Lindgren (1968, p. 353), the posterior benefits p.d.f., $f_{W(i, j)}$, is related to the i^{th} action, j^{th} commodity posterior yield ratio p.d.f., f_γ , by

$$\begin{aligned} f_{W(i, j)}(w) &= \frac{1}{2}(q_j w)^{-1/2} \left\{ f_\gamma \left[-(w/q_j)^{1/2} \right] \right. \\ &\quad \left. + f_\gamma \left[(w/q_j)^{1/2} \right] \right\}, \quad w > 0 \end{aligned} \quad (15)$$

where

$$q_j = \frac{1}{2}(b_j + e_j)Q_{0j}^2, \quad (16)$$

and where w is a particular benefit value.

To evaluate (15), note that f_γ is given by

$$f_\gamma(x) = \frac{1}{s(\hat{\gamma}_{ij})} f_{\gamma^*}[(x - \hat{\gamma}_{ij})/s(\hat{\gamma}_{ij})], \quad (17)$$

where x is a particular pollution level, and, from (10), f_{γ^*} is of the Student t form with $n_j - 2$ degrees of freedom.

The total benefits attributable to all J crops can now be written as

$$W(i) = \sum_{j=1}^J W(i, j). \quad (18)$$

Since (18) expresses $W(i)$ as a sum of independent random variables, its p.d.f., $f_{W(i)}$ say, is a J -fold convolution of the p.d.f.'s $f_{W(i, j)}$, $j = 1, 2, \dots, J$ (Feller (1971), pp. 143–148). Although it is difficult to obtain an analytical expression for $f_{W(i)}$, it can be evaluated by numerical methods, as demonstrated in the following empirical example.

III. An Application

Heck et al. (1982) concluded that ozone has the greatest crop production impact of the various air pollutants. Further, ozone in potentially damaging concentrations is thought to be the most widespread of these pollutants. We now apply the framework of the preceding section in order to assess the adequacy of the precision of existing yield response information for making estimates of the impacts of alternative ambient ozone standards upon the economic value of U.S. production of corn, cotton, soybeans, and wheat.³ By evaluating alternative yield response functional forms, we extend the analysis to model uncertainty.

One must know the values of specific parameters in order to implement the framework of section II. Calculation of the benefits functions requires estimates of the crop supply and demand relationships. Parameter values of the yield response functions are necessary to determine how alternative ambient ozone concentrations alter benefits.

Supply and Demand Relations

We employ changes in Marshallian surpluses to measure the differences in benefits across alterna-

³ The 1980 combined production of these crops comprised 64% of crop acreage, 70% of total crop value, and 65% of the value of agricultural exports for the United States (USDA (1981)).

tive ambient ozone levels. To arrive at the parameter values required for these calculations, a set of specific market relations having general equilibrium properties is estimated for each crop. The specifications reflect equilibrium adjustments and make the dimensionality of the estimation problem less than that found in an equivalent partial equilibrium system (Rausser and Just (1982)). The approach draws theoretical support from the Just et al. (1982, appendix D) proof that surpluses derived from general equilibrium specifications for a single market are identical to the sum of surpluses obtained from a system of partial equilibrium specifications.⁴ In the spirit of this approach, semi-equilibrium market relations for each of the four crops are

$$P_c^D = f(Q_c, R, T, WP, OSM, N_{-1}) \quad (19)$$

$$Q^S = f(P_{c-1}, S, P_j, T, QL) \quad (20)$$

$$Q^S = Q^D \quad (21)$$

where Q_c is the quantity of the particular crop produced in the current period, P_c is crop price, P_{c-1} is crop price in the previous period, Q^D and Q^S are, respectively, equilibrium consumption and supply, R is per capita disposable income, T is time, WP is a weighted price of other feed grain prices, OSM is oilseed meal price, N_{-1} is numbers of cattle on feed in the previous time period, S is stocks, P_j is an index of production costs, and QL is lagged production. Prices and income are expressed in actual dollars. For cotton, the demand structure excludes cattle numbers, time, and weighted price, but reflects world cotton stocks.

The system (19)–(21) was estimated for corn, soybeans, and wheat by the Zellner (1962) seemingly unrelated regression (SUR) procedure. Two-stage least squares, with the Cochrane-Orcutt iterative procedures for serial correlation, was used for the cotton system. All estimated market expressions were assumed to be linear in the original variables. The supply and demand parameters for corn, wheat, and soybeans were taken from SUR

⁴ The conditions for this Just et al. (1982) result are rather stringent. Most importantly, consistency between the results of the two approaches requires that the sequential, partial equilibrium approach reflect price changes for those markets in which surplus changes have already been calculated. Our specifications are really what Rausser and Just (1982) term semi- rather than general equilibrium models because they reflect only equilibrium adjustments in the named crop sector for given prices in other sectors.

TABLE 1.—SUPPLY AND DEMAND PARAMETERS^a

Crops	Supply Coefficients		Demand Coefficients	
	Own Price	Elasticity ^a	Own Price	Price Flexibility ^a
Corn ^b	0.0008 (3.211) ^d	0.31	−0.000089 (1.850)	0.24
Cotton ^c	0.9980 (1.821)	0.47	−0.1306 (1.602)	0.50
Soybeans ^b	0.0037 (4.662)	0.48	−0.0015 (2.296)	0.38
Wheat ^b	0.0044 (3.743)	0.59	−0.00081 (1.810)	0.52

Note: Prices are in actual dollars. Corn, soybeans, and wheat quantities are in bushels. Cotton quantities are in 500-pound bales.

^a Evaluated at mean quantity and price for 1960–1980 period.

^b Estimates from seemingly unrelated regression (SUR) supply and demand blocks for four feed grains (corn, barley, wheat, and grain sorghum) and soybeans.

^c Estimates from two-stage least squares and the Cochrane-Orcutt iterative procedure applied to expressions which are linear in the original variables.

^d Values in parentheses are *t*-statistics.

supply and demand blocks encompassing five major livestock feeds and feed grains. Data cover 1960 to 1980 and are from the USDA *Agricultural Statistics* annuals. The estimated supply and demand parameter values are presented in table 1. They are the *b* and *e* coefficients of (3) and (4) in section II.

Yield Response Information

The magnitudes of the yield response parameters used for the empirical versions of (7) are reported in table 2. They were derived from data on numerous crop cultivars (varieties), and were estimated by ordinary least squares for expressions linear and quadratic in the original variables.⁵ While recent biological evidence suggests that non-linear forms such as the quadratic more accurately describe plant response (Heck et al. (1983)), the linear form has been the mainstay of yield response research. Table 3 reports, in the form of

⁵ The data were taken from annual NCLAN reports (Research Management Committee (1981), (1982)). USEPA's SAROAD data base is the source of the ambient ozone information. Since responses to ozone may vary by region and cultivar, estimated response functions were tested for homogeneity with respect to proportionate response. Statistically significant differences usually were not present across cultivars. Separate representative cultivars were therefore selected for corn and for cotton. For soybeans and wheat, pooled response functions estimated from data for all cultivars for each crop were used to portray responses.

The ozone exposure (dose) in each of the yield response expressions was measured as a seven-hour seasonal mean concentration. The seven-hour period is from 9:00 a.m. to 4:00 p.m., the period in which stomatal activity and hence plant sensitivity to pollution is believed greatest.

TABLE 2.—ESTIMATES OF YIELD RESPONSE PARAMETERS^a

Crop and Model	Sample Size (<i>n</i>)	Intercept ($\hat{\alpha}$)	Slope ($\hat{\beta}$)	Standard Error <i>s</i> ($\hat{\beta}$)
Corn ^b				
Linear	40	13670.60	-50109.20	5582.50
Quadratic	40	12277.30	301726.70	26711.50
Cotton ^b				
Linear	24	1096.47	-3694.24	286.25
Quadratic	24	954.40	-17131.60	2202.30
Soybeans ^b				
Linear	30	386.71	-1336.38	266.79
Quadratic	30	361.30	-12022.40	2424.70
Wheat ^b				
Linear	32	4.95	-11.88	2.94
Quadratic	32	4.60	-75.99	17.25

^a Yield is in kilograms per hectare for corn and cotton, grams per plant for wheat, and grams per meter of row for soybeans.

^b Estimated from data reported in NCLAN Annual Reports (1981, 1982).

TABLE 3.—YIELD RATIO STATISTICS

Action (ppm)	Estimated Yield Ratio ($\hat{\gamma}_{ij}$) ^a		Standard Error of Ratio ($\hat{\gamma}_{ij}$)	
	Linear	Quadratic	Linear	Quadratic
Corn				
10% ozone reduction (0.048)	1.023	1.013	0.00253	0.00118
25% ozone reduction (0.040)	1.059	1.032	0.00659	0.00283
25% ozone increase (0.066)	0.941	0.959	0.00659	0.00362
Cotton				
10% ozone reduction (0.048)	1.021	1.010	0.00159	0.00123
25% ozone reduction (0.040)	1.053	1.023	0.00413	0.00294
25% ozone increase (0.066)	0.947	0.971	0.00413	0.00376
Soybeans				
10% ozone reduction (0.048)	1.021	1.019	0.00422	0.00374
25% ozone reduction (0.040)	1.055	1.044	0.01098	0.00895
25% ozone increase (0.066)	0.945	0.943	0.01098	0.01145
Wheat				
10% ozone reduction (0.048)	1.014	1.009	0.00340	0.00199
25% ozone reduction (0.040)	1.036	1.021	0.00885	0.00475
25% ozone increase (0.066)	0.964	0.973	0.00885	0.00608

^a The yield ratio is the estimated yield for action *i* relative to yield for the seasonal seven hour average ozone concentration associated with the current federal standard (0.053 ppm). These ratios were calculated from the information in table 2.

yield ratio statistics for each functional form, projected yields under hypothetical ambient ozone actions or levels relative to yields under the present standard of 0.12 ppm not to be exceeded more than once a year.⁶ These relative yield adjustments thus represent controlled experiment versions of the biological consequences of alternative regulatory options. In biological yield terms, they match or exceed the losses that Boyer (1982) attributes to insects, diseases, or weeds.

⁶ The yield adjustments portrayed in the ratios are measured against an assumed ambient ozone concentration of 0.053 ppm for a 1980 seasonal seven-hour average across all producing regions. This concentration represents an upper bound of the observed 1980 rural concentrations arising from the current Federal secondary ambient standard of 0.12 ppm.

In addition to the biological and economic consequences of the ozone exposures that result from the current ambient ozone levels, the consequences of assumed secondary ozone levels representing a 25% ozone increase and 10% and 25% ozone decreases are evaluated. Shifts in the equilibrium supply condition for each crop give economic meaning to the biological consequences of the alternative ambient standards. The supply shifts that the biological consequences induce are registered in changes in the economic surplus measures.

Expected Economic Surpluses

Integration of the areas under the supply and demand functions for each crop at relevant price

TABLE 4.—SUM OF ECONOMIC SURPLUSES FOR FOUR CROPS WITH ALTERNATIVE SECONDARY OZONE STANDARDS^a

Ambient Standard a_i	Expected Surplus ^b $E[W(i)]$		Change in Expected Surplus ^b $E[W(i)] - E[W(o)]$	
	Linear	Quadratic	Linear	Quadratic
0 (Current)	38.97	38.97	—	—
1 (0.048 ppm)	40.51	39.95	1.54	0.99
2 (0.040 ppm)	43.00	41.33	4.03	2.37
3 (0.066 ppm)	35.14	36.04	-3.83	-2.93

^aCalculated from information in tables 1 and 3.^bAll values are in billions of 1980 dollars.

and quantity equilibria provides measures of the economic surpluses associated with each ambient ozone level. Given the assumed linearity of the market relations, the integration can be accomplished by using expression (5). Table 4 reports these surpluses for the linear and the quadratic response models. For the analysis of the current 0.12 ppm standard, the consumption level for each crop is the 1978–80 arithmetic mean of 6,650 million bushels of corn, 9.08 million bales of cotton, 1,768 million bushels of soybeans, and 2,281 million bushels of wheat. The table states that the total economic surplus for the national consumption of these four intermediate commodities is estimated to be \$39 billion when the ambient ozone standard is 0.12 ppm; it does *not* say that the standard is responsible for the entire \$39 billion. The last column of the table represents the change in economic surplus predicted to result from altering the current standard of 0.12 ppm if the yield response is as portrayed in the linear and quadratic models.⁷

The Impacts of Specification and Precision

The empirical implementation of expressions (15)–(18) is the major focus of this paper. For given yield information, and when a particular ozone standard is to be enforced, we want to know the entire probability distribution of the economic surplus, not just the expected surplus. Rather than assuming that the estimated yield response param-

⁷ The model in (19)–(21) neglects the different cropping patterns and alternative input combinations growers might select as levels of ambient ozone change. In principle, this causes the estimated gains from an ozone decrease to be understated and the estimated losses from an ozone increase to be overstated. However, for the crops and the effects being considered, the resulting bias is likely to be small. Grower substitution possibilities are few and poor in most regions for the four crops in question.

FIGURE 1.—POSTERIOR DISTRIBUTIONS OF CHANGE IN GROSS ECONOMIC SURPLUS: LINEAR RESPONSE MODEL

eters are “true,” we wish to acknowledge statistical uncertainty explicitly by including it in the analysis. The inclusion provides insight into the adequacy of existing observations on the yield responses of corn, cotton, soybeans, and wheat to ambient ozone. Additional observations would reduce the variance of the yield response parameter, β , ultimately causing it to converge on some stable magnitude. We ask whether additional precision in the yield response results reported in NCLAN annual reports (Research Management Committee (1981, 1982)), and in Heck et al. (1982), is likely to influence the economic surplus estimates that could form a basis for decisions about allowable ambient ozone levels.

Figures 1 and 2 display the uncertainties in economic surpluses caused by the estimated parameters of the linear and the quadratic yield responses of tables 2 and 3. The figures result from an aggregation, by numerical implementation of (18), across the four crops. They represent the posterior density functions of the differences in economic surpluses between production under the current ambient standard of 0.12 ppm and alternative ozone levels (reading from left to right in the figures) of 0.066 ppm, 0.048 ppm, and 0.040 ppm.⁸ The scales on the vertical axes are probabilities per unit of output. Two features of these functions are

⁸ Posterior density functions for each of the four crops are available upon request.

FIGURE 2.—POSTERIOR DISTRIBUTIONS OF CHANGE IN GROSS ECONOMIC SURPLUS: QUADRATIC RESPONSE MODEL

worthy of note, particularly when one recalls (table 2) that the yield response estimates on which these surplus distributions are founded involved as few as 22 and no more than 38 degrees of freedom.

First, the mass of the surplus estimates at and in the immediate neighborhood of their means is very great for each ambient ozone level. Only the distributions for the 0.040 and 0.066 ppm levels exhibit much variability. In addition, any overlap between distributions is trivially small, thus allowing unique assignments of distributions of economic implications to each of the named alternative ozone levels. For the individual crop economic surplus distributions, there were two cases of overlap under the linear model and three cases under the quadratic model. In each case, however, the overlap occurred about one standard deviation from the mean of at least one of the overlapping distributions.

Second, the seeming adequacy for policy purposes of the precision manifested in the density functions of figures 1 and 2 holds for both the linear and the quadratic specifications, and for individual crops as well as their aggregations. The model specifications do affect the expected surplus estimates and the posterior distributions, however. In each case, the quadratic expected value for all actions is less in absolute magnitude than the linear, as noted in table 4. The yield responses for corn were the major source of the differences. While the choice of policy action would not change

under either model specification, the comparison suggests that model uncertainty may be more important than concerns over initial sample size. Knowledge of underlying biological processes could perhaps direct the choice of models. Alternatively, the acquisition of more observations from experiments might better now look toward broader and denser coverage of a response surface so as to enhance ability to discriminate among models, rather than toward replication of experiments involving application of a single model to a very small number of points on a response surface.

IV. Conclusions

We have presented and empirically implemented an analytical framework in which the adequacy of natural science information used in setting environmental regulations may be assessed. The adequacy of such information is determined here by the extent to which the variability in the yield response information affects the probabilities of overestimating ultimately realized economic surplus and thereby failing to plan for a more lax ambient standard, or by underestimating the realized surplus and thereby failing to plan for a stricter ambient standard. In effect, the framework explicitly captures the statistical and model uncertainty associated with yield response estimates and, by penalizing alternative ambient standards which are possibly too conservative or too optimistic, allows this uncertainty to be incorporated directly into the decision process.

By way of illustration, the framework has been applied to four major field crops having dissimilar growing requirements and diverse market relations. The framework was used to evaluate discrete ambient ozone standards differing by as little as 10% and by no more than 25% from the levels associated with the current ambient standard of 0.12 ppm. Relatively small variations in ozone levels should, in principle, enhance the relevance of good precision in yield response estimates. For all four crops, individually and in the aggregate, if possibilities for the grower to alter his cropping patterns are ignored, the analysis indicates that about 40 or fewer yield response observations similar to those found in Heck et al. (1982) appear adequate to discriminate among the differences in economic surplus that ambient ozone levels of 0.066, 0.053, 0.048, and 0.040 ppm generate. This finding would seem to say as much for the power

of the aforementioned linear and quadratic yield response experimental designs as it does for the role of the economic analysis.

Our treatment has employed only linear and quadratic yield response functions. We have no priors allowing us to choose between these functional forms. Nevertheless, in this analysis, a comparison of these two models did show substantial yield response and economic surplus differences, particularly for corn. These comparisons always indicated somewhat lower yield responses and economic surplus changes for the quadratic, with less variability also being present in the quadratic estimates. Both specifications are widely used in yield response research, with greater emphasis now being given to non-linear representations. The policy implications of the two models do not differ, however, as both the linear and the quadratic allowed unique assignments of economic surplus distributions to the named policy-action alternatives. Moreover, when the discrete policy-action alternatives were rank-ordered by their estimated economic surpluses, each model had the identical ordering. We do not know whether other yield response models would generate the same results. Nonetheless, the Bayesian approach we have adopted is equally applicable to assessments of the policy discrimination adequacy of the precision of yield response estimates obtained while using these other models.

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