Toward a Generalizable Measure of the Value of a Change in Pesticide Use

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Abstract. This study develops a comparable measure of pesticide risks. Based on revealed preference method an index system is developed for individual pesticides combining the information on different environmental and health risks. A data obtained from a survey of U.S. farmers has revealed that on average the adoption of Roundup Ready soybeans results in reduced toxicity of herbicides.

Introduction

The benefits of pesticides include improved yield and product quality. At the same time, pesticides can be harmful to human health and environment. Genetically engineered (GE) crop varieties are designed to simplify and provide additional options for pest management. It has been reported in recent literature that they may require fewer pesticide applications and therefore benefit the environment (Marra; Carpenter et al.). Several studies attempted to establish whether the adoption of GE crops for pest management reduces the use of pesticides, and found an overall downward trend in pesticide application rates on GE crops (Heimlich et al.; Carpenter; Carpenter and Gianessi; Hubbell et al.; Gianessi et al.). On the contrary, others found an increase in the total volume of pesticides applied (Benbrook; Fernandez-Cornejo and McBride). Such polar results are attributed to different measurement methods (Frisvold and Marra). Furthermore, analyses based only on the volume of the pesticides applied are inadequate for calculating any meaningful measure of pesticide use since they ignore crucial information about pesticide environmental effects (Frisvold and Marra; Levitan; OECD; Nelson and Miranowski). Therefore, information on environmental effects should be included in the analysis of the changes in pesticide use due to adoption of GE crops.

The dollar value that a particular pesticide adds to crop returns can be measured by calculating the value of comparative yield losses incurred when this pesticide is not used, coupled with its additional

cost. Monetizing the environmental and health improvements that result from changes in exposure to pesticides is more difficult, partially due to the numerous potential environmental effects, such as ground and surface water effects, human health effects, and wildlife effects.

Crop varieties tolerant to Roundup account for the largest share of the acreage planted to GE crops. Their adoption results in the substitution of a single broad-spectrum herbicide characterized by outstanding environmental properties for a variety of selective herbicides with varying levels of environmental effects (Malik et al.). The specific objective of this paper is to develop an economically consistent value of a marginal change in herbicide safety from the adoption of Roundup Ready (RR) soybeans. The empirical analysis is based on data obtained from a national survey of soybean farmers. First, an index system for individual herbicides that combines the information on their acute and chronic health risks with their toxicity to non-target organisms and the environment is developed. A key challenge is to choose the weights that will determine the relative effects of the individual components of the index. Second, a stated preference valuation technique is used to estimate farmers' valuation of a one-unit change in the pesticide risk index.

A Behavioral Model of Herbicide Choice

Herbicides are production inputs affecting farmer's profit. They also enter farmer's utility by affecting the environment and the health of people they care about. As shown by Beach and Carlson, an agricultural household model is appropriate to use in situations when agricultural inputs affect utility indirectly through its effect on profit and utility directly through environmental and health effects. The farmer's objective is to choose a herbicide product out of a set of available alternatives based on its production-related and safety attributes:

$$(1) \quad \begin{aligned} &\max_{\mathbf{h}^\pi, \mathbf{h}^e} U = U\left(c, \mathbf{h}^e; \mathbf{g}\right) \\ &s.t. \quad c = \left(p \cdot y(\mathbf{h}^\pi) - r\right) \times n, \end{aligned}$$

where $c(\cdot)$ is farmer's consumption; $\mathbf{h}^e$ is a vector of herbicide safety attributes; $\mathbf{g}$ is a vector of other utility arguments; p is the price the farmer expects to receive for his crop; $y(\cdot)$ is expected yield per acre, a function of the herbicide attributes related to profit, $\mathbf{h}^\pi$; r is per acre cost associated with application of herbicide; and n is the number of crop acres planted.

The farmer's valuation of change in the relative safety of the herbicides applied on RR soybeans (the Hicksian compensating surplus) is represented by the price, expressed in terms of income reduction, that the farmer would be willing to pay for the improved herbicide safety that would make him equally well off as under the conditions imposed by conventional soybeans:

(2) $\qquad Q = \pi_{CO} - e\,(\mathbf{h}^e_{RR},\ V^*\,(\pi_{CO},\mathbf{h}^e_{CO};\,\mathbf{g}\,);\,\mathbf{g}\,),$

where Q is Hicksian compensating surplus; π_{CO} is farmer's profit from conventional soybeans; $e(\cdot)$ is the expenditure function, the level of profit that solves for the reference level of utility (conventional soybeans) given a new level of herbicide safety, ceteris paribus; $\mathbf{h}^e_{RR}$ is a vector of safety attributes of the herbicides used on RR soybeans; $V^*(\cdot)$ is an indirect utility function representing the maximum utility level associated with conventional soybeans; and $\mathbf{h}^e_{CO}$ is a vector of safety attributes of the herbicides used on conventional soybeans. Equation (2) can be expressed in the equivalent form of an income compensation function (Willig), sometimes referred to as the willingness-to-pay (WTP) function:

(3) $\qquad Q = Q\,(\,\mathbf{h}^e_{CO},\,\mathbf{h}^e_{RR},\,\pi_0;\,\mathbf{g}\,)\,.$

Herbicide Risk Index

The potential change in the environmental and health impacts resulting from the adoption of the RR soybeans can be expressed as a difference in the pesticide risk indices calculated for RR and conventional soybeans. The indices combine all relevant information about pesticide environmental and health impacts. This section discusses issues relevant to the development of such indices.

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Several authors attempted to develop risk ratings of pesticides concentrating on a particular risk (Mulkey et al.; Theiling and Croft; Morse; Reus and Pak). But environmental and health effects of pesticides are numerous and complex. Some studies analyze expanded lists of possible environmental effects of pesticides, and develop methods to combine this information into a single indicator of risk (Fernandez-Cornejo and Jans; Kovach et al.). In addition to developing risk indices combining various pesticide risk information, Mullen et al. and Higley and Wintersteen also develop some methods to value changes in pesticide safety.

The process of summarizing the information on different pesticide risks into a single value is usually done in two steps (Kovach et al.; Higley and Wintersteen; Mullen et al.). First, risk criteria are established for different pesticide risk categories. Individual pesticides are assigned risk levels in each category based on these criteria. Second, this information is summarized into a single index number making it possible to compare different pesticides with respect to their overall risk.

The first step is straightforward. The information used is objective and is obtained from the standard tests on pesticides. To accomplish the second step it is necessary to establish the relative weights of the individual risk categories. Previous studies used stated preference information to develop these weights. In both cases (Higley and Wintersteen; Mullen et al.), survey respondents were asked to rate the importance of avoiding different pesticide risks on a certain scale. However, these ratings were not based on a cardinal scale, i.e. the ratings of the importance of different risks are not comparable with each other. Therefore, this method of rating cannot be used to weight different risks while combining them into a single risk index.

In addition, analytical methods that rely on stated preference information are often criticized for the hypothetical nature of the survey questions, answers to which may not be very informative about the actual preferences of the respondents (Kling). Therefore, it is possible to achieve improved reliability of the relative weights by relying on the revealed preference information. It was assumed here that the

farmers reveal their preferences for herbicide attributes, including different aspects of safety, by choosing the specific herbicide product out of the set of alternatives available to them.

Pesticide Environmental and Health Risk Criteria

Pesticides are strictly regulated in the United States through a complex process that leads to product registration. The EPA evaluates the information about a pesticide and approves its label and Material Safety Data Sheet (MSDS) that are intended to provide the public with general, technical, risk and safety information as well as serve as the legal notice of approved uses and rates for each pesticide. Since the labels and MSDSs follow established, uniform standards while presenting the information about pesticide risks, they are used as informational sources for the index developed in this study.

Four levels of risk (high, moderate, low, none) are established for each category of pesticide risks. The recognized potential routes of human acute exposure to pesticides are through ingestion of the residues in food and water, as well as dermal and inhalation exposure. Criteria for assigning human chronic risk level are based on the results of tests evaluating carcinogenity and reproductive, birth and developmental effects due to pesticide exposure. Pesticide environmental risks are established for such wildlife groups as mammals, fish and birds. Methods estimating the impact of pesticides on the quality of water resources concentrate on surface and groundwater contamination potential determined by pesticide persistence, water solubility, and mobility.

The Data

The data were generated by a computer-aided telephone survey of soybean farmers in 19 states conducted by Doane's Market Research in cooperation with North Carolina State University in 2002. The survey explored the issues relevant to the comparative economic analysis of conventional and RR soybeans. In particular, it concentrated on differences in herbicide use. In addition to the direct agronomic and economic differences, the survey also attempted to extract farmers' valuation of various indirect aspects of the herbicide use differences such as changes in environmental quality and health.

There were 610 surveys completed. The percent of respondents in each state approximately corresponded to the percent of total US soybean acreage by state. There were 1,769 individual herbicide choices made by the farmers in the sample, including 633 applications on RR soybeans, and 1136 on conventional soybeans. These herbicide choices were used to reveal farmers' preferences for herbicide attributes.

Estimation of the Herbicide Choice Model

Herbicide choices made by farmers can be used to estimate their preferences for herbicide attributes by applying the conditional logit procedure (McFadden) which allows considering the effects of choice characteristics on the choice probabilities. A broad set of herbicide attributes may affect farmer's choice. Since herbicides are used to control weeds, their effectiveness is one of the most important characteristics. In addition, the costs associated with herbicides determine the final profit. Herbicide persistence is related to both effectiveness and safety. Persistent herbicide will remain effective longer but will also expand the time when the potential exposure to its negative effects is possible.

Farmers may also be concerned about herbicide safety. Herbicide safety may affect production through deteriorated health of farm workers or quality of on-farm environmental resources such as soil and water. Farmers may also extract utility from fishing, hunting, swimming or other activities that are affected by herbicides. Finally, farmers may have some altruistic concerns for environmental preservation. Herbicide safety attributes considered are acute human toxicity to eyes and skin, by ingestion and inhalation, chronic human toxicity, fish, bird, mammal toxicity, and potential to contaminate ground and surface water resources.

The coefficients on herbicide risk characteristics obtained by estimating the herbicide choice model can be used to establish the relative weights of the risk index categories. Since different herbicide risks are not measured in the same units, the magnitude of the coefficients on the herbicide risk characteristics would not be directly indicative of the relative importance of different risks. At the same time, it is possible to rescale these measures of different risks to make them comparable. If an herbicide

presents a high risk in certain risk category, it is assigned a value equal to 3 in this category, if it presents a moderate risk, it is assigned a value of 2, if it presents a low risk, it is assigned a value of 1, and if it presents no risk, it is assigned a zero value. Table 1 present summary statistics of the herbicide choices.

Some of the herbicide safety characteristics were highly correlated. In addition, broadleaf and grass weed response variables calculated as an average percent of weed response within these weed classes can only be considered as proxies for the true measures of effectiveness. Resulting estimates may be biased because of the measurement errors in variables, in particular, if unobservable herbicide characteristics are correlated with observable characteristics used in estimation. A number of econometric tools were used to reveal the collinear variables: analysis of the correlation coefficients, tolerance factors of the linear regressions of the herbicide choices on herbicide characteristics, and R^2 statistics from regressing each of the explanatory variables on the others. As a result the mammalian, bird and fish risk variables were excluded from the model, and also the sum of inhalation and ingestion toxicities was used instead of each variable separately.

The model was estimated using the conditional logit procedure available in the LIMDEP package. The results support the theoretical model outlined in the second section and suggest that, in addition to the production-related characteristics, farmers care about herbicide safety. All characteristics considered except for the herbicide's persistence and groundwater risk are statistically significantly different from zero at the 99 percent level of confidence and have the expected signs (Table 2).

The coefficients on the risk variables were used to calculate the relative weights of the individual categories included in the herbicide risk index. The relative weights (Table 3) were calculated by dividing the coefficient on each index category by the sum of the coefficients on all included categories. The indices were calculated as the sum of the product of the herbicide risk ratings in each of the index categories and the relative weight of the category. Index values can vary from 0 to 3 with the latter representing the highest risk. The mean index value for this selection of herbicides is 1.53 with a standard

deviation of 0.36. *Alachlor* had the highest risk index (2.13). The safest herbicide was *glyphosate* with an index value of 0.63.

On-Farm Change in Herbicide Toxicity

Herbicide risk indices were used to calculate on-farm differences in the herbicide toxicity on conventional and RR soybeans. The number of herbicide choices at different stages of production and the number of applications for each herbicide varied across farmers. To obtain the appropriate measure of the herbicide toxicity per acre for each variety it was necessary to add up the toxicities of the individual herbicides used. To make the herbicide toxicity measure accurate it was also adjusted by the proportion of acreage treated.

The average on-farm herbicide toxicities per acre calculated based on the risk indices of the individual herbicides were obtained separately for RR and conventional (*CO*) soybeans. They were calculated by summing the risk index values, *index,* of the individual herbicides applied by a farmer multiplied by the number of applications of this herbicide, N, and adjusted for the proportion of the acreage treated, a:

$$(4) \qquad T_{CO} = \sum_{i=1}^{n} index_{CO,i} \times N_{CO,i} \times a_{CO,i} \, ,$$

$$(5) \qquad T_{RR} = \sum_{j=1}^{m} index_{RR,j} \times N_{RR,j} \times a_{RR,j} \, ,$$

where T_{CO} is the average toxicity per acre of the herbicides used on conventional soybeans; T_{RR} is the average toxicity per acre of the herbicides used on RR soybeans; $i : i = 1,...n$ denotes a herbicide applied on conventional soybeans; $j : j = 1,...m$ denotes a herbicide applied on RR soybeans. The change in the herbicide toxicity for each farmer is then:

$$(6) \qquad \Delta T = T_{RR} - T_{CO.}.$$

A total of 459 farmers reported their herbicide use on both varieties. Table 4 reports the average per acre herbicide toxicity on RR and conventional soybeans and the average per acre on-farm change in

herbicide toxicity. The average toxicity of the herbicides applied on conventional soybeans was higher by 1.02 index units indicating that adoption of RR varieties resulted in reduction of the average per acre toxicity of herbicides.

Valuation of the Changes in Herbicide Toxicity

The WTP function (Equation 3) represents a monetary value of the change in economic welfare that occurs for a given change in environmental quality. It was assumed that the farmer's WTP for changes in herbicide safety varies systematically with the vector of farm and farmer attributes and the change in herbicide safety:

(7) $Q = \varphi' \alpha + \beta \, \Delta T,$

where Q is the stated value of changes in herbicide safety on the RR variety as compared to the conventional variety; φ is a vector of attributes that affect the farmer's valuation; ΔT is a change in herbicide safety resulting from the adoption of the RR variety; and α, β are coefficients.

The value of environmental and health benefits associated with reduced toxicity of the herbicides used on RR soybeans may be affected by the farmer's perception of herbicide toxicity, exposure, and his notion of altruism. Certain farmer attributes associated with these factors may affect the valuation, for example, farmer's experience, education, environmental attitudes, income, and magnitude of the reduction in herbicide toxicity on his farm. It is difficult to find an appropriate measure for environmental attitudes. Conventional tillage systems cause soil erosion, while conservation tillage may reduce the erosion. At the same time, conservation tillage increases management and herbicide costs. It was assumed that a farmer who practices conservational tillage and considers it as beneficial to the environment will value the environmental benefits more than one who practices conventional tillage.

The percent of time a farmer spent in crop production is used as a proxy for the level of farmer's exposure to herbicides. A farmer who spends more time in crop production is assumed to be more likely to be involved in every day operations, including herbicide handling and application. This farmer is more

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likely to be concerned with adverse effects of herbicides on human health, and therefore, will give a higher value.

The data set contained a significant number of missing values of total household income. Since this characteristic was correlated with total farm acreage ($\rho=0.6$), farm acreage was used as a proxy for income to avoid the loss of degrees of freedom. In addition, the use of farm acreage instead of income resulted in the best fit of the model.

Farmers participating in the survey were asked whether they believe that the herbicides applied on RR soybeans are safer to humans and the environment as compared to the herbicides applied on conventional soybeans. If they responded positively, they were asked to assign a dollar value to these benefits on a per-acre, per-year basis. These values were used to estimate farmers' WTP for herbicide safety. Table 5 presents the summary statistics of the explanatory variables used in the valuation model.

The data set was characterized by a high degree of censoring of the value of changes in herbicide safety since a considerable number of responses were zero. Because it is necessary to account for these observations, the tobit model (Tobin) was used. A measure due to McKelvey and Zainova was used to measure the goodness of fit (Veall and Zimmerman).

Table 6 presents the estimation results of the relationship between stated values of benefits and actual changes in herbicide toxicities measured by the herbicide risk index. In addition, a farmer's time spent in crop production used as a proxy for the exposure level to herbicides, and a dummy variable for conservation tillage, representing the attitude toward the environment, also had explanatory power. Both of these variables have the expected signs. The results of our estimation also show that the higher level of education has negative effect on valuation, as well as farm acres in 2002 used as a proxy for income. We used the 85 percent level because our proxies for some of the true explanatory variables are fairly imprecise.

To obtain the marginal effects of the explanatory variables the coefficients in the Table 6 have to be adjusted for the probability that the observation will fall in the uncensored part of the distribution. The

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adjustment is a function of the explanatory variables, and therefore would be different for each observation. The marginal effect of the change in the herbicide toxicity was estimated to be 0.24. Based on this result the average farmer in this sample was willing to pay $0.24 per acre for a one-unit reduction in the herbicide toxicity as measured by the herbicide risk index developed in this study.

Conclusions

This paper develops a methodology analyzing environmental effects of pesticides, which could contribute to the development of a comparable measure of pesticide risk. Its primary application is in the area of valuation of the environmental effects of alternative pest management strategies, individual pesticides, and seed technologies.

The improvement on the previous attempts to develop pesticide safety rankings was made by creating a pesticide risk index, a single, simple measure of risk that combines complex information about environmental and health effects of pesticides. The revealed preference information is used to estimate the relative weights of the index categories, resulting in a greater reliability compared to the previous measures.

This paper also contributes to the literature on the environmental effects of GE crops. Based on the herbicide risk index the average herbicide toxicity per acre was calculated for conventional and RR soybeans. According to our results, herbicides used on RR soybeans are 1.02 index units safer compared to herbicides used on conventional soybeans. The value of this effect was estimated to be $ 0.24 per acre per year. For a 1,000-acre soybean farm, RR soybeans are worth $245 more to the average farmer just in terms of environmental and health benefits alone than are conventional soybeans.

The methodology developed here can be used in other applications as an input to evaluate the benefits and costs of seed biotechnologies in regulatory decisions. Without this input, evaluations could suffer from serious biases and result in erroneous conclusions. Further work in this area would include testing the proposed methodology on a larger data set containing more accurate measures of herbicide effectiveness and exposure to herbicides. In addition, since the results imply a positive welfare effect

associated with improved safety of herbicides applied on RR soybean varieties, the above method can be used further to explain the adoption of these varieties.

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Table 1. Summary Statistics of Characteristics of the Herbicides Choices (N=1769)

Herbicide Characteristics	Mean	Standard Deviation
Grass Weed Response (Percent)	67.16	28.52
Percent of Broadleaf Weed Response (Percent)	61.46	25.78
Herbicide Application Costs ($ per Acre)	15.13	5.17
Persistence (Days)	42.30	18.70
Eye Toxicity (0-3)	1.72	0.72
Dermal Toxicity (0-3)	0.83	0.68
Ingestion Toxicity (0-3)	0.69	0.49
Inhalation Toxicity (0-3)	0.99	0.50
Chronic Toxicity (0-3)	1.16	0.96
Fish Toxicity (0-3)	1.76	1.04
Bird Toxicity (0-3)	0.35	0.62
Mammal Toxicity (0-3)	1.59	0.68
Groundwater Risk (0-3)	1.51	0.83
Surface Water Risk (0-3)	2.11	0.89

Table 2. Estimation Results of the Herbicide Choice Model

Herbicide Characteristics	Coefficient	Standard Error
Application Cost	-0.11*	0.01
Broadleaf Weed Response	0.005*	0.001
Grass Weed Response	0.02*	0.001
Persistence	0.002	0.002
Groundwater Risk	0.01	0.04
Surface Water Risk	-0.32*	0.03
Eye Toxicity	-0.15*	0.04
Dermal Toxicity	-0.53*	0.06
A Sum of Ingestion and Inhalation Toxicities	-0.16*	0.03
Chronic Health Risk	-0.13*	0.03
Value of Log-Likelihood Function at Convergence	-5936.66	
N	1,769	
McFadden's Pseudo R^2	0.13	
Pearson's X^2	1,758	

* Indicating a coefficient statistically significantly different from zero at the 1 percent confidence level

Table 3. Relative Weights of the Herbicide Risk Index

Herbicide Characteristics	Relative Index Weight
Dermal Toxicity	0.36
Surface Water Contamination Potential	0.22
Ingestion Toxicity	0.11
Inhalation Toxicity	0.11
Eye Toxicity	0.10
Chronic Health Risk	0.10
Total	1.00

Table 4. Average Herbicide Toxicity per Acre (N=459)

Average Toxicity	Mean	Standard Deviation
Roundup Ready Soybeans	1.36	1.58
Conventional Soybeans	2.38	2.15
On-Farm Change	-1.02*	2.52

* Indicating a result statistically significantly different from zero at the 1 percent confidence level

Table 5. Summary Statistics of the Variable in the Valuation Model (N=459)

Variable	Mean	Standard Deviation
Stated Value of Improved Safety ($ per Acre per Year)	5.21	8.17
Change in Herbicide Toxicity	1.02	2.52
Farm Acres in 2002	1,193.0	1,016.7
Farmer's Age	54.0	11.0
Farmer's Education	13.5	2.1
Considers Conservation Tillage as Beneficial	0.78	0.41
Proportion of Work Time Spent in Crop Production	0.70	0.29

Table 6. Estimation Results for the Valuation Function

Explanatory Variable	Coefficient	Standard Error
Constant	-6.83	8.01
Change in Herbicide Toxicity	0.5*	0.35
Farm Acres in 2002	-0.001**	0.001
Farmer's Age	0.07	0.08
Farmer's Education	-0.76**	0.41
Considers Conservation Tillage as Beneficial	13.63***	2.36
Percent of Work Time Spent in Crop Production	0.04*	0.03
Value of Log-Likelihood Function at Convergence	-722.11	
McFadden's Pseudo-R^2	0.16	
MZ R^2	0.39	
Number of Valid Observations	320	
Number of Non-Censored Values	158	

*** Indicating a coefficient significant at the 5 percent level

** Indicating a coefficient significant at the 10 percent level

* Indicating a coefficient significant at the 15 percent level