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A Genetically Engineered Crop's Impact on Pesticide Use: A Revealed-Preference Index Approach

Olha Sydorovych and Michele C. Marra

A revealed-preference-based method is proposed for assessment of the environmental and human health impact of genetically engineered (GE) crops. This method employs the relative pesticide toxicity information from farmers' pesticide choices combined with volume of pesticides as an alternative to previous methods which are based on volume only, on number of pesticide applications, or on stated preferences. The method is applied to estimate the changes in the impact of herbicides after adoption of Roundup Ready (RR) soybeans in a way that is more meaningful from an environmental and health perspective. The results indicate that, on average, a reduction in herbicide human health and environmental impacts occurs when farmers adopt RR soybean varieties.

Key words: environmental impact, genetically engineered crops, pesticide risk index, revealed preference information, Roundup Ready soybeans

Introduction

The first generation of genetically engineered (GE) crops is designed to simplify and provide additional options for pest management. GE crops may allow the use of safer pesticides, and therefore their adoption may benefit human health and the environment as well (Carpenter et al., 2002; Marra, 2001).

Several studies have attempted to establish whether the adoption of the first-generation GE crops for pest management impacts pesticide use. While some find an overall downward trend in pesticide use as GE crops increase (Bennett, Morse, and Ismael, 2006; Carpenter, 2001; Gianessi et al., 2002; Heimlich, Fernandez-Cornejo, and McBride, 2000; Huang et al., 2003; Hubbell, Marra, and Carlson, 2000; Pray et al., 2001), others report that pesticide use increases with an increase in GE crops, with some asserting this is a cause for alarm (Benbrook, 2003; Fernandez-Cornejo and McBride, 2000). Such contradictory findings have been attributed to the differences in the approaches to measuring pesticide use: how pesticide use is recorded (pesticide active ingredient volume, formulated volume, number of applications), which factors are controlled for (the results would vary from region to region and from year to year depending on pest problems, weather conditions, cropping patterns, etc.), and the method of aggregation (Frisvold and Marra, 2004).

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Studies based on the volume of pesticides applied or the number of pesticide applications are inadequate to answer the question at hand. A measure of pesticide impact that is meaningful for regulatory and other policy decisions should capture changes in relative pesticide toxicity to humans and the environment, or the change in the environmental "footprint," brought about by adoption of GE crops (Carpenter, 2001; Carpenter et al., 2002; Fernandez-Cornejo and Jans, 1995; Heimlich et al., 2000; Levitan, 2000; Nelson and Miranowski, 1996; Wolfenbarger and Phifer, 2000). Few studies have attempted to address this issue. Qaim and Traxler (2005) conclude that adoption of GE soybeans results in an increase in the volume of herbicides applied and the number of herbicide applications, but they also introduce the distinction between different toxicity classes of herbicides. In their study, the increase takes place for the relatively safe herbicides, while the volume of the more toxic herbicides is reduced. Nelson and Bullock (2003) develop a measure of pesticide use that takes into account both volume applied and relative acute toxicity to humans by ingestion. They also find a reduction in herbicide impact associated with GE soybeans.

The objective of this paper is to propose a new and improved measure of pesticide use and to apply it to estimate the impact of Roundup Ready (RR) soybean adoption on herbicide use in the United States in a way that is useful for policy makers. RR soybean varieties account for the largest share of the acreage planted to herbicide-tolerant crops (70% in 2007) and of total soybean acreage (91% in 2007) [U.S. Department of Agriculture (USDA), 2007]. Because adoption of RR soybeans results in the substitution of a single, broad-spectrum herbicide characterized by favorable environmental properties (Malik, Barry, and Kishore, 1989) for a variety of selective herbicides with different levels of environmental effects, it is crucial to include this information in the assessment of the change in herbicide use and the environment as a result of adoption of RR soybeans.

To achieve this objective, we develop a herbicide risk index system using revealed-preference information to estimate the relative weights of the individual risk index components based on data obtained from a national survey of soybean growers. The herbicide risk index is used to assess the on-farm impact of RR soybeans on herbicide use for a sample of soybean farmers who planted both conventional and RR soybeans in 2001. The results are compared to alternative measures of herbicide impact, such as the changes in the volume of applied herbicides, herbicide active ingredients, and the number of herbicide applications for the same sample.

Development of the Herbicide Risk Index

Our herbicide risk index is designed to combine information about various herbicide environmental and human health risks to give a more meaningful picture of herbicide impact. The form of the index is expressed as:

$$(1) \quad \sum_{k=1}^K w_k r_k,$$

where w_k is the relative weight, or importance, placed on risk source r_k . There are K risk sources, and

$$\sum_{k=1}^K w_k = 1.$$

Since measurement units may vary for different risks, certain transformation is required for different measures of risk to represent them on a comparable scale.

Previous Pesticide Risk Indices

Most of the previous attempts to develop pesticide risk ratings concentrated on a specific pesticide risk (Morse, 1989; Nelson and Bullock, 2003; Reus and Leendertse, 2000; Theiling and Croft, 1988). A few others analyzed several potential risks and developed methods to combine this information into a single indicator (Fernandez-Cornejo and Jans, 1995; Higley and Wintersteen, 1992; Kovach et al., 1992; Mullen, Norton, and Reaves, 1997). Summarizing the information on different pesticide risks into a single index value is usually accomplished in two stages. First, risk criteria are established for different pesticide environmental and human health risks using the U.S. Environmental Protection Agency (EPA) toxicity categories as a base.

Second, the information is summarized into a single index number, making it possible to rank different pesticides with respect to their overall risk to human health and the environment. To accomplish this, it is necessary to establish the *relative* importance of the individual risk categories. Stated-preference information was used in previous attempts to develop these weights (Higley and Wintersteen, 1992; Mullen, Norton, and Reaves, 1997), when survey respondents were asked to rate the importance of avoiding different individual pesticide risks. However, the design of survey questions in these earlier studies did not allow ranking different risks *relative* to one another on a common scale. Therefore, such rankings cannot be used to establish the relative weights of the components of the index. In addition, analytical methods that rely on stated preferences are criticized for the hypothetical nature of the survey questions, answers to which may not be very informative about the actual preferences and behavior of the respondents (Kling, 1997).

We argue that improved reliability of the relative weights of pesticide risk categories could be achieved by relying on revealed-preference information. In this study, we use information on farmers' actual herbicide choices out of the set of available alternatives and various attributes of these choices, including production-related as well as human and environmental safety attributes, to estimate farmers' willingness to pay (WTP) for different safety attributes, and therefore the relative importance of individual herbicide risks to the farmers. The relative weights of different risks obtained in this manner are based on a cardinal scale and are potentially more reliable compared to the weights estimated in stated-preference-based studies.

Farmers are dealing with pesticides on an everyday basis. The majority of farmers also must familiarize themselves with the issues relevant to pesticide safety when they apply for the license allowing them to use restricted pesticides. Consequently, it is reasonable to assume they have more accurate knowledge of pesticide human and environmental risks compared to the general population. In addition, farmers are not only producers who use pesticides as productive inputs, but also consumers who are exposed to negative pesticide externalities. At the same time, we also acknowledge that the relative weights obtained in our study represent preferences specific to farmers, and it might not be appropriate to use them to exactly represent the societal weights.

A Behavioral Model of Herbicide Choice by Farmers

The choice of a herbicide out of the set of available alternatives by a farmer can be represented as a utility maximization problem. Herbicides are productive inputs affecting farmers' profits, thus indirectly affecting utility. Beach and Carlson (1993) also suggest considering the impact of some nonproductive herbicide attributes, such as water quality and user safety, on farmers' utilities. The impact of herbicides on a farmer's health and the health of family members and workers, as well as on the quality of on-farm environmental resources, such as soil and water, may enter the farmer's utility function directly in addition to indirectly through their impact on the production function and costs. Farmers may also derive utility from fishing, hunting, swimming, or some other recreational activities that are affected by herbicides, or they may have some altruistic concerns for environmental preservation.

We assume the representative farmer is maximizing the one-period utility of consumption and herbicide safety, subject to the following budget constraint:

$$(2) \quad \begin{aligned} \max_{c, h} U &= U(c, h^s(h); \mathbf{g}) \\ \text{s.t.: } c &= (p * y(h; \mathbf{f}) - r(h; \mathbf{l})) * A, \end{aligned}$$

where $c(\cdot)$ is a farmer's consumption, h^s is human and environmental safety associated with herbicide h , \mathbf{g} is a vector of structural preference parameters of the utility function, p is the price the farmer expects to receive for his/her crop, $y(\cdot)$ is expected yield per acre, \mathbf{f} is a vector of other parameters affecting yield, r is per acre costs of production, which are also affected by herbicide choice, \mathbf{l} is a vector of other parameters affecting production costs, and A is the number of crop acres.

The problem can be presented as the Lagrangean,

$$\max_{c, h} L = U(c, h^s(h); \mathbf{g}) - \lambda((p * y(h; \mathbf{f}) - r(h; \mathbf{l})) * A - c),$$

where λ is the Lagrange multiplier. At the optimum, the marginal utility of an additional unit of consumption equals the marginal utility of an additional dollar of profit ($\partial U / \partial c = \lambda$), and the marginal utility of herbicide safety equals the marginal utility of additional profit from a herbicide choice:

$$\left(\frac{\partial U}{\partial h^s} \frac{\partial h^s}{\partial h} = \lambda A \left(p \frac{\partial y}{\partial h} - \frac{\partial r}{\partial h} \right) \right).$$

The solution to this problem provides us with the marginal rate of substitution between herbicide safety and consumption:

$$(3) \quad \frac{\partial U / \partial h^s}{\partial U / \partial c} = \frac{\partial c / \partial h}{\partial h^s / \partial h}.$$

Equation (3) represents the costs (price) of added herbicide safety expressed in terms of foregone consumption. At the maximum, the numerator on the right is the ratio of herbicide price to the price of consumption representing the market tradeoff between herbicide choice and consumption, and the denominator adjusts the price of the herbicide to reflect its safety, which is required to equate market prices to the marginal rate of substitution.

Estimation of the Herbicide Choice Model

The herbicide use data were obtained from a national, computer-aided telephone survey of soybean farmers in 2002 conducted by Doane's Market Research. The survey explored issues relevant to the comparative economic analysis of conventional and RR soybeans. In particular, it concentrated on differences in herbicide use. Farmers selected to participate in the survey represent 19 major soybean growing states. The number of survey respondents in each state was selected based on the state's share of national soybean acreage in 2001. The majority of respondents operated large farms, and 45% were growing only RR soybeans in 2001. Thirty-three percent of respondents were partial adopters of RR technology, and 22% were growing conventional soybeans only.

The farmers' choice set consists of 46 herbicide alternatives. There were 1,769 individual herbicide choices made by 610 farmers participating in the survey.¹ These choices were used as a basis for the estimation of farmer preferences over various herbicide risks for the construction of our index. The appendix contains an example of the set of survey questions designed to extract information on herbicide use by the farmers.

Empirical Model of Herbicide Choice

In the empirical application of the behavioral model of herbicide choices by a farmer (2), the reduced-form, indirect utility function U of farmer i ($i = 1, \dots, I$) associated with the attributes of herbicide alternative j ($j = 1, \dots, J$) can be represented as:

$$(4) \quad U_{ij} = \beta_i' \mathbf{h}_{ij} + \varepsilon_{ij},$$

where \mathbf{h}_{ij} represents observed attributes of herbicide alternative j for farmer i , including the herbicide application costs, effectiveness, and safety, and β_i is a vector of coefficients for farmer i . Finally, ε_{ij} is the stochastic portion of the utility function of farmer i associated with herbicide alternative j .

The farmer observes all production-related and safety attributes of the herbicide choices and chooses herbicide alternative j that maximizes utility: $U_{ij} = \max(U_{i1}, U_{i2}, \dots, U_{iJ})$. If we also assume the coefficients vary across farmers with density $f(\beta)$, and ε_{ij} is an extreme-value i.i.d. random term, we can model the probability of choosing herbicide alternative j among J alternatives by farmer i as the integral of the conditional choice probability for herbicide alternative j by farmer i over all possible values of β_i ,

$$P_{ij} = \int_{i=1}^I \frac{\exp(\beta' \mathbf{h}_{ij})}{\sum_{j=1}^J \exp(\beta' \mathbf{h}_{ij})} f(\beta) d\beta,$$

leading to the mixed logit model (Train, 2003).

The mixed logit is often used to model consumer demand for products or services (Train, 2003), but it could also be employed to model the demand for inputs by producers. For example, Hubbell and Carlson (1998) use a special case of this model to explain farmers' choices of insecticides based on their attributes. The mixed logit model

¹ Individual farmers often used multiple herbicides. We assume the farmers' herbicide choices are based on weed pressure observed at the time of the decision and are independent of previous/other herbicide applications.

was selected for our analysis because it allows us to control for random preference variations across participating farmers, which would capture some unobservable farmer and farm attributes that may affect the herbicide choice.²

The farmer's WTP for the improvements in herbicide safety attribute k ($k = 1, \dots, K$) can be calculated as the marginal rate of substitution between this herbicide safety attribute and herbicide application costs,

$$WTP_{ik} = \frac{\partial U_{ij} / \partial h_{ijk}^s}{\partial U_{ij} / \partial h_{ij}^c} = \frac{\beta_{ik}^s}{\beta_i^c},$$

where β_{ik}^s is the estimated coefficient on herbicide safety attribute k , and β_i^c is the coefficient on herbicide application costs.³ These values are used to make judgments about the relative importance of different risks for the construction of the risk index.

Attributes of the Herbicide Choices

A number of herbicide attributes may affect the farmer's choice of herbicide product. Since herbicides are designed to control weeds, their effectiveness in dealing with weeds should be one of their most important attributes to the farmer. Herbicide effectiveness is measured as the percentage of broadleaf and grass weed control calculated as an average percentage control of a number of weeds within broadleaf and grass weed categories (calculations include all broadleaf or grass weeds for which information on percentage control was available).⁴

The costs associated with herbicide application, including the stage-specific herbicide application cost and materials cost per acre, determine profit, and therefore should also affect the choice. If a farmer reported multiple herbicides applied at the same stage on each crop variety, these herbicides were assumed to be applied as a tank mix, and the application costs were adjusted accordingly. The primary difference between herbicide choices made on conventional and RR varieties is that conventional farmers cannot apply *glyphosate* (Roundup) after crop emergence using broadcast spraying without causing crop injury, but they can still spray this herbicide between rows as a post-directed spray. Such applications are more costly compared to the broadcast applications (\$3.50 vs. \$10.50 per acre), as reflected in the farmers' post-emergent choice sets on conventional soybeans.

As noted previously, herbicide human health and environmental safety attributes may also be important for farmers' product choices. Beach and Carlson (1993) include herbicide user safety and water quality in a farmer's utility function and find statistically significant impacts of these variables. Hubbell and Carlson (1998) consider acute

² Some additional information, such as farmer education, age, experience, exposure to herbicides, etc., could be used to explain herbicide choices. When we attempted to incorporate some farmer information as choice-specific constants (see Greene, 2000, p. 859), we had to add 45 constants for each farmer-specific attribute. With such a large number of explanatory variables, the model failed to converge. The use of interactions among variables also led to an intractable empirical model. Instead, we use the mixed logit procedure to correct for some of the biases created by omitted variables since it allows the coefficient to vary across farmers.

³ We thank a reviewer for elucidating this point.

⁴ The survey did not contain information on the specific weeds the farmers were trying to control. The true herbicide effectiveness measure depends on weed populations particular to the location. Therefore, our average effectiveness measures are only proxies for the true measure.

mammalian, fish, and beneficial mite predator toxicity, as well as soil half-life of insecticides affecting water quality and some regulatory attributes affecting applicator and user safety, to explain farmer product choices. Alternatively, we investigate the impact of risk attributes considered in the previous pesticide risk index studies (Higley and Wintersteen, 1992; Kovach et al., 1992; Mullen, Norton, and Reaves, 1997) on farmers' choices of herbicides by using risk information available to the farmers from product labels and Material Safety Data Sheets (MSDSs). Only the risk attributes that are statistically significant in the herbicide choice model are later used in the construction of our risk index.

Pesticides are strictly regulated in the United States through a complex system leading to product registration and use. During the registration process, the EPA evaluates the information available for the pesticide and approves a product label and MSDS. The label and MSDS are intended to provide the farmers and the public with general, technical, risk, and safety information about pesticides, as well as serve as the legal notice of approved uses and rates. They contain information on product chemistry, physical and chemical characteristics, aquatic and wildlife toxicology, plant protection, reentry protection, nontarget insect toxicity, environmental fate, residual chemistry, and spray drift (Whitford, 2002). The labels and MSDSs follow established uniform standards for describing pesticide risk attributes and are used as informational sources for various pesticide risks in our study.

The EPA-recognized potential routes of human exposure to pesticides are through ingestion of the residues in food and water, as well as dermal and inhalation exposure. LD_{50} 's, which are estimates of material dosage that would result in the death of 50% of a population of test species under stated conditions (Rozman, Doull, and Hayes, 2001), are used to define the severity of acute pesticide impact after oral and dermal exposure.⁵ It is the primary way of expressing acute effects of solids and liquids that are swallowed, or contaminate the skin, and is usually expressed in terms of milligrams of material per kilogram of body weight. A similar value (LC_{50}) is developed for inhalation toxicity ("C" stands for concentration). Higher LD_{50} and LC_{50} values indicate lower risk. We also utilize the EPA rules to establish the effect of herbicides on the eyes, which is expressed in terms of potential irreversible or substantial eye injury after exposure (U.S. EPA, 2007). If the product label contains a statement indicating that such injury is possible—for example, "corrosive, causes substantial eye injury"—a herbicide is considered a high risk in the eye risk category.

EPA's criteria assessing chronic human health risks are based on the results of tests evaluating carcinogenic and reproductive, birth, and developmental effects of pesticides that are also reported on product labels and MSDSs. We assume a certain herbicide is considered to be a high risk to chronic human health if there is positive evidence of the presence of any of the above effects.

Pesticide residues may also contaminate surface and groundwater. Generally, all methods used to assess the impact of pesticides on the quality of water resources concentrate on leaching and runoff potential determined by the pesticide's persistence, water solubility, and mobility. We consider a herbicide a high risk if its label contains a special surface or groundwater advisory—for example, "This product has properties and characteristics associated with chemicals detected in groundwater," or "Under some

⁵ Beach and Carlson (1993) use LD_{50} values to represent human acute toxicity of pesticides in the farmers' utility function.

Table 1. Summary Statistics of the Attributes of Herbicide Choices and Expected Impact of the Attributes on the Probability of Herbicide Choice (N = 1,769)

Herbicide Attribute	Expected Impact ^a	Mean	Standard Deviation
Grass Weed Efficiency (%)	+	67.16	28.52
Broadleaf Weed Efficiency (%)	+	61.46	25.78
Herbicide Application Costs (\$/acre)	–	14.17	5.06
Application Rate (lbs. of AI/acre)	+/-	0.72	0.55
Acute Oral Toxicity (LD ₅₀)	+	3,409.70	1,917.21
Acute Inhalation Toxicity (LC ₅₀)	+	5.68	7.14
Acute Dermal Toxicity (LD ₅₀)	+	3,427.79	1,524.14
Acute Eye Effect (dummy, = 1 if high risk)	–	0.57	0.49
Chronic Health Risk (dummy, = 1 if high risk)	–	0.10	0.30
Surface Water Risk (dummy, = 1 if high risk)	–	0.12	0.32
Groundwater Risk (dummy, = 1 if high risk)	–	0.33	0.47
Aquatic Toxicity (LC ₅₀)	+	59.11	61.46

^a A "+" ("–") indicates that the higher value of the herbicide attribute would increase (decrease) the probability of the herbicide being chosen.

conditions, this product may have a high potential for runoff into surface water." In addition, we consider the herbicide's impact on fish and aquatic organisms expressed in terms of LC₅₀. Since a given herbicide does not affect all species at the same rate, the final aquatic toxicity level is assigned as the highest risk among all species for which information is reported.

Finally, the application rate may affect the farmer's perception of herbicide risk. Between two equally toxic herbicides, one that requires a higher application rate would be considered a higher risk. Moreover, it might be possible that the rate of application affects the farmer's perception of product effectiveness. We account for these possible impacts in the choice model by including the herbicide recommended label rate of application measured as the volume of herbicide active ingredients (AI) applied per acre, converted into pounds per acre.⁶

The information on herbicide attributes was obtained from a variety of sources (MSDSs and labels; ExToxNet, 2007; USDA, 2002; Iowa State University Extension Service, 2004; University of Florida Cooperative Extension Service, 2003). Table 1 presents the summary statistics of the attributes of herbicide choices made by the farmers and expected impacts of the attributes on the choice probability. Higher effectiveness of herbicides should positively affect the choice, while high costs should negatively affect the choice. Higher LD₅₀ and LC₅₀ values indicate lower risk and should positively affect the choice. The remaining risks—acute eye effect, chronic health risk, surface and groundwater risks—are measured using dummy variables indicating the level of risk. Therefore, higher values of these variables should negatively affect the choice.

⁶ The survey included questions asking farmers about application rates of each herbicide they used (see the appendix). In 20% of cases, farmers did not remember these rates. They reported the use of "label rates" in 12% of cases and used custom applications in 6% of cases. The coefficient of correlation between the remaining reported actual rates and label rates was 0.8. Given this high degree of correlation, we used recommended label rates in the analysis to preserve degrees of freedom.

Table 2. Mixed Logit Estimation Results of the Herbicide Choice Model (N = 1,769)

Herbicide Attribute	Coefficient Mean (Standard Error)	Coefficient Std. Dev. (Standard Error)
Grass Weed Efficiency (%)	0.017*** (0.004)	0.044*** (0.005)
Broadleaf Weed Efficiency (%)	0.002 (0.002)	0.001 (0.017)
Herbicide Application Costs (\$/acre)	-0.083*** (0.010)	0.002 (0.089)
Application Rate (lbs. of AI/acre)	0.797*** (0.077)	0.005 (0.728)
Acute Oral Toxicity (LD ₅₀)	0.001* (0.000)	0.001*** (0.000)
Acute Inhalation Toxicity (LC ₅₀)	-0.055 (0.024)	0.094*** (0.019)
Acute Dermal Toxicity (LD ₅₀)	0.001*** (0.000)	0.000 (0.000)
Acute Eye Effect (dummy, = 1 if high risk)	0.114 (0.077)	0.144 (0.498)
Chronic Health Risk (dummy, = 1 if high risk)	-1.162*** (0.232)	0.548 (0.537)
Surface Water Risk (dummy, = 1 if high risk)	-0.466*** (0.109)	0.049 (0.677)
Groundwater Risk (dummy, = 1 if high risk)	-0.109 (0.091)	0.134 (0.486)
Aquatic Toxicity (LC ₅₀)	0.002*** (0.001)	0.000 (0.004)
Log-Likelihood Value = -5,844		

Note: Single, double, and triple asterisks (*) indicate the coefficients are significantly different from zero at the $\alpha = 10\%$, $\alpha = 5\%$, and $\alpha = 1\%$ levels, respectively.

Estimation Results

The herbicide choice model [equation (4)] was estimated using the multinomial discrete choice (MDC) procedure available in the SAS software package. As shown by the estimation results reported in table 2, in addition to the production-related attributes, there appears to be an association between herbicide choice and several human and environmental safety attributes of herbicides applied. The coefficient means on herbicide acute oral and dermal toxicities, chronic health risk, surface water contamination potential, and aquatic toxicity are different from zero at standard levels of significance. The coefficient standard deviations also indicate that the farmers exhibit some random preference variations over the relative importance of some of the production-related and safety herbicide attributes.⁷

⁷ As stated earlier, our data did not allow us to control for possible variations in some farmer and farm characteristics that may affect herbicide product choice. Therefore, we assume the coefficients of the random components in the mixed logit estimation results capture some of the effects of these unobservable characteristics.

The mean coefficient estimates are used to calculate farmers' WTP for individual risks, and therefore the relative weights of the individual risk categories included in the herbicide risk index, and to generate the standard errors of the estimated relative weights by the bootstrapping technique (Krinsky and Robb, 1986). Using the bootstrapping technique, the estimated parameter vector ($\hat{\beta}$) and the variance-covariance matrix ($\hat{\Sigma}$) are used to generate 1,000 random draws from a multivariate normal distribution with mean $\hat{\beta}$ and variance-covariance matrix $\hat{\Sigma}$.

Since herbicide risks are measured in different units, regression coefficients must be semi-standardized by multiplying each coefficient by the standard deviation (S_k) of the corresponding risk attribute presented in table 1 (Kaufman, 1996). Such semi-standardized coefficients reveal the relative strength of each independent variable's effect and, if divided by the coefficient on application costs, farmers' WTP for different risks expressed in standardized units. The relative weights are calculated by dividing the generated semi-standardized coefficient associated with each index category by the sum of the generated semi-standardized coefficients on all included categories from the same draw:

$$w_k = \frac{\hat{\beta}_k^s S_k}{\sum_{k=1}^K \hat{\beta}_k^s S_k}.$$

The resulting mean relative weights and their standard errors are presented in table 3. The farmers, on average, place a large emphasis (49%) on acute human health risks of herbicides (including 9% placed on acute oral toxicity and 40% on acute dermal toxicity), 27% on chronic human health risks, and 24% on environmental risks (including 12% on surface water contamination potential and 12% on risk to aquatic organisms).

On-Farm Change in Herbicide Impact After Adoption of RR Soybeans

The risk index values of the individual herbicides are calculated as the sum of the products of the herbicide risk measures in each of the index categories and the estimated relative weights of each category [equation (1)]. We transform risk measures that use different units to a common scale, which bounds the resulting indices between zero and one, with one indicating the highest possible risk. Risks measured as LD_{50} and LC_{50} values, for which higher values indicate lower risk and there is no upper bound, are transformed as:

$$(5) \quad r_k = 1 - \frac{r_k^* - \min(r_k)}{\max(r_k) - \min(r_k)},$$

where r_k^* is the herbicide risk measure before transformation for risk source k , $\min(r_k)$ is the lowest observed risk value for risk source k , and $\max(r_k)$ is the highest observed risk value for risk source k (Diaz-Balteiro and Romero, 2004). The mean index value in the farmers' choice set is 0.43 with a standard deviation of 0.19. The safest herbicides in the set based on the label information and our criteria are Roundup, Frontier, and Pursuit (with index values of 0.09), and 2,4-D Amine has the highest risk ranking (0.83).

Table 3. Relative Weights of the Statistically Significant Herbicide Risk Index Categories

Herbicide Risk Attribute	Mean Relative Index Weight	Standard Error	Herbicide Risk Attribute	Mean Relative Index Weight	Standard Error
Acute Oral Toxicity	0.09	0.05	Surface Water Risk	0.12	0.02
Acute Dermal Toxicity	0.40	0.03	Aquatic Toxicity	0.12	0.03
Chronic Health Risk	0.27	0.04			

Note: Means were calculated based on 1,000 drawings from a multivariate normal distribution with mean $\hat{\beta}$ and variance-covariance $\hat{\Sigma}$.

The risk indices are used to calculate the on-farm differences in herbicide use between conventional and RR soybeans. To control for some possible spatial and temporal variations in herbicide use patterns, we selected a subsample out of survey responses consisting of 199 observations representing all participating farmers who were partial adopters of RR technology and planted both RR and conventional soybeans in 2001. These observations are used as a basis for estimating on-farm differences in herbicide use.

As noted previously, to obtain the appropriate measure of the herbicide use for the corresponding soybean type, we must take into account not only the applied volume of herbicides, but also their relative risk. In addition, the number of herbicide choices made at different stages of production and the number of applications of chosen herbicides varied across farmers. Consequently, our most accurate measure of herbicide use, risk-adjusted volume of herbicides applied, is calculated as the sum of application rates of individual herbicides, expressed as pounds of herbicide AI applied per acre, multiplied by the number of applications, the proportion of acreage treated with the corresponding herbicide, and the risk index of the corresponding herbicide.⁸ The change in the herbicide toxicity for each farmer is obtained by finding the difference in per acre risk-adjusted volumes of the herbicides applied on RR and conventional soybeans.

Calculations were performed 1,000 times for each set of simulated weights, and the average difference for all trials was estimated and is reported in table 4. The average per acre difference in herbicide use was estimated to be -0.09 risk-adjusted pounds per acre (equivalent to a 23% reduction on RR soybeans compared with conventional soybeans in our sample). This difference is statistically significantly different from zero at the 99% level of confidence.⁹

For comparison, the changes in the average herbicide use based on the volume of herbicides applied per acre and the number of herbicide applications, methods commonly used in previous literature (e.g., Benbrook, 2003; Carpenter, 2001; Gianessi et al., 2002; Hubbell, Marra, and Carlson, 2000), are estimated. We use two measures of volume: the total volume of herbicides applied and the volume in pounds of herbicide active ingredients. The average volume of herbicides applied on RR soybeans was significantly higher ($\alpha = 0.01$) compared to conventional soybeans when estimated based on either

⁸ A herbicide's risk-adjusted application rate is calculated as a product of the application rate expressed in pounds of AI and the risk index of the corresponding herbicide adjusted for the number of application and the proportion of acreage treated. The lower the risk index value, the lower is the risk-adjusted application rate.

⁹ It is possible that partial adopters planted RR soybeans on the plots characterized by higher weed pressure. In such cases, our results would underestimate the reduction in herbicide use on RR varieties.

Table 4. Average Herbicide Use per Acre for Conventional and RR Soybeans and On-Farm Differences of RR Soybeans as Compared to Conventional in 2001

Soybean Variety	Herbicide Use Measure (Mean)			
	Risk-Adjusted Volume of AI (lbs./acre)	Total Volume (lbs./acre)	Volume of AI (lbs./acre)	Herbicide Applications (no./acre)
RR Soybeans	0.29 (0.46)	3.60 (2.91)	1.47 (1.18)	1.81 (1.12)
Conventional Soybeans	0.39 (0.53)	2.47 (3.73)	0.92 (1.35)	1.95 (1.75)
On-Farm Difference	-0.09*** (0.51)	1.13*** (3.91)	0.55*** (1.52)	NS
Percent Change for RR Soybeans Compared to Conventional	-23%	+46%	+60%	

Notes: Triple asterisks (***) indicate coefficients significantly different from zero at the $\alpha = 1\%$ level. NS = not significant. Values in parentheses are standard deviations. The average values are calculated for 199 farms where both conventional and RR soybeans were grown in 2001.

volume measure (table 4). If "pounds on the ground" is the measure of herbicide use, the farmers applied on average an additional 1.13 pounds of herbicides on RR soybeans compared to conventional soybeans (equivalent to a 46% increase in volume). Also, the farmers applied on average an additional 0.55 pounds of herbicide active ingredients on RR soybeans (a 60% increase). We do not find a statistically significant difference in the number of herbicide applications on conventional and RR soybeans in our sample.

Finally, we explore how adoption of RR soybeans affects herbicide risk within each risk category considered in this study to investigate whether our conclusions about the impact of RR soybeans on environmental quality and human health are affected by the specific combination of risk categories combined into our index or assigned weights. If all considered risks are reduced on RR soybeans, we obtain further support for our conclusions. The results of this analysis are presented in table 5. Similar to the risk-adjusted volume of herbicides applied, the values presented for RR and conventional soybeans are estimated as the combined volume of herbicide AI in pounds per acre, adjusted for the relative risk ranking of the corresponding herbicides in each risk category, where risk rankings expressed in LD_{50} s and LC_{50} s are transformed using equation (5).

In all risk categories, except for herbicide ingestion and inhalation toxicities, herbicide choices made on RR soybeans on average demonstrate an improvement compared to conventional soybeans. The extent of risk reduction varies from 48% to 80%. The average difference in acute oral toxicity of herbicides used on conventional and RR soybeans is not statistically significant. The only risk increase (113%) is observed for the acute inhalation toxicity of herbicides. This result is driven by the fact that the acute inhalation LC_{50} value for Roundup is about 2.6 ppm, which is considered a low risk (U.S. EPA, 2007) but is representing a higher risk than the sample average of 5.68 ppm (table 1).

Table 5. Average Herbicide Application Rate per Acre Adjusted for the Risk Level in Each Risk Category for Conventional and RR Soybeans and On-Farm Differences of RR Soybeans as Compared to Conventional in 2001

Soybean Variety	Herbicide Application Rate Adjusted by Risk Level (Mean)							
	Acute Oral Toxicity	Acute Inhalation Toxicity	Acute Dermal Toxicity	Acute Eye Effect	Chronic Health Risk	Surface Water Risk	Ground Water Risk	Aquatic Toxicity
RR Soybeans	0.61 (0.81)	1.38 (0.89)	0.22 (0.60)	0.12 (0.33)	0.02 (0.13)	0.10 (0.52)	0.15 (0.56)	0.36 (0.93)
Conventional Soybeans	0.62 (0.88)	0.65 (1.10)	0.46 (0.64)	0.31 (0.53)	0.09 (0.31)	0.20 (0.69)	0.38 (0.82)	0.69 (0.99)
On-Farm Difference	NS	0.73*** (1.28)	-0.23*** (0.61)	-0.19*** (0.51)	-0.08*** (0.30)	-0.09** (0.66)	-0.24*** (0.76)	-0.33*** (0.94)
Percent Change in Risk for RR Soybeans Compared to Conventional		+113%	-51%	-62%	-80%	-48%	-62%	-48%

Notes: Double and triple asterisks (*) indicate coefficients significantly different from zero at the $\alpha = 5\%$ and $\alpha = 1\%$ levels, respectively. NS = not significant. Values in parentheses are standard deviations. The average values are calculated for 199 farms where both conventional and RR soybeans were grown in 2001.

Conclusions

This paper develops a new method for the assessment of the impact of GE crop adoption on pesticide use and environmental quality. Improvement on previous attempts to develop pesticide risk rankings was achieved by creating a risk index—a single, simple measure of risk that combines complex information about environmental and human health effects of herbicides into one value. The use of revealed-preference information to estimate the relative weights of index categories has resulted in weights based on a cardinal scale and characterized by improved reliability relative to pesticide risk indices based on stated-preference methods.

This method may help to resolve the current dispute in the literature and the popular press about the impact of GE crops on pesticide use and the environment. Our results suggest that the conclusions about the *impact* of GE crop adoption on pesticide use and the environment are highly dependent on the methods employed to measure pesticide use. In the case of RR soybeans we found that, even though the farmers on average applied a higher volume of herbicides (herbicide active ingredients) per acre of RR soybeans compared to conventional, when relative risk of herbicides is considered in the analysis, RR soybeans show an improvement compared to conventional soybeans. Since the reason for measuring differences in herbicide use in the first place is as an indicator of environmental impact, the measure of herbicide use based on relative risk should be superior to the measures based on volume alone.

As clarified above, we only attempt to evaluate the impact of RR soybeans on herbicide use by farmers in the United States, and the conclusions may vary from crop to crop and from one location to another. It is possible to use this methodology to assess the impacts of other GE crops on pesticide use or, indeed, pesticide use impacts in any context. We focus on only a few specific impacts GE crops may have on the environment. Issues such as possible development of resistance to herbicides, transfer of new genes into the wild, changes in tillage practices, and expansion of agricultural crop areas should all be considered to make a comprehensive assessment of the GE crops' impact on the environment. We believe this would be a fruitful area for future research.

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References

- Beach, D., and G. Carlson. "A Hedonic Analysis of Herbicides: Do User Safety and Water Quality Matter?" *Amer. J. Agr. Econ.* 75(1993):612–623.
- Benbrook, C. "Impacts of Genetically Engineered Crops on Pesticide Use in the United States: The First Eight Years." Tech. Paper No. 6, BioTechInfoNet, November 2003. Online. Available at http://www.biotech-info.net/Technical_Paper_6.pdf. [Retrieved October 2007.]
- Bennett, R., S. Morse, and Y. Ismael. "The Economic Impact of Genetically Modified Cotton on South African Smallholders: Yield, Profit, and Health Effects." *J. Develop. Stud.* 42(2006):662–677.
- Carpenter, J. "GM Crops and Patterns of Pesticide Use." *Science* 292(2001):637.
- Carpenter, J., A. Felsot, T. Goode, M. Hamming, D. Onstad, and S. Sankula. "Comparative Environmental Impacts of Biotechnology-Derived and Traditional Soybean, Corn, and Cotton Crops." Council for Agricultural Science and Technology, Ames, IA, 2002.
- Diaz-Balteiro, L., and C. Romero. "In Search of a Natural Sustainability Index." *Ecological Econ.* 49(2004):401–405.

- ExToxNet. Information on herbicide attributes. Oregon State University, Corvallis. Online. Available at <http://extoxnet.orst.edu>. [Retrieved October 2007.]
- Fernandez-Cornejo, J., and S. Jans. "Quality-Adjusted Price and Quality Indices for Pesticides." *Amer. J. Agr. Econ.* 77(1995):645–659.
- Fernandez-Cornejo, J., and W. McBride. "Genetically Engineered Crops for Pest Management in U.S. Agriculture: Farm-Level Effects." USDA, Economic Research Service, Washington, DC, 2000.
- Frisvold, G., and M. Marra. "The Difficulty with Data: How Sampling and Aggregation Can Affect Measures of Pesticide Use in Biotech Crops." Paper presented at 8th Annual International Consortium on Agricultural Biotechnology Research Conference, Ravello, Italy, 2004.
- Gianessi, L., C. Silvers, S. Sankula, and J. Carpenter. *Plant Biotechnology: Current and Potential Impact for Improving Pest Management in U.S. Agriculture. An Analysis of 40 Case Studies*. Washington, DC: National Center for Food and Agricultural Policy, 2002. Online. Available at <http://www.ncfap.org/40CaseStudies.htm>. [Retrieved October 2007.]
- Greene, W. H. *Econometric Analysis*, 4th ed. Upper Saddle River, NJ: Prentice-Hall, 2000.
- Helmlich, R., J. Fernandez-Cornejo, and W. McBride. "Genetically Engineered Crops: Has Adoption Reduced Pesticides Use?" *Agr. Outlook* (August 2000):13–17.
- Higley, L., and W. Wintersteen. "A Novel Approach to Environmental Risk Assessment of Pesticides as a Basis for Incorporating Environmental Costs into Economic Injury Levels." *Amer. Entomologist* 38(Spring 1992):34–39.
- Huang, J., R. Hu, C. Pray, F. Qiao, and S. Rozelle. "Biotechnology as an Alternative to Chemical Pesticides: A Case Study of Bt Cotton in China." *Agr. Econ.* 29(2003):55–67.
- Hubbell, B., and G. Carlson. "Effects of Insecticide Attributes on Within-Season Insecticide Product and Rate Choices: The Case of U.S. Apple Growers." *Amer. J. Agr. Econ.* 80(1998):382–396.
- Hubbell, B., M. Marra, and G. Carlson. "Estimating the Demand for a New Technology: Bt Cotton and Insecticide Policies." *Amer. J. Agr. Econ.* 82(2000):118–132.
- Iowa State University Extension Service. "Herbicide Effectiveness Ratings." 2004. Online. Available at <http://www.weeds.iastate.edu/reference/wc92/WC92-2004/HerbEffRating.pdf>. [Retrieved October 2007.]
- Kaufman, R. "Comparing Effects in Dichotomous Logistic Regression: A Variety of Standardized Coefficients." *Social Sci. Quart.* 77(1996):90–109.
- Kling C. "The Gains from Combining Travel Cost and Contingent Valuation Data to Value Nonmarket Goods." *Land Econ.* 73(1997):428–439.
- Kovach, J., C. Petzoldt, J. Degni, and J. Tette. "A Method to Measure the Environmental Impact of Pesticides." *New York's Food and Life Science Bulletin* 193(1992):1–8.
- Krinsky, I., and L. Robb. "On Approximating the Statistical Properties of Elasticities." *Rev. Econ. and Statis.* 68(1986):715–719.
- Leviton, L. "How To and Why: Assessing the Enviro-Social Impacts of Pesticides?" *Crop Protection* 19(2000):629–636.
- Malik J., G. Barry, and G. Kishore. "The Herbicide Glyphosate." *BioFactors* 2(1989):17–25.
- Marra, M. "Agricultural Biotechnology: A Critical Review of the Impact Evidence to Date." In *The Future of Food: Biotechnology Markets and Policies in an International Setting*, ed., P. Pardey, pp. 155–184. Washington, DC: International Food Policy Research Institute, 2001.
- Morse, R. "Bee Poisoning." Paper presented at 50th Annual Pest Control Conference, Ithaca, NY, 7–10 November, 1989.
- Mullen, J., G. Norton, and D. Reaves. "Economic Analysis of Environmental Benefits of Integrated Pest Management." *J. Agr. and Appl. Econ.* 29(1997):243–253.
- Nelson, G., and D. Bullock. "Simulating a Relative Environmental Effect of Glyphosate-Resistant Soybeans." *Ecological Econ.* 45(2003):189–202.
- Nelson, G., and J. Miranowsky. "Environmental Indicators: An Economic Approach." Staff Paper No. 96-E-491, Dept. of Agr. and Consumer Econ., University of Illinois, Urbana, 1996.
- Pray, C., D. Ma, J. Huang, and F. Qiao. "Impact of Bt Cotton in China." *World Develop.* 29(2001):813–825.
- Qaim, M., and G. Traxler. "Roundup Ready Soybeans in Argentina: Farm-Level and Aggregate Welfare Effects." *Agr. Econ.* 32(2005):73–86.

- Reus, J. A. W. A., and P. C. Leendertse. "The Environmental Yardstick for Pesticides: A Practical Indicator Used in the Netherlands." *Crop Protection* 19,8(12 September 2000):637–641.
- Rozman, K., J. Doull, and W. Hayes. "Dose, Time, and Other Factors Influencing Toxicity." In *Handbook of Pesticide Toxicology Principles*, ed., R. Krieger, pp. 1–94. London: Academic Press, 2001.
- Theiling, K., and B. Croft. "Pesticide Side Effects on Arthropod Natural Enemies: A Database Summary." *Agriculture, Ecosystems, and Environment* 21(1988):191–218.
- Train, K. *Discrete Choice Methods with Simulations*, Chapter 6. Cambridge, UK: Cambridge University Press, 2003.
- University of Florida Cooperative Extension Service, Institute of Food and Agricultural Science. "Weeds in the Sunshine: Approximate Herbicide Pricing—2003." Online. Available at <http://edis.ifas.ufl.edu/pdf/files/WG/WG05600.pdf>. [Retrieved October 2007.]
- U.S. Department of Agriculture, National Agricultural Statistics Service. *Agricultural Prices: 2001 Summary*. USDA/NASS, Washington, DC, July, 2002.
- . *Acreage*. USDA/NASS, Washington, DC, June 2007. Online. Available at <http://usda.mannlib.cornell.edu/usda/nass/Acre//2000s/>. [Retrieved October 2007.]
- U.S. Environmental Protection Agency. *Label Review Manual*. USEPA, Washington, DC. Online. Available at <http://www.epa.gov/oppfead1/labeling/lrm/>. [Retrieved October 2007.]
- Whitford, F. *The Complete Book of Pesticide Management: Science, Regulation, Stewardship, and Communication*. New York: John Wiley and Sons, 2002.
- Wolfenbarger, L., and P. Phifer. "The Ecological Risks and Benefits of Genetically Engineered Plants." *Science* 290(2000):2088–2093.

Appendix: An Example of the Set of Survey Questions Designed to Extract Herbicide Use Information

Now I want to ask you about your soybean weed control practices for non-Roundup Ready and Roundup Ready soybeans you planted in 2001.

- 13a. For the Roundup Ready soybeans you planted in 2001, how many of those acres did you treat at least once with a herbicide?

_____ acres treated at least once

- 13b. Thinking about your Roundup Ready varieties you planted in 2001, what specific herbicide or herbicides did you use pre-plant or at planting (report only the residual-type products and not the burndown products)?

[For each brand mentioned in Q.13b, ask:]

- 14a. How many of your Roundup Ready soybean acres in 2001 were treated with [brand]?
[If "Don't Know" >>> Your best estimate would be fine.]
- 14b. What was your average application rate per acre for [brand] in 2001 on your Roundup Ready soybeans?
- 14c. How many applications of [brand] did you make in 2001 on your Roundup Ready varieties?

This set of questions was repeated for each herbicide application stage:

- a. Pre-plant or at planting
- b. Pre-emergent
- c. Post-emergent

And for each soybean type:

- a. Roundup Ready soybeans
- b. Conventional soybeans