Assessing the risk of pesticide environmental impact in several Argentinian cropping systems with a fuzzy expert indicator

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Abstract

BACKGROUND: The introduction of transgenic soybean (Glycine max, L.) varieties resistant to glyphosate (GR soybeans) has rapidly expanded in Argentina, increasing pesticide use where only grasslands were previously cultivated. The authors compared an estimate of environmental risk for different crops and active ingredients using the IPEST index, which is based on a fuzzy-logic expert system. For IPEST calculations, four modules are defined, one reflecting the rate of application, the other three reflecting the risk for groundwater, surface water and air. The input variables are pesticide properties, site-specific conditions and characteristics of the pesticide application. The expert system calculates the value of modules according to the degree of membership of the input variables to the fuzzy subsets F (favourable) and U (unfavourable), and they can be aggregated following sets of decision rules. IPEST integrated values of \( \geq 7 \) reflect low environmental risk, and values of \(<7\) reflect high risk.

RESULTS: Alfalfa, soybean and wheat showed IPEST values over 7 (low risk), while maize had the lowest IPEST values (high risk). Comparing active ingredients applied in annual and perennial crops, atrazine and acetochlor gave the highest risks of environmental contamination, and they are mainly used in maize. Groundwater was the most affected compartment.

CONCLUSIONS: Fuzzy logic provided an easy tool combining different environmental components with pesticide properties to give a simple and accessible risk assessment. These findings provide information about active ingredients that should be replaced in order to protect water and air from pesticide contamination.

Keywords: pesticides; environmental impact; fuzzy logic

1 INTRODUCTION

The adoption of transgenic soybean (Glycine max, L.) varieties resistant to glyphosate (GR soybeans) has been extremely rapid in Argentina. The initial release of these soybean varieties occurred in 1996, and they accounted for 90% of total area planted with this crop in 1999. The rapid adoption of GR soybeans suggests that farmers perceive these transgenic varieties to be cost effective.1 Recent survey data showed that GR soybeans increased soybean productivity in Argentina by an average of 10%, with cost savings being somewhat more pronounced for smaller than for larger farms.2

Furthermore, soybean GR adoption expanded the agricultural frontier in Argentina. Areas that were traditionally devoted to extensive farming (i.e. dairy farms) on natural or seeded grasslands and woodland are rapidly being converted. Agricultural surface has been growing at a high rate during the last decade, not only with soybean but with winter or summer crops in rotation with soybean.3 Such abrupt changes in the ecosystem can have an effect on the presence and dynamics of insect pests, plant diseases and weed populations and possibly increases in pesticide use. The growing awareness of the risks related to the intensive use of pesticides has led to a more critical attitude by society towards agriculture.4

Several risk indicator models have been developed and are in use throughout the world for assessing environmental risk impact by pesticides, e.g. economic injury levels,5 EIQ6 and SYNOPS.7 All such indicators have strengths and weaknesses, as they cover different aspects of the risk connected with pesticide use and utilise different methods to assess these risks. None of them takes into account simultaneously air, water and soil pesticide impact. The environmental impact of a pesticide depends to a large extent on four criteria: (a) the amount of active ingredient applied and its site of application; (b) its partitioning and concentration in the air, surface water and groundwater compartments; (c) its rate of degradation in each compartment; (d) its toxicity to the species present in those compartments.8

In France, a set of agroecological indicators has been proposed to evaluate the environmental impact of farming systems,9 including a fuzzy expert system, IPEST, reflecting an expert

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perception of potential pesticide environmental impact. It takes into account some compartments in the environment (air, groundwater, surface water) using three types of variables: pesticide properties (Henry’s law constant, pesticide half-life, sorption coefficient, acceptable daily intake, aquatic toxicity, groundwater ubiquity score), site-specific conditions (slope, distance to superficial water source, dry matter content, soil pH, texture, crop coverage) and pesticide application factors (rate of application, drift, time of application). It has a modular structure and thus provides both an integrated indicator reflecting overall impact as well as more detailed information through its four modules. The European Union has compared and evaluated eight pesticide risk indicators developed to give recommendations for further use (IPEST among them). Tested indicators were recommended as useful tools for reducing the environmental impact of pesticides.

The present objective was to compare the relative risk IPEST indices calculated for various crop/pesticide combinations being used in the Argentinian humid pampa. Although these are only relative indices and therefore not able to provide absolute calculations of risk, this analysis can furnish a trend analysis of the possible environmental impacts resulting from changes in crops in this region.

2 MATERIALS AND METHODS

2.1 Study region

The Argentinian Pampas is a wide plain with more than 58 million ha of land of varying fertility suitable for cattle rearing and crop production. It extends from 30 to 40 °S latitude and 56 to 64 °W longitude. According to the rainfall and soil quality patterns, the region may be divided into humid, subhumid and semi-arid zones. The present work was developed in the subhumid region, where the average annual rainfall ranges from 1000 mm in the east, decreasing westward to 600 mm. Temperatures decrease from north to south.

The study area comprised 13 230 ha of very uniform soil and climate characteristics. Mixed cropping, in which cattle grazing for both beef and dairy production alternates with winter (wheat) and summer (sunflower, maize, soybean) crops, is the dominant use of land in farms from the study area. Predominant soils in the study area are Molisols, and they gradually change from loamy clay soils (heavy soils) in the west to loamy soils (light soils) in the east. These arable soils present relatively few limitations to crop production, and the majority are suitable for grazing and crop production. Well-drained and relatively well-drained soils on deep loess do not offer constraints to root extension and water lixiviation. Organic matter content varied from 2.3 to 3.5%, and pH values were 6.5–7.5. The relief is flat. Slope varied from 0.5 to 1%, and thus little run-off was observed. Climate is temperate, with 900 mm average annual rainfall distributed uniformly over the year. Mean temperature is 20 °C.

The database included pesticide treatments of 147 farms. Data on active ingredients, dose, time of application and spraying methods were collected for the 2000–2005 cropping seasons. Chemical soil variables (organic matter content, pH), distance to surface waters (lakes, pools, rivers), slope and crop cover during pesticide application were registered for the indicator calculation. The set of final data in the study consisted of 418 fields with alfalfa pastures and 700 with row crops: 412 with maize, 190 with soybean and 98 with wheat.

2.2 Pesticide environmental risk indicator

The indicator IPEST is based on a fuzzy expert system that reflects the potential environmental impact of the application of pesticides during a crop cycle. A pesticide application is defined as the application of a single active ingredient. However, during the crop cycle, several pesticides treatments can be applied.

Two steps are followed for index calculation: first, the index calculation for each active ingredient, IPESTa.i., and then the aggregation of all pesticide treatments during the crop cycle, IPEST.

For IPESTa.i. calculation, four modules are defined for each application, one reflecting the rate of application, the other three reflecting the risk for three major environmental compartments (groundwater, surface water, air). The input variables for these modules are pesticide properties ($K_{ow}$, Henry’s law constant, human acceptable daily intake, aquatic toxicity to fish, field pesticide half-life), site-specific conditions (slope, dry matter content, pH, soil texture, run-off, lixiviation rates) and characteristics of the pesticide application (time of application, vegetation cover). The expert system calculates the value of modules according to the degree of membership of the input variables to the fuzzy subsets F (favourable) and U (unfavourable), and they can be aggregated following sets of decision rules. The membership functions are based on data available in the literature or on the author’s expert knowledge. A dimensionless scale is used with values from 0 (unfavourable) to 10 (favourable). Sugeno’s inference model was used to compute the modules as well as the indicator.

IPEST is calculated by means of the following equations:

\[
IPEST = \text{MIN IPESTa.i.} - (\text{risk factor} \times k)
\]

where MIN IPESTa.i. is the minimum IPESTa.i. value for each active ingredient applied during the crop cycle,

\[
\text{Risk factor} = \frac{10 - \text{IPESTa.i.}}{10}
\]

and $k$ is a calibration factor necessary to give a scale between 0 and 10.

IPEST values of 7 or higher are acceptable values with no risk contamination, while values below 7 are related to pesticide contamination risks. A value of 7 is not a sharp threshold but only an arbitrary value to separate U and F.

In this example (Table 1), three active ingredients, acetochlor, atrazine and glyphosate, were applied in a maize field. Even when glyphosate had an IPESTa.i. over 7 (low environmental risk), aggregated IPEST reflected a high environmental risk related to atrazine and acetochlor IPESTa.i.

2.3 Statistics

Logistic regression was carried out to evaluate the effects of cropping systems (annual crops versus perennial pastures) and also of different annual crops (maize versus soybean versus wheat) on environmental pesticide contamination risks. Principal component analysis (PCA) was carried out to understand the contribution of active ingredients to environmental risk contamination in each crop.

3 RESULTS

3.1 Analysis of pesticide contamination by cropping system

The pesticide index showed high heterogeneity as a result of number of applications, toxicity and properties of active ingredients and applied doses.
Comparing the IPEST values obtained in annual crop fields versus alfalfa, the logistic regression model showed a significant effect ($\chi^2 = 173.88, P < 0.0001$) estimated by means of the following equation:

$$\text{logit}(P_i) = \frac{1}{1 + \exp(0.411421 - 1.76221 \times A)}$$  \hspace{1cm} (3)

where $A$ is the dummy variable, with $A_1$ representing alfalfa, and $A_0$ representing annual crops.

The environmental risk contamination probability ($P_i$) as a relative frequency percentage was calculated. In alfalfa, 79.4% of the fields had an IPEST index higher than 7 (Fig. 1A) (low pesticide environmental risk), and only 20.6% had IPEST values below 7 (see Section 3.3). Annual crops showed the opposite situation, with 41.9% of the fields higher than 7, and 59.1% below 7.

### 3.2 Pesticidal environmental risk contamination in different crops

In agricultural fields, the IPEST values obtained in annual crops were compared in order to calculate the environmental risks of maize, wheat and soybean. The logistic model showed a significant effect ($\chi^2 = 503.97; P < 0.0001$), estimated by means of the following equation:

$$\text{logit}(P_i) = \frac{1}{1 + \exp(-1.46634 + 3.80001[M] - 0.416394[W] - 0.787721[S])}$$  \hspace{1cm} (4)

where $M$, $W$ and $S$ are dummy variables with the following values: maize $M = 1$; wheat $W = 1$ and soybean $S = 1$.

The environmental risk contamination probability ($P_i$) as a relative frequency percentage (IPEST values lower than 7) was calculated. Maize had the lowest IPEST values (91.2% of fields had IPEST values below 7) (Table 2), while only 13.2 and 9.5% of soybean and wheat fields, respectively, were below 7 (Fig. 1B).

#### Table 1. IPEST calculation for pesticide applications during maize crop cycle

<table>
<thead>
<tr>
<th>Active ingredient</th>
<th>Dose (kg Al ha$^{-1}$)</th>
<th>Contamination risk module value$^a$</th>
<th>Risk factor (equation (2))</th>
<th>MIN</th>
<th>IPEST (equation (3))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air</td>
<td>Surface water</td>
<td>Groundwater</td>
<td>IPESTa.i.$^b$</td>
<td>$K$</td>
</tr>
<tr>
<td>Acetochlor</td>
<td>2</td>
<td>10</td>
<td>6.62</td>
<td>8.45</td>
<td>6.72</td>
</tr>
<tr>
<td>Atrazine</td>
<td>2</td>
<td>10</td>
<td>6.6</td>
<td>6.53</td>
<td>5.84</td>
</tr>
<tr>
<td>Glyphosate</td>
<td>2</td>
<td>10</td>
<td>7.28</td>
<td>10</td>
<td>7.85</td>
</tr>
</tbody>
</table>

$^a$ Module values calculated according to the membership of input variables to favourable and unfavourable subsets and aggregated.$^b$

$^b$ Calculated by the aggregation of dose, air, surface water and groundwater module values following fuzzy logic decision rule sets.$^{10}$

#### Figure 1. Relative frequencies of total relatively favorable (■ IPEST ≥ 7) and relatively unfavorable (□ IPEST < 7) IPEST values for all pesticide applications during crop cycle in alfalfa vs annual crops (A) and in maize, wheat and soybean (B).

#### Table 2. Field distribution by IPEST values in row crops and alfalfa in the study area

<table>
<thead>
<tr>
<th>Crop</th>
<th>IPEST &lt; 7</th>
<th>IPEST &gt; 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>86</td>
<td>332</td>
</tr>
<tr>
<td>Maize</td>
<td>376</td>
<td>36</td>
</tr>
<tr>
<td>Soybean</td>
<td>18</td>
<td>172</td>
</tr>
<tr>
<td>Wheat</td>
<td>13</td>
<td>85</td>
</tr>
</tbody>
</table>

#### 3.3 Pesticide environmental risk contamination and active ingredients

In alfalfa, six active ingredients (2,4-DB, flumetsulam, glyphosate, cypermethrin, dimethoate and pirimicarb) were applied in 80% of the treatments sprayed from 2000 to 2005, and their relative frequency is shown in Fig. 2A. The PCA analysis showed that 63% of IPESTA.i. variance could be explained by two components that were positively correlated with flumetsulam ($r = 0.84$), cypermethrin ($r = 0.56$), glyphosate ($r = 0.54$) and 2,4-DB ($r = 0.53$) with low environmental risk. IPEST values below 7 (Fig. 1A) were related to mixtures of these active ingredients in high application rates.

In maize, five active ingredients (2,4-D, acetochlor, atrazine, cypermethrin and glyphosate) were used in 92.31% of the treatments sprayed from 2000 to 2005, and their relative frequency is shown in Fig. 2B. The PCA analysis showed that 65% of IPESTA.i. variance could be explained by two components that were positively correlated with glyphosate ($r = 0.74$) and 2,4-D ($r = 0.82$) and negatively with atrazine ($r = -0.67$) and acetochlor ($r = -0.35$). Glyphosate and 2,4-D mixtures are frequently applied 20–40 days before maize seeding, and IPEST values over 7 for this treatment showed no risk of pesticide environmental contamination. IPESTA.i. values with atrazine and acetochlor were
below 7 in 97% of applications. IPESTa.i. values for groundwater and surface water compartments were below 7 in 95.4% of atrazine applications and in 100% of acetochlor treatments. As atrazine was also applied in mixtures with 2,4-D, glyphosate or cypermethrin, IPEST values for these mixtures were also always below 7.

In GR soybean, three active ingredients (2,4-D, glyphosate and cypermethrin) were applied in 92.5% of the treatments, and their relative frequency is shown in Fig. 2C. PCA analysis showed that 75% of IPESTa.i. variance could be explained by two components that were positively correlated with glyphosate \( r = 0.45 \), cypermethrin \( r = 0.70 \) and 2,4-D \( r = 0.77 \), indicating low environmental risk for these active ingredients. IPEST values for mixtures of these active ingredients were below 7 in only 0.03% of treatments when rates of application were higher than recommended for weed control. The groundwater compartment was affected with these applications.

In wheat, 2,4-D and glyphosate represented 70% of the treatments, and only 13% of applications were below 7 for mixtures of these active ingredients (Fig. 2C) when rates of application were higher than recommended for weed control. PCA analysis showed that one component explained 87% of variance, and 2,4-D and glyphosate were positively correlated with it \( r = 0.93 \) for both herbicides. Low risk of environmental contamination was observed.

IPESTa.i. estimations were largely governed by pesticide properties in relation to site-specific conditions. Acetochlor and atrazine were attributed the highest environmental risk. As these herbicides are heavily used in maize in pre-emergence treatments for broadleaf and grass weed control, this crop poses more risks than wheat or soybean. Atrazine is highly persistent in soil and moderately to highly mobile (Table 3), posing risks of groundwater contamination. Acetochlor is more adsorbed by soil colloids than atrazine (Table 3) and leaches very little. Organic matter content varied from 2.3 to 3% with loamy sandy soils. Acetochlor and atrazine have been classified as restricted-use pesticides owing to their toxicity and potential for groundwater contamination respectively.

Glyphosate and cypermethrin are strongly adsorbed in soils (Table 3). They do not leach appreciably and have low potential for run-off, with a low persistence. 2,4-D is mobile but with a very low persistence for groundwater contamination (Table 3). Glyphosate and 2,4-D are considered general-use pesticides owing to their slight toxicity. Cypermethrin is toxic to fish.

### 4 DISCUSSION

In the agricultural systems, alfalfa, soybean and wheat showed high IPEST values and therefore low environmental risk by pesticides used during the crop cycle. Maize was the annual
crop with the lowest IPEST values compared with wheat and soybean. Similar tendencies were observed in these crops in Inland Pampa. A atrazine and acetochlor applications in maize gave the highest risks of environmental contamination. Atrazine residues in groundwater have been observed as a consequence of pre-emergence weed control applications, and it is the second most frequently detected pesticide in EPA’s National Survey of Pesticides in Drinking Water Wells. Acetochlor lacks the potential to leach to groundwater at detectable residue concentrations. However, two soil degradation product residues are very commonly found in groundwater. Glyphosate is strongly adsorbed to soil, with little potential for leaching to groundwater. Transport of glyphosate may only be caused by an interaction of high rainfall events shortly after application on wet soils. Even when glyphosate was the most applied herbicide in Argentina, the risk of environmental contamination was low.

Cypermethrin is not found in groundwater because it is highly adsorbed in soil colloids and has very low solubility. While 2,4-D is one of the most mobile pesticides, its very rapid mineralisation (50% of the applied dose in 10 days) lessens some of its potentially adverse effects on the environment (groundwater and surface water contamination).

An operational concept of sustainability is often not clearly defined in terms of sustainable parameters. In this work, fuzzy logic provides a simple tool that serves as a basis to combine different environmental components with pesticide properties to give a single assessment helping to improve the selection of less harmful pesticides.

5 CONCLUSIONS
The results obtained show that alfalfa, wheat and soybean had low pesticide environmental impact, while maize showed the highest risk of impact. Therefore, the replacement of harmful active ingredients in maize (atrazine and acetochlor) should be taken into account. In alfalfa, wheat and soybean, the application of this indicator may be helpful for considering the use of new active ingredients and their relationship with sustainable systems.

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