Historical trends of the ecotoxicological pesticide risk from the main grain crops in Rolling Pampa (Argentina)

Ferraro, D.O.; Ghersa, F; de Paula, R.; Duarte Vera, A.C.; Pessah, S.

*Corresponding author  
E-mail: ferraro@agro.uba.ar
Abstract

We showed the results of the first long-term analysis (1987-2019) of pesticide impact in the main agricultural area of Argentina. Using a clear and meaningful tool, based not only on acute toxicity but also on scaling up the results to total sown area, we identified time trends for both total pesticide impact and the ecoefficiency of modal pesticide profiles. By the end of the time series, soybean showed a pesticide impact four times greater than maize crop in the studied area. However, the time trend in the last years showed a sustainable pattern of pesticide use, with an improvement in the ecoefficiency. Oppositely, maize showed a relatively constant ecoefficiency value during most of the time series, suggesting a possible path towards an unsustainable cropping system. Findings from this study suggest that some efforts have to be made to improve the pest management decisions towards a more efficient pesticide profiles in maize crop and to keep improving the ecotoxicity pesticide profile in soybean crops because of its large sown area in the studied area.

Introduction

Modern agriculture includes the use of pesticides that have positively impacted cropping systems with a significant increase in yields [1]. However, the potential environmental costs of this intensification process has become a cause for concern [2]. Particularly, rising pesticide use (herbicides, insecticides and fungicides) has been related to both human health and environmental degradation processes [3,4]. Moreover, the global increase of pesticide-resistant organism could lead to a potential rise in pesticide dosage required for the future pest management [5]. Thus, an understanding and a practical
assessments of the impact of agrochemical inputs are essential goals for designing sustainable cropping systems [6]. In this sense, a sustainability assessment can be made by using an indicator’s fixed absolute values, or its temporal trajectory, as a proxy for forecasting the future state of a system [7]. The use of long-term approaches has furthered the understanding of the evolution of farming systems [8] and helped to infer future transitions toward sustainable or unsustainable system states [9]. However, data from long-term analyses of pesticide use in the recent literature are scarce [10-12].

There exists an array of indices to measure a pesticide’s toxicity, which provide a hazard assessment of pesticide use with different approaches [13,14]. Almost all these indices are built by combining toxicological data relating to a target pesticide into a single score [11]. However, some indices have several flaws in terms of both transparent comparisons as well as weighting methods [15,16]. A comprehensive assessment requires quantitative indicators as well as system-oriented and diagnostic characteristics. The need to include the above-mentioned aspects in pesticide risk assessment implies the use of quantitative modeling. In addition, models should be able to integrate different types of information, which are not always expressed in the form of empirically based functional relationships but may represent a desirable state regarding the acceptance (or not) of a hazard level [17].

This paper assessed changes in pesticide risk in the main cropping region of Argentina between 1987 and 2019 using a fuzzy-logic based ecotoxicity hazard indicator [6,18]. In recent decades, the main cropping regions of Argentina have been subject to an intensification process of crop production (i.e. higher yields), as determined by the adoption of no-tillage system [19], the increase in input use (e.g. pesticides and fertilizers), and technological adjustments in crop management (Manuel-Navarrete et al., 2009a; Viglizzo et
al., 2003). However, as in the main cropping systems worldwide, the potential impact as well, as the long-term dynamics due to recent technological changes, still remain controversial [20-22]. We analyzed a 32-year period of pesticide use in soybean and maize in the Rolling Pampa (Argentina). In addition, we used crop yields and sown area in order to assess, not only the impact per unit area, but also its possible impact associated with the sown area and the pesticide ecoefficiency (i.e yield achieved per unit of environmental hazard).

**Material and Methods**

**Study region**

We used data on pesticides, crop yield, and sown area from the Rolling Pampa, the main cropping region of Pampa Region [23]. A pesticide time series was built using the annual profile of pesticides used in the soybean and maize crops. Both crops contributed to 85% and 78% of total sown area at regional and country level, respectively [24]. The Rolling Pampa is the subregion of the Río de la Plata grasslands with more than 100 years of cropping history [25]. Traditionally a mixed grazing-crop area, the spread of no-tillage in the mid-1990s as well as the wheat–soybean double cropping and the lower cost of inputs (fertilizers, pesticides) led to a rapid expansion and intensification of agricultural production [26]. During the entire long-term period, the changes in the cropping systems of the studied area were mainly represented by three major technological changes: 1) the adoption of no-tillage system (NT); 2) the adoption of genetically-modified organisms (GMO); and 3) the start of systematic fertilization (F). No-tillage minimizes soil mechanical disturbance consequently reducing soil erosion and carbon loss processes, as it
leaves a greater percentage of soil covered with plant residues [27]. The change from the conventional tillage system to no-tillage system has also led to a shift in weed control strategy, from a tillage-based scheme to a pesticide-based management strategy. The GMO adoption started in 1996, when the first GMO crop introduced in Argentine agriculture was released, the glyphosate-tolerant soybeans (RR) [28]. The cultivation of RR soybeans, along with transgenic corn hybrids resistant to Lepidoptera (released in 1998) showed an explosive adoption rate among Pampean farmers. It is estimated that 99% of soybeans and 83% of maize crops in Argentina are GMO [29]

The fuzzy-logic pesticide indicator (RIPEST)

To assess long-term pesticide hazard dynamics we used RIPEST [6]. RIPEST is a simple fuzzy-based model [30] to estimate the ecotoxicological hazard of pesticides in agricultural systems. The model allows to assess the ecotoxicological hazard for 1) insects, 2) mammals, and 3) the joint hazard of both impacts. The RIPEST structure comprises three main elements: 1) input variables, 2) fuzzy subsets for defining system processes or attributes based on input values and 3) logical nodes for weighting partial indications into a single system performance. The three input variables that describe the toxicity and the amount of active ingredients utilized in each field are: (1) oral acute lethal dose 50 for rats, (2) contact acute lethal dose 50 for bees; and (3) the dose applied for each pesticide application. Therefore, each active ingredient was characterized by means of two different toxicity values: (1) mammal toxicity and (2) insect toxicity. In order to assess the magnitude of the impact of each application, the values of mammal and insect toxicity were measured using the concept hazard quotient [31] defines as:
Tmam [TUm] = D / LD50r

Tins [TU] = D / LD50b

where, Tmam is the mammal toxicity of each pesticide application; Tins the insect toxicity of each pesticide application; D the dose applied (g formulated product/ha); LD50r the oral acute lethal dose 50 for rats (mg formulated product/1000 g rat weight); LD50b the contact acute lethal dose 50 for bees (µg formulated product/bee); and TU and TUm the toxic units for insects and mammals, respectively. After calculating the Tmam and Tins of single active ingredient formulations and mixtures, RIPEST use the sum of the toxic units (TU) of all the pesticides applied in each field order to calculate the overall toxicity value [32,33]:

Sum Tmam [TUm] = \sum_{i}^{n} T_{mam}  \quad (3)

Sum Tins [TU] = \sum_{i}^{n} T_{ins}  \quad (4)

where Sum Tmam is the mammal toxicity of all the pesticides applied; Sum Tins the insect toxicity of all the pesticides applied; and n the number of pesticide applications on each field, during a single cropping cycle. Then, Sum Tmam and Sum Tins values were used to calculate two different indexes: (1) mammal index (M) and (2) insect index (I), according with linear membership in a 0-100 scale. For this scaling, RIPEST uses the Tmam and Tins the highest value for the most toxic pesticides for mammals and insects [6]. These pesticides are Zeta-cypermethrin 0.2 at 200g/ha and Methidathion 0.4 at 1500 g/ha. Both pesticides involve the highest toxicity registered in the Argentinean National Service for Sanitary and Quality of Agriculture and Food (SENASA 2018) and defines the value of I and M index = 100, respectively. Finally, in order to calculate the overall pesticide impact of pesticides, the (M) and (I) indexes are integrated by two fuzzy rules of the form IF
(antecedent)-THEN (consequent) to assemble the pesticide index (P) which indicates the overall impact of pesticide on each analyzed field. P index also range from 0 to 100. In RIPEST the rule node is calculated as follows:

R1) IF (M is 100) AND (I is 100) THEN P = 100
R2) IF (M is 100) AND (I is 0) THEN P = 90
R3) IF (M is 0) AND (I is 100) THEN P = 90
R4) IF (M is 0) AND (I is 0) THEN P = 0

where, R1 to 4 are fuzzy rules; M is the mammal index; I is the insect index; P is the Pesticide index. Finally, the values of all rules are integrated in a single crisp value by defuzzification process using the weighted average method [34].

Data sources and analysis

Data on pesticide use per hectare were defined following prescriptions for each crop during the whole studied period based on a national reference publication “Márgenes Agropecuarios” (http://www.margenes.com) for all years from 1987 to 2019. Crop yields and sown area were extracted from the Agricultural Estimates of the Ministry of Production and Labor of the Argentine Republic (http://datosestimaciones.magyp.gob.ar/) for the same time period. As the tillage system has shifted from conventional to no-tillage regime, different pesticide profiles were registered for each tillage systems in each crop in the time interval 2002-2007 (soybean) and 2002-2012 (maize). During this period, total values were calculated using data of sown area under these two different tillage systems [35,36]. Before and after these periods each crop under different tillage systems share the same pesticide profile. Final P index value is expressed in a 0-100 scale and represents the
ecotoxicological hazard of pesticides applied per hectare. In order to scale the P values for
the total sown area, we represent the P index using units (units. ha⁻¹). The pesticide
ecoefficiency (i.e yield achieved per unit of environmental hazard) was calculated as the
cost–benefit ratio of the yield to environmental impacts. To detect possible monotonic
trends in the time series we used the Mann-Kendall test [37]. Pesticide data used in the
analysis have been provided as supplementary information.

**Results**

Pesticide index (P) showed both different values and time trends in soybean and
maize crops (Fig. 1). Soybean showed the highest P value at the beginning of the studied
period and decreased until the early-2000, while maize crop started the time series showing
extremely low P values (Fig. 1).

Fig 1. P index [P units. ha⁻¹] for soybean (solid line) and maize (broken line) cropping
systems from 1987 to 2019. Time series also shows temporal trend of P index for cropping
systems under conventional tillage (CT: closed symbols) and no-tillage (NT: open symbols)
for both crops. Mann-Kendall test for monotonic trend: Soybean CT (tau = -0.06, P = 0.69);
Soybean NT (tau = -0.33, P = 0.06). Maize CT (tau = 0.63, P = 0.002); Maize NT (tau = -
0.53, P = 0.006).

However, by the end of the period, the soybean crop showed a remarkable P index
decrease, resulting in similar values for both crops in the last year analyzed (Fig. 1). The
high ecotoxicological hazard per hectare (i.e P index) that the soybean crop exhibited
during most of the time series was enhanced by the large sown area occupied by this crop in the studied area (Fig. 2).

Fig. 2. Total sown area (Mha) under soybean (upper panel) and maize (lower panel) crops from 1987 to 2019. The dotted lines show the evolution of area under no-tillage during the studied period. The vertical lines define the time period when the sown area of each crop exhibited differential pesticide usage according to the tillage system (CT and NT). Mann-Kendall test for monotonic trend of total area: Soybean (tau = 0.48, P < 0.001); Maize NT (tau = -0.02, P = 0.79).

The increase in the sown area with soybean crop was significant in the period 1987-2019, something that did not occur with corn, which exhibited increases and decreases without a defined pattern (Fig. 2). When P index values were scaled by sown area of each crop, soybean values were one order of magnitude higher than maize in most of the period studied (Fig. 3).

Fig. 3. Total P index units [Million of units] under soybean (upper panel) and maize (lower panel) crops. Mann-Kendall test for monotonic trend: Soybean (tau = 0.16, P = 0.20); Maize (tau = 0.71, P < 0.001). The vertical lines define the time period when the sown area of each crop exhibited differential pesticide usage according to the tillage system (CT and NT).

There were also trend differences between crops as soybean showed no significant increase in total P units and maize exhibited a significant increase of P units from 1987 to
The decreasing trend observed in soybean P index (Fig. 1) explained the gap narrowing between the impacts of soybean and maize, which still remained wide by the end of the period, as soybean and maize showed 59 M and 13 M units, respectively (Fig. 3). Both crops showed a monotonic increasing trend in total yield in the studied area (Fig. 4).

Fig. 4. Total yield (Mt) under soybean (solid line) and maize (broken line) crops from 1987 to 2019. Mann-Kendall test for monotonic trend: Soybean (tau = 0.61, P < 0.001); Maize (tau = 0.47, P < 0.001).

However, when both total impact (Fig. 3) and yield (Fig. 4) were integrated in a single ecoefficiency indicator the time trends were different between crops (Fig. 5).

Soybean crop showed a significant positive trend in ecoefficiency, with a remarkable improvement from the early-2010 (Fig. 5). Oppositely, maize crop showed an overall negative trend in ecoefficiency, mainly related to a significant decrease when the pesticide profile of no-tillage began to be considered (Fig. 5).

Fig. 5. Ecoefficiency (t/P) of soybean (upper panel) and maize (lower panel) crops from 1987 to 2019. Ecoefficiency is based upon the ratio of crop yield to P index. Mann-Kendall test for monotonic trend: Soybean (tau = 0.31, P = 0.004); Maize (tau = -0.44, P < 0.001). The vertical lines define the time period when the sown area of each crop exhibited differential pesticide usage according to the tillage system (CT and NT).

In a relative time-trend analysis of both total pesticide impact (Fig. 4) and the ecoefficiency (Fig. 5) using a common base (1987=1), soybean crop showed no significant
trend during the studied period for either measure, but maize showed an almost six-fold increase in total impact, measured as the total number of P units (Fig. 6).

Fig. 6. Relative values (Base 1987 =1) of Total P index units (Total P index units_rel: upper panel) and Ecoefficiency (Ecoefficiency_rel: lower panel) of soybean (solid lines) and maize (broken lines) crops from 1987 to 2019. Mann-Kendall test for monotonic trend: Soybean Total P index units_rel (tau = 0.16, P = 0.20); Maize Total P index units_rel (tau = 0.70, P < 0.001); Soybean Ecoefficiency_rel (tau = 0.31, P = 0.004); Maize Ecoefficiency_rel (tau = -0.44, P < 0.001). The vertical lines define the time period when the sown area of each crop exhibited differential pesticide usage according to the tillage system (CT and NT).

When ecoefficiency was analyzed in relative terms, soybean and maize crops not only showed opposite time trends (Fig. 5) but also different magnitudes in these changes. As maize showed a negative trend, in relative terms, reaching a relative value of 0.52 by the end of the period, ecoefficiency of the soybean crop remarkably increased, showing a relative final value of 7.22 in 2019 (Fig. 6). Pesticide profiles in both crops showed noticeable changes in the 1987-2019 period in the quantity of active ingredient used as well as in the specific toxicity of the pesticides (Tables 1 and 2).

Table 1. Toxic units for mammals (TUm) and insects (TUi) of pesticides used in soybean crop for the years 1987, 1993, 1999, 2007, 2013 and 2019. TS: Tillage system

| TS | Year | a.i.            | % a.i. | Dose (g/ha) | TUm  | TUi  |
|----|------|-----------------|--------|-------------|------|------|
| CT | 1987 | Parathion-methyl| 1      | 500         | 250.00 | 12500 |
|    |      | Trifluralin     | 0.48   | 2000        | 0.19 | 9.60 |
|    |      | Glyphosate      | 0.36   | 500         | 0.09 | 1.80 |
|    |      | Total           |        | 3000        | 250.3 | 12511 |
|    | 1993 | Chlorpyrifos + Cypermethrin | 0.5 + 0.05 | 700 | 5.42 | 7453 |
|    |      | Haloxyfop-P-methyl | 0.52  | 350 | 0.61 | 1.82 |
|    |      | Bentazone       | 0.6    | 800         | 0.34 | 2.4  |
|    |      | Trifluralin     | 0.48   | 2000        | 0.19 | 9.60 |
|    |      | 2,4-DB          | 0.76   | 20          | 0.01 | 0.15 |
| Year | a.i. | % a.i. | Dose (g/ha) | TUm | TU i |
|------|------|--------|-------------|-----|------|
|      | 1987 | Alachlor | 0.48 | 1200 | 0.62 | 36.0 |
|      |      | Atrazine | 0.9  | 1100 | 0.53 | 9.90 |
|      |      | Total    |      | 2300 | 1.15 | 45.9 |
|      | 1993 | Alachlor | 0.48 | 3500 | 1.81 | 105.0 |
|      |      | Atrazine | 0.9  | 3500 | 1.69 | 31.5 |
|      |      | Total    |      | 7000 | 3.49 | 136.5 |
|      | 1999 | Acetochlor | 0.84 | 2000 | 0.87 | 8.40 |
|      |      | Atrazine | 0.9  | 1000 | 0.48 | 9.00 |
### Results from the studied period in the entire database of pesticide usage in soybean

The ecotoxicity hazard of the pesticides used, the soybean showed no important changes in the total toxic units for insects (TU\textsubscript{i}) until the end of the period studied when final values were one order of magnitude lower than the rest of the database (Table 1).
ecotoxicity assessment, measured in toxic units for mammals (TUm), showed the highest
toxicity values at the beginning of the time series, mainly due to the used of an extremely
toxic compound (Parathion-methyl) that was banned by 1990s. In the following years, the
total number of TUm remained in the range of 5-13 TUm, until Chlorpyriphos and
Endosulfan were replaced by less toxic insecticides (Table 1). In maize, the main change in
insect ecotoxicity (TUi) was observed because of the adoption of insecticides in the
analyzed pesticide profiles (Table 2). However, pesticide usage data showed a breakpoint
toward lower doses and less toxic compounds in maize which resulted in fewer toxic units
for insects by the end of the time series. Finally, mammal toxicity of pesticides usage in
maize crop showed a constant and positive increase from 1.15 Tum, for the pesticide profile
in 1987, up to 5.24 TUm in 2019 (Table 2).

Discussion

Agricultural intensification relies on ecosystem assessment in order to move
towards sustainable farming systems. However, this assessment should include both present
and near future effects on key ecosystem processes in order to infer ecosystem time trends
[38]. Regarding pesticide use, long-term monitoring represents a critical step for
sustainability assessment as data on pesticide use remains scattered and not necessarily
publicly available [39]. This is often the situation in developing countries where data on
both pesticide monitoring and actual amount of pesticides use at national and regional are
difficult to find [40]. In this paper, we cope with this problem by using standard pesticide
regimes registered in one of the main cropping areas of Argentina as a proxy of the actual
use of pesticides. This assumption may imply a significant caveat to be considered when
analyzing our results, particularly when this regime is scaled-up using the sown area for
assessing an overall pesticide hazard in maize and soybean crops. In this sense, the lack of
direct information on the use of pesticides could incorporate some bias in the observed
absolute values. However, both the data integrity on pesticide use regimes and the
evolution of the sown area in both crops and under different tillage systems allows
evaluating the observed trends and using them as reliable indicators of long-term change in
the systems studied [41].

Environmental assessment should not only include the spatial and temporal
dimensions, but it should also rely on meaningful metrics [42]. Concerning pesticide use,
there are plenty of indicators based in commercialized volume, dose applied, exposure or
several ecotoxicity values [43]. However, indicators based solely on the weight of pesticide
applied can result in ambiguous or incorrect conclusions, because pesticides used in
cropping systems involve a variety of toxicity profiles. This has led to a switch in current
risk assessments from quantity-based [44] to toxicity-based indicators [45]. In this work,
we used a toxicity-based indicator which follows a hazard quotient approach [12,46]. The
selected indicator is free from most of the previous concerns about the environmental
impact quotient (EIQ) developed previously [47]. Most of these concerns are related to
numerical calculations with ordinal values, the undermining of important pesticide risk
factors, the lack of supporting data for assigning some partial risk values and the strong
correlation between field EIQ and pesticide use rate [12,15,16]. The acute toxicity on insect
and mammals were integrated using fuzzy logic as a tool. The fuzzy logic approach has
been previously used in pesticide assessment [18,48] and is very useful in order to develop
a continuum process of ecosystem monitoring. The explicit nature of both membership
functions and fuzzy if-then rules set up a conceptual assessment framework that could be
easily improved in the future by the inclusion of new rules for weighting indicator scores in
different situations [49]. This is a critical issue when modeling and building sustainability indicators as its characterization should be literal, and system-oriented [38]. Moreover, the scores derived from RIPEST involve the distance between observed values and some reference values rather than an absolute value, which rarely reveals whether the impact of a system is acceptable or not [50].

Our study is, as far as we know, the first long-term analysis of pesticide risk in cropping systems of Argentina. Previous long-term analysis showed that pesticide impact decreased in UK from 1992-2008, but also that this pattern is crop-dependent, with an initial risk decrease followed by a long stabilized period [11]. Data from herbicide use in USA from 1990-2015 showed that acute toxicity decreased for the six main crops; particularly both maize and soybean showed a decrease in acute toxicity per hectare [12]. Our results did not show a common time trend in ecotoxicity risk among crops. Results showed two temporal dynamics of pesticide impact, which were related to the analyzed crop. Soybean showed high temporal variability due to both technological changes associated to tillage system shift and a national ban of highly toxic compounds [51-53]. Pesticide regulations shows differences in Argentina in relation to EU countries mainly associated with the timing of prohibition and restriction (Iturburu et al., 2019). However, several organophosphorus, all organochlorine pesticides (OCPs) have been restricted since 1991 and totally banned by 1998 [51,52,54]. By this time, the observed soybean time-trend showed a significant decrease both per area and total impact due to pesticide profiles as well as by the end of the studied period when impact reduction was mainly due to lower applied doses.

The Mann-Kendall statistical test only evaluates monotonic trends over the entire 32-year period. However, partial trends may be important, even where the overall trend is
non-significant [12]. A partial positive trend in pesticide impact was observed both in soybean and maize crops during the period of no-tillage adoption. Pesticide risk increased in this period due to the double effect of the increase in the sown area and the shift towards systems with greater use of pesticides. When tillage is reduced, farmers become more reliant on other weed and pest control practices, and at least some of the widespread increase in pesticide use could be attributable to adoption of conservation tillage practices [55]. However, by the end of the time series (the period when no-tillage was fully adopted) the observed trend was different between crops. Although the sown area increased in both crops, total pesticide impact in these last years decreased in soybean because of a significant low pesticide use in the modal profiles. Otherwise, maize kept the toxicity profiles relatively constant during half of the time series, but the sown area increment resulted in a significant partial incremental pesticide impact trend. Soybean production showed a continuous improvement in its toxicity indicators, something opposite to what was observed in the corn crop. Maize has a continuous increased in ecotoxicity risk, boosted mainly by a higher dose trend. This result seems to be contrary to technological changes in maize, mainly represented by the incorporation of the genetic modification that confers resistance to insects (i.e. Bt-corn) as early as 1996 [56]. However, around the same period, herbicide resistance has been extensively documented in this productive area [57,58], which led to an increase in the use of herbicides [59]. This process was also enhanced by the relative increase in rotation of winter fallows without crop coverage due to the noticeable reduction of sown area with wheat and barley [60].

Environmental monitoring should encourage pesticide use changes towards more sustainable trajectories. However, the adoption of these changes depends on the way the observed trends are communicated and highlighting potential tradeoffs in pesticide
assessment by using both impact and return metrics [61]. Ecoefficiency is a key indicator for showing an improved measure of sustainability because it links environmental impacts directly with some kind of economic performance, possibly leading towards sustainable development [62]. Time-trends of soybean showed a significant increase in ecoefficiency, particularly in the last years analyzed. Soybean dependence on herbicides has risen as a result of weed-related problems. However, RIPEST is sensible to acute toxicity defined mainly for highly toxic insecticides, and the modal pesticide soybean profiles showed a constant reduction not only in the number but also in the acute toxicity of insecticides used. Oppositely, the maize crop did not show improvements in ecoefficiency. As we previously mentioned, during this period some innovations have been adopted to increase yield and reduce the risk of crop loss [56]. These objectives were met as shown by the constant increase in total yield, remarkably during the last 10 years of the data analyzed. However, these improvements were not fully reflected in the ecoefficiency. This pattern is clearer when the ecoefficiency values are expressed in a common base, related to initial values. The constant value of relative ecoefficiency in maize crop is showing a possible path towards an unsustainable cropping system.

Finally, some areas for improvement in pesticide impact assessment has should not be overlooked. We reported data on environmental impact based on ecotoxicity. However, there are some issues to consider such as pesticide fate and transport, which is especially critical when assessing sensitive areas such watersheds and the urban-rural interface. However, data on long-term ecotoxicity trends, both on total impact and when using the ecoefficiency concept, should help to push for sustainable intensification by identifying negative trends and highlighting a potential tradeoff between crop productivity and environmental impact. The ultimate challenge is to reinforce high crop yield time-trends.
while simultaneously incentivizing the efficient use of pesticides to minimize this potential tradeoff between crop productivity and environmental impact.

Acknowledgements

This material is based upon work supported by the University of Buenos Aires (UBA); the National Council for Scientific Research (CONICET); and the National Agency for Science Promotion (ANPCyT) of Argentina (PICT 2016-3216)

Supporting Information

S1 Table. Data for pesticide use
S2 Table. Data for sown area and yields

References

1. Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, et al. (2011) Solutions for a cultivated planet. Nature 478: 337.

2. Pretty J (2008) Agricultural sustainability: concepts, principles and evidence. Philosophical Transactions of the Royal Society B: Biological Sciences 363: 447-465.

3. Imfeld G, Vuilleumier S (2012) Measuring the effects of pesticides on bacterial communities in soil: a critical review. European Journal of Soil Biology 49: 22-30.
407 4. Li Z, Jennings A (2017) Worldwide Regulations of Standard Values of Pesticides for Human
408 Health Risk Control: A Review. International journal of environmental research and public
409 health 14: 826.

410 5. Hillocks RJ (2012) Farming with fewer pesticides: EU pesticide review and resulting challenges
411 for UK agriculture. Crop Protection 31: 85-93.

412 6. Ferraro DO, Duarte Vera AC, Pessah S, Ghersa F (2020) Environmental Risk Indicators for
413 Weed Management: A Case Study of Ecotoxicity Assessment Using Fuzzy Logic. In:
414 Chantre GR, González-Andujar JL, editors. Decision Support Systems for Weed
415 Management. Switzerland: Springer Nature AG 2020. pp. 191-209.

416 7. Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable
417 intensification of agriculture. Proceedings of the National Academy of Sciences 108:
418 20260-20264.

419 8. Chantre E, Cardona A (2014) Trajectories of French Field Crop Farmers Moving Toward
420 Sustainable Farming Practices: Change, Learning, and Links with the Advisory Services.
421 Agroecology and Sustainable Food Systems 38: 573-602.

422 9. Ferraro DO, Benzi P (2015) A long-term sustainability assessment of an Argentinian agricultural
423 system based on emery synthesis. Ecological Modelling 306: 121-129.

424 10. Osteen CD, Szmedra PI (1989) Agricultural pesticide use trends and policy issues: US
425 Department of Agriculture, Economic Research Service.
11. Cross P, Edwards-Jones G (2011) Variation in pesticide hazard from arable crop production in Great Britain from 1992 to 2008: An extended time-series analysis. Crop Protection 30: 1579-1585.

12. Kniss AR (2017) Long-term trends in the intensity and relative toxicity of herbicide use. Nature communications 8: 1-7.

13. Feola G, Rahn E, Binder CR (2011) Suitability of pesticide risk indicators for less developed countries: a comparison. Agriculture, ecosystems & environment 142: 238-245.

14. Calliera M, Marchis A, Bollmohr S, Sacchettini G, Lamastra L, et al. (2013) A process to provide harmonised criteria for the selection of indicators for pesticide risk reduction within the framework of the sustainable use directive. Pest management science 69: 451-456.

15. Kniss AR, Coburn CW (2015) Quantitative evaluation of the environmental impact quotient (EIQ) for comparing herbicides. PloS one 10: e0131200.

16. Dushoff J, Caldwell B, Mohler CL (1994) Evaluating the environmental effect of pesticides: a critique of the environmental impact quotient. American Entomologist 40: 180-184.

17. Rajaram T, Das A (2010) Modeling of interactions among sustainability components of an agro-ecosystem using local knowledge through cognitive mapping and fuzzy inference system. Expert Systems with Applications 37: 1734-1744.

18. Ferraro DO, Ghersa CM, Sznajder GA (2003) Evaluation of environmental impact indicators using fuzzy logic to assess the mixed cropping systems of the Inland Pampa, Argentina. Agriculture, Ecosystems & Environment 96: 1-18.
19. Manuel-Navarrete D, Gallopín G, Blanco M, Díaz-Zorita M, Ferraro DO, et al. (2005) Systems analysis of agriculturization in the Argentine wet Pampas and its surrounding regions: sustainability, knowledge gaps, and policy integration. Santiago: ECLAC: Serie Medio Ambiente y Desarrollo 118, CEPAL. 63 p.

20. Arancibia F (2016) Regulatory Science and Social Movements: The Trial Against the Use of Pesticides in Argentina. Theory in Action 9.

21. Viglizzo EF, Ricard MF, Jobbágy EG, Frank FC, Carreño LV (2011) Assessing the cross-scale impact of 50 years of agricultural transformation in Argentina. Field Crops Research 124: 186-194.

22. Kudsk P, Mathiassen SK (2020) Pesticide regulation in the European Union and the glyphosate controversy. Weed Science 68: 214-222.

23. Hall A, Rebella C, Ghersa C, Culot P (1992) Field-Crop Systems of the Pampas. In: Pearson CJ, editor. Ecosystems of the World. The Netherlands: Elsevier. pp. 413-449.

24. MinAgri (2018) Estimaciones agrícolas (Series of agricultural statistics by crop, year, province and department of the Argentine Republic). In: 2019] AawmgavA, editor.

25. Soriano A, León RJC, Sala OE, Lavado RS, Deregibus VA, et al. (1991) Río de la Plata grasslands. In: Coupland RT, editor. Ecosystems of the world 8A Natural grasslands Introduction and western hemisphere. New York: Elsevier. pp. 367-407.
26. Manuel-Navarrete D, Gallopín G, Blanco M, Díaz-Zorita M, Ferraro D, et al. (2009) Multi-causal and integrated assessment of sustainability: the case of agriculturization in the Argentine Pampas. Environment, Development and Sustainability 11: 612-638.

27. Lal R, Follett RF, Kimble J, Cole CV (1999) Managing U.S. cropland to sequester carbon in soil. Journal of Soil and Water Conservation 54: 374-381.

28. Trigo E, Cap E (2003) The impact of the introduction of transgenic crops in Argentinean agriculture. AgBioForum 6: 87–94.

29. Burachik M (2010) Experience from use of GMOs in Argentinian agriculture, economy and environment. New biotechnology 27: 588-592.

30. Zadeh LA (1965) Fuzzy sets. Information and Control 8: 338.

31. Norton SB, Rodier DJ, van der Schalie WH, Wood WP, Slimak MW, et al. (1992) A framework for ecological risk assessment at the EPA. Environmental toxicology and chemistry 11: 1663-1672.

32. Newman M (2010) Acute and cronic lethal effects to individuals. In: Newman MC, editor. Fundamentals of Ecotoxicology. Chelsea, MI: Ann Arbor Press. pp. 247-272.

33. Rose DG (1998) Environmental Toxicology: Current Developments. Amsterdam, The Netherlands: Gordon and Breach Science Pub. 397 p.

34. Takagi T, Sugeno M (1985) Fuzzy identification of systems and its applications to modeling and control. IEEE Transactions on Systems, Man, and Cybernetics 15: 116.
35. AAPRESID (2019) Evolución de la superficie en Siembra Directa en Argentina.
https://www.aapresid.org.ar/wp-content/uploads/2018/03/Estimacio%C3%B1n-de-superficie-en-SD.pdf.

36. Peiretti R, Dumanski J (2014) The transformation of agriculture in Argentina through soil conservation. International Soil and Water Conservation Research 2: 14-20.

37. McLeod AI (2005) Kendall rank correlation and Mann-Kendall trend test. R Package Kendall.

38. Hansen JW (1996) Is agricultural sustainability a useful concept? Agricultural Systems 50: 117.

39. Mancini F, Woodcock BA, Isaac NJB (2019) Agrochemicals in the wild: Identifying links between pesticide use and declines of nontarget organisms. Current Opinion in Environmental Science & Health 11: 53-58.

40. Lewis KA, Tzilivakis J, Warner DJ, Green A (2016) An international database for pesticide risk assessments and management. Human and Ecological Risk Assessment: An International Journal 22: 1050-1064.

41. Smith C, McDonald G (1998) Assessing the sustainability of agriculture at the planning stage. Journal of environmental management 52: 15-37.

42. Thomson A, Ehiemere C, Carlson J, Matlock M, Barnes E, et al. (2020) Defining Sustainability as Measurable Improvement in the Environment: Lessons from a Supply Chain Program for Agriculture in the United States. In: Khaiter PA, Erechotchoukova MG, editors. Sustainability Perspectives: Science, Policy and Practice: A Global View of Theories,
43. Juraske R, Antón A, Castells F, Huijbregts MAJ (2007) PestScreen: A screening approach for scoring and ranking pesticides by their environmental and toxicological concern. Environment International 33: 886-893.

44. Benbrook CM (2012) Impacts of genetically engineered crops on pesticide use in the US--the first sixteen years. Environmental Sciences Europe 24: 24.

45. Möhring N, Gaba S, Finger R (2019) Quantity based indicators fail to identify extreme pesticide risks. Science of The Total Environment 646: 503-523.

46. Stoner KA, Eitzer BD (2013) Using a hazard quotient to evaluate pesticide residues detected in pollen trapped from honey bees (Apis mellifera) in Connecticut. PLoS One 8: e77550.

47. Kovach J, Petzoldt C, Degni J, Tette J (1992) A method to measure the environmental impact of pesticides. New York’s Food Life Sci Bull 139: 1-8.

48. Roussel O, Cavelier A, van der Werf HMG (2000) Adaptation and use of a fuzzy expert system to assess the environmental effect of pesticides applied to field crops. Agriculture, Ecosystems and Environment 80: 143-158.

49. Ferraro DO (2009) Fuzzy knowledge-based model for soil condition assessment in Argentinean cropping systems. Environmental Modelling & Software 24: 359-370.
50. Acosta-Alba I, Van der Werf HM (2011) The use of reference values in indicator-based methods for the environmental assessment of agricultural systems. Sustainability 3: 424-442.

51. Konradsen F, van der Hoek W, Cole DC, Hutchinson G, Daisley H, et al. (2003) Reducing acute poisoning in developing countries—options for restricting the availability of pesticides. Toxicology 192: 249-261.

52. SENASA (2011) Servicio Nacional de Sanidad y Calidad Agroalimentaria. Resolución 511/2011. Available in: https://wwwsenasagobar/.

53. Iturburu FG, Calderon G, Amé MV, Menone ML (2019) Ecological Risk Assessment (ERA) of pesticides from freshwater ecosystems in the Pampas region of Argentina: Legacy and current use chemicals contribution. Science of The Total Environment 691: 476-482.

54. SENASA (2018) Registro nacional de terpeutica vegetal (National registry of vegetal therapeutics). 2018 ed. Buenos Aires, Argentina.

55. Racovita M, Obonyo DN, Craig W, Ripandelli D (2015) What are the non-food impacts of GM crop cultivation on farmers’ health? Environmental Evidence 4: 17.

56. Blanco CA, Chiaravalle W, Dalla-Rizza M, Farias JR, García-Degano MF, et al. (2016) Current situation of pests targeted by Bt crops in Latin America. Current Opinion in Insect Science 15: 131-138.
57. Ferraro DO, Gthersa CM (2013) Fuzzy assessment of herbicide resistance risk: Glyphosate-resistant johnsongrass, Sorghum halepense (L.) Pers., in Argentina's croplands. Crop Protection 51: 32-39.

58. Valverde BE, Gressel J (2006) Dealing with the evolution and spread of Sorghum halepense glyphosate resistance in Argentina. Buenos Aires: Consultancy report to SENASA. Available: http://www.sinavimo.gov.ar/files/senasareport2006.pdf.

59. Rubione C, Ward SM (2017) A New Approach to Weed Management to Mitigate Herbicide Resistance in Argentina. Weed Science 64: 641-648.

60. de Abelleyra D, Verón S (2020) Crop rotations in the Rolling Pampas: Characterization, spatial pattern and its potential controls. Remote Sensing Applications: Society and Environment: 100320.

61. Ferraro DO, Gagliostro M (2017) Trade-off assessments between environmental and economic indicators in cropping systems of Pampa region (Argentina). Ecological Indicators 83: 328-337.

62. Caiado RGG, de Freitas Dias R, Mattos LV, Quelhas OLG, Leal Filho W (2017) Towards sustainable development through the perspective of eco-efficiency - A systematic literature review. Journal of Cleaner Production 165: 890-904.
Figure 4
Figure 6