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Article

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1 Suitability of pesticide risk indicators for less developed countries: a comparison

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12 Abstract

13 Pesticide risk indicators provide simple support in the assessment of environmental and health
14 risks from pesticide use, and can therefore inform policies to foster a sustainable interaction of
15 agriculture with the environment. For their relative simplicity, indicators may be particularly
16 useful under conditions of limited data availability and resources, such as in Less Developed
17 Countries (LDC). However, indicator complexity can vary significantly, in particular between
18 those that rely on an exposure-toxicity ratio (ETR) and those that do not. In addition, pesticide
19 risk indicators are usually developed for Western contexts, which might cause incorrect
20 estimation in LDCs. This study investigated the appropriateness of seven pesticide risk
21 indicators for use in LDCs, with reference to smallholding agriculture in Colombia. Seven
22 farm-level indicators, among which 3 relied on an ETR (POCER, EPRIP, PIRI) and 4 on a
23 non-ETR approach (EIQ, PestScreen, OHRI, Dosemeci et al., 2002), were calculated and then
24 compared by means of the Spearman rank correlation test. Indicators were also compared
25 with respect to key indicator characteristics, i.e. user friendliness and ability to represent the
26 system under study. The comparison of the indicators in terms of the total environmental risk

1 suggests that the indicators not relying on an ETR approach cannot be used as a reliable proxy
2 for more complex, i.e. ETR, indicators. ETR indicators, when user-friendly, show a
3 comparative advantage over non-ETR in best combining the need for a relatively simple tool
4 to be used in contexts of limited data availability and resources, and for a reliable estimation
5 of environmental risk. Non-ETR indicators remain useful and accessible tools to discriminate
6 between different pesticides prior to application. Concerning the human health risk, simple
7 algorithms seem more appropriate for assessing human health risk in LDCs. However, further
8 research on health risk indicators and their validation under LDC conditions is needed.

9

10 **Keywords**

11 Pesticide use, environmental risk, occupational health risk, assessment, indicator, Colombia

12

13 **1. Introduction**

14 Pesticide risk indicators can support the assessment of environmental and health risks from
15 pesticide use. They can be utilized by different kinds of users, such as farmers, extension
16 agents, policy-makers, regulatory agencies and academia (Levitan, 2000). They serve as a
17 basis for the evaluation of different pest management strategies (Levitan, 2000; Greitens and
18 Day, 2007), and for the development, monitoring and assessment of environmental and health
19 policies (Levitan, 2000; Maud et al., 2001; Falconer, 2002; Finizio and Villa, 2002). Thus,
20 pesticide risk indicators can signal risky agricultural practices and inform interventions and
21 policies to foster a sustainable interaction of agriculture with the environment on which
22 agriculture itself relies. The contribution of pesticide risk indicators, and more in general of
23 sustainability indicators, in helping minimising the impact of agriculture on the environment
24 has been recognized not only in academia, but in the policy arena, which has often taken a

1 proactive role in stimulating research on sustainability indicators in agriculture (e.g. CEC,
2 1999; OECD 1999 and 2001).

3 Simplicity is a generally acknowledged feature of indicators. This often makes them
4 acceptable, usable even with scarce data, quick to calculate and easy to communicate,
5 although at the expense of a more realistic representation of pesticide impacts (van der Werf,
6 1996; Castoldi et al., 2007). In this regard, indicator-based assessment methods gain a
7 comparative advantage over alternative assessment systems, such as direct measurements or
8 simulation modelling, which instead require more qualified expertise, economic resources and
9 data which might not always be available.

10 However, the level of complexity of pesticide risk indicators can also vary significantly. Two
11 broad typologies of indicators can be identified (Reus et al., 2002). The first includes user
12 friendly assessment tools, usually with few input data requirements, and a scoring table based
13 on rather simple algorithms which are often constructed on the basis of expert judgment.
14 These indicators usually score pesticide properties first, which are then multiplied by the
15 application rate. Finally, the scores are aggregated by summation. The second typology
16 includes indicators using a risk-ratio, or exposure-toxicity ratio (ETR) approach, i.e. “the ratio
17 between exposure (usually the concentration in a certain environmental compartment) and
18 toxicity for relevant organisms” (Reus et al., 2002). These indicators are considered to better
19 represent and quantify environmental risks from pesticide use, but have the drawbacks of
20 requiring more detailed input data and the support of computer modelling (Reus et al., 2002;
21 Castoldi et al., 2007). These indicators use the application rate to calculate pesticide
22 concentrations, which are then scored by environmental compartment. The compartment
23 scores can then be integrated by summation or by multiplication. Thus, from a mathematical
24 perspective, the most significant difference between ETR and non-ETR indicators is how the
25 application rate is included in the risk estimation.

1The extent to which simple and complex pesticide risk indicators provide convergent
2assessment results is an open issue. Convergent results would allow for considering simple
3indicators as proxy to the more complex ones, and therefore allow them to be used as easy-to-
4use diagnostic tools. However, previous comparative studies highlighted a divergence rather
5than a convergence in assessment results (e.g. Maud et al., 2001; Reus et al., 2002).

6The quest for simple but reliable assessment methods is particularly relevant in Less
7Developed Countries (LDC). In effect, not only are LDCs often characterised by particularly
8serious pesticide-related externalities (e.g. Pimentel et al., 1992; Ecobichon, 2001), but also
9by a general limited ability in environmental and agricultural research and monitoring. The
10latter can be in broad terms related to two issues, i.e. lack of skilled human resources, with
11brain drain and de-qualification affecting many countries (UNESCO, 2009), and lack of
12infrastructure (e.g. information technology, laboratories) and financial resources to access and
13produce reliable data and information (Zhen and Routray, 2003; UNESCO, 2009).

14Furthermore, one open issue is that pesticide risk indicators are usually developed for
15productive and pedoclimatic conditions in Western countries, which might imply, especially
16for indicators relying on expert judgement, an incorrect assessment of pesticide risks in LDCs.
17Pesticide risk indicators have been used in LDCs, but usually with a preference for simple,
18non-ETR types (e.g. Muhammetoglu and Uslu, 2007; Pradel et al., 2009), an exception being
19a study of Kookana et al. (2007). However, while comparative evaluations of pesticide risk
20indicators exist (e.g. Maud et al., 2001; Reus et al., 2002; Stenrod et al., 2008), they do not
21refer to the conditions of resource availability usually encountered in LDCs. Moreover,
22comparative evaluations of indicators have neglected human health risk indicators. Analysing
23also this kind of indicators is of fundamental importance in LDCs, because pesticide
24application practices often differ significantly from those adopted in Western countries
25(Matthews, 2008). Such differences in contextual factors, in particular pesticide application

1 techniques, suggest that the applicability of health risk indicators in LDCs might be limited,
2 and call for the need for contextualizing pesticide risk, e.g. to understand the determinants of
3 exposure more than to quantify levels of risk (Blanco et al., 2005).

4 Consequently, it is not clear what indicators might be more appropriate to assess
5 environmental and health risks from pesticide use, and thus properly inform agricultural
6 management, under pesticide application practices typical of LDCs. The objective of this
7 study was to investigate the appropriateness of seven pesticide risk indicators for use at farm
8 level in LDCs, with particular reference to smallholding agriculture in the Colombian Andean
9 region. With reference to this area, two research questions drove the study:

- 10 i) Can simple pesticide risk indicators be used as proxies for more complex ones,
11 thus facilitating the task of risk assessment?
- 12 ii) What is the most appropriate indicator to assess pesticide risk to human health and
13 the environment?

14 The paper is structured as follows. Firstly, a short description of the indicators selected, study
15 area, data used and comparative procedure adopted are provided. Secondly, the results are
16 presented separately for environmental and human health risk indicators. Finally, results are
17 discussed with reference to the two research questions, and conclusions on the use of pesticide
18 risk indicators in the context of LDCs are drawn.

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23 **2. Method**

24 **2.1. Indicators**

1 Agriculture, Ecosystems and Environment 142 (2011) 238–245, DOI: 10.1016/j.agee.2011.05.014

1Seven farm-level indicators (i.e. EIQ, PestScreen, EPRIP, PIRI, POCER, OHRI and the
2indicator proposed by Dosemeci et al., 2002) were selected so that i) every environmental and
3health compartment was considered by at least two of the selected indicators and ii) both
4simple, i.e. non-ETR, and complex, i.e. ETR, indicators were represented (Table 1).

52.1.1. Coverage of environmental and health compartments

6Three indicators, i.e. PestScreen (Juraske et al., 2007), EPRIP (Padovani et al., 2004; Trevisan
7et al., 2009), and PIRI (Kookana et al., 2005), focus exclusively on environmental risks,
8whereby risk to consumer health is implicitly and partly included, since drinking water
9contamination and ingestion of contaminated food are part of the environmental risk
10assessment. Two indicators, i.e. OHRI (Bergkvist, 2004) and the indicator developed by
11Dosemeci et al. (2002), focus solely on occupational health risk, whereby only the pesticide
12operator is considered. The remaining two indicators, i.e. EIQ (Kovach et al., 1992) and
13POCER (Vercruyssen and Steurbaut, 2002), include an environmental risk component and an
14occupational health risk component, whereby both assess the risk to agricultural workers in
15addition to pesticide operators and POCER also considers bystanders' risk to pesticide
16exposure (a short description of the indicators is given in the supplementary data files).

172.1.2. Representation of ETR and non-ETR indicators

18Four indicators were chosen that do not rely on an ETR approach, i.e. they transform
19variables into scores which, in turn, are aggregated empirically (EIQ, PestScreen, OHRI and
20the indicator from Dosemeci et al., 2002), and three indicators were chosen which rely on the
21ETR approach (POCER, EPRIP, PIRI). The first four indicators are considered simple
22indicators because they do not make use of site specific data (e.g. pedoclimatic conditions)
23and because pre-calculated hazard scores are multiplied with application rates by the end-user,
24which results in low data requirements. The latter three indicators take into account site
25specific data, make use of the ETR approach and are more data demanding.

12.1.3. Further indicator characteristics

2PestScreen, POCER, EPRIP and PIRI all implement at least some of the suggestions made in
 3earlier studies for the development of more accurate pesticide risk indicators (Levitan, 1997
 4and 2000; Maud et al., 2001; Reus et al., 2002). Among these suggestions were: to be
 5analogous to the technical concept of risk, to have large potential ranges to allow for
 6differentiation between pesticides, to include application rate, application factors and
 7environmental conditions, to give separate rankings for different compartments (including
 8human health). On the other hand, EIQ is one of the most dated, but also one of the most
 9widely used indicators, with numerous applications in LDCs (e.g. Muhammetoglu and Uslu,
 102007; Pradel et al., 2009).

11Finally, all indicators chosen present a relative outcome. That is, instead of providing an
 12absolute value, the assessment provides a qualitative statement on the relative risks a pesticide
 13application or control strategy might have in comparison to the application of another
 14pesticide or to a control strategy based on different pesticides.

15

16**Table 1. Risk indicators considered in this study by environmental and health compartments**

Indicator	Environment				Beneficial arthropods	Pesticide operator	Health		Calculation methodology	
	Soil	Air	Surface water	Groundwater			Farm worker	Consumer	ETR	Non-ETR
EIQ			*	*	*	*	*	*		*
PestScreen	*	*	*	*				*		*
POCER	*		*	*	*	*	*	*	*	
EPRIP	*	*	*	*				*	*	
PIRI			*	*				*	*	
OHRI						*				*
17 Dosemeci et al. (2002)						*				*

18

192.2. Data

202.2.1. Data and study area

1The data necessary to calculate the indicator rankings were mainly derived from an existing
2georeferenced dataset produced in a previous study in the *vereda* (community) called La
3Hoya, located in the Department of Boyacá, in the eastern chain of the Colombian Andes
4(Feola, 2010a). For many aspects such as pesticide application technique or socio-
5demographic structure, this study area may be considered typical of the broader Andean
6region (Feola, 2010a) and very similar to other rural areas in LDCs (Matthews, 2008).

7Vereda La Hoya ranges from 2,700 to 3,250 masl over an area of 8.4 km² (840 ha), and has a
8population of about 750 inhabitants. It is a rural region mainly dedicated to the cultivation of
9potato (MADR, 2006). The production of potato in Vereda La Hoya relies mainly on
10smallholders, who cultivate an average of 3 hectares subdivided into different plots. The land
11is cultivated in two cycles a year (September to February and March to August). Average
12productivity rates range between 15 and 17 ton/ha (MADR, 2006). Potato crops in this region
13are vulnerable to three major pests: the soil-dwelling larvae of the Andean weevil
14(*Premnotrypes vorax*), the late blight fungus (*Phytophthora infestans*) and the Guatemalan
15potato moth (*Tecia solanivora*). To protect the crop from these pests, the use of chemical
16pesticides, in particular insecticides and fungicides, is widespread among smallholders (Feola
17and Binder, 2010b). The most common way of applying pesticide is by means of a lever-
18operated knapsack sprayer (20-25 litres), which is filled from a bigger tank, usually of about
19200 litres, where the pesticide mix is prepared.

20Also as a result of the misuse of personal protective equipment (PPE), high levels of
21pesticide-related health risk have been observed in the region (Cardenas et al., 2005; Ospina
22et al., 2008; Feola, 2010b). Regarding adverse environmental effects, both Schoell and
23Binder (2009) and Feola and Binder (2010b) reported that farmers in Vereda La Hoya
24observed a pesticide-related reduction of soil biodiversity in recent years. Finally, pesticide
25overuse has attracted the concern of governmental agencies because of its economic

1drawbacks (MADR, 2004). In this respect, Feola and Binder (2010b), showed that some of
2the farmers tend to use pesticides ineffectively, with a persistent overuse.

3The data used in this study to calculate the indicator values were gathered through a survey
4carried out in La Hoya in 2007 (Feola and Binder, 2010c). The data consisted of detailed
5information on 72 farmers' safety practices (e.g. hygiene and use of personal protective
6equipment) and pesticide applications on one selected plot. The reference period for the data
7was one entire agricultural cycle (March to August 2007).

8

92.2.2. *Additional data*

10Additional data necessary to calculate the indicators was gathered from various sources.
11Pesticide properties were obtained through the Pesticide Properties Database (PPDB, 2009).
12Climatic data, such as precipitation and temperature (for the years 1994-2003), were obtained
13from the Instituto de Hidrologia, Meteorologia y Estudios Ambientales de Colombia. For the
14reference period the temperature was between an average minimum of 5.7 °C and an average
15maximum of 20 °C. Total annual precipitation in the reference period was 343.5 mm. For soil
16parameters, the classification of "clay loam" was used (Binder and Patzel, 2001). According
17to Leuenberger (2005) average organic carbon content in the study area was 6.4%. Mean bulk
18density was assumed to be 0.9 tons per m³ according to Binder and Patzel (2001). Soil loss
19was adapted from Binder and Patzel (2001) and assumed to be 9.6 tons per hectare and year.
20The distance of the plot to water bodies was calculated with the software ESRI ArcGIS 9.3.
21An overview of the data used to calculate the indicators is available in the supplementary data
22files.

23

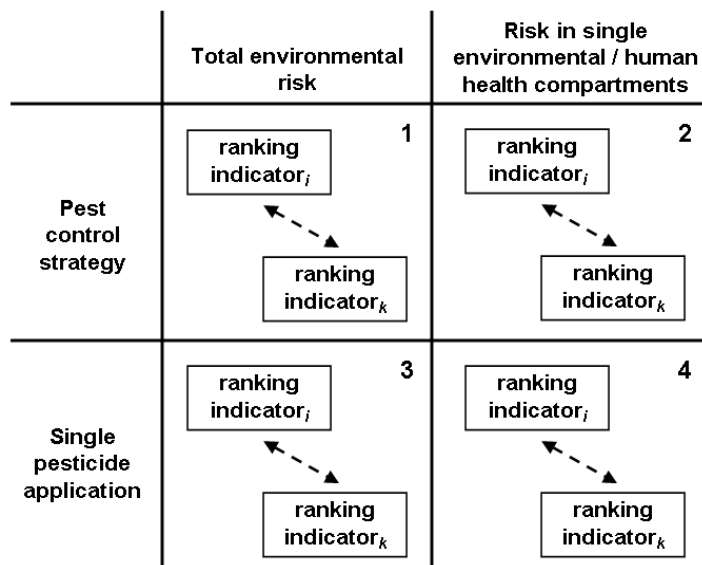
242.3. Procedure

1The study consisted of three phases. First, the indicator values were calculated for the pest
2control strategy and for single pesticide applications. A pest control strategy is defined for
3each of the 72 farmers as the total amount of pesticide applied by active ingredient (examples
4of pesticide application patterns and strategies can be found in Feola and Binder, 2010b, and
5Juraske et al., 2011). For EIQ and EPRIP, the number, frequency and sequence of applications
6also contributes in differentiating among pest control strategies, since they propose how to
7calculate the cumulative risk which occurs when several applications of different active
8ingredients are used within the same pest control strategy. Concerning the single pesticide
9applications, the 72 farmers applied pesticides a total of 1772 times to their fields during the
10agricultural cycle considered. These applications were aggregated by summing up all
11applications of a particular pesticide during each of the five production phases (i.e. sowing of
12the potato, emergence of the shoot, weeding, earthing up, and maintenance). For example, if a
13farmer applied carbofuran four times with varying application rates during the emergence of
14the potato shoot, the indicator values were calculated for all four applications taken together.
15Accordingly, the amount of applications analysed decreased to 581. In sum, 72 pest control
16strategies, i.e. each strategy consisting of all applications for each single farmer, and 581
17pesticide applications, were considered.

18Second, the indicator rankings were compared by means of the Spearman rank correlation
19test, in accordance with Maud et al. (2001) and Reus et al. (2002), and using the software
20PASW Statistics 18.0. Not only were the indicators compared with respect to their overall
21outcome (Figure 1, quadrant 1), but also every individual environmental and health risk
22component that the indicators have in common (Table 1) was compared separately (Figure 1,
23quadrant 2). Furthermore, the indicators were compared with regard to both the 518 pesticide
24applications and the 72 control strategies (Figure 1, quadrants 3 and 4). Since only EIQ and
25EPRIP propose how to calculate the cumulative risk accruing when several applications of
26different active ingredients are used within the same pest control strategy, the other indicator's

1 values for the pest control strategies were simply summed up from those of the single
2 applications, as proposed by Kovach (1992). Due to the lack of daily meteorological data, the
3 groundwater module of POCER was not calculated through the suggested PESTLA model,
4 but through the groundwater module of the PIRI indicator. PestScreen, which does not
5 propose rankings for single environmental compartments, was compared to other indicators
6 only with respect to the total environmental risk. In addition, the comparison was carried out
7 separately for environmental and occupational health indicators (Figure 1).

8 Third, a comparison based on key indicator characteristics was made, taking into account each
9 indicator's user friendliness (i.e. data availability, calculation procedure, and interpretation of
10 ranking) and ability to represent the specific system under study (i.e. compartments
11 considered, use of site specific data). The former refers to the procedural dimension of
12 sustainability assessment (Binder et al., 2010), and concerns the indicator best suited to
13 practical use in LDCs. The latter refers to the systemic dimension of sustainability assessment
14 (Binder et al., 2010), and entails the coverage of all relevant ecosystem and human system
15 (i.e. health) compartments. This also entails the use of site specific information, which might
16 significantly alter the estimated level of risk associated with a given application of pesticide
17 due to, for instance, the influence of environmental characteristics such as soil composition on
18 the persistence of active components in the ecosystem under study (the details of the criteria
19 used for this comparison are given in the supplementary data files).



1

2Figure 1. Comparative analysis of the indicator rankings. The subscripts *i* and *k* indicate indicators
3among the ones compared in the study.

4

53. Results

63.1. Comparison of indicators based on rankings: environmental risk

73.1.1. Total environmental risk

8Four indicators aggregate the risk to the different environmental compartments into an overall
9risk value, namely EIQ, PestScreen, POCER and EPRIP. The highest and significant
10correlations between rankings were those between EIQ and PestScreen (both non-ETR) and
11between POCER and EPRIP (both ETR). The latter decreased when control strategy instead
12of single applications was considered, while all other correlations increased. EIQ and
13PestScreen showed a high correlation with the application rate (Table 2).

14

15

1**Table 2. Correlation between rankings of the 581 pesticide applications, and between rankings of the 72**
2**control strategies (in *italics*) for total environmental risk (Spearman correlation test)**

	EQ	PestScreen	POCER	EPRIP	Application rate
EQ	1.00				
PestScreen	0.96 **	1.00			
POCER	-0.08 *	-0.18 **	1.00		
EPRIP	0.12 **	0.02	0.74 **	1.00	
3 Application rate	0.96 **	0.98 **	-0.27 **	-0.03	1.00

4

53.1.2. Risk to surface water and groundwater

6Four indicators rank the risk to surface water, namely EQ, POCER, EPRIP and PIRI, while
7three of these, i.e. EQ, EPRIP and PIRI, also rank the risk to groundwater. The rankings for
8all indicators correlated with each other, albeit with differing strength. Regarding the risk to
9surface water, EPRIP was the only indicator for which the correlation with the other
10indicators was smaller when the control strategy rather than the single applications was
11considered, while, for the risk to groundwater, this also occurred for PIRI. EQ, POCER and
12PIRI had significant correlations with the application rate. In general, correlations between
13rankings of the latter (i.e. POCER, EPRIP, PIRI) tended to be higher than those between
14rankings of ETR and non-ETR indicators (i.e. EQ) (Tables 3 and 4).

15

16**Table 3. Correlation between rankings of the 581 pesticide applications, and between rankings of the 72**
17**control strategies (in *italics*), for risk to surface water (Spearman correlation test)**

	EQ	PestScreen	POCER	EPRIP	Application rate
EQ	1.00				
PestScreen	0.99 **	1.00			
POCER	0.18	0.18	1.00		
EPRIP	0.05	0.05	0.34 **	1.00	
18 Application rate	0.98 **	0.98 **	0.12	0.01	1.00

19

20

1**Table 4. Correlation between rankings of the 581 pesticide applications, and between rankings of the 72**
2**control strategies (in *italics*), for risk to groundwater (Spearman correlation test)**

	EIQ	POCER	EPRIP	PIRI	Application rate
EIQ	1.00				
POCER	0.45 **	1.00			
EPRIP	0.18 **	0.74 **	1.00		
PIRI	0.40 **	0.64 **	0.43 **	1.00	
3 Application rate	0.86 **	0.34 **	0.04	0.33 **	1.00

4

53.1.3. Risk to soil and beneficial arthropods, birds and bees

6Two indicators, namely POCER and EPRIP (both ETR), rank the risk to soil. They correlated
7significantly at 0.01 level (Spearman correlation test 0.82); POCER also correlated
8significantly with the application rate (Spearman correlation test 0.42).

9The risks to beneficial arthropods, birds and bees are each ranked by EIQ and POCER.
10Significant correlations (at 0.01 level) between the two rankings were observed for the risk to
11birds, both when single applications and control strategy are considered (Spearman
12correlation test 0.43 and 0.35 respectively). Regarding the risk to bees, the two rankings
13correlated significantly (at 0.01 level) only when the control strategy was considered
14(Spearman correlation test 0.43). Concerning risk to beneficial arthropods, the two rankings
15were significantly, but negatively, correlated (Spearman correlation test -0.5) when single
16applications were considered. Finally, for all three compartments, and for both control
17strategy and single applications, EIQ always correlated significantly at 0.01 level and very
18strongly (Spearman correlation tests > 0.94) with the application rate (Tables showing the
19correlations for these three compartments are given in the supplementary data files).

20

21

22

13.2. Comparison of indicators based on rankings: health risk

Four indicators rank the risk to the pesticide operator, namely EIQ, POCER, OHRI and the indicator from Dosemeci et al. (2002). The latter only provides an assessment of the control strategy. When single applications were considered, all rankings correlated with each other significantly (Table 5). Both EIQ and POCER also correlated significantly with the application rate, while OHRI does not include the application rate in its algorithm. However, the rankings correlated less strongly, and in some cases not significantly, when the control strategy was considered (Table 5). The highest correlations were observed between EIQ and POCER, both of which also significantly and strongly correlate with the application rate (Table 5).

11

12**Table 5. Correlation between rankings of the 581 pesticide applications, and between rankings of the 72**
 13**control strategies (in *italics*), for risk to pesticide operator (Spearman correlation test)**

	EIQ	POCER	EPRIP	PIRI	Application rate
EIQ	1.00				
POCER	0.51 **	1.00			
EPRIP	0.13	0.61 **	1.00		
PIRI	0.58 **	0.70 **	0.31 **	1.00	
14 Application rate	0.94 **	0.38 **	0.30	0.49 **	1.00

15

16Two indicators rank the risk for farm workers, namely EIQ and POCER. The two rankings
 17correlated significantly at the 0.01 level and rather strongly, considering both single
 18applications and control strategies (Spearman correlation tests 0.56 and 0.49 respectively).
 19Both indicators correlated significantly with the application rate (Table given in the
 20supplementary data).

21

22

13.3. Comparison of indicators based on key indicator characteristics

The results of the comparison based on key indicator characteristics are shown in Table 6 (the details of the criteria used for this comparison are given in the supplementary data files).

4

5**Table 6. Comparison based on key indicator characteristics of the selected indicators.**

	EIQ	EPRIP	PIRI	Application rate
EIQ	1.00			
EPRIP	0.10 *	1.00		
PIRI	0.50 **	0.79 **	1.00	
6 Application rate	0.94 **	-0.08 *	0.34 **	1.00

7

83.3.1. User friendliness

Data for calculating the majority of the indicators are easily available. Data availability in this analysis does not concern data about the pesticides used by farmers, which are assumed to be available and relatively easy to collect e.g. through a survey, but instead other inputs such as parameters related to their physical and chemical properties, or toxicity.

Data for some pesticides are missing in the indicators' internal databases, and in this study were substituted with the values (for EIQ and PestScreen) or property parameters (for POCER, EPRIP, and PIRI) of pesticide belonging to the same chemical classes. Regarding the health risk component of POCER, the low score in Table 6 depends on the actual, but probably temporary impossibility of accessing the EUROPOEM database, on which this indicator relies. The indicator proposed by Dosemeci et al. (2002) only requires information on pesticide use practices, although rather detailed, and not on pesticide properties.

EIQ and PestScreen can be calculated without a highly specialist knowledge of pesticides and have a simple calculation algorithm. POCER, in particular regarding the groundwater and

1health modules, needs a higher level understanding of the model used and tends to require a
2significant amount of time for the calculations.

3All indicators except EIQ provide thresholds on which basis pesticide risk classes can be
4identified, but only EPRIP and PIRI provide such thresholds for both the risk associated with
5single pesticide applications and for the control strategies. However, PIRI is less transparent
6than EPRIP on the value at which such thresholds are set.

73.3.2. *Ability to represent the system*

8EIQ and PestScreen do not make use of site specific information, while POCER, EPRIP and
9PIRI do, thus providing a more appropriate representation of the specific system under
10analysis. The indicators also differ in terms of environmental compartments considered, and
11therefore on their ability to produce a comprehensive overview of risk in the environmental
12system, with PestScreen, POCER and EPRIP covering the most compartments. Concerning
13health risk, OHRI and the indicator proposed by Dosemeci et al. (2002) are limited to the
14occupational health of the farm worker.

15

164. Discussion

174.1. *Simple versus complex indicators*

18Comparison of the indicators with regard to the total environmental risk suggests that simple
19indicators not relying on an ETR approach cannot be used as a reliable proxy for more
20complex indicators, i.e. those relying on an ETR approach. In effect, the values of the former
21(i.e. EIQ, PestScreen) tended to correlate weakly with those of the latter (i.e. EPRIP, POCER
22and PIRI) when the total environmental risk was considered (Table 2). When single
23compartments were considered, the correlation between the indicator rankings was stronger,
24which confirms the results of other studies (Maud et al., 2001; Reus et al., 2002). However,

1the correlations between non-ETR and ETR indicator values for single compartments were
2rather weak in the majority of cases (Tables 3 and 4 and supplementary material; Spearman
3correlation test < 0.6). This confirms the key role played by the calculation method, and in
4particular by the way the pesticide dose data are mathematically included in the formulas, and
5by the way compartment scores are aggregated into a total score, in determining the rankings.
6Moreover, for both the total environmental risk and the risk in selected compartments, the
7correlations among all indicators were weaker or not significant when the pest control strategy
8instead of the single applications was considered (Tables 2 to 4 and supplementary material).
9This underlines the importance of the aggregation procedure, i.e. from single pesticide
10applications to pest control strategy, adopted for the different indicators. For EIQ, PestScreen
11and POCER the individual values of each pesticide applications were summed up. In this
12procedure, the number of treatments may have a greater impact on the final risk ranking than
13the impacts of single pesticides, because less and more risky pesticides are equally weighted.
14At the other extreme, EPRIP is the only indicator among those analysed in this study, which i)
15gives more weight when high risk occurs in an environmental compartment, ii) relies on a
16probability function in order to account for a possible cumulative effect of exceeding two
17thresholds of risk, and iii) accounts for the degradation occurring between single pesticide
18applications. While some aspects of the aggregation procedure and scoring system are still
19undergoing validation (Balderacchi and Trevisan, 2010), these are clear strengths of EPRIP in
20comparison with other indicators.

21As also found by Maud et al. (2001), simple indicators tended to be driven by the application
22rate, which instead was less dominant in determining the values of ETR indicators, since these
23accord more weight to pesticide properties and environmental conditions such as distance to
24water body or slope. This difference between the two types of indicators was also tested by
25calculating ETR indicators using average values for the site specific parameters (not shown in

1the present paper). This significantly improved the correlations, proving the essential
2difference marked by using site specific parameters, and also confirmed the good correlation
3between PestScreen and EPRIP found by Juraske et al. (2007) using constant site specific data
4for EPRIP.

5An additional contribution to the difference in risk rankings between non-ETR and ETR
6indicators might come from the fact that EIQ and PestScreen adopt low ranges of values,
7which are likely to distort the differences in risk between pesticides with different properties,
8as pointed out by other studies (e.g. Dushoff et al., 1994).

9Finally, concerning the human health risk the results show a more complex picture, especially
10when the pest control strategy is considered. Correlations between rankings of different
11indicators, both ETR and non-ETR, tended to be weak and to change significantly when the
12control strategies instead of the single applications were considered. These differences were
13very likely to depend not on the calculation procedure (ETR vs. non-ETR), but on the
14radically different attribution of risk potential to different factors in the indicators, i.e. misuse
15of protective equipment and highly toxic pesticides in POCER, powder formulations and large
16plot areas in OHRI, misuse of personal protective equipment and hygiene habits in Dosemeci
17et al (2002). Since no other similar comparison of health pesticide risk indicators exists in the
18literature, it was not possible to compare these results with those of other studies. Further
19research in this direction is recommended.

20

214.2. *Use of risk indicators in developing countries*

22LDCs are often characterized by particularly serious pesticide-related externalities but also by
23a general lack of resources, i.e. data, and expertise dedicated to environmental (Zhen and
24Routray, 2003; UNESCO, 2009) and health protection (Feola, 2010b), and the promotion of

1 sustainable agricultural production. In this context, the availability of a simple but reliable
2 pesticide risk indicator would be particularly relevant.

3 With regard to total environmental risk, the result seems to exclude the possibility of using
4 simple, i.e. non-ETR, indicators as proxies for more complex, i.e. ETR, indicators in the
5 assessment of farm-level pesticide-related risk (see also section 4.1). However, recent
6 developments of EPRIP (Trevisan et al., 2009), and in particular the provision of a freely
7 accessible user-friendly software with an internal database, have reduced the complexity of
8 this indicator and made its use relatively simple, even with a data requirement comparable to
9 that of EIQ and PestScreen (Table 6). Moreover, EPRIP is also the indicator that more strictly
10 complies with the other requirements identified by previous studies for the development of
11 more accurate pesticide risk indicators (i.e. Levitan, 1997 and 2000; Maud et al., 2001; Reus
12 et al., 2002). Nevertheless, non-ETR indicators remain very useful and accessible tools for
13 discriminating between different potentially risky pesticides prior to application. In this
14 regard, PestScreen is probably to be preferred to EIQ for it not only includes half life values
15 for single media but makes use of the overall environmental persistence.

16 Concerning risk in single environmental compartments, the use of single components of
17 different indicators might be considered. For example, PIRI proposes a convincing calculation
18 approach for risk to surface water organisms, with the inclusion of the main transport routes,
19 and accounting for possible site specific mitigation measures, which can be useful for
20 monitoring purposes. The choice of the indicator to be used for a single environmental
21 compartment is likely to depend on the specific research, management or policy needs, on the
22 availability of data and other necessary resources, and on an accurate analysis of the
23 characteristics of the different indicators.

24 With regard to human health risk indicators, the results do not give strong support for one
25 specific indicator among those analysed. Because uncertainties still exist in the literature on

1human exposure to pesticide during pesticide application and other operations, it might be
2preferable to avoid using indicators based on exposure models. In addition, these models are
3usually developed under European conditions, while it has been shown that in developing
4countries such as the study area, pesticide application techniques and chemicals used might
5differ extensively from those conditions (Feola and Binder 2010a and 2010b). In fact,
6following Blanco et al. (2005), it might be less important to accurately quantify the exposure
7of farmers to pesticides than to understand the determinants of exposure, both in terms of risk
8factors (e.g. misuse of personal protective equipment, hygiene habits) and of determinants of
9risky behaviour (e.g. cost of protective equipment, social norm) (Feola and Binder, 2010a).
10Consequently, algorithms such as the OHRI or the indicator proposed by Dosemeci et al.
11(2002) would seem more appropriate in assessing human health risk in developing countries
12than POCER. They provide a simple algorithm with limited data requirements and can
13support the identification of the most risky practices in pesticide handling and application.
14However, these indicators might also suffer from a bias towards North American or European
15application techniques, since in OHRI parameter values are partly drawn from UKPOEM
16(UKPOEM, 1992) and in Dosemeci et al. (2002) are mainly drawn from studies in North
17America and Europe. Further research on the validation of such parameter values in these
18algorithms under the pesticide application conditions found in many developing countries is
19needed.

20

215. Summary of conclusions

22This study investigated the appropriateness of seven pesticide risk indicators for use at farm
23level in Less Developed Countries, with particular reference to smallholding agriculture in the
24Colombian Andean region. The comparison of the indicators with regard to the total
25environmental risk suggests that simple indicators not relying on an exposure-toxicity ratio

1 approach cannot be used as reliable proxies for more complex ones, i.e. indicators based on an
2 exposure-toxicity ratio approach. The choice of the indicator to be used for a single
3 environmental compartment is likely to depend on specific research, management or policy
4 needs, on the availability of data and other necessary resources, and on an accurate analysis of
5 the characteristics of the various indicators. ETR indicators, such as EPRIP show a
6 comparative advantage over non-ETR in best combining the need for a relatively simple tool
7 to be used in contexts of limited data availability and resources, such as those usually
8 characterizing Less Developed Countries, and that of a reliable estimation of environmental
9 risk. Indicators not based on an exposure-toxicity ratio approach such as PestScreen remain
10 useful and accessible tools for discriminating between different pesticides prior to application.
11 Concerning the human health risk, simple algorithms such as the OHRI or that proposed by
12 Dosemeci et al. (2002) seem more appropriate than complex ones in assessing human health
13 risk in Less Developed Countries. This study also pointed out the need for further research on
14 health risk indicators and their validation under the conditions encountered in Less Developed
15 Countries.

16

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21

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1

1 Suitability of pesticide risk indicators for Less Developed Countries: A 2 comparison

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Supplementary data

13

14

15 A - Short description of the indicators

16

17 EIQ

18 The Environmental Impact Quotient (EIQ) (Kovach et al., 1992) estimates the environmental
19 impact of a pesticide by aggregating the hazard posed to farm workers, consumers and the
20 local environment in one score. Each of these three components in the equation is given equal
21 weight, but within each component, factors are given a different weighting (1, 3 or 5) in order
22 to represent their importance. Similarly, toxicological data, which are drawn from different
23 sources and databases, are normalized into a three level scale depending on their danger, i.e. 1
24 for low, 3 for medium and 5 for high toxicity.

25

26
$$\text{EIQ} = \{C[(\text{DT} \times 5) + (\text{DT} \times \text{P})] + [(C \times ((S + \text{P})/2) \times \text{SY}) + L] + [(F \times R) + (D \times$$

27
$$((S + \text{P})/2) \times 3) + (Z \times \text{P} \times 3) + (B \times \text{P} \times 5)]\} / 3$$

29

30 Where: DT = dermal toxicity; C = chronic toxicity; SY= systemicity; F = fish toxicity; L =
31 leaching potential; R = surface loss potential; D = bird toxicity; S = soil half-life; Z = bee
32 toxicity; B = beneficial arthropod toxicity; P = plant surface half-life.

33 An EIQ field use rating (FUR) allows the EIQ to be calculated for pest control strategies
34 (equation 2).

35

36
$$\text{EIQ (FUR)} = \text{EIQ} \times (\% \text{ active ingredient}) \times \text{rate}$$

37 PestScreen

1

1 PestScreen was developed as a screening tool to provide a relative assessment of pesticide
2 hazards to human health and the environment (Juraske et al., 2007). The indicator provides a
3 ranking approach, which not only includes data on toxic effects and bioaccumulation, but also
4 on persistence and mobility of pesticides in the environmental compartments. The indicator
5 provides a simple categorical distinction between pesticides as a function of application dose,
6 and three hazard categories, i.e. fate, exposure and toxicity.

7

$$8 \quad \text{PestScore} = D * [(\sum F_{i=2} / 2) + E_{i=1} + (\sum T_{i=4} / 4)]$$

9

10 Where: D = application dose; $\sum F_{i=2}$ is the sum of overall persistence and long-range transport
11 potential; E is the intake fraction; $\sum T_{i=4}$ is the sum of toxicity for rats, bees, fish and humans.

12 Each hazard category is given the same weight, and is scored on a 1 to 4 scale, i.e. low to very
13 high concern. The hazard category's sub-scores are calculated using physical and chemical
14 properties and cut-off criteria.

15

16 POCER

17 The pesticide occupational and environmental risk indicator (POCER) was developed by
18 Verduyck and Steurbaut (2002). It consists of ten modules covering both human health and
19 environmental risk, which are based on the modules of Directive 91/414/EC (CEC, 1994) for
20 the evaluation and acceptance of plant protection products in the European Union. A risk
21 index is calculated for each module as the quotient of the estimated human exposure of the
22 predicted environmental concentration and a toxicological reference value. The latter are
23 endpoints defined by the Annex VI of the Directive 91/414/EC (CEC, 1994). For example, the
24 risk index for the worker is calculated as

25

$$26 \quad \text{RI}_{\text{worker}} = \text{DE} \times \text{Ab}_{\text{DE}} / \text{AOEL}$$

27

28 Where DE is the dermal exposure (mg/person/day), Ab_{DE} is the dermal absorption factor
29 (fraction), and the AOEL is the Acceptable Operator Exposure Limit (mg/kg body
30 weight/day).

31 The ten risk indices are aggregated into a total risk indicator by transforming each index into a
32 value ranging from 0 to 1. In order to do that, a lower and an upper limit have to be
33 established for the ten risk indices. The risk of a pesticide to the different components
34 depends on the extent to which the lower limit is exceeded. Finally, the total risk of a
35 pesticide is calculated by summing the values of the ten components (i.e. assuming equal
36 weight).

37

38

39

40 EPRIP

41 The Environmental Potential Risk Indicator for Pesticide (EPRIP) was first developed by
42 Padovani et al. (2004) and then updated by Trevisan et al. (2009) to improve the indicator,

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1

land in particular its applicability to different weather conditions. EPRIP is based on an ETR approach, by using the predicted environmental concentration estimated at local scale divided by short-term toxicological parameters (i.e. LD₅₀, NOEL). The ETR values are then normalized into risk points (RP) using a scale ranging from 1 to 5, where 1 represents no risk and 5 represents very large risk. Finally, to obtain the overall EPRIP score, the RP values for the different compartments are multiplied as follows:

7

$$8 \quad \text{EPRIP} = \text{RP}_{\text{gw}} \times \text{RP}_{\text{sw}} \times \text{RP}_{\text{s}} \times \text{RP}_{\text{a}} + 25 \times \text{N}_4 + 50 \times \text{N}_5$$

9

10 Where RP_{gw} is the risk point for groundwater, RP_{sw} is the highest risk point among six different values for surface water, RP_s is the risk point for soil, RP_a is the risk point for air, N₄ is the number of RP values equal to 4 and N₅ is the number of RP values equal to 5.

13

14 **PIRI**

15 The Pesticide Impact Rating Index (PIRI) (Kookana et al., 2005) assesses the off-site migration potential of pesticides and risk of surface and groundwater contamination. PIRI makes use of an exposure-toxicity ratio approach and is based on an ad hoc developed software package. The risk assessment is based on pesticide use; the pathway through which the pesticides are released to the water resources (drift, runoff, erosion, leaching) and the value of the water resources threatened. Each component is quantified using pesticide characteristics (e.g. toxicity to organisms at different trophic levels, i.e. fish, daphnia, algae), environmental and site conditions (e.g. organic carbon content of soil, water input, slope of land, soil loss, recharge rate, depth of water table).

24

25 **OHRI**

26 The Operator Health Risk Indicator (OHRI) (Bergkvist, 2004) provides a measure of risk to the pesticide operator. It combines data on hazard and exposure and combines them with data on intensity of pesticide use. The toxicity values were drawn from the EU risk phrases defined in Annex II of the EU Directive 67/548/EEC as amended by the EU Directive 2001/59/EC and scored by the authors. The protective factors of different pieces of personal protective equipment, used to calculate the indicator's value, are drawn mainly from the UKPOEM (1992).

33

$$34 \quad \text{OHRI} = \text{AT} \times \text{OT} \times \text{FT} \times \text{AMO} \times \text{PMO}$$

35

36 Where: AT = area treated; OT = operator toxicity; FT = formulation type; AMO = application method; PMO = use of personal protective equipment.

38

39 **Dosemeci et al. (2002)**

40 Dosemeci et al. (2002) developed a quantitative method for estimating the intensity of exposure to pesticides in the agricultural sector. The algorithms developed, i.e. a detailed and a general one, consider different factors which contribute to the exposure of the operator to

1
pesticides. The exposure scores assigned to each factor are mainly derived from empirical
2 studies in the scientific literature.

3

$$4 \quad \text{Intensity level} = [(Mix \times Enclosed) + (Appl \times Cab) + Repair + Wash] \times PPE \times \\ 5 \quad \quad \quad Repl \times Hyg \times Spill$$

7 Where: *Mix* is a score for the method of pesticide mixing; *Enclosed* is a score for whether or
8 not an enclosed mixing system is used; *Appl* is a score related to the application method; *Cab*
9 refers to whether or not a tractor with enclosed cab and/or charcoal filter is used; *Repair* is a
10 score for the status of maintenance of the equipment; *Wash* is a score for the practice of
11 washing the equipment after pesticide application; *Repl* is a score for the rate of replacement
12 of old protective gloves; *Hyg* is a score for the practices of personal hygiene; *Spill* is a score
13 for whether or not clothes are changed after a spill.

14

15

1

1B- Overview of data requirements

2

3 **Table 7. Data used to calculate the indicators**

Data	Indicators*						Dosemeci et al. (2002)
	EQI	Pest Screen	POCER	EPRIP	PIRI	OHRI	
PESTICIDE APPLICATION							
Application method			*			*	*
Application rate	*	*	*	*	*		
Duration of re-entry			*				
Exposure area for bystanders			*				
Frequency of application	*	*	*	*	*		
Inhalation exposure for the applicator			*				
Minimum number of days from application of pesticides to first rainfall/irrigation					*		
Parcel area			*	*	*	*	
Parcel perimeter				*			
Safety practices (washing, changing clothes, etc.)							*
Use of personal protective equipment			*			*	*
Transfer factor for re-entry			*				
Width of buffer zone					*		
Work rate (ha/h)			*				
PESTICIDE PROPERTIES							
Henry constant				*			
k _{oc}				*	*		
Long range transport potential		*					
Mode of action	*						
Molecular weight				*			
Overall persistence		*					
Pesticide composition (active ingredients)	*	*	*	*	*		
Pesticide formulation (liquid/powder)			*			*	
Pesticide half-life in soil	*		*	*	*		
Pesticide solubility in water				*			
Plant surface residue half-life	*						
Vapour pressure				*			
TOXICITY							
Acceptable daily intake (ADI)		*					
Acceptable operator exposure limit (AOEL)			*				
EC ₅₀ algae			*	*	*		
EC ₅₀ daphnia			*	*	*		
LC ₅₀ earthworms			*	*			
LC ₅₀ fish	*	*	*	*	*		
LC ₅₀ rabbit/rat	*						
LD ₅₀ bees		*	*				
LD ₅₀ birds			*				
LD ₅₀ rat		*		*			
Long-term health effects	*						
Operator toxicity						*	
Toxicity to bees	*						
Toxicity to beneficial arthropods	*		*				
Toxicity to birds	*						

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1 **Table 7 (continued). Data used to calculate the indicators**

Data	Indicators*						Dosemeci et al. (2002)
	EIQ	PestScore	POCER	EPRIP	PIRI	OHRI	
SOIL							
Bulk density of soil			*	*			
Estimated average soil loss during period of interest					*		
Slope of land to water body				*	*		
Soil depth			*				
Soil moisture					*		
Soil organic carbon content				*	*		
Soil type				*	*		
WATER BODIES							
Annual recharge rate				*			
Depth of nearest water body			*	*			
Depth of water table				*	*		
Diameter of nearest water body					*		
Distance from edge of crop to water body				*	*		
Groundwater and runoff potential	*						
Recharge rate during period of interest					*		
Water table thickness				*			
Width of nearest water body			*	*			
METEOROLOGICAL CONDITIONS							
Average maximum air temperature during period of interest					*		
Maximum daily rain				*			
Mean annual precipitation				*			
Mean annual temperature				*			
Total rainfall during period of interest					*		
OTHER DATA							
Body weight of birds			*				
Body weight of bystanders			*				
Crop interception factor			*	*			
Daily food intake by birds			*				
Dermal absorption factor			*				
Drift			*				
Drinking water standard				*			
Intake fraction		*					
Leaf area index			*				
2 Total irrigation during period of interest					*		

3* An asterisk indicates that the data was used in calculating the respective indicator.

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5The specific values used to calculate the indicators, as well as sources and assumptions made, are to be found in Rahn, E., 2010. Environmental and health risk indicators to assess pesticide use. A comparison of different indicators for the case of potato production in La Hoya, Colombia. Master thesis, Department of Geography, University of Zurich, Switzerland.

1C – Criteria for the comparison based on key indicator characteristics

2Table 8. Criteria for the comparison based on key indicator characteristics and corresponding scores.

Criteria	Scores	*	**	***
User friendliness	Data availability	Not available (additional assumptions needed)	Available for some pesticides	Easily available
	Calculation procedure	Calculation procedure knowledge-intensive and time-consuming	Calculation procedure either knowledge intensive or time-consuming	Calculation procedure neither knowledge intensive nor time-consuming
	Score interpretation	Relative comparison (ranking)	Risk classes given when single applications are considered	Risk classes given both when single applications and control strategy are considered
Ability to represent the specific system under study	Site specific data	No site specific data used	-	Site specific data used
	Compartments considered (environment)	One-two compartments	Three compartments	Four-Five compartments
	Compartments considered (health)	One compartment	Two compartments	Three compartments

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6D - Additional tables

7Table 9. Correlation between rankings of the 581 pesticide applications for risk to soil (Spearman correlation test)

	EPRIP	POCER	Application rate
EPRIP	1.00		
POCER	0.82 **	1.00	
Application rate	0.07	0.42 **	1.00

9 * p > 0.05; ** p > 0.01

10

11Table 10. Correlation between rankings of the 72 control strategies for risk to soil (Spearman correlation test)

	EPRIP	POCER	Application rate
EPRIP	1.00		
POCER	0.38 **	1.00	
Application rate	0.14	0.32 **	1.00

13 * p > 0.05; ** p > 0.01

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19Table 11. Correlation between rankings of the 581 pesticide applications for risk to beneficial arthropods (Spearman correlation test)

1Agriculture, Ecosystems and Environment 142 (2011) 238–245, DOI: 10.1016/j.agee.2011.05.014

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	EQI	POCER	Application rate
EQI	1.00		
POCER	-0.50 **	1.00	
Application rate	0.98 **	-	1.00

1 * p > 0.05; ** p > 0.01

2

3**Table 12. Correlation between rankings of the 72 control strategies for risk to beneficial arthropods**
4**(Spearman correlation test)**

	EQI	POCER	Application rate
EQI	1,00		
POCER	0,09	1,00	
Application rate	0,99 **	0,09	1,00

5 * p > 0.05; ** p > 0.01

6

7**Table 13. Correlation between rankings of the 581 pesticide applications for risk to birds (Spearman**
8**correlation test)**

	EQI	POCER	Application rate
EQI	1.00		
POCER	0.43 **	1.00	
Application rate	0.94 **	0.25 **	1.00

9 * p > 0.05; ** p > 0.01

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11**Table 14. Correlation between rankings of the 72 control strategies for risk to birds (Spearman**
12**correlation test)**

	EQI	POCER	Application rate
EQI	1.00		
POCER	0.35 **	1.00	
Application rate	0.96 **	0.28 *	1.00

13 * p > 0.05; ** p > 0.01

14

15**Table 15. Correlation between rankings of the 581 pesticide applications for risk to bees (Spearman**
16**correlation test)**

	EQI	POCER	Application rate
EQI	1.00		
POCER	0.05	1.00	
Application rate	0.96 **	0.90 *	1.00

17 * p > 0.05; ** p > 0.01

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23**Table 16. Correlation between rankings of the 72 control strategies for risk to bees (Spearman correlation**
24**test)**

	EQ	POCER	Application rate
EQ	1.00		
POCER	0.43 **	1.00	
Application rate	0.97 **	0.34 **	1.00

1 * p > 0.05; ** p > 0.01

2

3**Table 17. Correlation between rankings of the 581 pesticide applications for risk to farm worker**
4**(Spearman correlation test)**

	EQ	POCER	Application rate
EQ	1.00		
POCER	0.56 **	1.00	
Application rate	0.91 **	0.51 **	1.00

5 * p > 0.05; ** p > 0.01

6

7**Table 18. Correlation between rankings of the 72 control strategies for risk to farm worker (Spearman**
8**correlation test)**

	EQ	POCER	Application rate
EQ	1.00		
POCER	0.49 **	1.00	
Application rate	0.97 **	0.46 **	1.00

9 * p > 0.05; ** p > 0.01

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