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Pesticide environmental accounting: a decision-making tool estimating external costs of pesticides

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Abstract In cost-benefit analyses of pesticide use an area-based measure of both costs and benefits is needed for spatial analysis of net benefits. The pesticide environmental accounting (PEA) tool provides a monetary estimate of environmental and health impacts per hectare-application of pesticide (Leach and Mumford 2008). The model combines the Environmental Impact Quotient method (rating human health and eco-toxicological behaviour of specific pesticides) with absolute estimates of external pesticide costs in the UK, USA and Germany. The model converts external costs of a pesticide to other countries using GDP per capita and % GDP from agriculture. For many countries, resources are not available for intensive assessments of external pesticide costs. Economic and policy applications include rationalising pesticide choice, estimating impacts of pesticide reduction policies or calculating benefits from technologies that replace pesticides [sterile insect technique (SIT) or biological pesticides such as *Metarhizium*]. PEA is a logical integration of diverse data and approaches. The assumptions provide transparency and consistency but at the cost of specificity and precision, a reasonable trade-off for a method that provides both comparative estimates of pesticide impacts and area-based assessments of absolute impacts. The method has been applied to cost-benefit analyses of SIT in fruit flies (two species) and pesticide choice in Desert Locust (DL) campaigns in Africa. An example of external cost calculations for sugar beet herbicides in Europe is presented. There are also planned uses in public health mosquito control.

Keywords Pesticide environmental accounting · Externalities · Herbicides · Sugar beet · Environmental impact

1 Introduction

Indirect or external costs of pesticides include monitoring for contamination of soil, drinking water or food, poisoning of applicators, produce pickers and consumers, impacts on non-target organisms such as bees, beneficial insects, fish, birds, etc. These costs are external to the individual decision maker because they are usually absorbed by society (Baumol and Oates 1988; Pretty et al. 1999). Pesticide externalities result in sub-optimal economic and policy solutions and failure to recognise and apportion external costs of pesticides can result in inappropriate balances of net costs and benefits arising from pesticide use decisions (Leach and Mumford 2008). The difficulty of calculating external costs of pesticide use for applications of individual pesticides and their varying formulations has meant that it has not been done

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at a practical level. The pesticide environmental accounting tool (PEA) was developed to address this failing and provides a system to rapidly estimate the environmental and public health impacts of pesticides in € per hectare per application. The model is of particular value in assessments with strong spatial elements, such as area-wide pest control (the sterile insect technique and locust control) or regional pest/pesticide policies with geographical bases (such as the widespread replacement of pesticides by alternative technologies).

Various attempts have been made to describe and quantify the negative impacts that pesticides have on the environment and human health. These include research in the USA (Pimentel et al. 1992; Pimentel 2005; Tegtmeier and Duffy 2004), in the UK (Pretty et al. 2000) and in the UK, USA and Germany (Pretty et al. 2001). However, these several accounting attempts have considered the combined costs of all pesticides for each country and not the costs of individual pesticides at a local scale (Leach and Mumford 2008).

Kovach et al. (1992) considered the problem in terms of local farm level decisions on pesticide choice and produced a system for calculating the environmental impact of a pesticide in terms of a quotient that summarized the environmental and public health impact of an individual pesticide. Their EIQ (Environmental Impact Quotient) system also allowed application rates and formulation type to be taken into account when comparing the relative effects of one pesticide application against another.

The pesticide environmental accounting (PEA) system is a hybrid of these two approaches, with some further developments: coupling the general costs of all pesticides used for several known countries with the eco-toxicological behaviour of specific pesticides, and incorporating a calculation that extrapolates the results to other countries. The model is transparent, logical and consistent in application between cases within the area of use, and open to revision and refinement as further data becomes available.

The system was initially developed for citrus pest management in the Mediterranean basin, but other applications have been and continue to be explored, including appraisal of locust management in West Africa (Leach et al. 2009), as a component of pest risk analysis for potential quarantine pests and comparative cost estimates of novel genetically modified (GM) technology versus traditional pesticide-based applications in vector control for malaria and dengue. In this paper a further example is demonstrated, estimating the indirect costs per hectare of different herbicide regimes used for weed control in sugar beet in Germany to provide insight into potential societal effects of using sugar beet with particular GM traits for resistance to a specific herbicide (Glyphosate).

2 Method

The method, data handling and philosophy of the PEA is described in detail in Leach and Mumford (2008). Economic data from the original studies (summarised in Pretty et al. 2001) were updated for 2009/2010 prices using national treasury data and converted to Euros, where necessary, from an online historical exchange rate database (OANDA 2010). GDP per capita data (mean of IMF, World Bank and CIA Fact Book data) and % GDP from agriculture (EarthTrends 2010) were also updated.

Details of five example sugar beet herbicide regimes used in Germany were taken from various sources (Table 1). Scenario 1 was based on recommended dose rates for Glyphosate in German sugar beet (BVL 2010). Scenarios 2, 3 and 4 were based upon regimes described by Gehring (2010). Scenario 5 was based on manufacturer's recommendations (BASF 2010).

Toxicity data and environmental behaviour of each of the active ingredients were taken from the Pesticides Property Database (PPDB 2010) and entered into the PEA. The application rates and active ingredient (a.i.) concentration described in Table 1 were applied for each active ingredient. Two of the assessed herbicides (Betanal and Rebell) contained multiple active ingredients. In these cases the external costs of each ingredient were calculated separately and then summed to provide a cost for the whole product. The external cost of Goltix Gold was calculated twice because its application rate in Regime 3 was lower than its rate in Regimes 2 and 4.

3 Results

Table 2 presents PEA outputs of estimated external costs. The results are presented as € per hectare for each active ingredient at each of the various concentrations and summed annual field application rates described in Table 1. The Environmental Impact Quotient of the pure active ingredient (a.i. EIQ) is shown in the EIQ row of Table 2 and ranges between

Table 1 Example sugar beet herbicide regimes in Germany modelled using PEA

Regime	Trade name	Application rate (l/ha)	Active ingredient	Concentration (g/l)
1 Roundup ready beet	Roundup	5.00	Glyphosate	360
2	Betanal Expert	3.75	Phenmedipham	75
			Ethofumesate	151
			Desmedipham	25
	Goltix Gold	4.00	Metamitron	700
3	Betanal Expert	3.75	Phenmedipham	75
			Ethofumesate	151
			Desmedipham	25
	Goltix Gold	3.50	Metamitron	700
	Fusilade Max	1.00	Fluazifop-*P*-butyl	107
4	Betanal Expert	3.75	Phenmedipham	75
			Ethofumesate	151
			Desmedipham	25
	Goltix Gold	4.00	Metamitron	700
	Debut	0.06	Triflusulfuron methyl	486*
5	Rebell	5.00	Chloridazon	400
			Quinmerac	50
	Spectrum	0.90	Dimethenamid-P	720

The application rate is the total for a year

[a] Triflusulfuron methyl herbicide concentration is in g/kg

20.3 for Chloridazon and 36.7 for Dimethenamid-P. The a.i. EIQ gives a measure of the overall *hazard* of the technical material. The field use EIQ rating gives a more useful measure of field risk by multiplying this a.i. EIQ hazard with formulation concentration and the field application rate, which adds a measure of *exposure*. The field use EIQ values in the bottom row show much greater variance, ranging from the minimum for Triflusulfuron methyl (0.9) which has a medium a.i. EIQ, moderate concentration but very low application rate, through to the highest for Metamitron (90.1) with a slightly higher a.i. EIQ, high concentration and high application rate.

Externality estimates are broken down into their constituent parts (Applicator, Picker… Beneficial [arthropod] effects) and reflect both the field rate EIQ combined with the recategorised distribution of externality estimates (€/kg of a.i.) from the accounting studies (summarised by Pretty et al. 2001).

The active ingredient with the highest risks (and thus costs) was Metamitron at 4 l/ha (Regime 2 and 4). Most of these costs were concentrated in human health effects. The acute dermal toxicity of the pure chemical, like all the other herbicides listed, was low, thus reducing its impact on applicators and pickers. However, the majority of human health cost in this case was caused by possible chronic reproductive/teratogenic effects combined with high leachability into water sources. As mentioned above, the high concentration of the a.i. in the formulation and relatively high application rate presented greater risk and thus higher costs.

Triflusulfuron methyl has the lowest estimated externality costs despite the very similar EIQ of the technical material. The PPDB showed Triflusulfuron methyl having possible chronic reproductive/teratogenic and mutagenic/oncogenic effects. However, the fact that it was unlikely to reach ground water because of low leachability, combined with much smaller amounts of the technical material being applied (ca. 30 g per hectare cf. approximately 2.8 kg/ha for Metamitron), meant that the risks and thus external costs were considerably reduced in field use.

Four out of five of the regimes assessed with the PEA contained three or more active ingredients so it is important to consider the total risks and costs of each regime. In two regimes, five different active ingredients were combined in different concentrations and applications rates. Table 3 shows the summed costs for each regime (€ per hectare per year).

Spectrum and Betanal Expert at €2.35 and €3.60 per hectare, respectively, had the lowest impacts but were

Table 2 Breakdown of sugar beet herbicide externalities by active ingredient at the field application rates and concentrations described in Table 1

Chemical name: Formulation:	Roundup Glyphosate 360 g/l	Betanal Expert Phenmedipham 75 g/l	Betanal Expert Ethofumesate 151 g/l	Betanal Expert Desmedipham 25 g/l	Goltix Gold Metamitron 700 g/l	Goltix Gold Metamitron 700 g/l
Applicator effects[a]	0.16	0.03	0.06	0.01	0.31	0.27
Picker effects[a]	0.03	0.01	0.01	0.00	0.06	0.05
Consumer effects[a]	3.38	0.66	1.33	0.22	6.57	5.74
Ground water[a]	0.46	0.09	0.18	0.03	0.45	0.39
Aquatic effects[a]	0.62	0.12	0.25	0.04	0.61	0.53
Bird effects[a]	0.22	0.04	0.09	0.01	0.85	0.74
Bee effects[a]	0.33	0.07	0.13	0.02	0.65	0.57
Beneficials effects[a]	0.22	0.08	0.09	0.03	0.42	0.37
Total[a]	5.42	1.10	2.13	0.37	9.91	8.67
EIQ	22.7	36.0	29.0	32.7	32.3	32.3
% ai in formulation	36%	8%	15%	3%	70%	70%
Rate (kg formulation per ha)	4.00	3.75	3.75	3.75	4.00	3.50
EIQ Field Use Rating	32.6	10.1	16.4	3.1	90.5	79.2

Chemical name: Formulation:	Fusilade Max Fluazifop-*P*-butyl 107 g/l	Debut Triflusulfuron methyl 486 g/kg	Rebell Chloridazon 400 g/l	Rebell Quinmera 50 g/l	Spectrum Dimethenamid-P 720 g/l
Applicator effects[a]	0.01	0.00	0.22	0.03	0.07
Picker effects[a]	0.00	0.00	0.04	0.01	0.01
Consumer effects[a]	0.25	0.07	4.69	0.59	1.54
Ground water[a]	0.02	0.00	0.32	0.04	0.10
Aquatic effects[a]	0.02	0.01	0.43	0.05	0.14
Bird effects[a]	0.02	0.00	0.30	0.04	0.20
Bee effects[a]	0.01	0.00	0.23	0.03	0.08
Beneficials effects[a]	0.03	0.01	0.30	0.08	0.20
Total[a]	0.37	0.10	6.54	0.86	2.35
EIQ	28.0	30.7	20.3	31.0	36.7
% ai in formulation	11%	49%	40%	5%	73%
Rate (kg formulation per ha)	1.00	0.06	5.00	5.00	0.90
EIQ Field Use Rating	3.0	0.9	40.7	7.8	24.1

These costs are adjusted for GDP per capita and % GDP from agriculture for Germany. The two Metamitron (Goltix Gold) values show externality estimates for 4.0 and 3.5 l/ha/year application rates, respectively

[a] Costs per hectare given in €

always used in conjunction with higher impact products with higher externality costs. The only programme using a single active ingredient (Regime 1, glyphosate) had the lowest overall external costs at €5.42 per hectare, more than four Euros per hectare lower than Regime 5, its nearest competitor.

Regimes 2 and 4 were assessed to be the most damaging (€13.51 and €13.61 per hectare, respectively). In both cases Metamitron made up more than 70% of the external costs.

4 Discussion

The purpose of this paper is not to provide a detailed analysis of sugar beet herbicides in Germany but to highlight how the PEA facilitates rapid analysis of pesticide externalities. In using available ecotoxicological data and environmental behaviour from independent databases and combining that with externality estimates from peer reviewed sources, PEA allows transparent and unbiased comparisons

Table 3 Summary externality costs for five example herbicide regimes (€ per hectare per year) in German sugar beet

	Trade name, a.i and concentration	Externality (€/hectare)
Regime 1	Roundup	
	Glyphosate 360 g/l	5.42
	Total	5.42
Regime 2	Betanal Expert	
	Phenmedipham 75 g/l	1.10
	Ethofumesate 151 g/l	2.13
	Desmedipham 25 g/l	0.37
	Sub total	3.60
	Goltix Gold	
	Metamitron 700 g/l	9.91
	Total	13.51
Regime 3	Betanal Expert	
	Phenmedipham 75 g/l	1.10
	Ethofumesate 151 g/l	2.13
	Desmedipham 25 g/l	0.37
	Sub total	3.60
	Goltix Gold	
	Metamitron 700 g/l	8.67
	Fusilade Max	
	Fluazifop-P-butyl 107 g/l	0.37
	Total	12.63
Regime 4	Betanal Expert	
	Phenmedipham 75 g/l	1.10
	Ethofumesate 151 g/l	2.13
	Desmedipham 25 g/l	0.37
	Sub total	3.60
	Goltix Gold	
	Metamitron 700 g/l	9.91
	Debut	
	Triflusulfuron methyl 486 g/kg	0.10
	Total	13.61
Regime 5	Rebell	
	Chloridazon 400 g/l	6.54
	Quinmera 50 g/l	0.86
	Subtotal	7.40
	Spectrum	
	Dimethenamid-P 720 g/l	2.35
	Total	9.75

between individual pesticides. At this stage it does not attempt to capture the full complexity of pesticide and metabolite behaviour and their effects in the environment. However, it provides a compromise between overarching detail and ease of use and understanding.

In the worked example, we predict that Regime 1, using a single product, offers lower external costs compared with the four other regimes and thus suggests that GM herbicide tolerant varieties of sugar beet may offer benefits to society (a saving of more than €4 per hectare per herbicide application compared with other regimes). However, it also highlights that different combinations of active ingredients may offer lower risks and lower externality costs provided they were efficacious and within the terms of licensing and registration. External costs can be calculated on a national level if the total area of treatment is known, and this could be used in policy decisions on choices of alternative technology. The PEA does not provide any information on benefits of pesticide use, which may differ between products. This would also need to be considered in policy choices.

It is important to stress that the PEA does not offer externality assessments (benefits or costs) of GM crops themselves. In the United States in 2005, GM crop production systems accounted for reductions in pesticide use compared with non-GM crop production systems by over 31 million kg, with 27 million kg of that reduction being attributed to herbicide resistance traits (Sankula 2006). Conversely, the proliferation of GM crops has also led to concerns of weed shifts and weed resistance as the number of hectares and use of glyphosate increase (Dill et al. 2008). To date, biotypes of 20 species have been reported to be resistant to glycine herbicides worldwide (Heap 2010). The balancing of such issues would remain firmly in the purview of decision makers and risk managers.

The PEA is designed to fulfil several roles:

(a) An estimate of indirect cost of pesticide/mycopesticide use by a consistent, transparent process that includes the ecotoxicological behaviour of a specific pesticide.
(b) The system can be used as a method for identifying pesticides with the largest indirect costs to achieve pesticide rationalisation targets.
(c) A tool for use in predictive or retrospective assessments of technical or policy changes or the introduction of new standards.

The methodology also provides a means for checking consistency. For example, when the model produces an unexpected, counterintuitive output it can be challenged by examining the model more closely to understand why the model produced that output and to check that the general assumptions are reasonable for that particular case.

Under many conditions it may be necessary to adjust inputs to match local conditions, for example in tropical climates environmental conditions may mean that pesticide degradation rates estimated under laboratory or temperate field conditions are not appropriate. In such cases more reasonable degradation rates, based on local empirical evidence, could be applied.

PEA has been used to calculate the benefits of replacing conventional pesticides with SIT in two species of Tephritid fruit flies in Mediterranean countries (Knight 2007; Larcher Carvalho 2007, 2009) and in the retrospective assessment of pesticide externalities in a national Desert Locust campaign in Senegal (Leach et al. 2009). In US agriculture, PEA has been used to estimate the impact of climate change on the external costs of pesticide applications (Koleva and Schneider 2009). Planned future uses include its role in a system for the prospective calculation of pesticide impacts to control introductions of non-native invasive species and the calculation of benefits of GM mosquito releases against diseases such as dengue in Central America or malaria in Africa.

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