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Probability functions to build composite indicators: A methodology to measure environmental impacts of genetically modified crops

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ABSTRACT

There is an on-going debate on the environmental effects of genetically modified crops to which this paper aims to contribute. First, data on environmental impacts of genetically modified (GM) and conventional crops are collected from peer-reviewed journals, and secondly an analysis is conducted in order to examine which crop type is less harmful for the environment. Published data on environmental impacts are measured using an array of indicators, and their analysis requires their normalisation and aggregation. Taking advantage of composite indicators literature, this paper builds composite indicators to measure the impact of GM and conventional crops in three dimensions: (1) non-target key species richness, (2) pesticide use, and (3) aggregated environmental impact. The comparison between the three composite indicators for both crop types allows us to establish not only a ranking to elucidate which crop is more convenient for the environment but the probability that one crop type outperforms the other from an environmental perspective. Results show that GM crops tend to cause lower environmental impacts than conventional crops for the analysed indicators.

1. Introduction

Since the adoption of genetically modified (GM) crops in 1996 there has been an on-going debate about the impacts of GM crops. A vast scientific research on the agronomic, economic and environmental effects of GM crops has been conducted since their adoption. Most of this research is carried out at farm-level in specific countries for different crops. Recently, a number of reviews of both the agronomic and economic impacts of GM crops worldwide has been published (Areal et al., 2013a; Brookes and Barfoot, 2008, 2012, 2013; Carpenter, 2010; Park et al., 2011; Qaim, 2009). Brookes and Barfoot (2008, 2013) and Qaim (2009) provide an overview of agronomic and economic of insect resistant (Bt) and herbicide tolerant (HT) crops by using available impact studies. Areal et al. (2013a) and Carpenter (2010) compiled data from a number of peer-reviewed studies to carry out further statistical analysis (i.e. meta-analysis). The mentioned reviews indicate that GM crops overall tend to outperform conventional counterparts in agronomic (i.e. higher yields) and economic terms (i.e. higher gross margins per hectare), being results more evident for Bt traits. Areal et al. (2013a,b) show that the agronomic and economic performance of GM crops occurs in both developing and developed countries, providing evidence that the adoption of GM crops in developing countries may contribute to increase global food security.

Potential environmental effects associated with the adoption of GM crops have been analysed at different levels: crop biodiversity, farm and landscape scales (Carpenter, 2011). Concerns on crop genetic biodiversity have been raised with the introduction of GM crops due to both the agricultural risks on cross-pollination between neighbouring GM and conventional fields through pollen transfer and seed (Bannert, 2006; Bonny, 2008; Breckling et al., 2011; Devos et al., 2005, 2009; Graef et al., 2007; Hayes et al., 2004; Riesgo et al., 2010) and the fact that breeding programmes are concentrated on a smaller number of high-value cultivars (Ammann, 2006). A reduction of crop genetic biodiversity may have significant consequences on the vulnerability of agricultural systems since crop diversity contributes to minimise the risk of harvest failures due to climate change, especially in poor farming systems (Frison et al., 2011; Padulosi et al., 2011). Declining crop genetic biodiversity may also erode the nutritional enrichment of diets based on greater supply diversity and increases potential risks for health (Jacobsen et al., 2013). However, despite the concerns on crop diversity several studies show that GM crops have not negatively affected genetic crop diversity in a significant manner (Bowman et al., 2003; Gepts and Papa, 2003; Sneller, 2003; Paluadelmás et al.,

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2009) or even that GM crops have actually increased crop diversity (Bhattacharjee, 2009; Gressel, 2008).

GM crops impacts at farm and landscape levels include any effects on organisms that live within or outside the farm (i.e. non-target soil organisms, weeds, non-target above-ground invertebrates and birds) and effects on pesticide[1] use. Potential environmental benefits of the adoption of HT crops have been raised by some authors, such as the substitution of selective herbicides (usually harmful for the environment) for less toxic broad-spectrum herbicides (e.g. glyphosate), savings associated with low herbicide use and the adoption of conservation tillage practices (Devos et al., 2008; Dewar et al., 2003; Ervin et al., 2000; Nelson and Bullock, 2003; Smyth et al., 2011; Sydorovych and Marra, 2007; Qaim, 2009; Wolfenbarger and Phifer, 2000). However, the decrease in the total quantity of herbicides applied per unit surface area only occurs at early stages of HT crops adoption (Bonny, 2008; Owen and Zelaya, 2005; Shaner, 2000), but a rise in the quantity of herbicides is expected in late stages of adoption due to the presence of resistant weeds. It is worth mentioning that some of these potential impacts such as the substitution of selective herbicides and the adoption of conservation tillage practices are not directly caused by the GM plant but by the farm management practices associated with the cultivation of HT crops. In the case of Bt crops some authors pointed out a positive impact caused through the reduction of pesticide use not only on GM fields but also on neighbouring conventional fields ("halo effect") (Carrière et al., 2003; Wan et al., 2012; Mannion and Morse, 2012). One of the earliest studies on farm biodiversity was the UK Farm Scale Evaluations (FSE) of genetically modified herbicide tolerant (GMHT) crops, which included analysis on sugar beet, winter oilseed rape (WOSR), spring oilseed rape (SOSR) and maize (Squire et al., 2003; Heard et al., 2003a,b; Haughton et al., 2003). The main results from the UK FSE regarding invertebrates indicate that whereas certain species such as butterflies may be negatively affected by the adoption of some GMHT crops (HT sugar beet and HT SOSR) other species such as springtails and some of their predators were more abundant. Also butterflies were positively affected by the adoption of HT maize (Haughton et al., 2003). With respect to plant densities less densities were found in HT beet and HT oilseed rape whereas more plant density was found in HT maize than in their conventional counterparts (Heard et al., 2003a). As a result of research studying the environmental effects associated with the adoption of GM crops a number of reviews have been published compiling data and given an overview of environmental impacts of GM crops (Ammann, 2006; Carpenter, 2011; Sanvido et al., 2007; Wesseler et al., 2011).

Environmental effects of GM crops when compared to their conventional counterparts are diverse in the literature, being measured those impacts using an array of indicators such as number of individuals, number of individuals per 100 plants, mg per square metre, number of sprays, kg of active ingredient, kg of pesticide per ha and litre per ha. Considering the type of impact, these eight indicators can be grouped into: (a) indicators related to measuring impacts on non-target key species richness (see Table A1 in the Appendix) and (b) indicators related to the pesticide[2] use (see Table A2 in the Appendix).

In addition to these indicators, some studies used some indicators to assess the risk of pesticides on humans and animals in order to evaluate the environmental impact of GM crops. The biocide index (Jansen et al., 1995) and the field use rating of the Environmental Impact Quotient (EIQ) developed by Kovach et al. (1992) are usually used to measure and compare the relative environmental impacts of GM crops (Morse et al., 2006; Brookes and Barfoot, 2005, 2008, 2013; Smyth et al., 2011). The EIQ is a tool to assess specific pesticide risk to farmers, consumers and the environment. More specifically environmental and health impacts of pesticides are calculated by incorporating potential toxicity values for specific pesticides considering the degradation and transportation rates (Knox et al., 2012). The main difficulty to use these indicators is data requirements on the type and rate use of pesticides.

In this paper we are interested on taking advantage of the information published to date on some environmental effects of GM crops when compared to conventional crops, in order to obtain some conclusions on the potential environmental impacts of GM crops adoption.[3] We propose first to build a composite indicator that allows to aggregate data published by several authors on environmental effects of GM and conventional crops.[4] Different normalisation procedures are analysed in order to aggregate the different indicators forming the composite indicator. Robustness of the constructed composite indicators is assessed by assigning different weights to the indicators and changing the aggregation method. Secondly, a meta-analysis of environmental impacts of GM and non-GM crops is conducted to examine whether GM crops performs environmentally better than their conventional counterparts.

2. Methods

Composite indicators aim to aggregate indicators that measure impacts on different fields (e.g. economic, social and/or environmental dimensions) in order to obtain a unique value. In this paper we are not interested in measuring dimensions like economic or social impacts of GM crops but environmental. Taking advantage of how a composite indicator is built we develop a methodology to aggregate data on some key environmental impacts of GM crops that have been published in a number of scientific articles.

The main issues in building a composite indicator are related to normalisation, weighting and aggregation of indicators as well as the robustness of the composite indicator. Nardo et al. (2005) and OECD (2008) suggest a number of alternative techniques for this purpose, explaining their pros and cons. The most popular methods are based on the weighted sum of indicators (Andreoli and Tellarini, 2000; Rigby et al., 2001; Gómez-Limón and Riesgo, 2009), principal component analysis (Sands and Podmore, 2000), analytic hierarchy process (Pirazzoli and Castellini, 2000), geometric average (Qiu et al., 2007; Gómez-Limón and Sánchez-Fernández, 2010) or multiattribute utility functions (Van Calker et al., 2006). The weight given to each indicator shows their contribution to the final composite indicator. We use here two aggregation rules of individual indicators: additive and multiplicative aggregation. The additive approach[5] is based on a linear weighted aggregation rule implying total compensation among indicators (i.e. allow to compensate one

[1] Pesticide use includes both herbicides and insecticides use.

[2] See footnote 1.

[3] Please note that this paper only compares the environmental effects of GM and conventional crops, but organic crops are not included in the analysis. An analysis including organic crops cannot be performed since there is no enough published data available to perform the statistical analysis (data on non-target species richness and pesticide use for both organic and GM crops in similar edafoclimatic conditions). However, a comparative analysis of the environmental performance of both organic and GM crops would be of interest. Some meta-analysis conduct a comparative analysis of the environmental effects caused by organic and conventional crops (Mondelaers et al., 2009; Azadi and Ho, 2010; Tuomiso et al., 2012). Results show that organic farming has generally lower environmental impacts per unit of area than conventional farming.

[4] This paper is focused on the environmental impacts associated with the cultivation practices of GM crops at farm level.

[5] $CI_a = \sum_i w_i \cdot I_i$, where CI is the composite indicator following an additive approach, I_i is the indicator and w_i is the weight.