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Quantity based indicators fail to identify extreme pesticide risks

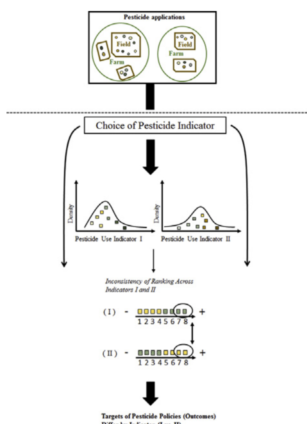
Niklas Möhring [a,*], Sabrina Gaba [b], Robert Finger [a]

[a] Agricultural Economics and Policy Group, ETH Zürich, Switzerland
[b] USC 1339, Centre d'Etudes Biologiques de Chizé, INRA, 79360 Villiers en Bois, France

HIGHLIGHTS

- Current pesticide policies are mainly based on quantitative indicators.
- We compare consistency of quantitative indicators with pesticide risks.
- Highly detailed panel data on pesticide use of Swiss crop farmers is used.
- We find a good average consistency but no explanatory power for extreme risks.
- The use of purely quantitative indicators might lead to adverse policy outcomes.

GRAPHICAL ABSTRACT



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ABSTRACT

As a matter of policy, minimizing human health and environmental risks associated with pesticide use is a major challenge but necessary for improving agricultural sustainability. Efficient and effective policies that encourage the use of less risky pesticides, such as pesticide taxes, necessitate a precise and realistic quantification of potential adverse effects. Various indicators are currently utilized in policies and they focus mainly on a purely quantitative dimension of the pesticides used, which can lead potentially to unfavorable outcomes of pesticide policies. A unique dataset applied to pesticide use by Swiss farmers in winter wheat and potato production, demonstrates that on average the two most important quantitative indicators show a significant correlation with pesticide risks as expressed by the Danish Load Indicator. However, they have almost no explanatory power for extreme risks (e.g. most intensive use patterns for pesticides with unfavorable toxicity profiles). Results remain stable over a range of aggregation levels, from application- to farm-level indicators of pesticide use. These findings render the commonly used, quantitative indicators ineffective to reduce potential environmental and human health risks of pesticides and, in the worst case, lead to misinformed market-based pesticide policies consequential to National Action Plans.

1. Introduction

Current agricultural production systems often rely on an intensive use of pesticides and other agrochemical inputs. Pesticides are tightly regulated in many countries, subject to rigorous testing and highly

* Corresponding author.
E-mail address: nmoehring@ethz.ch (N. Möhring).

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conservative risk assessment paradigms. However, the use of pesticides can still present potential risks to human and environmental health (Strange and Scott, 2005; Damalas, 2009; Beketov et al., 2013; Malaj et al., 2014; Stehle and Schulz, 2015). The introduction of effective policies to reduce adverse effects of pesticides, while maintaining production levels, is a major challenge on the way to achieving improved sustainability in agriculture (Tilman et al., 2002). In the European Union, the US and China, public policies have been established to address pesticide risks and stricter pesticide policies are also being implemented in several other countries (Lefebvre et al., 2015; Pimentel and Burgess, 2014; Osteen and Fernandez-Cornejo, 2013; Zhang and Wen, 2008; Sun et al., 2012; MAAF, 2015; Bundesrat, 2017; Böcker et al., 2018). However, the effectiveness of current policies has been questioned recently (e.g. Hossard et al., 2017; Finger, 2018). The focus of this research was to evaluate pesticide use/risk indicators utilized for the purposes of informing market-based pesticide policy and high-level reduction targets related to National Action Plans.

Setting up policies which promote a reduction in the impacts of pesticides on the environment and human health is far from straightforward. Pesticides are highly heterogeneous with respect to properties, application regimes and their potential impact on the environment and human health. For instance, in the EU alone, a range of 494 active substances for pesticides, with potentially different adverse effects, are currently authorized (EU, 2017). The choice of suitable pesticide indicators to quantify pesticide use is therefore essential to define efficient and effective policy measures.

Currently, implemented indicators differ significantly. For example, there are simple, purely quantitative indicators like the Quantity of Active Ingredients (QA) and the Treatment Frequency Index (TFI), which abstract from inherent pesticide properties, to very detailed, risk-adjusted indicators such as the Load Index (LI). QA is a simple measure of kilograms of pesticides used per area. TFI measures the intensity of applications, i.e. quantity applied per unit of cropped area in relation to the recommended dosage (Coll and Wajnberg, 2017). The LI indicator accounts for application intensity as well as a broad range of potential environmental and health risks for each pesticide (Miljøministeriet, 2012; Kudsk et al., 2018). The indicator chosen differs across countries and institutions. For example, France uses the QA and TFI indicators to set targets for pesticide policies (MAA, 2017). Furthermore, QA and TFI are applied as key indicators for pesticide use statistics by institutions worldwide (Eurostat, 2017; USDA, 2017; JKI, 2017; MAA, 2017) and are standard indicators for studies on the economics of pesticide use (Ghimire and Woodward, 2013; Hossard et al., 2014; Gaba et al., 2016; Perry et al., 2016; Lechenet et al., 2017). The Danish Load Index (LI) is currently the only risk-based indicator implemented in European pesticide policies which holistically assesses potential environmental and health risks of pesticides on a product level. As with the purely quantitative QA and TFI indicators, this allows pesticide risks to be upscaled along a gradient of temporal and spatial resolution (Kudsk et al., 2018). Since 2013, it has been used in Denmark for the assessment of policy targets and at the same time as the basis for pesticide taxation (Böcker and Finger, 2016; Kudsk et al., 2018).

However, it is hypothesized that large quantities of pesticides, as indicated by high QA or TFI indicator values, may not inherently mean higher risks for human health and the environment (e.g. high LI indicator values). For example, Kniss (2017) recently showed that herbicide use trends for major crops in the US were reversed when the assessment was switched from quantity-based to toxicity-based indicators. More importantly, the use of quantity-based indicators compared to risk-adjusted indicators may lead to major shifts in policy targets if indicators rank pesticide use inconsistently. These policy targets include, for example, the reduction of temporal or spatial "hotspots" and extreme application regimes (over a given cropping season), as extreme applications are major contributors to the negative effects of pesticides on human health (Larsen et al., 2017) and the environment (Relyea and Hoverman, 2006; Gordon et al., 2012; Bundschuh et al., 2013, Topping and Elmeros, 2016). Along these lines, Larsen et al. (2017) conclude that there is a need for the implementation of pesticide policies that tackle extreme applications. Market-based policy measures such as specific taxes, quotas or subsidies can complement regulatory frameworks and admission procedures in achieving this target (Baumol et al., 1988). However, a misspecification of policy targets may result in biased policy incentives and finally, adverse policy outcomes. Depending on the degree of inconsistencies between indicators, indicator choice may therefore have severe implications for policy outcomes. Although a well-informed policy discussion is of vital importance, there is a lack of studies which quantify the extent of inconsistencies between pesticide use indicators in a common, robust framework.

This research gap was addressed by investigating the consistency of pesticide use rankings between the purely quantitative, but widely used QA and TFI indicators and the LI indicator. The focus goes beyond average consistency by analyzing consistency for "extreme" application regimes as well as temporal and spatial "hotspots". Throughout the article, we refer to extreme applications as the most intensive use patterns and highest risk scenarios and profiles compared to all other applications, i.e. the upper tails of the observed distributions of pesticide applications. In the analysis, across-indicator consistency was tested using a unique panel dataset of pesticide applications in real farming conditions in Switzerland for two major crops, potatoes and winter wheat. These crops were chosen because potatoes are characterized by the highest average pesticide use and winter wheat is the most abundant crop in European (and Swiss) arable crop production. Pesticide application patterns of farmers, including choices made regarding the products used, their concentration, spatial distribution of application, and their timing, are strongly heterogeneous across farmers. A comparison of indicators on "real" application data was therefore necessary to derive meaningful policy recommendations, especially regarding risks from the most intensive pesticide use patterns. The analysis started off by comparing the structure of the indicators. Then correlation coefficients were used to test the consistency of indicator rankings over the whole distribution. Secondly, copulas were used to analyze tail dependence between pesticide use indicators. This meant focus could be placed on across-indicator consistency for extremes, i.e. observations in the tails of the distribution. The detailed dataset allowed the robustness of results to be assessed on different aggregation levels and for different pesticide types (i.e. all pesticides, herbicides and fungicides).

Current pesticide policies aim to reduce negative environmental and health effects of pesticides. Market-based policy measures achieve this target by incentivizing a change in the farmers' application behavior. The objective of this paper is to show that the choice of underlying pesticide indicators can crucially shift policy targets and incentives, and in the worst-case lead to adverse outcomes of pesticide policies. The analysis emphasizes that the comparison of indicators should not merely be based on their average fit. In fact, quantity-based indicators are found to be unsuitable to proxy high-risk situations.

2. Background

2.1. Current pesticide policies

Since 2012, European Union member states have to draw up National Action Plans (NAPs) for a "Sustainable use of pesticides" with the goal of reducing "risks and impacts of pesticide use on human health and the environment" (Directive 2009/128/EC). The revision of existing, and implementation of new pesticide policies is an ongoing process. In the EU, Directive 2009/128/EC demands that EU member states review NAPs every five years and the EU commission has recently announced a "REFIT" evaluation of all EU pesticide legislation (EC, 2015). Furthermore, adverse effects from pesticide use are at the top of the policy agenda in other countries like Switzerland, the US or China (Bundesrat, 2017; Pimentel and Burgess, 2014; Osteen and Fernandez-Cornejo, 2013; Zhang and Wen, 2008; Sun et al., 2012). Policy measures