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Pesticide runoff from energy crops: A threat to aquatic invertebrates?

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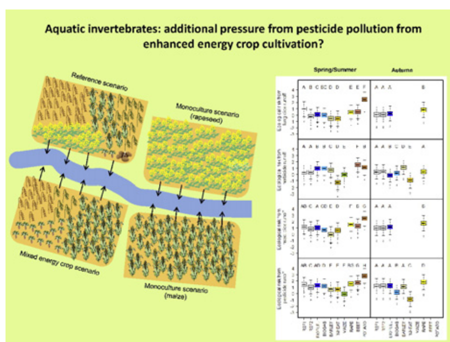
HIGHLIGHTS

- We modelled runoff-related pesticide input into streams for energy crop scenarios.
- We assessed risks for aquatic invertebrates based on pesticide toxicity.
- Potato fungicides and insecticides posed the highest risk for invertebrates.
- High risk for invertebrates was also associated with sugar beet and rapeseed.
- Comparable low pesticide risk from maize, barley, and wheat cultivation.

GRAPHICAL ABSTRACT



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ABSTRACT

The European Union aims to reach a 10% share of biofuels in the transport sector by 2020. The major burden is most likely to fall on already established annual energy crops such as rapeseed and cereals for the production of biodiesel and bioethanol, respectively. Annual energy crops are typically cultivated in intensive agricultural production systems, which require the application of pesticides. Agricultural pesticides can have adverse effects on aquatic invertebrates in adjacent streams. We assessed the relative ecological risk to aquatic invertebrates associated with the chemical pest management from six energy crops (maize, potato, sugar beet, winter barley, winter rapeseed, and winter wheat) as well as from mixed cultivation scenarios.

The pesticide exposure related to energy crops and cultivation scenarios was estimated as surface runoff for 253 small stream sites in Central Germany using a GIS-based runoff potential model. The ecological risk for aquatic invertebrates, an important organism group for the functioning of stream ecosystems, was assessed using acute toxicity data (48-h LC_{50} values) of the crustacean *Daphnia magna*. We calculated the Ecological Risk from potential Pesticide Runoff (ERPR) for all three main groups of pesticides (herbicides, fungicides, and insecticides). Our findings suggest that the crops potato, sugar beet, and rapeseed pose a higher ecological risk to aquatic invertebrates than maize, barley, and wheat. As maize had by far the lowest ERPR values, from the perspective of pesticide pollution, its cultivation as substrate for the production of the gaseous biofuel biomethane may be preferable compared to the production of, for example, biodiesel from rapeseed.

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1. Introduction

The European Union (EU) has set ambitious targets for the use of renewable energy to combat climate change and to ensure the energy supply (EC, 2009). In addition to a 20% share of renewable energy in gross final energy consumption by 2020, the EU aims to reach a 10% share of biofuels in the transport sector by the same year (EC, 2009). Advanced biofuels, based on inedible parts of plants such as straw or wood, are suggested to require at least 10 years for commercial-scale production (EASAC, 2012). Hence, the major burden of the EU biofuel target is most likely to fall on those biofuels that have already been introduced and that are produced from edible parts of annual agricultural crops, e.g. biodiesel from rapeseed and bioethanol from cereals (EASAC, 2012). Assuming that current annual energy crops and technologies are used, approximately 21 million ha (approximately 21% of the arable land in the EU) would be needed to achieve the 10% biofuel target (EASAC, 2012). Up to now, the sharpest increase in the cultivation of energy crops was recorded for Germany with an increase from 0.9 million ha in 2000 to 2.1 million ha in 2014 (approximately 18% of Germany's arable land; mainly rapeseed for biodiesel and silage maize for biogas production).

Annual energy crops are typically cultivated in intensive agricultural production systems, which usually require the use of pesticides. Numerous studies have shown that pesticides from diffuse agricultural sources pose a significant threat to the biodiversity of aquatic ecosystems as well as their ecosystem processes that provide important services for human societies (Beketov et al., 2013; Schäfer et al., 2012; Stehle and Schulz, 2015). This raises the question of the relative ecological risks for aquatic ecosystems from different energy crops, which originates from the related chemical pest management.

A first modelling study on the effects of energy crops on the aquatic community was limited to the risk from herbicides (Love et al., 2011). In this study, the effects of 14 energy crop rotation scenarios on the bluegill (*Lepomis macrochirus*) were evaluated for four watersheds in Michigan, USA, by using the Soil and Water Assessment Tool (SWAT). Results suggested that the application of herbicides in today's biofuel crops such as rapeseed and maize may cause large-scale exceedance of 96-h median lethal effect concentrations (LC_{50}) and, therefore, have widespread adverse effects on the bluegill population (Love et al., 2011). Nordborg et al. (2014) combined the pesticide emission inventory model with a model for the impact assessment of freshwater ecotoxicity, USEtox, to compare the Potential Freshwater Ecotoxicity Impacts (PFEIs) of eight biofuel feedstock production case studies. They found that rapeseed and wheat had the highest PFEIs values per ha and year of cultivated crop, while the perennial crop Salix had by far the lowest value. However, the results for the different crops need to be interpreted with caution as they were strongly influenced by the high variation of field width and pedoclimatic parameters (e.g., soil characteristics and average temperature) between the different cultivation sites (e.g., rapeseed and wheat in Germany compared to soybean and sugar cane in Brazil) (Nordborg et al., 2014). In addition to these two modelling studies, a literature review on energy crops and their pesticide requirements concluded that the potential effects of large-scale expansion of energy crop cultivation will depend on the future design of crop rotations and cropping systems (Bunzel et al., 2014a). However, a spatially explicit comparison of the risk from pesticide exposure for different energy crops and cultivation scenarios applied to a single set of agricultural stream sites is lacking.

Aquatic invertebrates play a key role in many ecosystem processes such as nutrient cycling and organic matter decomposition (Wallace and Webster, 1996). Thus, they are widely used as an indicator of the ecological status of stream ecosystems, for example, in the European Water Framework Directive. A recent study showed that particularly aquatic invertebrates are at risk from effects of toxicants in the EU, with pesticides playing a dominant role (Malaj et al., 2014).

Against this background, we compared the pesticide exposure from six different energy crops and related cultivation scenarios and assessed the related risks for aquatic invertebrates for 253 small stream sites in Central Germany. We estimated pesticide- and crop-specific pesticide input via surface runoff for the different cultivation scenarios. To this end, the GIS-based runoff potential (RP) model (Schriever et al., 2007a) was modified to account for substance-specific properties. The risks for invertebrates were assessed using acute toxicity data (48-h LC_{50} values) of the crustacean *Daphnia magna*.

2. Material and methods

2.1. Site selection

We analysed 253 sites located at small agricultural streams in Central Germany, where agricultural land use accounts for approximately 53% of total area. In the last century, the promotion of agricultural bioenergy production by the German government (e.g., by adopting the Renewable Energy Sources Act and establishing political subsidy tools (Thraen et al., 2012)) has increased the share of arable land used for energy crop cultivation in Central Germany (e.g., from 6.5% and 14% to 10% and 17.4% for maize and rapeseed, respectively).

The investigated sites were a subset from the dataset used in Bunzel et al. (2014b), where the potential effects of diffuse and point sources of pesticides on the macroinvertebrate community were evaluated. For those sites, model input data (land use, topography, precipitation, and soil) was readily available. Sites were included in our study if they had at least 20% arable land in the 1.5 km upstream corridor (Section 2.2), which was determined using a layer for "arable land" from the ATKIS database, provided by the German Federal Agency for Cartography and Geodesy (Table 1).

2.2. Model

In this study, we focused on the pesticide exposure via surface runoff because it is one of the most important pathways for pesticides to enter streams (Huber et al., 2000; Reichenberger et al., 2007). We quantified the ecological risk for invertebrates by adapting the GIS-based runoff potential (RP) model (Schriever et al., 2007a). The RP model is a simplified version of a model by the Organization of Economic Cooperation and Development (OECD, 1998) and can be used for the spatially explicit prediction of pesticide exposure (Schriever et al., 2007b). Based on this concept, we calculated the Ecological Risk from potential Pesticide Runoff (ERPR) by taking into account the toxicological sensitivity of the benchmark organism *D. magna* to various pesticides. We grouped pesticides according to the pest they control: fungicides (fungi), herbicides (weeds), and insecticides (insects). Throughout this paper, we define "pesticides" as the biologically active chemical part, i.e. the active ingredient.

The RP model assumes that the loss of a generic substance with generalized compound characteristics (constant application rate of 1 g/ha and soil organic carbon sorption coefficient of 100) results from a single application in a two-sided 100 m stream corridor extending 1500 m upstream of a site (Schriever et al., 2007a). The dissolved amount of the generic substance that potentially reaches the stream site ($gLoad_{generic}$) is calculated for each rainfall event over a specified time period (see Text S1 in Supplementary information (SI) for details). RP model predictions matched reasonably with measured pesticide exposure in small agricultural streams and correlated with an invertebrate metric designed to indicate pesticide stress (Burgert et al., 2011; Liess et al., 2008; Schriever et al., 2007b).

In contrast to Schriever et al. (2007a), we calculated the gLoad not for a generic substance but for specific pesticides to enable a comparison of the predicted pesticide exposure from different energy crops and crop cultivation scenarios (Section 2.3). First, we applied pesticide- and crop-specific application rates D_j and pesticide-specific soil organic carbon sorption coefficients $K_{OC,\ specific}$. Furthermore, we extended the model by adding the following parameters: crop-specific proportion of