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Direct and indirect effects of climate change on herbicide leaching — A regional scale assessment in Sweden

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HIGHLIGHTS

- 67 crop-herbicide combinations were simulated with a regionalized version of MACRO.
- MACRO-SE successfully distinguished leachable and non-leachable herbicides.
- Direct effects of climate change led to small reductions in leachate concentration.
- Indirect effects doubled the area at risk of groundwater contamination.
- Indirect effects of climate change should be investigated alongside the direct.

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ABSTRACT

Climate change is not only likely to improve conditions for crop production in Sweden, but also to increase weed pressure and the need for herbicides. This study aimed at assessing and contrasting the direct and indirect effects of climate change on herbicide leaching to groundwater in a major crop production region in south-west Sweden with the help of the regional pesticide fate and transport model MACRO-SE. We simulated 37 out of the 41 herbicides that are currently approved for use in Sweden on eight major crop types for the 24 most common soil types in the region. The results were aggregated accounting for the fractional coverage of the crop and the area sprayed with a particular herbicide. For simulations of the future, we used projections of five different climate models as model driving data and assessed three different future scenarios: (A) only changes in climate, (B) changes in climate and land-use (altered crop distribution), and (C) changes in climate, land-use, and an increase in herbicide use. The model successfully distinguished between leachable and non-leachable compounds (88% correctly classified) in a qualitative comparison against regional-scale monitoring data. Leaching was dominated by only a few herbicides and crops under current climate and agronomic conditions. The model simulations suggest that the direct effects of an increase in temperature, which enhances degradation, and precipitation which promotes leaching, cancel each other at a regional scale, resulting in a slight decrease in leachate concentrations in a future climate. However, the area at risk of groundwater contamination doubled when indirect effects of changes in land-use and herbicide use, were considered. We therefore concluded that it is important to consider the indirect effects of climate change alongside the direct effects and that effective mitigation strategies and strict regulation are required to secure future (drinking) water resources.

1. Introduction

The conditions for crop growth and productivity are likely to improve in Sweden and other Nordic countries in a changing climate due to an expected northward shift of thermally suitable crop production (e.g. Trnka et al., 2011). Adaptation to changes in climate that influence crop production is highly probable including, for example, changes in the timing of crop cultivation and selection of other crop types or cultivars (Olesen et al., 2011, 2012). Climate not only affects crop growth

Abbreviations: GCM, global climate model; FST, FOOTPRINT soil type; PAS, pesticide application scenario, a unique combinations of a certain pesticide compound used on a certain crop at a certain time with a certain dose; LOD, limit of detection; GSS, Southern plains of Götaland, in Swedish: *Götalands Södra Slättbygder.*

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and productivity, but also the spatial and temporal distribution and proliferation of weeds, insect pests and pathogens (e.g. Patterson et al., 1999). A northward shift of weeds, pests and diseases might be expected (e.g. Olesen et al., 2011) due to faster development, reproduction and increased survival rates (Patterson et al., 1999), which might lead to dramatic changes in crop health in Sweden (Roos et al., 2011). Thus, there is an increasing concern amongst scientists, regulatory authorities, stakeholders and the general public about water quality and contamination due to increased pesticide use as a consequence of climate change (Bloomfield et al., 2006; Delpla et al., 2009; Solheim et al., 2010; Kattwinkel et al., 2011; Henriksen et al., 2013).

Changes in climate will influence pesticide fate directly by changes in climate variables such as temperature and precipitation (Nolan et al., 2008; Lewan et al., 2009). These direct effects of climate variables may sometimes counteract one another. For example, higher temperatures or higher soil moisture contents will increase degradation rates, whereas higher rainfall will generally increase leaching, especially if macropore flow is triggered more often (see e.g. Bloomfield et al., 2006; Beulke et al., 2007). Pesticide fate and behaviour will also be influenced by many indirect effects of climate change including, for example, changes in cropping patterns and crop growth (Olesen et al., 2011; Fogelfors et al., 2009), pesticide application rates (Koleva et al., 2009; Kattwinkel et al., 2011), and soil conditions affecting fate processes such as changes in soil organic carbon content or climate induced freezing/thawing cycles (Stenrød et al., 2008).

Although the range of possible influencing factors is quite well understood, the impact of climate change on pesticide fate and transport in the environment has only rarely been assessed quantitatively. Beulke et al. (2007) performed a modelling study assessing the effects of climate change on the transport to groundwater and surface water of several different representative pesticides. Steffens et al. (2013, 2014) demonstrated the effect of model structural, parameter and climate uncertainty on predictions of pesticide losses to tile drains from a heavy clay soil under present and future climate conditions. Ahmadi et al. (2014) modelled changes in atrazine losses to surface water via surface run-off at the watershed scale for a large ensemble of climate model projections. Most of these studies only considered the potential direct impacts of climate change. Bloomfield et al. (2006), Beulke et al. (2007), as well as Steffens et al. (2013, 2014) hypothesized that the indirect effects of climate change might be more significant for future pesticide losses than direct effects, but to our knowledge only a few studies have explicitly attempted to quantify such effects. Kattwinkel et al. (2011) assessed the effects of climate change on the exposure of surface water to agricultural insecticides and concluded that the combined effect is likely to be stronger than the direct or indirect effects of climate change (i.e. changes in land-use and insecticide use) alone. A report issued by the Danish Environmental Protection Agency also assessed the direct and indirect effects of climate change on pesticide leaching at two different sites and for two different agricultural production systems in Denmark for the year 2050 (Henriksen et al., 2013). The indirect effects accounted for changes in crop rotation as well as crop and pest management. They found that the direct and indirect impacts of climate change on leaching risks were small on sandy soils, but more significant for loamy soils prone to macropore flow.

Groundwater supplies half of the drinking water in Sweden. These drinking water resources are highly valuable and also very slow and expensive to remediate (Vonberg et al., 2014), so their protection is of paramount importance both today and in the future. Herbicides pose the biggest threat for groundwater contamination by pesticides as they are usually much more mobile than fungicides or insecticides. The aims of this study were therefore to assess and contrast the direct and indirect effects of climate change on herbicide leaching to groundwater in a major crop production region of south-west Sweden. The indirect effects included changes in land-use (crop distribution) and herbicide use in a future climate. We used MACRO-SE, a regionalized version of MACRO 5.2 (Larsbo et al., 2005), to simulate the leaching of herbicide compounds presently registered for use in Sweden under both present (1970–1999) and future conditions (2070–2099). As a reality check, the simulations for present conditions were compared with monitoring data for herbicides in groundwater. For the future, we defined three herbicide use scenarios that were driven by five different climate scenarios for the end of the century to account for climate uncertainty.

2. Material and methods

2.1. The modelling tools MACRO and MACRO-SE

MACRO 5.2 is a one-dimensional physically based model of water flow and solute transport in soil based on a dual-permeability approach. It is used for pesticide registration, both for active ingredients within the European Union (FOCUS, 2000, 2001), and in Sweden for product registration. Richard's equation is used to calculate water flow in the soil matrix and a kinematic wave equation for preferential water flow via macropores. The saturated hydraulic conductivity of the soil matrix governs the partitioning of water flow between matrix and macropore systems. Solute transport in the matrix follows the convection–dispersion equation. A proxy parameter for the unknown geometry of soil macropore structure (Gerke and Van Genuchten, 1996) controls the rate for exchange of water and solutes between the two pore systems via diffusion and convection. A complete water balance is simulated: root water uptake is calculated using the model described by Jarvis (1989), flow and transport to drainage systems is calculated by the Hooghoud equation and seepage potential theory, and the potential evapotranspiration is estimated based on the Penman–Monteith equation (Larsbo and Jarvis, 2003). First-order kinetics for pesticide degradation are calculated with the rate coefficient given as a function of soil temperature and moisture content. Sorption is simulated with a Freundlich sorption isotherm and assumed to be proportional to the organic carbon content of the soil. For a detailed description of the model, the reader is referred to Larsbo et al. (2005) and Jarvis and Larsbo (2012).

MACRO-SE is a regionalized version of MACRO 5.2, currently under development by the Centre for Chemical Pesticides (CKB), Swedish University of Agricultural Sciences (SLU). It combines soil maps, detailed information on land-use (arable land), crop area and climate data with a set of empirical pedotransfer functions (Moeys et al., 2012) and other parameter estimation routines to provide a complete parameterization of MACRO 5.2 at regional scales. The soil maps are based on the FOOTPRINT soil type (FST) classification (Centofanti et al., 2008). The original classification, designed to characterize a limit number of soil types to support European wide modelling of pesticide leaching to groundwater and surface waters, was adapted to Swedish conditions. Each FST is defined by a hydrological class, topsoil and subsoil texture and topsoil organic matter content. More details on MACRO-SE are given in the Supplementary material.

2.2. Study region

We focused our study on the southern part of a major crop production region in Sweden (GSS, the southern plains of Götaland, see Fig. 1) located in the county of Scania in Southern Sweden. The total land area in Scania is 1100 Mha of which 46% is agricultural land (40% arable land, 6% permanent grassland), 37% forest, and 9% urban land. The proportion of agricultural land is even higher in the GSS region (61%). In a national context, this is very high as only 8% of the total land area of Sweden is agricultural land, whereas 69% is forested (SJV, 2014). Agriculture in Scania is also more intensive than in the rest of Sweden: it contributes almost 50% of the total production on less than 20% of the agricultural area (excluding grasslands; based on SJV, 2014) with 60% of the national pesticide usage (SCB, 2011).