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Integrating chemical fate and population-level effect models for pesticides at landscape scale: New options for risk assessment

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ABSTRACT

Any attempt to introduce more ecological realism into ecological risk assessment of chemicals faces the major challenge of integrating different aspects of the chemicals and species of concern, for example, spatial scales of emissions, chemical exposure patterns in space and time, and population dynamics and dispersal in heterogeneous landscapes. Although these aspects are not considered in current risk assessment schemes, risk assessors and managers are expressing increasing interest in learning more about both the exposure to and the effects of chemicals at landscape level. In this study, we combined the CASCADE-TOXSWA fate model, which predicts the fate of pesticides in an interconnected system of water bodies with variable hydrological characteristics, with the MASTEP mechanistic effect model, which simulates population dynamics and effects of pesticides on aquatic species at the scale of individual water bodies. To this end, we extrapolated MASTEP to the scale of realistic landscapes and linked it to dynamic exposure patterns. We explored the effects of an insecticide on the water louse *Asellus aquaticus* for a typical Dutch landscape covering an area of about 10 km^2 containing 137 water bodies (drainage ditches) with a total length of about 65 km and different degrees of connectivity. Pesticide treatments used in potato crop were assumed to result in a spray-drift input of 5% (non-mitigated) and 1% (mitigated) of the amount of pesticide applied into parts of the water body network. These treatments resulted in highly variable exposure patterns both in space and time. The effects of the pesticide on the species were investigated by comparing two scenarios with low and high individual-level sensitivity. We found that downstream transport of the pesticide led to exposure of water bodies that did not receive direct spray-drift input, even though this particular pesticide was assumed to dissipate rapidly from water. The observed differences in population-level effects and recovery patterns ranged from no observable effects in the low spray-drift and low sensitivity scenario to severe reduction of abundances in the high spray-drift and high sensitivity scenario. These results illustrate the sensitivity of our modelling approach, but also show the need for precise calculations of pesticide inputs and model parameterisation. Our study demonstrates the potential of coupled fate-and-effect to explore realistic scenarios at the scale of heterogeneous landscapes. Such scenarios could include the application of multiple pesticides to one or more crop types. Spatial realism of the landscape represented in the model ensures realistic consideration of population growth and dispersal as the two main recovery mechanisms. Future options for the landscape-scale fate-and-effect simulation approach include exploring the effects of mitigation measures on the risk estimates at landscape scale and hence represent a step towards risk management.

1. Introduction

Environmental risk assessment (ERA), which is a part of the regulatory registration procedure for chemicals, aims to protect the environment from unacceptable ecotoxicological effects that chemicals such as pesticides may have (Hommen et al., 2010). The term ‘unacceptable effects’ is often interpreted as meaning that recovery of potentially affected populations does not occur within a given period of time after the effect occurred. Thus,

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identifying factors that prospectively determine population effects and recovery is a key issue in this context.

Pesticides are applied to protect crops from diseases, thereby optimising the productivity of crop farming. Applications usually take place at the spatial scale of crop fields and landscapes. Nevertheless, research on the impact of pesticides on populations is still focussing on the edge-of-field scale in ERA. This may be caused in part by the intrinsic complexity of the interactions between chemical pollution and ecosystem function and population dynamics (Cairns and Niederlehner, 1996; Van den Brink, 2008). While current ERA procedures mostly involve measuring the effects of chemicals at the level of individuals, in terms of environmental protection it is crucial to analyse and understand chemical effects at the spatial scale of the application, i.e. the landscape scale, and hence at the population or meta-population level. Additionally, the exposure of water organisms to pesticides is known to be highly variable in space and time, as considered for example in the FOCUS surface water scenarios (FOCUS, 2001), so it appears necessary to assess exposure and effect patterns in a spatially explicit way (Schwarzenbach et al., 2006). Both the extrapolation problem, from individuals to populations (Forbes et al., 2008), and the demand for spatially explicit exposure assessment, pose a challenge to ecological research in the field of pesticides ERA.

Ecological modelling approaches can serve as a tool to extrapolate from individual- to population-level effects of chemicals (Galic et al., 2010; Thorbek et al., 2010). They allow individual mortality and sub-lethal effects to be translated into the sustainability of populations. It is especially the combination of population modelling and explicit representations of space which has a high potential in terms of integrating chemical exposure with the resulting effects on population dynamics and ecosystem functioning. Individual-based models (IBM) can easily deal with the demand for a spatially explicit representation of the environment, and at the same time incorporate ecological processes such as the density dependence of growth and mortality, individual movement and individual variations in life-history parameters (Grimm and Railsback, 2006).

Here we focus on ERA of aquatic macroinvertebrates, which have important functions in aquatic ecosystems regarding energy and nutrient cycling (Bellisario et al., 2012; Dangles et al., 2002; Lecerf and Richardson, 2010). Species such as the detritivore *Asellus aquaticus* (water louse) consume decaying vegetation, protozoa or algae, as well as invertebrate animals, thereby making energy available for higher trophic levels. Such arthropod macroinvertebrates can be very sensitive to insecticides (Maltby et al., 2005). Regular exposure to pesticides resulting from crop treatments may cause effects on sensitive macroinvertebrate species in terms of reduced abundances, as has been reported in semi-field studies (Arts et al., 2006; Van Wijngaarden et al., 2004).

A useful concept to assess factors influencing the ecotoxicological effects on populations is the ‘population vulnerability’ concept developed by Van Straalen (1994). It considers three factors affecting the vulnerability of populations: external exposure, intrinsic sensitivity and population sustainability. External exposure is determined by pesticide applications and their subsequent dissipation and distribution in the landscape. Intrinsic sensitivity is related to the effect of chemicals at the individual level. Population sustainability describes the potential of a population to recover from toxic effects through demographic dynamics and recolonisation. The reproductive strategy of a species plays an important role in this respect, as species with a high reproductive output and/or large number of generations per year have a higher potential to compensate for pesticide mortality than those with lower ones (Niemi et al., 1990). The second factor determining the recovery is immigration into affected water bodies, which is influenced by the dispersal behaviour of the species and the presence of other (source) populations in the neighbourhood. Taking potential population recovery from pesticide exposure into account thus requires the effects of pesticides to be assessed in a spatially explicit representation of the environment.

A spatially explicit model for the aquatic domain is MASTEP (Van den Brink et al., 2007), an IBM that simulates the response of *A. aquaticus* to pesticide exposure in aquatic systems, mimicking exposure scenarios used for the registration of pesticides in the EU (FOCUS, 2001). An adapted version of the MASTEP model has been used to assess the influences of the timing of pesticide exposure during the year and landscape connectivity on recovery times of *A. aquaticus* (Galic et al., 2012). However, neither of the versions of MASTEP fully represented population dynamics and the heterogeneous and dynamic distribution of pesticides in an explicitly represented landscape.

We therefore introduce an extension of MASTEP that simulates population dynamics, their relation with the dynamics of pesticide concentrations, and the effects of pesticides on aquatic species within a stylised but realistic landscape. Our MASTEPregional model allows water body networks to be defined, previously calculated pesticide concentration time series to be assigned to single water bodies, and population dynamics, including effects of pesticides and recovery, to be simulated. It thus provides a flexible platform for performing spatially explicit and realistic integrated risk analyses at the landscape scale.

To demonstrate the potential of MASTEPregional, we used it in a case study in which the effects of concentrations of the insecticide λ-cyhalothrin, as calculated with the CASCADE-TOXSWA chemical fate model, on *A. aquaticus* were simulated for a typical network of water bodies in a Dutch landscape covering an area of about 10 km^2. The aim of this case study was not to perform a risk assessment for this specific compound, as this would require further testing and data collection. Rather, we wanted to demonstrate the sensitivity of MASTEPregional as regards detecting effects, or no effects, in worst- and best-case scenarios. The paper also discusses the potential of approaches such as MASTEPregional for use in higher-tier environmental risk assessment in the future.

2. Materials and methods

This section only presents an overview of the rationale and the main elements of our model. A detailed model description using the ODD format (Grimm et al., 2010) and more information about model development and testing, summarised in a TRACE document (Schmolke et al., 2010) are available in the Supporting Information.

2.1. Modelled landscape

The catchment area in our case study represents a typical Dutch agricultural landscape in the north-east of the Netherlands in the Klazinaveen-Zwartemeer region. The area, with a size of approximately 10 km^2, is drained by a network of open drainage ditches with bottom widths between 0.5 and 3 m and a total length of 65 km (Kruijne et al., 2008; Fig. 1). The modelled water network consisted of 137 water bodies (referred to as sections below).

A typical crop grown in the area is potato. An insecticide commonly used in potato crops is λ-cyhalothrin, a pyrethroid compound with relatively low application rates but high aquatic toxicity (Van Wijngaarden et al., 2006). We assumed that potato crops in sub-areas within the total area were being treated with λ-cyhalothrin, resulting in spray-drift input into the water bodies. The respective section numbers were 33, 125, 29, 28, 23, 130, 19, 141 and 20 for sub-area 1 and 6, 59, 58, 57 and 5 for sub-area 2 (indicated by red dashed lines in Fig. 1). As assumed in current risk assessment, we considered spray drift to be the main mechanism responsible for the pesticide input into the water bodies. We