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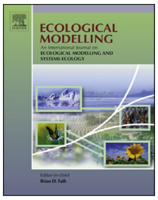

Modelling direct and indirect effects of herbicides on non-target grassland communities

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ABSTRACT

Natural grassland communities are threatened by a variety of factors, such as climate change and increasing land use by mankind. The use of plant protection products (synthetic or organic) is mandatory in agricultural food production. To avoid adverse effects on natural grasslands within agricultural areas, synthetic plant protection products are strictly regulated in Europe. However, effects of herbicides on non-target terrestrial plants are primarily studied on the level of individual plants neglecting interactions between species.

In our study, we aim to extrapolate individual-level effects to the population and community level by adapting an existing spatio-temporal, individual-based plant community model (IBC-grass). We analyse the effects of herbicide exposure for three different grassland communities: 1) representative field boundary community, 2) *Calthion* grassland community, and 3) *Arrhenatheretalia* grassland community. Our simulations show that herbicide depositions can have effects on non-target plant communities resulting from direct and indirect effects on population level. The effect extent depends not only on the distance to the field, but also on the specific plant community, its disturbance regime (cutting frequency, trampling and grazing intensity) and resource level.

Mechanistic modelling approaches such as IBC-grass present a promising novel approach in transferring and extrapolating standardized pot experiments to community level and thereby bridging the gap between ecotoxicological testing (e.g. in the greenhouse) and protection goals referring to real world conditions.

1. Introduction

Worldwide, the use of herbicides on conventionally managed arable fields is common practice for controlling weeds and safeguarding yields (Ecobichon, 2001; van der Werf, 1996; Wilson and Tisdell, 2001). Depending on wind conditions and application methods it is almost inevitable that small amounts of these herbicides spread into habitats in the vicinity of agricultural fields (field boundaries), i.e. non-target areas (de Snoo and van der Poll, 1999). Spray-drift is largely driven by spatial and temporal variability of environmental, ecological and agricultural conditions, e.g. the composition and structure of the landscape, weather events, spray-drift variability and application technology. Since herbicides are developed to control specific plant species considered as harmful within an agricultural field, i.e. weeds, and have lethal effects on those target species, plant individuals occurring in field boundaries have a potentially high risk to be affected in a similar way when exposed to deposits (de Snoo and van der Poll, 1999; Kleijn and Snoeijing, 1997; Kleijn and Verbeek, 2000; Marrs et al., 1993). To mitigate exposure of those communities, measures like the use of drift reducing spray nozzles or consideration of buffer zones are regularly applied. However, such measures cannot always fully eliminate drift exposure.

Field boundaries are quite diverse. They include herbaceous field margins like ditches or river banks as well as hedges or forest edges. In some cases, meadows and grasslands are located in immediate proximity. Due to the use of fertilizers and management activities, field boundaries are characterized by a medium to high nutrient availability and disturbances such as trampling and mowing. Grassland communities are crucial for maintaining biodiversity within European landscapes. Natural grassland communities are threatened by climate change and increasing land use. Food and energy production by agriculture reduces the area available for

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semi-natural grassland communities. The use of plant protection products (synthetic or organic) is mandatory in agricultural food production. To avoid adverse effects on natural grassland communities within the agricultural areas strict regulations for synthetic plant protection products are in place in Europe and environmental risk assessments are conducted. The basis of these risk assessments are standardized biotests conducted at individual-level in the laboratory (e.g. OECD guideline studies (OECD, 2006a,b)). In contrast to the level of individual plants, the European Food and Safety Authority (EFSA) developed specific protection goals towards the protection on population and community level (EFSA, 2014). Specific protection goals for non-target terrestrial plants are primary production, nutrient cycling, water regulation, provision of habitat and food, among others. These goals can be met by protecting populations, functional groups, and/or communities considering diversity, population abundances, and/or biomass. Therefore, current individual-level OECD guidelines seem not to be sufficient to address these specific protection goals.

The scientific community has largely neglected to study species interactions, historically measuring the effects of herbicides on individual plants rather than communities (Dalton and Boutin, 2010). The number of existing experimental studies on the level of plant communities (de Snoo and van der Poll, 1999; Kleijn and Snoeijing, 1997; Marrs et al., 1993; Schmitz et al., 2014) is small which can mainly be attributed to the complexity of those trials with regard to variability, labour, and costs. Although duration of these community experiments available from the literature was up to three years, from the perspective of vegetation analysis the study periods were rather short. While longer experiments may provide new insights in plant community dynamics impacted by chemical stressors, the complexity of community-level experiments as well as the needed time and resources make it unlikely that empirical long term studies will be available in the future. Therefore, mechanistic computer models can provide an alternative approach to better understand non-target community effects. These mechanistic modelling approaches should be designed in a way that the available knowledge can be integrated and, hence, community interactions emerging from the models can be validated and tested. As stated above, most studies investigate the effects of herbicides on single plant species. In addition, competition of plant species depends on the direct neighbourhood. Therefore, the model approach should be individual-based and spatially explicit.

In our study, we adapt an existing spatio-temporal, individual-based plant community model (IBC-grass, Körner et al., 2014; May et al., 2009; Weiss et al., 2014) to analyse population and community level effects of herbicide exposure for grassland communities. IBC-grass simulates herbaceous plant community patterns on a local scale (patch of approx. 3 m^2) by taking below- and above-ground interactions between individuals into account. To explore realistic herbicide effects at the individual-level we add a toxicological submodel to IBC-grass. The effect rate on the simulated vegetation patch is gained from a species effect distribution calculated by the exposure model Xplicit (Schad and Schulz, 2011; Schad 2013). Xplicit simulates herbicide exposure in field boundaries and calculates effect rates on plant individual-level depending on the specific spatial location of the patch in the landscape as well as on the ecotoxicological standard tests used for environmental risk assessment of herbicides in Europe (OECD, 2006a,b). We simulate the effect of herbicide exposures to three different plant communities: 1) a representative field boundary community, 2) a *Calthion* grassland community and 3) an *Arrhenatheretalia* grassland community. The communities differ in their regional species pool, management regime and resource level, which are determining factors for the composition and dynamics of grassland communities. We expect that (i) herbicide exposure will influence the interactions and resource competition between plant individuals and therefore cause direct and indirect effects on population and community level, and (ii) community response to herbicide exposure will depend on the specific species pool, management regime and resource level. For each community, we simulate local community patches at different distances to the treated arable field to account for effects of buffer zones as a potential mitigation measure.

2. Methods

2.1. Plant communities

A representative 'field boundary community' is based on a recent literature review on species found in such habitats in Europe (Kolja Bergholz unpublished, see in Appendix A, Table A.1 in Supplementary data for species list). In addition, we include two grassland communities with different management regimes and nutrient levels, which are common in Central Europe: (i) *Calthion*, which is a plant community that occurs in wet meadows with medium nutrient availability and (ii) a representative *Arrhenatheretalia* community that occurs in fertile meadows often used as pastures with high nutrient availability. To assess the species pool of those communities we reviewed vegetation surveys by Dierschke and colleagues (Dierschke, 2004; Dierschke et al., 2004; Fischer, 1985) and included expert knowledge (Michael Ristow, personal communication, see in Appendix A, Tables A.2 and A.3 in Supplementary data for species lists). The environmental conditions for these two communities differ in their nutrient availability and the amount of cutting events per year (Table 1).

2.2. The IBC-grass model

Plant community dynamics are driven by abiotic as well as biotic factors. Environmental characteristics such as nutrient levels, light and disturbances by either agricultural managements (e.g. by tractor crossings) or herbivory (e.g. grazing and trampling) determine the abiotic conditions in the community. Over time, plant individuals compete for resources and space. Thereby, the specific trait characteristics of a plant individual determine the growth potential and competitive strength.

IBC-grass is a well-established plant community model, which simulates local dynamics taking into account those main drivers. We base our approach on the published IBC-grass model of Weiss et al. (2014) enhancing it by adding an herbicide effect module and improving existing submodels. The flowchart (Fig. 1) gives a general overview of the considered processes in IBC-grass, main state variables can be found in Table 2. A detailed description of the base model and our modifications following the ODD protocol (Grimm et al., 2010, 2006) including all state variables and equations can be found in Appendix B in Supplementary data. In the following we give a summary of the main aspects, approaches and modifications in IBC-grass.

2.2.1. Trait-based approach

IBC-grass makes use of a trait-based approach, which classifies species into plant functional types (PFTs) according to their specific trait characteristics (Table 3), i.e. one PFT represents one or several plant species, which can be expected to respond in a similar way to abiotic and biotic conditions, e.g. resource competition, grazing intensities. Thus, general processes in grassland communities are captured whilst being transferable and general enough to allow conclusions for several grassland communities.

Overall, six different trait syndromes are considered in the standard IBC-grass model (Table 3). All plant species of the regional species pool (see Appendix A in Supplementary data) are parameterized using the trait data bases BiolFlor, LEDA and cloPla3 (Kleyer