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Modelling of low input herbicide strategies for the control of wild oat in intensive winter wheat cropping systems

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ABSTRACT

Weeds are causing significant yield losses in intensive winter wheat cropping systems worldwide. Prospective weed control strategies aim to reduce herbicide inputs in order to diminish the environmental, food safety and operator risks. The objective of this study is to make a long-term comparison of herbicide saving weed control strategies in intensive winter wheat cropping systems. The herbicide saving weed control strategies are compared with emphasis on herbicide input, crop yield, economic net return and weed population dynamics. The modelling approach is based on existing models for calculation of crop yield loss, herbicide dose-response, weed seed bank development and economic net return. The model is parametrised for wild oat in winter wheat. Field experiments were conducted for model parameter estimation. Three herbicide saving weed control strategies were compared, namely the economic threshold strategy as well as two reduced herbicide dose strategies. The two reduced dose strategies differed in their intensity of dose reduction and thus in their risk for potential efficacy failure. The modelling results could show that, depending on the risk level, reduced dose strategies can decrease herbicide inputs by 21% respectively 59%, compared to the economic threshold method. Differences between the three herbicide saving weed control strategies regarding yield and economic net return were negligible. From the consumer and environmental safety point of view, the high potential for herbicide input reduction makes the reduced herbicide dose methods favourable. However, the benefit for farmers is questionable due to the absence of an actual economic benefit and the enhanced risk of efficacy failure and herbicide resistance development.

1. Introduction

Winter wheat (*Triticum aestivum* L.) is one of the major crops in Europe and other areas with temperate climate and often rotated with other cereal crops or oilseed rape (*Brassica napus* L.). Effective weed control is a necessity, since weeds are the most yield reducing biotic factor in those cropping systems (Oerke, 2006). Since the discovery of phenoxy herbicides in the 1940's, herbicides have become the major tool for weed control, mainly due to their attractive cost-effectiveness ratio (Håkansson, 2003). However, in recent years political and social pressure has increased, aiming the overall reduction of pesticide inputs into the environment ('t Mannetje et al., 2005; Kudsk and Streibig 2003). In addition to the variety of non-chemical weed control options available (summarised by Upadhyaya and Blackshaw, 2007), three practical strategies for the reduction of herbicide inputs are conceivable:

1) Site specific herbicide application (Christensen et al., 2003).
2) Reduction of the herbicide treatment frequency by the use of economic thresholds (Cousens et al., 1986; Gerowitt and Heitefuss, 1990; Zanin et al., 1993).
3) Reduction of herbicide dose rates (Brain et al., 1998; Travlos, 2012).

The objective of this study is to compare three herbicide saving chemical weed control strategies; the economic threshold method as well as two reduced herbicide dose approaches. The three strategies are compared regarding their long-term effect on crop yield, weed seed input into the soil seed bank, herbicide input and economic net return. Discussion of the results will be done with respect to two conflicting perspectives; the farmer's perspective with main focus on production risks and an economically optimised production process as well as the consumer and environmental safety

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perspective with focus on the reduction or prevention of pesticide use.

The presented modelling approach is based on a combination of deterministic sub-models covering the weed life-cycle as well as economic aspects of the simulated chemical control options. The sub-models are describing the following experimentally derived data: crop yield loss in dependency of weed biomass, herbicide dose-dependent seed production as well as herbicide efficacy. The field experiments were realised in South Western Germany between 2009 and 2013. Parameter estimates which were not covered by own experiments were derived from literature.

The described model is parameterised for wild oat (*Avena fatua* (L.)) in winter wheat, one of the most abundant weed species in temperate agricultural regions worldwide (Beckie et al., 2012). Wild oat is an obligate inbreeding summer annual grass species, producing up to 1000 seeds per plant (Rauber, 1977). The major determinant for winter wheat yield loss is competition for nitrogen and phosphorus, due to its large root system (Haynes et al., 1991; Satorre and Snaydon, 1992).

Wilson and Wright (1990) found winter wheat yield losses higher than 50% at wild oat densities exceeding 30 plants m^{-2}. The authors could further demonstrate that, in comparison to other major weeds in winter wheat, wild oat shows the highest competitiveness based on percentage yield loss per plant.

Wild oat was chosen deliberately for this study due to a lack of knowledge regarding its demography under winter wheat competition. Furthermore, only little knowledge about the economics of wild oat control in winter wheat is available to date.

2. Materials and methods

2.1. Model structure

The presented modelling approach comprises seven sub-models arranged in sequence (Fig. 1). Hereinafter, the sub-models are described in their consecutive order.

In sub-model 1, wild oat seedling density (*SD*) is converted into wild oat seedling biomass (*SB*) (Eq. (1.1)). This step is required, since the subsequent herbicide dose-response sub-model is based on weed biomass. A linear relationship between weed seedling density m^{-2} and weed seedling biomass m^{-2} is assumed for the period of chemical weed control measures (between the two leaf growth stage and early tillering of wild oat).

$$SB = a * SD \tag{1.1}$$

Furthermore, wild oat biomass (*SB*) is converted into relative wild oat biomass (Eq. (1.2)) by dividing *SB* by the total biomass per m^2 (wild oat biomass plus winter wheat biomass). SB_{rel} serves as input variable for sub-model 3.

$$SB_{rel} = (SB/(SB + WB)) * 100 \tag{1.2}$$

Winter wheat biomass (*WB*) was set to 400 g dry biomass m^{-2}. This value represents the average winter wheat biomass between the two leaf growth stage and early tillering of wild oat and is only valid for the tested specific experimental site and agronomic practice. This simplification was done since no interspecific competition between winter wheat and wild oat was detectable at this early growth stage and for the plant densities covered by the experiments (data not shown).

Calculations of sub-models 2 and 3 are based on herbicide dose equivalents (HDE) for better comparison of herbicide dose rates. HDE is the applied herbicide rate *i* relative to its recommended field rate. The value is ranging between 0 and 1 whereby 1 is representing the maximum recommended dose rate. This approach allows direct comparison between herbicides with different active ingredients and recommended dose rates.

Sub-model 2 is calculating the HDE dependent residual wild oat biomass (SB_{HDE}). For this purpose, herbicide dose-response data was normalised with respect to the untreated control. Values represent relative residual biomass and range between 1 for the untreated control and approach 0 for high HDE's. The dose-response model is following the three-parameter log-logistic dose-response function according to Streibig (1988) (Eq. (2.1)). Parameter *c* is the residual wild oat biomass per unit HDE as $HDE_i \to 1$. Parameter e_i denotes the ED50 value of herbicide *i*, which is the relative dose at which herbicide efficacy is at 50%. b_i denotes the slope around the inflection point e_i. For herbicides fenoxaprop-P and pinoxaden, the two-parameter model was used with c set to 0. The residual wild oat biomass (SB_{HDE}) is calculated by multiplying wild oat biomass (*SB*), derived from sub-model 1, with the normalised dose-response function. SB_{HDE} is transformed into relative residual weed biomass SB_{rel} according to Eq. (1.2) and serves as input variable for sub-model 5.

$$SB_{HDE} = SB*(c + (1-c)/(1 + \exp(b_i*\log(HDE_i/e_i))) \tag{2.1}$$

$$SB_{HDE_{rel}} = \left(SB_{HDE}/(SB_{HDE} + WB)\right) * 100 \tag{2.2}$$

Sub-model 3 is calculating the herbicide dose dependent wild oat seed production m^{-2} (SI_{HDE}).

SI_{HDE} is based on previous calculation of the maximum potential seed production (Eq. (3.1)) in absence of a herbicide (SI_{max}). The model is following a hyperbolic function which is equivalent to the yield loss model proposed by Cousens (1985). Parameter C denotes the slope for small relative wild oat biomass (SB_{rel}), respectively the amount of seeds produced per unit relative wild oat biomass. Parameter D denotes the maximum seed production m^{-2} for $SB_{rel} \to 100$.

The herbicide dose dependent seed input (SI_{HDE}) is calculated by multiplication of $SI_{\max}$ with a two-parameter log-logistic dose-response model as described in Eq. (2.1). Parameter h_i denotes the HDE of herbicide *i* at which 50% inhibition of seed production occurs and b_i denotes the slope around h_i (Eq. (3.2)).

$$SI_{max} = C * SB_{rel}/\left(1 + C * SB_{rel}/D\right) \tag{3.1}$$

$$SI_{HDE} = SI_{max} * \left(1/\left(1 + \exp\left(g_i * \log\left(HDE_i/h_i\right)\right)\right)\right) \tag{3.2}$$

Soil seed bank gain of newly produced seeds (SSB_{new}, Eq. (4.1)) is a function of herbicide dose dependent seed production and seed losses through harvest (*s*) and predation (*p*). The soil seed bank decline is described by the seed mortality of new and old seeds ($m_{new/old}$), and losses through germination (Eq. (4.2)). Seedling density in year t + 1 (SD_{t+1}, Eq. (4.3)) is described by soil seed bank content of newly produced seeds (SSB_{new}) and seeds from the previous seasons (SSB_{old}) as well as their respective germination rates ($v_{new/old}$).

$$SSB_{new} = SI_{HDE} * (1-p) * (1-s) \tag{4.1}$$

$$SSB_{old} = (1 - m_{old} - v_{old}) * SSB_{old}^{t-1} + (1 - m_{new} - v_{new}) * SSB_{new}^{t-1} \tag{4.2}$$

$$SD_{t+1} = (v_{new} * SSB_{new}) + (v_{old} * SSB_{old}) \tag{4.3}$$

Winter wheat yield ($Y_{SB_{rel}}$) in dependency of relative wild oat residual biomass ($SB_{HDE_{rel}}$) is calculated according to Cousens, 1985:

$$Y_{SB_{rel}} = Y_{wf} * \left(1 - I * SB_{HDE_{rel}}/\left(1 + I * SB_{HDE_{rel}}/A\right)\right) \tag{5}$$

Y_{wf} denotes the weed free winter wheat yield, *I* is the fraction of yield loss per unit relative weed biomass as $SB_{HDE_{rel}} \to 0$ and *A* denotes the maximum relative yield loss as $SB_{HDE_{rel}} \to 100$.