Simulation model for longterm management of *Avena fatua* L. in winter wheat

Simulationsmodell zur langfristigen Kontrolle von Avena fatua L. in Winterweizen

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Abstract

Decision support systems (DSS) are used for weed control decisions worldwide. Several DSS for weed management have been published. However they mostly rely on full herbicide dosages and do not take weed population dynamics into account. We developed a modular DSS for long-term *Avena fatua* L. control in winter wheat. The DSS was parameterized with three year field experiment datasets covering yield loss data, density-dependent population dynamics data as well as data on dose dependent herbicide efficacy and dose-dependent population dynamics. The DSS aims to control the *A. fatua* in the long run. Our hypothesis is that the optimized DSS reduces herbicide input while keeping the population density at low level, maintaining high grain yields and net return.

The DSS comprises four sub-models calculating crop yield loss, *A. fatua* population dynamics as well as dose dependent herbicide efficacy and economics of the weed control decision. The economic sub-model calculates net return in dependency of the herbicide dosage and thus the resulting crop yield.

First results of a 10-year simulation showed that herbicide input could be reduced by 40% compared to the economic threshold strategy, while the population density of *A. fatua* is controlled.

Up to now the DSS has been parameterized for the herbicides Ralon Super, Axial 50 and Broadway. The results show the great potential of reducing herbicide input and point out the importance of including population dynamics models into DSS

Keywords: Decision support system, dosage reduction, population dynamics, weed control

Zusammenfassung

Entscheidungssysteme finden weltweit Einsatz bei der Unterstützung der Unkrautkontrolle. Bisher sind einige Entscheidungssysteme verfügbar. Diese berücksichtigen in der Regel die volle Herbizidaufwandmenge und beinhalten keine Modelle zur Populationsdynamik der Unkräuter. Wir haben ein Entscheidungssystem zur langfristigen Kontrolle von *A. fatua* in Winterweizen entwickelt, welches mit 3-jährigen Feldversuchsdatensätzen zu Ertragsverlustswirkung und dichteabhängiger Populationsdynamik, sowie zu Herbizidwirkung und aufwandmengenabhängiger Populationsdynamik parametrisiert wurde. Das Entscheidungssystem zielt darauf ab, *A. fatua* langfristig zu kontrollieren. Unsere Hypothese ist, dass der Herbizideintrag mithilfe des Entscheidungssystems verringert, und gleichzeitig eine hohe Unkrautkontrollwirkung sowie ein hoher Kornertrag und Deckungsbeitrag erzielt werden kann.

Das Entscheidungssystem beinhaltet vier Untermodelle zur Berechnung von Ertragsverlusten, *A. fatua* Populationsdynamik, Herbizidwirkungen sowie zur ökonomischen Bewertung der Entscheidung zur *A. fatua*-Kontrolle. Das ökonomische Untermodell berechnet den Deckungsbeitrag in Abhängigkeit der Herbizidaufwandmenge und des daraus resultierenden Kornertrags.

Erste Ergebnisse einer Simulation über einen Zeitraum von 10 Jahren zeigten, dass der Herbizideintrag im Vergleich zur Strategie der ökonomischen Schadensschwelle um 40% verringert werden kann und gleichzeitig die *A. fatua*-Population kontrolliert wird.

Bisher wurde das Entscheidungssystem für die Herbizide Ralon Super, Axial 50 und Broadway parametrisiert. Die Ergebnisse zeigen das große Potential zur Reduzierung von Herbizidenaufwandmengen und zeigen auf, wie wichtig es ist populationsdynamische Modelle in Entscheidungssysteme einzubeziehen.

Stichwörter: Aufwandmengenreduktion, Entscheidungssystem, Populationsdynamik, Unkrautkontrolle

Introduction

Several studies have shown that weed management strategies can be considerably improved when computerized expert systems, decision models and population-dynamic models are applied (WILES *et al.*, 1996). Economic weed thresholds have been determined in winter cereals to decide about the need of chemical weed control methods (NIEMANN, 1986; GEROWITT and HEITEFUSS, 1990; PALLUT, 1992; ZANIN *et al.*, 1993). There are several weed management support tools and simulation models available (e.g. BERTI and ZANIN, 1997; PANNELL *et al.*, 2004; BENJAMIN *et al.*, 2010; BELTRAN *et al.*, 2012). However some have not been calibrated to empirical datasets rather than to expert knowledge due to lack of current data. Some models include eco-physiological sub-models, making the system very complex. The former DSS PC-Plant Protection, nowadays included in the DSS Crop Protection Online, works with reduced herbicide dosages to minimize the herbicide input (RYDAHL, 1999). GONZALES-ANDUJAR *et al.* (2010 and 2011) developed AVENA-PC and LOLIUM-PC, in which herbicide application rates are also adjusted to the present weed density and thus herbicide input could be significantly reduced while maintaining yields at the same level as full-dose treatments. However, the control decision is not met in consideration of economical optimization or with regard on the population density in the following season. Furthermore, they partly observed increased seed input by weeds due to heavily reduction of application rates by about 60%. BRAIN *et al.* (1999) showed that it is possible to reduce herbicide application rates up to 20% of the recommended dosage without significant reductions of wheat yield. He linked herbicide dosage and crop yield in his model, making it possible to restrict yield losses to certain levels. However, this model did also not include the effect of reduced herbicide dosages on weed seed production, potentially leading to a population increase in the following years. It has been shown for *Avena sterilis* and other weed species, that herbicide dosage can be reduced by 50% while still achieving high control efficacy and little seed production, both being not different to the effect of full label-recommended dosage (RASMUSSEN, 1993; SCHRÖDER *et al.*, 2007; TRAVLOS, 2012).

We developed a basic modular modelling approach, which includes reduced herbicide dosages and their effect on population dynamics. The presented basic modeling approach contains sub-models for weed density dependent crop yield loss, for density dependent and herbicide dose-dependent weed population dynamics, for herbicide dose-response relationships as well as for the economic evaluation of weed management decisions. Thus the effect of weed control decisions on weed infestation of the following season can be modeled.

Field studies in winter wheat were carried out on Ihinger Hof Research Station, Baden-Württemberg, from 2009 to 2013, to assess yield loss data and population dynamic parameters for *A. fatua*. Data were analysed to find general patterns for weed biomass dependent winter wheat yield loss and *A. fatua* population dynamics to form the basis for a decision support system for *A. fatua* control in winter wheat.

Our hypothesis is that herbicide dosages can be reduced while weed infestation will not increase in the following season, due to decreased seed production by herbicide treated plants. Furthermore this herbicide dosage should guarantee an optimum economic net return.

Exemplary we modeled the effect of the economic threshold strategy beside the new model approach for comparison of *A. fatua* population development, cumulative herbicide input, yield and net return.

Material and Methods

The DSS is set up as modular system and comprises four submodels. The input variable is *A. fatua* density (*SD)*, which is transformed via a linear relationship into *A. fatua* seedling biomass (*SB*), according to Eqn 1.

$$SB = a * SD \qquad \text{Eqn (1)}$$

In the herbicide efficacy submodel the residual biomass (*SB_u*) in dependence of the herbicide dosage (*U*) is calculated.

The herbicide efficacy submodel follows the two-parametric log-logistic function, where the upper limit is set to 1 and the lower limit was set to 0 (Eqn 2). The parameter *e* denotes the ED50 value, the dose at which herbicide efficacy is at 50%, and *b* denotes the slope around e (STREIBIG *et al.*, 1993). For estimating the parameters, biomass data from field experiments were normalized with respect to the data of the respective untreated control, to obtain a dimensionless response between 0 and 1.

$$SB_U = SB * (1/(1 + \exp(b * \log(e/U))))$$ Eqn (2)

The expected seed input per m^{-2} in year t (SI_{SB}^t) of the untreated *A. fatua* biomass (*SB*) follows the hyperbolic function, known as yield loss function (COUSENS, 1985), where C gives the initial seed input and D stands for the maximum seed input for SB → ∞ (Eqn 3).

$$SI_{SB}^t = C * SB/(1 + C * SB/D)$$ Eqn (3)

The herbicide dose-dependent seed input in year t (SI_U^t) is given by Eqn 4, where SI_{SB}^t is multiplied with the normalized dose-dependent seed input function, corresponding to the two-parametric log-logistic function described in Eqn 2. For estimating the parameters, seed input data from the field experiments were normalized with respect to the data of the respective untreated control, to obtain a dimensionless response between 0 and 1.

$$SI_U^t = SI_{SB}^t * (1/(1 + \exp(g * \log(h/U))))$$ Eqn (4)

The soil seed bank is divided into 2 cohorts, a cohort with newly produced seeds SSB_{new}^t and a cohort SSB_{old}^t with seeds from the previous season, as proposed by COUSENS *et al.* (1986). With the information about the seed input the new seed bank cohort SSB_{new}^t was calculated, whereas the parameter *p* stands for seed losses via predation and *s* for losses via harvest (Eqn 5). For calculation of the older seed bank cohort, the parameters germination rate $v_{new/old}$ and mortality rate $m_{new/old}$ were taken into account.

$$SSB_{new}^t = SI_u^t * (1 - p) * (1 - s)$$ Eqn (5)

$$SSB_{old}^t = (1 - v_{old} - m_{old}) * SSB_{old}^{t-1} + (1 - v_{new} - m_{old}) * SSB_{new}^{t-1}$$ Eqn (6)

$$SD^{t+1} = (v_{new} * SSB_{new}^t) + (v_{old} * SSB_{old}^t)$$ Eqn (7)

The expected winter wheat yield in dependence of the residual *A. fatua* biomass (Y_{SBu}) is calculated according to the yield loss model of COUSENS (1985) in the yield submodel, where the parameter I describes the initial yield loss for SB_U → o and A describes the maximum yield loss for SB_U →∞ (Eqn 8).

$$Y_{SB_U} = Y_{wf} * (1 - I * SB_U/(1 + I * SB_U/A))$$ Eqn (8)

Finally, in the economic submodel, the optimum herbicide dosages, which give the maximum winter wheat yield, was calculated by differentiating Eqn 9 with respect to *U*. P_y is the price per ton winter wheat, P_U the price per unit herbicide, C_1 the fixed production costs and C_2 the variable costs for herbicide application.

$$NR_{SB_U} = (P_y * Y_{SB_U}) - P_U * U - C_1 - C_2$$ Eqn (9)

For the simulation model, there were two restrictions included into the model: Herbicide efficacy must be at least 90% and seedling density must not increase. Whenever there was a conflict between those two restrictions, maximum seedling density in year t+1 was set to the initial seedling density of year 1. Furthermore, if SD^{t+1} will be below the economic threshold of the respective herbicide, no application will take place in year t.

For comparison of the model results, the economic threshold model was selected, in which herbicide application takes place if the economic yield loss caused by the present *A. fatua* density is higher than the costs for herbicide application. The economic threshold was calculated separately for each herbicide and was at 6 plants m^{-2} for Axial 50, at 5 plants for m^{-2} for Ralon Super and at 3 plants m^{-2} for Broadway.

For comparison of the two models, two common rules were set up: The initial herbicide treatment is the one which gives the highest net return and the herbicide rotation follows the fixed sequence Ralon® Super – Broadway™ – Axial® 50.

For direct comparison of herbicide input, herbicide rates were transformed into herbicide dosage equivalent (HDE), ranging from 0 (no herbicide application) to 1 (full dosage). Recommended field rates were 0.9 l ha^{-1} of Axial 50, 1.0 l ha^{-1} of Ralon Super and 220 g ha^{-1} of Broadway. Initial SSB_{new}^{t-1} was 70 seeds m^{-2} respectively 210 seeds m^{-2} and SSB_{old}^{t-1} was 30 respectively 90 seeds m^{-2} for initial seedling densities of 10 and 30 plants m^{-2}.

The parameterization of the DSS was based on field experiments from different sites, which were carried out from 2009 to 2013 on Ihinger Hof research station in southern Germany. These included density dependent yield loss and population dynamics experiments (2 years, 3 sites, each 3 replications) as well as herbicide dose-response experiments and herbicide dose-dependent population dynamics experiments with the herbicides Axial 50, Ralon Super and Broadway (1 year, 2 sites, each 3 replications). In the yield loss experiments *A. fatua* seeds were sown in 5 different densities into the field after sowing of winter wheat. At the 2-leaf-stage of *A. fatua* 0.5 m^2 of each plot were harvested to determine *A. fatua* density and seedling biomass. At time of *A. fatua* termination 0.5 m^2 were harvested to determine the amount of panicles and additional five plants were harvested for determination of seed production. Winter wheat was harvested with a plot combine for yield determination. In the dose-response experiments *A. fatua* seed were sown in equal densities into the plots after sowing of winter wheat. In the 2-leaf-stage of *A. fatua* herbicides were applied at different dosages (100%, 75%, 50%, 37.5%, 25%, 12.5% and 0% of the recommended field rate) with a plot sprayer and a volume of 200 l ha^{-1}. Four weeks after herbicide application 0.5 m^2 were harvested from each plot to determine the residual biomass of *A. fatua*. At time of *A. fatua* termination population dynamics parameters were determined in an area of 0.5 m^2.

Parameters from Eqns 5 and 6 are taken from COUSENS *et al.* (1986) and from Eqn 9 from expert's knowledge. We assumed fixed germination, mortality and predation rates due to the reason that they can highly vary between different environments and are influenced by different factors (MICKELSON and GREY, 2006; DAVIS *et al.*, 2013).

An overview on the values of the different parameters used in the model is given in Table 1.

Tab. 1 Overview on the parameter values used in the model.

***Tab. 1** Übersicht über die im Modell verwendeten Parameterwerte.*

Submodel	Eqn	Herbicide	Parameter	Value	Unit
Biomass transformation	1		a	0.29	
Herbicide efficacy submodel	2	Ralon Super (fenoxaprop-P-ethyl)	U	0-1	l ha^{-1}
			b	1.846	
			e	0.064	l ha^{-1}
		Axial 50 (pinoxaden)	U	0-0.9	l ha^{-1}
			b	2.498	
			e	0.147	l ha^{-1}
		Broadway (florasulam + pyroxsulam)	U	0-220	g ha^{-1}
			b	0.622	
			e	3.004	g ha^{-1}
Population dynamics submodel	3		C	231.03	
			D	11329.16	
	4	Ralon Super	g	4.2	
			h	0.109	l ha^{-1}
		Axial 50	g	2.878	
			h	0.13	l ha^{-1}
		Broadway	g	1.079	
			h	14.066	g ha^{-1}
	5		p	0.1	
			s	0.1	
	6		mold	0.65	
			mnew	0.57	
			vold	0.1	
			vnew	0.1	
Yield loss submodel	8		Ywf	7	t ha^{-1}
			I	0.02	
			A	0.558	
Economic submodel	9		Py	200	€ t^{-1}
			C1	550	€
			C2	10	€
		Ralon Super	P_U	21.5	€ l^{-1}
		Axial 50	P_U	36.46	€ l^{-1}
		Broadway	P_U	0.059	€ g^{-1}

Results

Results of the field experiments showed that seed production as well as residual biomass of *A. fatua* decreased in a log-logistic manner with increasing herbicide dosage. This was found for Axial 50, Ralon Super (Fig. 1) and Broadway. Axial 50 and Ralon Super showed very high efficacies. Application rates of both Axial 50 and Ralon Super could be reduced to 50% (0.45 respectively 0.5 L ha^{-1}) while no seeds were produced. Even at 37.5% of the recommended field rate of Axial 50 and 25% of Ralon Super, *A. fatua* seed production was very low. If treated with Broadway, *A. fatua* produced seeds even at the highest recommended field rate.

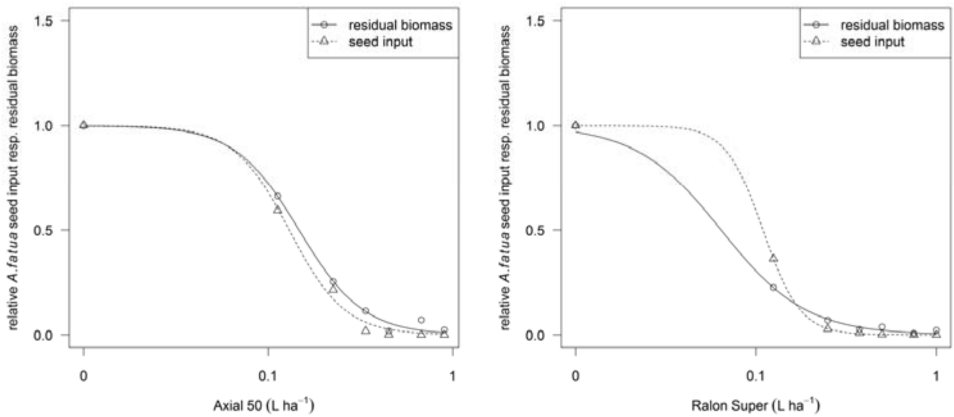

Fig. 1 Relative seed input and residual biomass of *A. fatua* in dependency of the dosage of Axial 50 (left) and Ralon Super (right).

Abb. 1 *Relativer Sameneintrag und relative Restbiomasse von* A. fatua *in Abhängigkeit der Aufwandmengen von Axial 50 (links) und Ralon Super (rechts).*

Results of our simulation model revealed a high potential for reducing herbicide rates for *A. fatua* control. Seedling densities steadily decreased over the 10 years period due to low seed input, while herbicide application rates were kept at low levels (Tab. 2). HDEs were 0.21 and 0.32 for Ralon Super, 0.354 for Axial 50 and 0.46 for Broadway for an assumed initial seedling density of 10 plants m^{-2}. For an assumed initial seedling density of 30 plants m^{-2} the required herbicide input was similar. HDEs were 0.21 to 0.48 for Ralon Super, 0.39 and 0.40 for Axial and 0.46 for Broadway. Cumulative HDE was 3.29 and 3.48 for initial seedling densities of 10 and 30 plants m^{-2} over a supposed time period of ten years. This is a reduction in herbicide input of about 50% compared to the economic threshold strategy, where in 7 out of 10 years herbicides were applied at full rates (cumulative HDE=7) (Tab. 3). When applying the economic threshold strategy, population densities climbed up after the seasons, where seedling densities were below the economic threshold, due to high seed input of not controlled *A. fatua* plants. Cumulative grain yield and net return were similar for both strategies.

Tab. 2 Results of the simulation model over a time period of 10 years for initial *A. fatua* seedling densities of assumed 10 and 30 plants m^{-2} respectively.

Tab. 2 *Ergebnisse des Simulationsmodells für einen Zeitraum von 10 Jahren für eine angenommene* A. fatua *Ausgangsdichte von 10 bzw. 30 Pflanzen m^{-2}.*

	Simulation model						
Year	Seedling density [m^{-2}]	Herbicide	Dosage [l/g ha^{-1}]	HDE	Yield [t ha^{-1}]	Net return [€ ha^{-1}]	Seed Input [m^{-2}]
1	10	RalonSuper	0.32	0.32	6.98	829	6.8
2	3.6	Broadway	102.94	0.46	6.98	831	24.8
3	3	Axial50	0.354	0.39	6.98	825	10.3
4	1.7	RalonSuper	0.21	0.21	6.99	834	6.9
5	1.1	Broadway	102.94	0.46	7.00	833	7.4
6	0.9	-	0	0	6.96	843	60.5
7	5.2	Axial50	0.354	0.39	6.98	823	17.9
8	3.1	RalonSuper	0.21	0.21	6.99	833	12.4
9	1.9	Broadway	102.94	0.46	6.99	832	13.2
10	1.6	Axial50	0.354	0.39	6.99	826	5.7
Σ				3.29	69.84	8309	

Year	Seedling density [m^{-2}]	Herbicide	Dosage [l/g ha^{-1}]	HDE	Yield [t ha^{-1}]	Net return [€ ha^{-1}]	Seed Input [m^{-2}]
1	30	RalonSuper	0.478	0.48	6.97	824	3.5
2	9.5	Broadway	102.94	0.46	6.96	826	63
3	7.5	Axial50	0.359	0.4	6.97	821	24.5
4	4.26	RalonSuper	0.23	0.23	6.99	832	11.6
5	2.2	Broadway	102.94	0.46	6.99	832	15
6	1.8	Axial50	0.354	0.39	6.99	826	6.4
7	1.1	RalonSuper	0.21	0.21	7.00	835	4.3
8	0.7	Broadway	102.94	0.46	7.00	833	4.6
9	0.6	-	0	0	6.98	845	37.8
10	3.2	Axial50	0.354	0.39	6.99	824	11.3
Σ				3.48	69.84	8298	

Discussion

Already existing models showed that reduction of herbicide rates is possible without affecting crop yield (BRAIN *et al.*, 1999; GONZALES-ANDUJAR *et al.*, 2010 and 2011). However the reduced rates often resulted in a population density increase. With our experimental data sets we could show, that reduced herbicide rates lead to decreased seed production of *A. fatua*. At higher dosages of Ralon Super and Axial *A. fatua* produced even no seeds. This is only true for application timing at the two-leaf stage. Efficacy and thus seed production may be influenced by later application timing. By including these functions into a simulation model, we could simulate that it is possible to reduce herbicide rates, while keeping the population density at low levels over a period of 10 years. Compared to the economic threshold strategy, which also aims to reduce herbicide input, herbicide rates could be reduced by 50% without economical disadvantages. The population density decline between two years was partly very high which can be explained by the high mortality rates assumed by COUSENS *et al.* (1986) and which have been used for this model. However these rates are similar to those published by MICKELSON and GREY (2006), where mortality rates ranged from 15 to 88% leading to a high annual decline in the *A. fatua* seed bank.

Tab. 3 Results of the economic threshold strategy over a time period of 10 years for initial *A. fatua* seedling densities of 10 and 30 plants m^{-2} respectively.

Tab. 3 *Ergebnisse der Ökonomischen Schadensschwellen-Strategie für einen Zeitraum von 10 Jahren und einer* A. fatua *Ausgangsdichte von 10 bzw. 30 Pflanzen m^{-2}.*

	Economic threshold						
Year	Seedling density [m^{-2}]	Herbicide	Dosage [l/g ha^{-1}]	HDE	Yield [t ha^{-1}]	Net return [€ ha^{-1}]	Seed Input [m^{-2}]
1	10	Broadway	220	1	6.97	822	31
2	5.6	-	0	0	6.79	807	361
3	30.8	Axial50	0.9	1	6.99	805	6.6
4	10.6	RalonSuper	1	1	7.00	818	0.1
5	2.7	-	0	0	6.89	829	177.8
6	15.1	Broadway	220	1	6.96	819	45.4
7	8.6	Axial50	0.9	1	7.00	806	2.1
8	2.6	-	0	0	6.9	829	172.3
9	14.6	RalonSuper	1	1	7.00	818	0.1
10	4.8	Broadway	220	1	6.99	824	15.2
Σ				7	69.49	8177	

Year	Seedling density [m^{-2}]	Herbicide	Dosage [l/g ha^{-1}]	HDE	Yield [t ha^{-1}]	Net return [€ ha^{-1}]	Seed Input [m^{-2}]
1	30	RalonSuper	1	1	6.99	817	0.2
2	9.2	Broadway	220	1	6.98	822	28.6
3	4.6	-	0	0	6.82	814	301
4	25.7	Axial50	0.9	1	6.99	805	5.7
5	8.8	RalonSuper	1	1	7	818	0.1
6	2.3	-	0	0	6.91	832	148.8
7	12.6	Broadway	220	1	6.97	820	38.5
8	7.2	Axial50	0.9	1	7	807	1.8
9	2.2	-	0	0	6.91	833	145.7
10	12.3	RalonSuper	1	1	7	818	0.1
Σ				7	69.57	8186	

The simulation model has been parameterized only for *A. fatua* to demonstrate the possibilities of including herbicide efficacy-based population dynamics into a decision support system. Since the efficacy of the herbicides on other weeds may differ, reduced application rates should be adjusted with respect to the weed species which shows the lowest susceptibility to the respective herbicide. Reducing herbicide application rates is often criticized with respect to the development of herbicide resistant biotypes. RENTON *et al.* (2013) simulated the influence of reduced rates on the development of monogenic and polygenic resistance in annual ryegrass with an individual-based model and showed with their simulation results, that reduced rates may fasten the development of polygenic resistance under certain circumstances. However, they also mentioned that it is not clear yet in which situations it will really make a difference in the field, due to many influencing factors. With economic threshold strategy it is more likely to select for target-site resistance, due to a high selection pressure given by high dosages. In contrast, with the strategy of our simulation model one may argue it selects on polygenic non-target site resistance due to reduced rates. The simulation model keeps the soil seedbank and thus the genetic variation constantly small with an average yearly seed input of around 18 seed m^{-2}. This withdraws one important prerequisite for resistance development: a large population size (BARTON, 2010; DÉLYE *et al.*, 2013), in contrast to the economic threshold strategy, which leads to a higher average annual seed input (around 75 seeds m^{-2}) and especially to a sharp increase in the soil seedbank after not-spraying, giving a more favourable basis for resistance development in terms of a large population size.

This simulation model shows the great potential of minimizing herbicide input while controlling the population density in the long run. The results point out the importance of including population dynamics into a decision support system.

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