Precision weed control: a spatially explicit individual based model

Präzise Unkrautkontrolle: ein räumlich-explizites, Individuen-basiertes Modell

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Abstract

Yield reduction through competition between crop and weeds is a major challenge for farmers. Therefore, most fields in Europe are treated with herbicides or mechanical methods for weed control nowadays. Modern techniques like high precision GPS, image recognition and robotics enable autonomous and site specific weed control. In the future, it might be possible to manage weeds on a plant-by-plant basis. This would provide great opportunities for the conservation of weed diversity. The implementation of such management schemes requires the understanding of the competition process in a spatial context. We present a spatially explicit individual-based model suitable to simulate the effect of precise weed control measures for specific plants. Growth models in form of differential equations are set up for each individual plant. Competition is formulated dependent on the spatial configuration of both weeds and crops. First simulation results with a parametrisation for wheat and *Viola arvensis* are presented. Without any control measures, crop growth curves show a large variability, whereas an efficient weed control (efficacy 95%) results in nearly uniform growth curves. This was corroborated in an experiment with wheat and *V. arvensis* for the same spatial configuration as in the model. Further development of the model will include multispecies situations as well as long-term population dynamics of the different species.

Keywords: competition, individual based, plant-plant interaction, simulation model, spatial explicit

Zusammenfassung

Ertragsverluste durch Unkrautkonkurrenz stellen seit jeher eine große Herausforderung für die Pflanzenproduktion dar. Daher werden die meisten Äcker in Europa heutzutage mit Herbiziden oder mechanischen Methoden zur Unkrautbekämpfung behandelt. Moderne Techniken wie hochpräzises GPS, Bilderkennung und Robotik ermöglichen eine autonome und ortsspezifische Unkrautbekämpfung. In Zukunft könnte es sogar möglich sein, Unkräuter auf Einzelpflanzenbasis zu bekämpfen. Dies würde eine große Chance für die Erhaltung der Unkrautvielfalt eröffnen. Die Umsetzung solcher Managementkonzepte erfordert das Verständnis der Konkurrenz im räumlichen Kontext. Wir stellen ein räumlich explizites individuelles Modell vor, das geeignet ist, die Wirkung von präzisen Unkrautbekämpfungsmaßnahmen für bestimmte Pflanzen zu simulieren. Für jede einzelne Pflanze wird ein Wachstumsmodell in Form von Differentialgleichungen aufgestellt. Die Konkurrenz wird in Abhängigkeit von der räumlichen Konfiguration von Unkräutern und Kulturpflanzen formuliert. Erste Simulationsergebnisse mit einer Parametrisierung für Weizen und *Viola arvensis* werden vorgestellt. Ohne Kontrollmaßnahmen zeigen die Pflanzenwachstumskurven eine große Variabilität, wohingegen eine effiziente Unkrautbekämpfung (Wirksamkeit 95 %) zu nahezu einheitlichen Wachstumskurven führt. Dies wurde in einem Experiment mit Weizen und *V. arvensis* für die gleiche räumliche Konfiguration wie im Modell bestätigt. Die Weiterentwicklung des Modells wird Multispezies-Situationen sowie langfristige Populationsdynamiken der verschiedenen Arten einbeziehen.

Stichwörter: Individuen-basiert, Konkurrenz, Pflanze-Pflanze Interaktion, räumlich explizit, Simulationsmodell

Introduction

Arable weeds are a major threat for agriculture worldwide (OERKE, 2006). They cause large yield losses as competitors for crops. Therefore, great efforts are made to minimize this danger mainly by using herbicides (DAVIS and FRISVOLD, 2017).

The introduction of highly efficient herbicides in combination with large sprayers reduce the weed pressure uniformly over the field, which results in an equally and in most places inappropriate herbicide application. But modern technique enables farmers to apply herbicide site specific (CHRISTENSEN et al., 2009). The control of segments of sprayer boom up to the direct control of specific nozzles make it possible to reduce the herbicide load (TIMMERMANN et al., 2003; HAMOUZ et al., 2013; CASTALDI et al., 2017). Coming developments in robotics will even outcompete this development.

Autonomous devices and robots can work throughout the day without labour costs. Furthermore, autonomous devices will be able to treat plant-by-plant. For agriculture, the most interesting part will be competition and thus the yield effect. Currently management decisions are made on field level, which is sufficient as long as the management is on field level. Plant-by-plant management requires a much more differentiated decision making based on the effect on yield of single plants. Up to now, the knowledge on plant – plant interactions in agricultural situations is very much limited to one or two species situations. Knowledge on complex multispecies interactions, which is the case for weed plants in a crop, is rare.

Given the possibility to manage single plants and given the knowledge of the effect of single plants weed populations could be managed in a way that allows the population to survive and in the same time optimize the development of the crop. Different management preferences could be installed on the same field. Vegetation could be managed to an optimum value for yield and ecology. Still the necessary knowledge is missing to establish a weed management on this precision level. To get insights on the competition situation on the field, we have developed a simulation model on a spatial-temporal scale that includes individual based competition.

Model

General concept

The model structure combines individual based models with stochastic elements. Whereas the spatial configuration of the crop is fixed by the cultivation, weeds emerge randomly from the seedbank (Fig. 1). The position of each plant is recorded. The growth of individual crop plants and weeds is modeled by a differential equation taking into account the mutual competition between weeds and crop plants and within weeds. The competition depends on the distance between the plants. The model in the presented form is developed with Wolfram Mathematica 12.3 (WOLFRAM RESEARCH, INC., 2021).

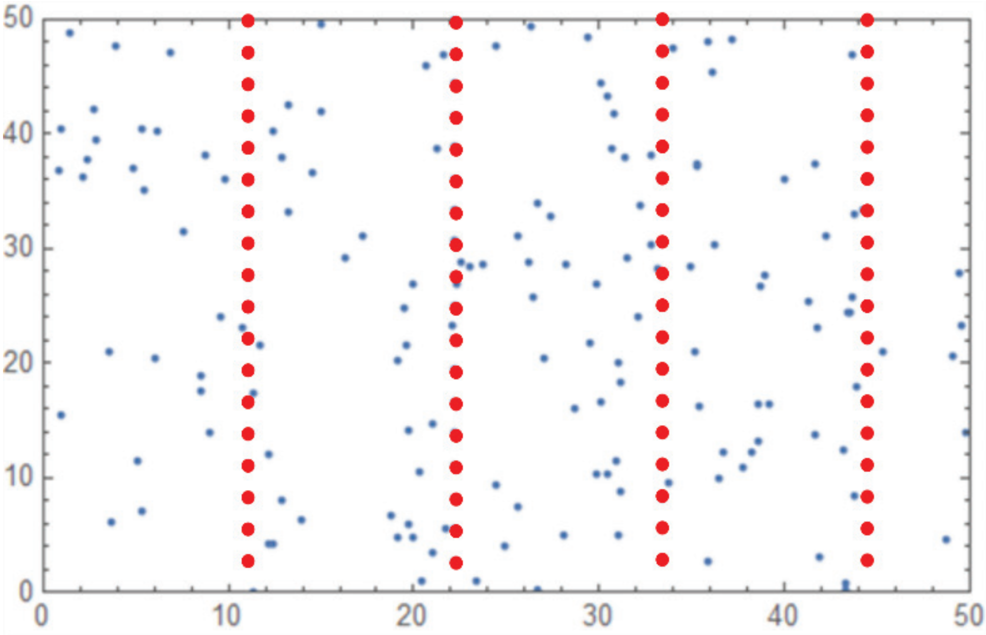

Figure 1 Spatial configuration of crop (red) and weed (blue) plants (units are cm).

Abbildung 1 *Räumliche Verteilung der Kultur (rot) und des Unkrauts (blau). Die Angaben sind in cm.*

Plant growth model

For the height of each plant y_i, a growth equation is set up (Form. 1), which is coupled with the other plants via the interaction or competition term α_{ij} (Form. 3). The parameterization is given in Table 1.

Formula 1 Growth function

Formel 1 *Wachstumsfunktion*

$$\frac{d\,y_i}{dt} = r_i\, y_i - \mu_i\, y_i(1 + \sum_{j=1}^{n} \alpha_{ij} y_j)$$

The coefficients(α_{ij}) (Form. 3) are elements of the community matrix *A* (Form. 2), which comprises the interactions between the plant species. The matrix *A* consists of four submatrices describing the interactions between crop plants within the submatrix *CC*, the action of crop plants on weeds (*CW*), the action of weeds on the crop plants (*WC*), and the interaction between weeds (*WW*).

Formula 2 Community matrix

Formel 2 *Gesellschaftsmatrix*

$$A = \begin{pmatrix} CC & WC \\ CW & WW \end{pmatrix}$$

The diagonal elements of the community matrix *A* α_{ii} are intrinsic factors guaranteeing the retardation of growth. All other elements depend on the mutual distance d_{ji} between plant "*i*" and plant "*j*", where *a* denotes a threshold value for the strength of the interaction and γ is a form factor. The coefficient w_{ij} is specific for the type of interaction resp. competition between plants: crop-crop, crop-weed, weed-crop, and weed-weed.

Formula 3 Spatial interaction

Formel 3 *Räumliche Interaktion*

$$\alpha_{ij} = w_{ij} Exp[-\left(\frac{d_{ij}}{a}\right)^{\gamma}]$$

Management

Formula 4 Effect of weed control

Formel 4 *Effekt der Unkrautkontrolle*

$$\mu_c(t) = h(t - t_{app}) d_{max} e^{-\frac{(t-t_{app})}{\tau}} a(P_i)$$

Weed control is taken into account by adding a further mortality term μ_c (Form. 4) to the differential equations for the weed. h is the Unitstep function, t_{app} is the application time, d_{max} maximum mortality rate and τ is the recovery time of the weed following the control measure. The index "*i*" refers to weed plants, P_i is the location and *a(Pi)* indicates, whether weed control has been performed at this location.

Via the *a(Pi)* term, spatial patterns of weed control can be realized (Form. 5).

Formula 5 Growth function including weed control

Formel 5 *Wachstumsfunktion einschließlich der Unkrautkontrolle*

$$\frac{d\,y_i}{dt} = r_i\, y_i - \mu_i\, y_i (1 + \sum_{j=1}^{n} \alpha_{ij} y_j) \text{-} \mu_c(t)\, y_i$$

First model application

As a first parametrization of the model, we choose wheat as crop and *Viola arvensis* as the single weed. We used data from our experiments to estimate growth rates and other parameters (cf tab. 1). The following simulations were obtained for the spatial configuration in Figure 1.

Table 1 Model parameters. The indices refer to the plant types. Parameters with an asterisk were estimated from a preliminary analysis of our experimental data; all other parameters were tuned manually

Tabelle 1 *Modellparameter. Die Indizes beziehen sich auf die Art der Pflanze (Winterweizen oder* V. arvensis*). Parameter mit Stern wurden in einem Vorversuch bestimmt; alle anderen Parameter wurden händisch angepasst*

Parameter	Value	Description
r_i	0.05 [1/day]	growth rate crop *
r_j	0.06 [1/day]	growth rate weed
μ_i	0.027 [1/day]	respiration rate crop*
μ_j	0.027 [1/day]	respiration rate weed
α_{ii}	0.22	retardation factor crop*
α_{jj}	0.16	retardation factor weed
w_{ij}	0.16	competition factor weed crop
w_{ij}	0.14	competition factor crop weed
w_{ij}	0.04	competition factor weed weed
w_{ij}	0.001	competition factor crop crop*
a	10 [cm]	half range of interaction

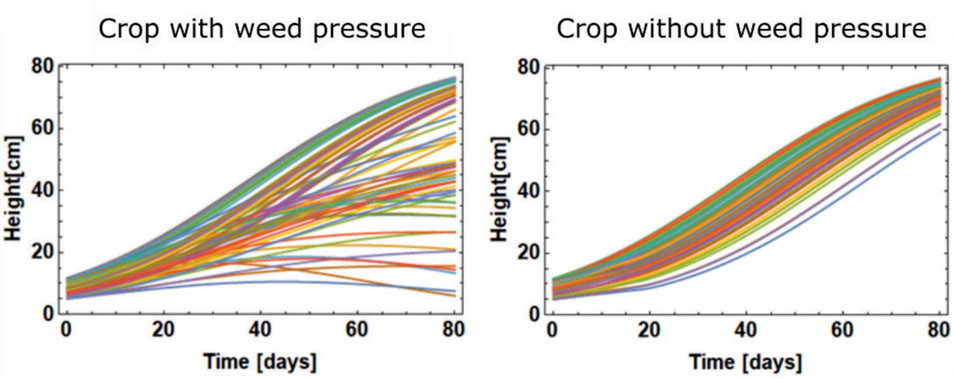

Figure 2 Growth curves of wheat plants with (left) and without efficient weed control (right)

***Abbildung 2** Wachstumskurven von Weizenpflanzen mit (links) und ohne Unkrautkontrolle.*

Without any control measures, crop growth curves show a large variability, whereas an efficient weed control (efficacy 95%) results in nearly uniform growth curves (Fig. 1).

Experimental verification

An experiment with wheat and *V. arvensis* was conducted corresponding to the spatial configuration given in Figure 1 in 2020/21 in Braunschweig. Thus, wheat plants were exposed to varying degrees of competition through *V. arvensis*. The height of single plants was regularly measured. Data analysis is not complete yet, but first results (Fig. 3) shows wheat growth curves under high weed pressure and without weed pressure. The experimental results correspond quite well to our simulation results (Fig. 2).

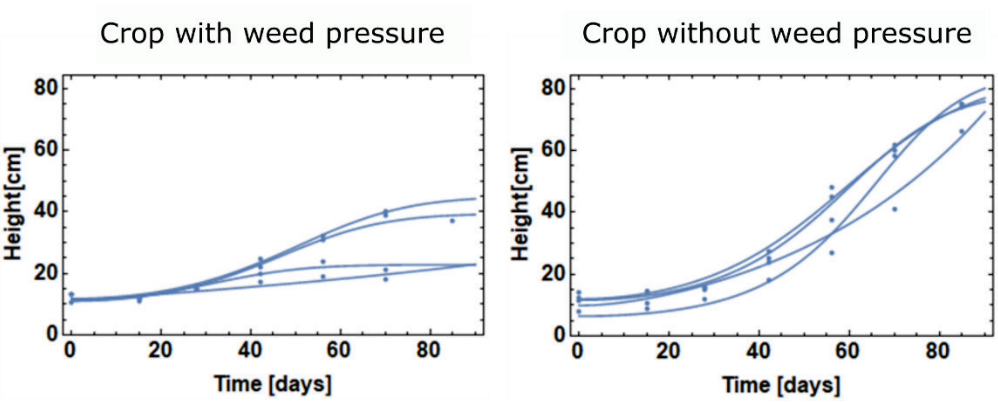

Figure 3 Measured growth curves of four wheat plants with (left) and without efficient weed control (right).

***Abbildung 3** Experimentell bestimmte Wachstumskurven von je vier Weizenpflanzen mit (links) und ohne Unkrautbekämpfung (rechts).*

Outlook

A spatial explicit model of plant growth based on individuals is a valuable tool for planning a meaningful management of crops and weeds plant-by-plant especially when using robots. The presented model is a first step in that direction. Still, the multispecies level needs to be extended. The community matrix for the example can be extended to several weed species in a straight forward way. Furthermore, the inclusion of fertilization, crop rotation, and weed control are necessary steps to come to a more realistic simulation of a field. To enable long term predictions, the model will be embedded in a time discrete and time continuous structure integrating growth processes and discrete stochastic processes like emergence, seed survival and others. In the future, models as presented here, might work as a tool to support decision making in weed management in the planning stage and on a yearly/daily level.

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