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Decision Support Systems for Weed Management in North China Plain Winter Wheat Production Systems

Dissertation
in fulfilment of the requirements for the degree
"Doktor der Agrarwissenschaften"
(Dr. sc. agr. / Ph. D. in Agricultural Sciences)
to the
Faculty of Agricultural Sciences
by
Alexander Menegat

born in Villingen-Schwenningen, Germany
2013

This thesis was accepted as a doctoral dissertation in fulfilment of the requirements for the degree "Doktor der Agrarwissenschaften” (Dr. sc. agr. / Ph. D. in Agricultural Sciences) by the Faculty of Agricultural Sciences at University of Hohenheim on 01.06.2012.

Date of oral examination: 28.09.2012

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Abbreviations and acronyms

∞	Infinity
D	Weed density
I	Yield per unit weed density
M_t	Number of mature weed plants
NR	Economic net profit
RU	Reproduction units
S_t	Number of produced seed per plant
SB	Weed seedling biomass
SD	Weed seedling density
SI	Weed seed input
SSB	Soil seed bank
Y	Yield
YL	Yield loss
Z_t	Emerged weed seedlings
2,4-D	(2,4-dichlorophenoxy)acetic acid
%	Percent
a.i.	Active ingredient
ACCase	Acetyl coenzyme A carboxylase
ALS	Acetolactate synthase

CAU	China Agricultural University
CCA	Canonical correspondence analysis
cm	Centimetre
DFG	Deutsche Forschungsgemeinschaft/German Research Foundation
DM	Dry matter
DSS	Decision support system
ED_{50}	Herbicide dose at which plant response is reduced by 50%
EPSPS	Enolpyruvylshikimate 3-phosphate synthase
ETH	Economic threshold based weed control strategy
F0	Dark fluorescence yield
Fm	Maximal fluorescence yield
Fv/Fm	Maximum quantum efficiency of PSII
GPS	Global positioning system
ha	Hectare
HTT	Hydro thermal time
IRTG	International Research Training Group
IWM	Integrated weed management
K	Potassium
kg	Kilogram
kPa	Kilo pascal
L	Litre
M	Mol

m	Metre
m^2	Square meter
mm	Millimetre
MOE	Ministry of Education of the Peoples Republic of China
N	Nitrogen
N_{min}	Soil available mineral nitrogen
NCP	North China Plain
NPK	Nitrogen-phosphorus-potassium fertilizer
NWC	No weed control
OPT	Optimized weed control strategy
P	Phosphorus
PSII	Photosystem two
RA	Risk-averse weed control strategy
RF	Resistance factor
RTK	Real time kinematic
s	second
t	Ton
TKM	Thousand kernel mass
TT	Thermal time
UHO	University of Hohenheim
°C	Degree centigrade
°E	Degree east/longitude
°N	Degree north/latitude

1 General Introduction

China is one of the fastest growing economies in the world where substantial economic, social and political changes took place in the past 20 years. The Chinese agriculture is affected by this changes in several ways. On the one hand the 1.3 billion people need to be fed while the area of arable land is decreasing caused by urbanization and land degradation. On the other hand, due to the high labour demand of a fast growing industrial sector, a shift of labour from agriculture to industry can be observed. In the past these challenges were met by maximizing yields through maximizing the use of resources.

Thus additional problems occur like massive nitrogen depositions into ground and surface water as well as gaseous nitrogen emissions, soil salinization due to constant irrigation as well as accumulation of pesticide residues in the food chain and environmental resources. Up to now, the rapid growing demand for food left no room for the development of a sustainable agricultural system. Additionally a boosting demand for meat and secondary processed food products can be observed, which will further force the demand for primary agricultural products like wheat and maize.

One of the main Chinese production areas for wheat and maize is the North China Plain (NCP) . The University of Hohenheim (UHO) maintains a close research cooperation with the China Agricultural University (CAU) aiming a sustainable improvement of the current cropping system in the NCP. Since 2004 the International Research Trainig Group (IRTG) , funded by the Deutsche Forschungsgemeinschaft (DFG) and the Ministry of Education (MOE) of the Peoples Republic of China, is focusing on the reduction of negative side effects of the intensive agricultural system practiced in the NCP, by identifying, measuring and modelling certain aspects of the NCP cropping system. In total eleven subprojects are working in the three research areas Material Flows and Pollution Analysis, Cropping Systems and Farm Level Assessment as well as Regional and Sectoral Assessment. The Department of Weed Science of the University of Hohenheim is part of the IRTG since 2008 and focuses on the development of a decision support system for weed management for the NCP cropping systems. The major objective of the decision support system is the reduction of negative side effects of herbicide use. This has to be achieved by improving herbicide selection, timing and dosage and by implementing integrated weed control measures into the actual cropping system towards a combination of chemical and non-chemical weed control measures. Ecological and economical consequences for farmers have to be considered as well as food safety issues of consumers.

1.1 Agricultural practice in the North China Plain region

The North China Plain is located in the north-eastern part of China and comprises parts of the seven provinces Beijing, Tianjin, Hebei, Shandong, Henan, Anhui and Jiangsu (Figure 1.1). The NCP covers an area of 31 million hectares whereof around 18 million hectares are used for agriculture. This accounts for 18% of the total agriculturally used area in China (Liu et al., 2001). By the year 2010 168 million inhabitants lived in this region of tension marked by rapid urbanisation and industrialization on the one hand and intensive agriculture on the other hand. However, 50% of the total national wheat production and around 30% of the national maize production has its origin in the NCP (Wu et al., 2006).

The studies presented in this thesis focus on the provinces Hebei and Shandong, which are characterized by the typical double cropping system of winter wheat (*Triticum aestivum* L.) followed by summer maize (*Zea mays* L.) in one year. Major constraints for crop production in the NCP are the climatic preconditions. The characteristic continental monsoon climate, with low rainfall during the winter wheat growing period and low radiation with high temperatures in summer during the summer maize growing period, is the major yield limiting factor (Figure 1.2). The average precipitation during the winter wheat growing period varies between 90 mm and 300 mm which makes irrigation inevitable (Wu et al., 2006). Around 71% of the cultivated land is irrigated, consuming 70% of the total water supply. The annually overuse of groundwater led into an ongoing decline of the groundwater level. The groundwater level decline affects crop production costs by the fact that intervals between the drilling of wells become shorter and exploiting cost increase due to increasing well depths, which range already between 40 m and 100 m (Liu et al., 2001).

Beneath the double cropping system of winter wheat followed by summer maize several other crops became important in the NCP region. In the past three years an increasing production of cotton and spring maize could be observed, which may be attributed to the higher economic profits which can be achieved with these crops.

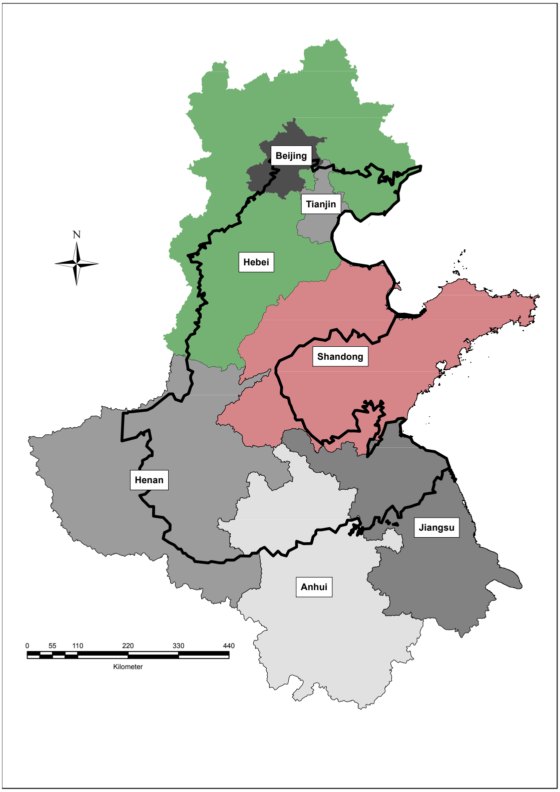

Figure 1.1: Provinces of the North China Plain (marked by bold line). Main focus regions of this study are the provinces Hebei (green) and Shandong(red)

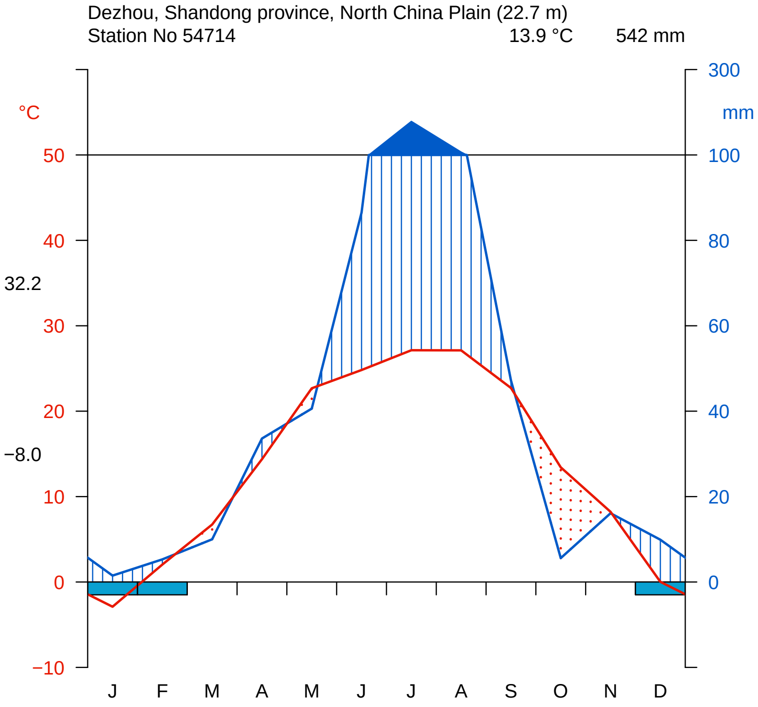

Figure 1.2: Climate diagram for Dezhou (N 37°45 E 116°31), central North China Plain. Frost likelihood is shown with flat rectangles underneath the 0°C axis. The blue vertical pattern depicts the humid months, while the red dots indicate when aridity prevails. In both cases, the corresponding areas give an idea of the intensity of the water surplus or shortage.
Data source: China Meteorological Administration.

1.2 Weed control practice in the North China Plain double cropping system

In the past 20 years weed control practice changed from hand weeding to mainly chemical measures in the present. Herbicide use was not very common before the 1980's, since Chinese herbicide consumption increased from 23,000 tons to more than 3.4 million tons in 2010 (CAYB, 2011). This development is caused by several aspects:

- An increasing profitability of crop production was caused by steady increasing yields. Average winter wheat yields for instance increased from 0.6 t ha^{-1} in the 1960's to 4.7 t ha^{-1} in 2010. The increased economic profit for farmers has made the use of herbicides affordable.

- Around 50% of the rural household labour is already working outside of the agricultural sector. The current labour input is approximately 3.3 persons per hectare (Löw, 2003) and the amount of land farmed by one family is steadily increasing which further encourages the use of herbicides (Su and Ahrens, 1997). Hand weeding is often no longer manageable and the use of herbicides became inevitable to maintain stable yields.

- Another key determinant may be the risk avoidance behaviour of the farmers. Because of the increased input of agricultural production factors like fertilizer and irrigation water, farmers don't tolerate yield losses, or rather economic losses, caused by weeds anymore. Studies by Löw (2003) in the North China Plain region confirm the positive correlation of for instance fertilizer consumption and pesticide use.

Results of surveys conducted in 2009 and 2010 in the framework of this thesis indicate that more than 80% of the winter wheat - maize fields are treated with herbicides. About 15% of the interviewed farmers don't use herbicides because labour for hand weeding was not a limiting factor. Only 5% of the farmers covered by this study refused the use of herbicides in general.

Up to now the herbicide choice is very limited. The main herbicides in winter wheat are 2,4-D and tribenuron-methyl followed by iodosulfuron, isoproturon, haloxyfop, clodinafop and fenoxaprop. For maize atrazin is still the most important herbicide followed by dicamba, mesotrione and foramsulfuron. Recently more and more herbicide resistant weed populations were confirmed, mainly populations of Flixweed (*Descurainia sophia* L.) which are resistant against tribenuron-methyl and Japanese foxtail (*Alopecurus japonicus* L.) populations which are resistant against haloxyfop (Cui et al., 2008; Yang et al., 2007).

1.3 Objectives of this thesis

General aim of this thesis is to develop a decision support system for weed management in North China Plain winter wheat production systems. Beyond the implementation of the model framework, the second focus is on the development of a rapid herbicide resistance screening method. This method should be capable to replace classical methods and support a proper herbicide selection of the decision support system in terms of herbicide resistance avoidance.
The major objectives are as follows:

- to get an overview on the most abundant weed species in North China Plain winter wheat fields,
- to evaluate possible integrated weed control strategies which can be included into the decision support system
- to develop a first approach of a decision support system for weed management in North China Plain winter wheat production systems
- to develop a rapid screening method for the detection of herbicide resistance in weeds for prospective herbicide resistance monitoring in the North China Plain region

Figure 1.3 shows the workflow for the realization of the decision support system. Green background colour marks the working packages which were realized during the first phase of the project and which are part of this thesis. Work pages marked in white will be part of the second phase of the project and will be worked out be the next PhD-student generation.

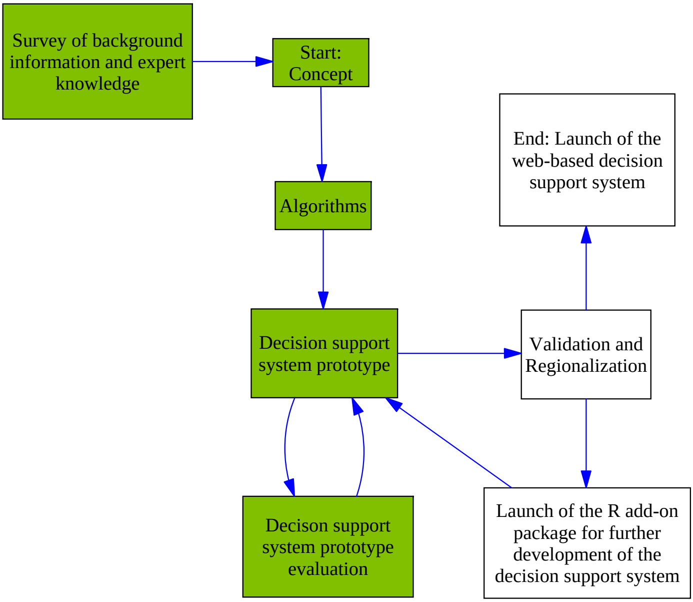

Figure 1.3: Working procedure for the development of the decision support system. Green background colour marks the steps which have been finished within this thesis. Work pages marked in white will be part of the second phase of the project and will be worked out be the next PhD-student generation.

1.4 Publications

The thesis consists of three articles which have been submitted to peer-reviewed and international high standard referenced journals:

1. Menegat A., O. Jäck, J. Zhang, K. Kleinknecht, B. U. Müller, H.-P. Piepho, H. Ni & R. Gerhards 2012. *Calystegia hederacea* WALL. abundance and response to winter wheat (*Triticum aestivum* L.) density and nitrogen fertilization in the North China Plain. *Weed Technology*, under review.
2. Menegat A., O. Jäck, C. Hao, H. Ni & R. Gerhards 2012. Integration of yield loss functions, herbicide dose-response and population dynamics in a modular weed management decision support model. *Weed Research*, under review.
3. Menegat A., Y. Kaiser & R. Gerhards. 2012. Chlorophyll fluorescence imaging microscreening: a new method for rapid detection of herbicide resistance in weeds. *Weed Research*, under review.

Beyond the publications presented in this thesis, four contributions to conference proceedings of international scientific symposiums were published as well as one more paper as co-author submitted. These articles are the interim reports of the research project and document the working progress of this thesis.

- Menegat A., C. Hao, H. Ni & R. Gerhards 2010. Multivariate analysis and description of weed abundance and weed competitiveness in North China Plain winter wheat production systems. *Proceedings 15th EWRS Symposium*, Kaposvar, Hungary.
  ISBN:978-963-9821-24-8

- Menegat A., Y. Kaiser, A. Stephan, H. Ni & R. Gerhards 2011. Chlorophyll fluorescence microscreening as a rapid detection method for herbicide resistance in grass weeds in North China Plain winter wheat production systems and beyond. *Proceedings 23rd Asian-Pacific Weed Science Society Conference*, Cairns, Australia.
  ISBN:978-0-987-1961-0-1

- Menegat A., C. Hao, H. Ni & R. Gerhards 2011. Weed species abundance in North China Plain winter wheat fields. *Proceedings 23rd Asian-Pacific Weed Science Society Conference*, Cairns, Australia.
  ISBN:978-0-987-1961-0-1

- Jäck O., A. Menegat, M. Weis, H. Ni & R. Gerhards 2011. Introduction of a nondestructive method for the investigation of herbicide efficacy in greenhouse bioassays based on image analysis. *Proceedings 23rd Asian-Pacific Weed Science Society Conference*, Cairns, Australia.
  ISBN:978-0-987-1961-0-1

- Hao C., A. Menegat, R. Gerhards & H. Ni 2012.Predicting Grabgrass emergence in Maize. *Weed Science*, submitted.

Aim of the **first article** presented in this thesis is to provide the basis for the development of a decision support system for weed management in NCP winter wheat fields. First, the major weed species and their abundance are presented based on a two year weed survey in more than 100 winter wheat fields in the NCP provinces Hebei and Shandong. Second, the effect of changes in fertilization practice and sowing density on weed competitiveness will be demonstrated. It is assumed that prospective changes in fertilization and general cropping practice will significantly affect weed species competitiveness and weed species composition. The article shows how the adjustment of these agronomic measures can help to reduce weed competitiveness and therefore to reduce the need for chemical weed control to an acceptable level.

Calystegia hederacea WALL. abundance and response to winter wheat (*Triticum aestivum* L.) density and nitrogen fertilization in the North China Plain

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Submitted to:
Weed Technology (2012)
Allen Press Inc., Lawrence, Kansas, USA

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2 *Calystegia hederacea* WALL. abundance and response to winter wheat (*Triticum aestivum* L.) density and nitrogen fertilization in the North China Plain

2.1 Summary

Japanese bindweed was found to be one of the most abundant and most difficult to control weed species during a two year weed survey in more than 100 winter wheat fields in the North China Plain region. Multivariate data analysis showed that Japanese bindweed is most abundant at sites with comparative low nitrogen fertilization intensities and low crop densities. To gain deeper insights into the biology of Japanese bindweed under various nitrogen fertilization intensities, winter wheat seeding rates, herbicide treatments and their interaction, a two year field experiment was performed. In unfertilized plots a herbicide efficacy of 22% for 2,4-D, and of 25% for tribenuron-methyl was found. The maximum herbicide efficacy in N_{min} fertilized plots was 32% for 2,4-D and 34% for tribenuron-methyl. In plots fertilized according the farmer's practice a maximum herbicide efficacy of 72% for 2,4-D and of 64% for tribenuron-methyl could be observed. Furthermore medium and high seeding rates improved the herbicide efficacy by at least 39% for tribenuron-methyl and 44% for 2,4-D compared to the low seeding rate. Without herbicide treatment neither different fertilization strategies nor different seeding rates affected Japanese bindweed density. The results indicate a positive correlation between increasing seeding rates and herbicide efficacy as well as increasing fertilization intensity and herbicide efficacy. Compared to the farmer's practice fertilization winter wheat yields were not significantly lower due to N_{min} fertilization when combined with high winter wheat seeding rates.

2.2 Introduction

The North China Plain (NCP) is one of the major crop production regions in China. In total 75% of the national wheat and 35% of the national maize production are harvested in this region (CAYB, 2011). In the NCP a double cropping system is usually followed where winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) are grown in a single year. The cropping system is characterized by high inputs of fertilizer, irrigation water and pesticides (Löw, 2003). Since the introduction of herbicides in China in the 1960's, weed control in the NCP has changed from hand weeding towards chemical control methods. The herbicide treated agricultural area in China has increased from less than one million hectares in the 1970's to more than 60 million hectares in 2000 (Zhang et al., 2003). Chemical weed control in winter wheat includes treatments in spring mainly with 2,4-D or tribenuron-methyl, followed by up to three times of hand weeding until harvest. The two mentioned herbicides are most common due to their comparatively low costs. The intensive use of herbicides has not eliminated weed problems. Farmer's report increasing abundance of difficult to control weed species like Japanese bindweed (*Calystegia hederacea* WALL.) since the 1980's. This is probably caused by low control efficacies of the standard weed control measures. Japanese bindweed is a perennial climbing weed, propagating by rhizomes and occasionally by seeds (Rhui-cheng and Brummitt, 1995). Data about the yield reductive effect of Japanese bindweed is still lacking. However, due to its climbing growth habitus (Figure 2.1) farmers are facing problems like lodging and in particular serious difficulties during wheat harvest. These problems are predominant rather than the yield reduction. Up to now there is no selective herbicide available which controls Japanese bindweed effectively, thus integrated control methods have to be considered. For other bindweed species effective control can be achieved by repeated tillage combined with several herbicide treatments under fallow conditions (Stone et al., 2005), but the economic reliance of NCP farmer's on the practiced double cropping system makes fallow an unacceptable option.

Due to the ongoing modernization of the Chinese agriculture, there is a chance to link Japanese bindweed control strategies to prospective agronomic changes in this system. Above all, the impact of changes in fertilization strategies and crop density on Japanese bindweed biology

Figure 2.1: Japanese bindweed infested winter wheat prior to harvest

has to be considered. Gao et al. (2009) and Fang et al. (2010) reported yield increasing effects as well as improved nitrogen use efficiency of winter wheat under increased winter wheat seeding rates. So far the effects of varying seeding rates on weed biology have not been evaluated under NCP growing conditions. In addition strong efforts were made in the past to reduce fertilizer inputs. Several studies were conducted in the NCP with focus on the effect of reduced nitrogen fertilizer inputs. A promising method for reducing nitrogen inputs could be the N_{min} method. For this method the applied nitrogen fertilizer amount is determined by deducting the amount of soil N_{min} in the root zone from the target N value, which is estimated based on yield target and crop N uptake (Wehrmann et al., 1982; Chen et al., 2006a; Meng et al., 2012). Zhao et al. (2006) conducted a four-year study in the NCP with the result that the implementation of N_{min}-based fertilization strategies did not reduce yield of winter wheat while reducing the nitrogen leaching losses substantially. Similar results can be found in studies by Zhao (1997), Chen et al. (2004),Cui (2005) and Chen et al. (2006a). Our hypothesis is that the efficacy of chemical control measures can be improved by lowering Japanese bindweed competitiveness through changes in seeding rate and/or fertilization strategy. The first objective of this study is to assess Japanese bindweed abundance in dependency of nitrogen fertilization intensity and winter wheat seeding rate. Secondly the actual abundance of Japanese bindweed in NCP winter wheat fields in relation to other main weed species will be assessed. For this purposes a two year weed survey in more than 100 winter wheat fields in the NCP was conducted. To gain deeper insights into the biology of Japanese bindweed under various nitrogen fertilization intensities, winter wheat seeding rates, herbicide treatments and their interaction, a two year field experiment was performed. The experimental factors shall be investigated with regard on their effect on winter wheat yield and yield components as well.

2.3 Materials and Methods

Weed surveys conducted in the North China Plain region Weed surveys were carried out in 2009 and 2010. Surveys took place at winter wheat tillering (GS 20 - 25). During this period weeds had emerged, but herbicide application had not yet taken place. Only fields with a typical double-cropping system of winter wheat and summer maize were sampled. Counties with different major cropping systems than the double cropping system were disregarded. At each sampling site four sub-samples were randomly selected with a size of 1.0m*1.0m. The distance between the field margin and the sub-samples was at least 5 m, to minimize its impact on weed species composition. In this way 106 winter wheat fields were surveyed over a period of two years.

Weed species abundance was summarized by three quantitative measures according to Thomas (1985). Frequency of species k (F_k) was the number of fields where species k was present, expressed as percentage of the total number of sampled fields. Field uniformity (U_k) stands for the number of sub sumples at one sampling site in which species k occurred, expressed as percentage of the total number of sub samples. Mean field density of species k was calculated by totalling the field density of species k, divided by the total number of surveyed fields (D_k). To summarize the species abundance, the mentioned measures were combined into the single value relative abundance (RA_k) which was calculated according to (Thomas, 1985). Weed species were subsequently ranked according to RA_k.

In each subsample, winter wheat density was determined and averaged over the sub-samples. In addition soil samples to a depth of 30 cm were taken in each subsample and mixed for further analyses. For soil nitrate analyses the soil samples were sieved to 2 mm and homogenized. 100 g of the soil sample was mixed with 100 ml of a 0.01 M $CaCl_2$ –solution and shaken for 30 min. The solution was filtered with a folded filter paper and soil nitrate content was measured reflectometrically with test strips (Reflectoquant Nitrate Test, Merck, Germany) and a portable reflectometer (RQflex®10, Merck, Germany).

In addition to the mentioned agronomic factors crop density and fertilization intensity, several environmental constraints namely soil type, soil pH, latitude as well as precipitation and temperature sum for the winter wheat cropping period were assessed. All assessed variables were used to perform the multivariate analysis but due to the focus of this paper on agronomic constraints only results for crop density and nitrogen fertilization intensity are presented. Canonical Correspondence Analysis (Braak, 1986) was realized in the statistical language *R* (*R* Development Core Team 2010) respectively with the *R* add-on package vegan (Oksanen, 2011). Species that occurred in less than three fields as well as sites with no weed occurrence were deleted from the data set. The CCA was finally done for 10 species with a relative abundance $RA_k > 4.0$. The significance of all constraints was tested by a permutation test with 1000 cycles.

The primary result of a CCA is an ordination diagram, which consists of the following elements: points for species and arrows for the quantitative agronomic variables. The diagram can be interpreted in the following way: the coordinates of the species points are the values of the species of the two principal axes (CCA1 and CCA2). The arrow for agronomic variables points in the direction of maximum change of the variable across the diagram. Its length is proportional to the rate of change in this direction (Braak, 1987). The values of the species increase towards the arrow head of the environmental variable and decrease in the opposite direction. The endpoint reflects the relative positions of the weighted average of each species with respect of the environmental variable (Braak, 1986). In general the approximate ranking of weighted averages for a particular variable can be seen from the order of the endpoints of the perpendiculars of the species along the axis for that variable. For better interpretability of the ordination diagram, contours of the agronomic variables are displayed additionally within the ordination diagram (Dixon, 2003).

Field experiment site description and general crop management procedures The field experiments were conducted during the cropping seasons 2010/2011 and 2011/2012 as an on-farm approach on a local farmer's field in Beijing, Shangzhuang Village, China (N 40° 7.84, E 116° 9.98). The experimental site is characterized by a double cropping system of winter wheat followed by summer maize in one year. Soil type at the experimental site is a calcareous alluvial soil (calcareous cambisol, FAO Classification) with a loamy texture. The long-term yearly precipitation is 480 mm whereof 115 mm account for the winter wheat cropping period. In accordance with the farmer's practice in that region, the experimental site was irrigated four times, once in autumn after sowing and three times from the beginning of growth period in spring until harvest. In total, 350 mm of irrigation water were added in each winter wheat growing season using a movable sprinkler system. The initial soil nitrogen content in October was 22 kg ha^{-1} as nitrate and 5 kg ha^{-1} as ammonium in 2010 and 25 kg ha^{-1} as nitrate and 4 kg ha^{-1} as ammonium in 2011 at a soil pH of 7.5. Winter wheat was sown at the beginning of October after tilling the soil with a rotary tiller to a depth of 10 cm and harvested at the beginning of June. A winter wheat row spacing of 12.5 cm was realized with a conventional seed drill with double-disk openers and simultaneous fertilizer deposition.

Experimental design The experiment comprised three factors with three levels each: seeding rate, fertilizer and herbicide. The treatment factors fertilizer and seedling rate were randomized as a strip-plot design with four replicates. The factor fertilizer was randomized among columns, while the factor seeding rate was randomized among rows. Thus, rows and columns of a replicate formed the main plots for seeding rate and fertilizer, respectively. Each column was subsequently divided into three sub-columns. The intersection of sub-columns with rows of a replicate defines the subplots of the design. As a result we had nine subplots within each main plot. Within each fertilizer-main plot we randomized the herbicide treatments according to a 3 x 3 Latin square design (Figure 2.2). This design was chosen deliberately in order to provide high precision for herbicide comparisons. The chosen experimental design allows investigations of the interaction between experimental factors as well as their main effects.

Seeding rates Winter wheat cultivar Jingdong12 was used in three seeding rates with a thousand kernel weight of 41.6 g. For the low seeding rate 187 kg ha^{-1} were used aiming an initial crop density in spring of 150 plants m^{-2}. The medium seeding rate meets the farmer's practice with 273 kg ha^{-1}, aiming for a crop density of 250 plants m^{-2}. For the high seeding rate 378 kg ha^{-1} was used, aiming for a crop density of 350 plants m^{-2}. The discrepancy between seeding rates and target crop density take account for high winter wheat seedling losses due to frost damage in the NCP region.

Fertilization strategies In addition to an unfertilized control a fertilization strategy according to farmer's practice (subsequently named 'farmer's practice'), and an optimized fertilization strategy according to soil mineral nitrogen content analysis (subsequently named 'N_{min}'), as proposed by Chen et al. (2006b) and Cui (2005), were applied. Farmer's practice fertilization implied three fertilizer applications during the winter wheat cropping period. The first fertilization was carried out simultaneously to winter wheat sowing with an amount of 59 kg N ha^{-1} (standard mineral NPK compound fertilizer, 15% N, 15% P, 15% K). For the second fertilization at the beginning of winter wheat tillering, a total nitrogen amount of 166 kg ha^{-1} (urea) was applied as top-dressing followed by irrigation. For the third fertilization at the beginning of winter wheat stem elongation 51 kg N ha^{-1} were applied (urea) as top-dressing followed by irrigation. In total 276 kg N ha^{-1} were used in the farmer's practice fertilization plots. As basis for the fertilizer treatments according to the N_{min} method, soil nitrogen analyses were done for each plot prior to the fertilization decision at the beginning of winter wheat regreening. Samples of each sub-plot were mixed, sieved to a particle size of 2 mm and extracted with a 0.01 M $CaCl_2$- solution. Nitrate and ammonium contents of the soil solutions were analyzed by Continuous Flow Analysis (TRAACS 2000, Bran and Luebbe, Germany). Fertilization took place in spring at the beginning of winter wheat tillering. Due to sufficiently high soil nitrogen contents at winter wheat growth stages stem elongation and flowering, no additional fertilizations were carried out. The amount of nitrogen to be applied was calculated according the estimated yields for the respective seeding rates. Therefore, between 138 kg N and 306 kg N ha^{-1} were applied. The crop density dependent nitrogen demand was added as a 1:1 mixture of NPK and urea fertilizer as top-dressing followed by irrigation. Based on the results of He et al. (2007), an air-born nitrogen deposition of 20 kg ha^{-1} was included in the nitrogen demand calculation. For the nitrogen demand calculation, an average grain protein content of 14% was assumed.

Herbicide treatments Beside an untreated control, treatments with 2,4-D at a rate of 427.5 g a.i. ha^{-1} and tribenuron-methyl at a rate of 85.5 g a.i. ha^{-1} were realized. Both herbicides as well as their respective dosages are the most common and are widely used in the NCP winter wheat cropping system against broadleaved weed species. Herbicides were applied by a one nozzle backpack-sprayer at a spray volume of 200 l ha^{-1}. The herbicide efficacy (HE) was calculated according to the equation 2.1:

$$HE = \frac{NWC - WC}{NWC} * 100 \tag{2.1}$$

where NWC stands for Japanese bindweed densities (plants m^{-2}) in plots without chemical weed control and WC for Japanese bindweed density in plots with chemical weed control.

Sampling procedure Plant samplings were done at the time of winter wheat flowering. Therefore each subplot contained a separated sampling area of 3 m^2 which was separated from the subplot area reserved for the final winter wheat harvest. Japanese bindweed density and biomass as well as winter wheat biomass were assessed by harvesting 0.5 m^2 per subplot. For wheat and Japanese bindweed biomass determination plant material was separated and dried at 40°C for 7 days. For the final winter wheat grain and straw yield determination 3 m^2 per plot were harvested by hand. Ears were separated from straw and threshed out with a mechanical laboratory thresher. Grain nitrogen content was determined by an elementary analyzer (vario Max CNS, Elementar GmbH, Germany).

Statistical analysis Data were analyzed by mixed models using SAS PROC MIXED (SAS 2011). The model used for analysis was:

$$\begin{aligned} Y_{ijkqr} &= \mu + rep_r + \alpha_i + \beta_j + \gamma_k \\ +(\alpha\beta)_{ij} &+ (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} \\ &+g_{ijr} + h_{qjr} + v_{ir} + w_{jr} + e_{ijkqr} \end{aligned} \tag{2.2}$$

with the dependent variable Y_{ijkqr}, μ is the overall mean, rep_r is the $r-th$ replication, α_i is the effect of the $i-th$ seeding rate, β_j is the effect of the $j-th$ fertilizer treatment, γ_k is the $k-th$ herbicide treatment, $\alpha\beta_{ij}$ is the $ij-th$ seeding rate-by-fertilizer treatment interaction, $\alpha\gamma_{ik}$ is the $ik-th$ seeding rate-by-herbicide treatment interaction, $\beta\gamma_{jk}$ is the $jk-th$ fertilizer treatment-by-herbicide treatment interaction, $\alpha\beta\gamma)_{ijk}$ is the ijk-th seeding rate-by-fertilizer treatment-by-herbicide treatment interaction, g_{ijr} is the $i-th$ row effect of the Latin square within the $jr-th$ fertilizer-by-replication combination, h_{qjr} is the $q-th$ column effect of the latin square within the $jr-th$ fertilizer-by-replication combination, v_{ir} is the main-plot error in the $r-th$ replication for the $i-th$ seeding rate, w_{jr} is the main-plot error in the $r-th$ replication for the $j-th$ fertilizer treatment and e_{ijkqr} is the residual error. The error-effects were the only random effects. The Kenward-Roger method (Kenward and Roger, 1997) was used to approximate the denominator degrees of freedom for the computed tests.

Variance homogeneity and the normal distribution of the residuals were checked visually. In cases, that did not meet the preconditions to perform the mixed model analysis, the data was transformed by a square root transformation. Displayed means requiring a transformation are back transformed from the transformed scale and therefore represent estimates of medians rather than expected values (Piepho, 2009). Means were compared for statistically significant differences by Fisher's least significant differences (LSD).

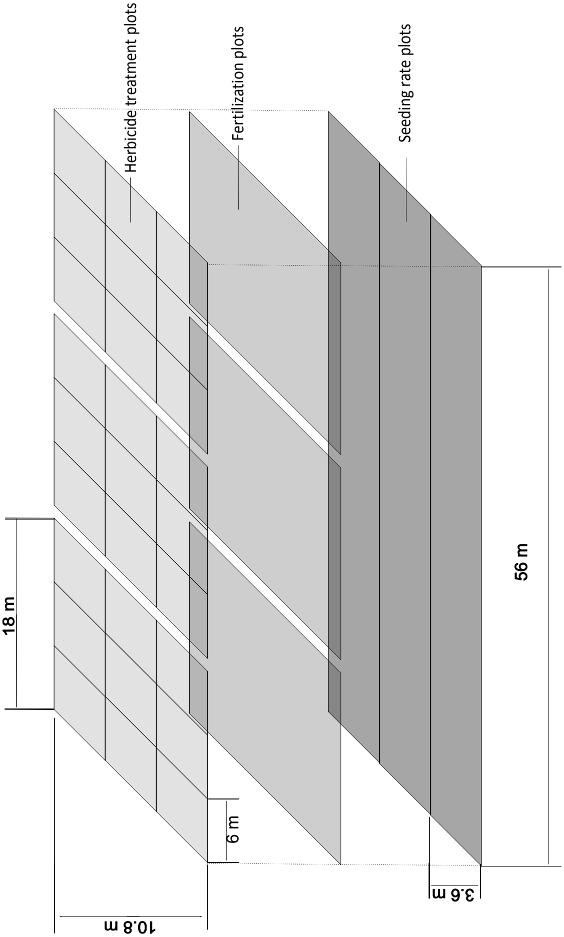

Figure 2.2: Field experiment layout per replicate

2.4 Results and Discussion

Japanese bindweed abundance in North China Plain winter wheat fields Species mean field densities suggest comparatively low weed pressure even for the most abundant species (Table 2.1). This may be attributed to the intensive use of herbicides on the one hand and to frequent hand weeding measures on the other hand. Evidence from the literature for this finding is not available. Likewise notable is the low species diversity found in NCP winter wheat fields. Thus only 16 species were found with a relative abundance >1. Nine out of these 16 species were found in less than 10% of the investigated fields. One explanation for this phenomenon could be the intensive use of fertilizers for the past 20 years and the related selection of nitrophilic weed species. This hypotheses is supported by the result, that five out of the 10 most abundant weeds were found on sites with soil nitrate contents in spring higher than 200 kg ha^{-1} (Figure 2.3). Results by Haas and Streibig (1982), Iqbal and Wright (1997) and Andreasen et al. (2006) for instance describe a positive correlation between fat-hen (*Chenopodium album* L.) biomass accumulation and increased nitrogen fertilization rates. Similar results were found by Mokhtassi-Bidgoli et al. (2013) for flixweed (*Descurainia sophia* L.), which produces significant more biomass and seeds under high nitrogen fertilization as well. However, sheperd's purse (*Capsella bursa-pastoris* L.) is classified as a poor competitor under high fertility conditions (Paul and Ayres, 1990; Andreasen et al., 2006). The position of sheperd's purse in the biplots (Figure 2.3 and Figure 2.4) near the origin indicate the low discriminating power of nitrogen fertilization intensity and crop density for this species and thus demonstrates Japanese bindweed was found in 14% of the investigated winter wheat fields with a mean field density of 8 shoots m^{-2} (Table 2.1). Japanese bindweed ranks beneath flixweed, shepherd's purse and goosefoot as one of the most abundant species in NCP winter wheat fields. Sites with comparative moderate soil nitrogen contents in spring (100 – 150 kg soil nitrate-N ha^{-1}) are preferred by Japanese bindweed. Regarding crop density, the species prefers low winter wheat densities with less than 100 plants m^{-2} (Figure 2.4).

Table 2.1: Ranking of the most abundant weed species in NCP winter wheat fields according to their relative abundance (RA_k). MFD= Mean field density. Frequency=frequency of species occurrence.

Code	Common name	EPPO Code	Relative abundance RA_k	Frequency [%]	MFD [plants/m^2]
1	Flixweed	DESSO	96.04	76.56	18.48
2	Shepherd's purse	CAPBP	43.68	37.50	6.63
3	Fig-leafed goosefoot	CHEFI	31.86	15.63	12.39
4	Japanese bindweed	CAGHE	24.26	14.06	8.13
5	Fat-hen	CHEAL	23.91	12.50	8.47
6	Goatgrass	AEGSQ	16.41	15.63	1.92
7	Bastard alkanet	LITAR	15.52	12.50	2.97
8	Japanese brome	BROJA	13.86	7.81	4.69
-	Volunteer barley	HORVU	10.91	9.38	0.31
9	Conoid catchfly	SILCD	7.96	7.81	0.86
10	Wild oat	AVEFA	4.50	4.69	0.19
-	Harrif	GALAP	3.85	1.56	1.76
-	Japanese foxtail	ALOJA	2.89	3.13	0.05

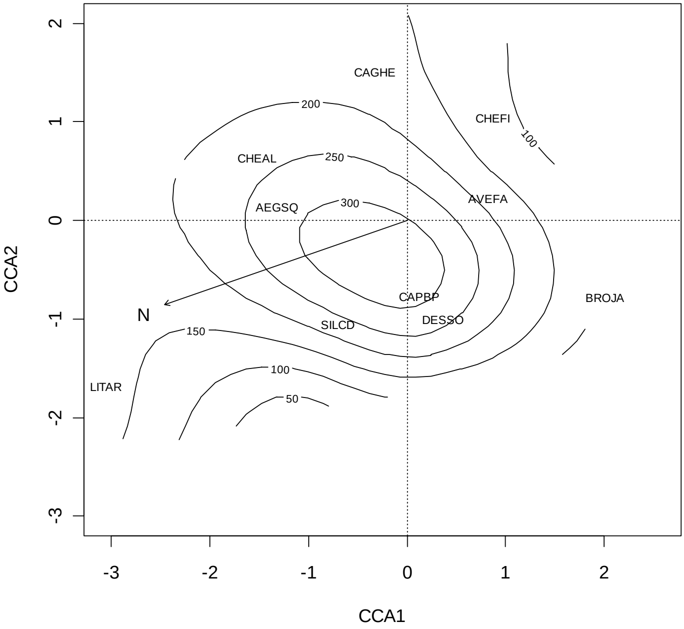

Figure 2.3: Ordination diagram for the agronomic variable soil nitrate content (N). Isobars= soil nitrate content [kg ha^{-1}]. For species EPPO code see Table 2.1

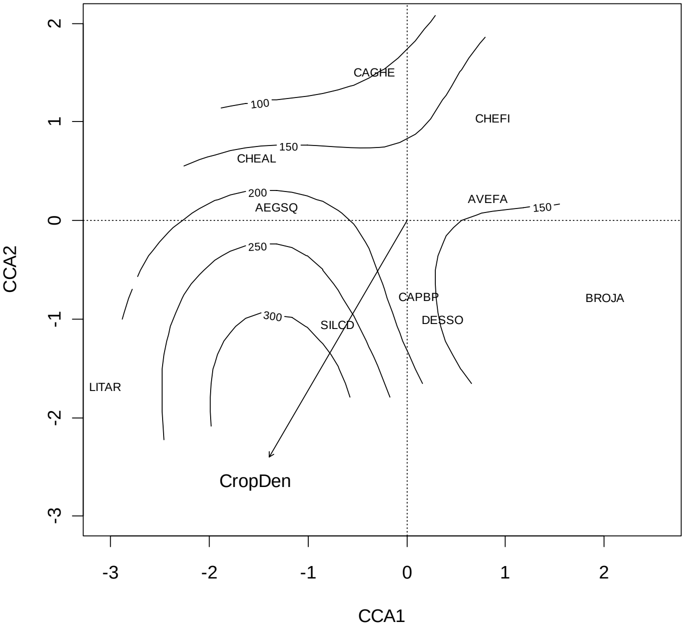

Figure 2.4: Ordination diagram for the agronomic variable winter wheat density (CropDen). Isobars = winter wheat density [plants m^{-2}]. For species EPPO code see Table 2.1

Effect of fertilization strategy, herbicide treatment and sowing density on Japanese bindweed in field experiments Japanese bindweed was the major weed species at the experiment location. Other weed species present in the experimental field occurred in negligible densities.

At the time of winter wheat flowering significant influences of fertilizer treatment on herbicide efficacy and thus on Japanese bindweed density could be observed (Table 2.2 top). The various fertilization strategies did not significantly influence the species density when considering plots without herbicide treatment. Vertical assessment of unfertilized control plots shows a herbicide efficacy of 22% for 2,4-D, and 25% for tribenuron-methyl. In plots fertilized according N_{min}, both herbicide treatments lead to significantly reduced Japanese bindweed densities compared to the untreated control, although density values are only slightly lower compared to the unfertilized control. In plots fertilized according to the farmer's practice both herbicide treatments led to significant density reduction compared to unfertilized control plots and plots fertilized according the N_{min} method. The maximum herbicide efficacy in Nmin plots was 32% for 2,4-D and 34% for tribenuron-methyl. In plots fertilized according the farmer's practice a maximum herbicide efficacy of 72% for 2,4-D and 64% for tribenuron-methyl could be calculated.

For both tested herbicides a significant promoting effect of the farmer's practice fertilization strategy on herbicide efficacy was found. In this context Shaw et al. (1985) reported significantly inhibited basipetal movement of 2,4-D to the roots in field bindweed (*Convolvulus arvensis* L.). The authors suggested that deficiencies of N or P limit the protein synthesis and thus inhibits the carrier protein-mediated uptake and basipetal movement of 2,4-D. An explanation for the enhanced efficacy of tribenuron-methyl under high nitrogen availability could not be found in literature so far. At the time of winter wheat flowering significant influences of winter wheat seeding rate on herbicide efficacy could be observed (Table 2.2, bottom). Horizontal assessment of Table 2.2 shows no significant difference between seeding rates on herbicide efficacy. Although horizontal density differences are not significantly different, it should be mentioned that medium and high seeding rates compared to the low seeding rate improved the herbicide efficacy by at least 39% for tribenuron-methyl and 44% for 2,4-D. Vertical comparison in Table 2.2 (bottom) confirms the significant density reduction of Japanese bindweed under medium and high winter wheat seeding rates.

Japanese bindweed biomass was significantly influenced by fertilization strategy, seeding rate and herbicide treatment (Table 2.3). Both, N_{min} fertilization and farmer's practice fertilization reduced the bindweed biomass significantly compared to the unfertilized control. Same result was found for the herbicide treatments with 2,4-D and tribenuron-methyl. With increasing seeding rates a significant reduction of the species biomass could be observed as well.

It can be concluded that increased winter wheat seeding rates inhibit Japanese bindweed competitiveness due to the biomass reductive effect which may lead to the observed enhanced herbicide susceptibility under high seeding rates. Evidence from literature for this hypothesis is not available so far. As expected from the survey results, reduced fertilization intensity and low winter wheat seeding rates are promoting Japanese bindweed biomass accumulation and hence the species competitiveness. Therefore the hypotheses gained from the weed survey could be confirmed.

Table 2.2: Effect of fertilization strategy (top) and seeding rate (bottom) on Japanese bindweed density (plants m^{-2}) and herbicide efficacy (%).

	Fertilizer treatment					
	Unfertilized control		N_{min}		Farmer's practice	
Herbicide treatment						
No weed control	36	a A*	38	a A	39	a A
2,4-D (427.5 g a.i. ha^{-1})	28	ab A	26	b A	11	b B
Tribenuron-methyl (85.5 g a.i. ha^{-1})	27	b A	25	b A	14	b B

	Winter wheat seeding rate					
	187 kg ha^{-1}		273 kg ha^{-1}		378 kg ha^{-1}	
Herbicide treatment						
No weed control	34	a A*	39	a A	41	a A
2,4-D (427.5 g a.i. ha^{-1})	29	a A	16	b A	18	b A
Tribenuron-methyl (85.5 g a.i. ha^{-1})	30	a A	16	b A	20	b A

* Means in the same column followed by a common lowercase letter are not significantly different at p=0.1. Means in the same row followed by a common capital letter are not significantly different at p=0.1.

Effect of fertilization strategy and sowing density on winter wheat yield and yield components Winter wheat yield and biomass accumulation was influenced by an interaction of seeding rate and fertilization strategy. With increasing fertilization intensity winter wheat biomass was significantly increased compared to the unfertilized control plots for all tested seeding rates (Table 2.4). Only within the N_{min} fertilization strategy winter wheat biomass increase was significant along increased seeding rates. Farmer's practice plots accumulated on average 46% more biomass compared to the unfertilized plots and 28% more biomass compared to the N_{min} treated plots. This result goes in line with the weed suppressive effects discussed before.

Plots fertilized according to farmer's practice showed highest yields (Table 2.5). Changes in seeding rate did not influence yields within the fertilization strategies. The chosen winter wheat cultivar seems to be able to compensate reduced seeding rates by increased production of biomass. Regarding nitrogen use efficiency the chosen cultivar seems not to be suitable for reduced nitrogen fertilization intensities when considering the yield effects. Probably this finding can be compensated by splitting the N_{min} fertilization in two to three treatments as suggested by Meng et al. (2012) and Chen et al. (2006a).

The trait ears m^{-2} was influenced by both fertilization strategy and seeding rate (Table 2.6). The farmer's practice fertilization strategy and the highest seeding rate resulted in significantly increased numbers of ears m^{-2}. In contrast the highest seeding rate resulted in a significant reduction of grains per ear by 30%. Both fertilization strategies resulted in an increased number of grains per ear. Grain protein content of the unfertilized control was significantly lowered compared to the fertilized plots. With increased seeding rates the grain protein content was significantly increased as well, whereas the harvest index was only slightly increased by increased fertilization intensity. Grain protein content was furthermore increased by 2,4-D treatment. This is a known phenomenon which was also reported in the study by Pellett and Saghir (1971). This field experiments demonstrated that reduced nitrogen fertilizer inputs affect both, crop and weed. The results show that due to increased winter wheat seeding rates crop competitiveness against Japanese bindweed was enhanced which led into reduced bindweed biomass accumulation and enhanced susceptibility to herbicides.

Table 2.3: Effect of fertilization strategy, seeding rate and herbicide treatment on Japanese bindweed biomass at beginning of winter wheat flowering.

	Japanese bindweed dry matter (g m^{-2})	
Fertilizer treatment		
Unfertilized control	6.1	a*
N_{min}	5.8	b
Farmer's practice	4.0	b
Winter Wheat seeding rate		
187 kg ha^{-1}	6.5	a
273 kg ha^{-1}	5.2	b
378 kg ha^{-1}	4.2	c
Herbicide treatment		
No weed control	6.5	a
2,4-D (427.5 g a.i. ha^{-1})	4.8	b
Tribenuron-methyl (85.5 g a.i. ha^{-1})	4.6	b

* Means in the same column followed by a common letter are not significantly different at p=0.05.

Table 2.4: Effect of seeding rate and fertilizer treatment on winter wheat biomass at flowering (g ATM m^{-2})

	Fertilizer treatment					
	Unfertilized control		N_{min}		Farmer's practice	
Winter wheat seeding rate						
187 kg ha^{-1}	601	a A*	685	a B	877	a C
273 kg ha^{-1}	572	a A	711	a B	870	a C
378 kg ha^{-1}	645	a A	713	b AB	768	a B

* Means in the same column followed by a common lowercase letter are not significantly different at p=0.05. Means in the same row followed by a common capital letter are not significantly different at p=0.05.

Table 2.5: Effect of seeding rate and fertilizer treatment on winter wheat yield (t ha^{-1}).

	Fertilizer treatment					
	Unfertilized control		N_{min}		Farmer's practice	
Winter wheat seeding rate						
187 kg ha^{-1}	4.2	a A*	4.9	a B	6.0	a C
273 kg ha^{-1}	3.8	a A	4.4	a B	5.6	a C
378 kg ha^{-1}	4.2	a A	5.1	a B	5.4	a B

* Means in the same column followed by a common lowercase letter are not significantly different at p=0.05. Means in the same row followed by a common capital letter are not significantly different at p=0.05.

Table 2.6: Effect of fertilizer treatment, seeding rate and herbicide treatment on yield components of winter wheat.

	Winter wheat yield components			
	Ears m^{-2}	Grains ear^{-1}	Grain protein content (%)	Harvest index
Fertilization strategy				
Unfertilized control	413 a	32 a	14.3 a	0.57 a
N_{min}	445 a	35 b	15.0 b	0.56 a
Farmer's practice	546 b	34 ab	15.0 c	0.60 b
Winter Wheat seeding rate				
187 kg ha^{-1}	407 a	40 a	14.8 a	0.59 a
273 kg ha^{-1}	439 a	33 b	14.9 ab	0.59 a
378 kg ha^{-1}	559 b	29 c	15.2 b	0.59 a
Herbicide treatment				
No weed control	462 a	33 a	14.8 a	0.57 a
2,4-D (427.5 g a.i. ha^{-1})	463 a	34 a	15.1 b	0.58 a
Tribenuron-methyl (85.5 g a.i. ha^{-1})	474 a	33 a	14.9 a	0.58 a

* Means in the same column followed by a common letter are not significantly different at p=0.05.

To minimize crop yield losses under N_{min} fertilization, cultivars with high nitrogen use efficiency have to be preferred and fertilization measures have to be split in the future. Therefore additional field experiments have to be conducted to test different cultivars on their performance under the described agronomic changes. To prevent increasing problems with Japanese bindweed due to reduced fertilizer inputs, farmers can consider increased winter wheat seeding rates combined with chemical weed control measures. Both tested herbicides were not able to control Japanese bindweed density by more than 72%. Therefore other herbicides have to be tested regarding their control efficacy. To prevent problems in the short term at sites with high Japanese bindweed pressure we suggest a pre-harvest application with glyphosate. This measure would at least minimize difficulties during harvest. Further research has to be done for detailed description of Japanese bindweed biology regarding emergence patterns, density dependent yield reduction and population dynamics.

The **second article** gives an overview on the modelling approach of the decision support system and is documenting the model construction. The model approach focuses on chemical weed control measures although the possibility for integration of non-chemical weed control measures is given. The article highlights the potential of reducing the herbicide use to a minimum while maintaining the current yield potentials, economic net returns and avoiding the development of herbicide resistant weed populations. The agronomic preconditions described and discussed in the first article served as basis for the developed modelling approach.

Integration of yield loss functions, herbicide dose-response and population dynamics in a modular weed management decision support model

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Submitted to:
Weed Research (2012)
Wiley-Blackwell, Hoboken, NJ, USA

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3 Integration of yield loss functions, herbicide dose-response and population dynamics in a modular weed management decision support model

3.1 Summary

Avena fatua L. (wild oat) is considered as one of the most abundant and most competitive grass weed species in intensive cereal cropping systems worldwide. The objective of this study was to develop a computerized decision model for control of *A. fatua* in winter wheat based on results of dose-response studies, yield-loss functions and population dynamic parameter derived from field trials. A maximum yield loss of 40% was measured for *A. fatua* densities higher than 200 plants m^{-2} or respectively 60 g weed DM m^{-2} prior to weed control decision. Yield loss functions were equal in both years. Seed production tended to be reduced under dry and warm weather conditions. A maximum of 6,000 seeds m^{-2} were produced at highest weed density. Four different decision rules were simulated over a period of five years based on the presented experimental data. Weed control decisions were aimed to minimize yield losses due to weed competition and reduce weed seed density. The model output demonstrates that grain yield, accumulated over five years of simulation, was equal for all decision rules except for the untreated control where 30% yield loss was calculated. Accumulated herbicide rates were reduced by 40% in the economic threshold strategy and by 50% in the 'optimized' decision rule compared to the strategy with the full dose in every year. Only the 'optimized' decision rule and the full dose-strategy were able to reduce the population density. The simulation highlights the potential for herbicide dosage reduction in intensive winter wheat cropping systems.

3.2 Introduction

Avena fatua L. (wild oat) is considered as one of the most abundant and most competitive grass weed species in intensive cereal cropping systems worldwide, with an economic weed threshold of 2-3 plants m^{-2} (Cousens et al., 1986). It is an annual grass emerging predominately in early spring and maturing shortly before harvest of winter wheat. During a weed survey in two provinces of the North China Plain (NCP), *Avena fatua* L. was determined as one of the most abundant weed species (Menegat et al., 2011). The common production practice in the (NCP) is a double cropping system of winter wheat (*Triticum aestivum* L.) followed by summer maize (*Zea mays* L.) in one year (Liu et al., 2005). Despite of intensive use of herbicides combined with mechanical weeding, population densities of *A. fatua* in winter wheat have even increased (Dauerlein et al., 2003). Several reasons for high weed infestations are being discussed including inappropriate timing and application technology, wrong selection of herbicides and herbicide resistant weed populations. Expert systems and decision rules for weed control in winter wheat and other crops in the NCP are still lacking. Several studies in other agricultural areas 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; Cousens et al., 1986; Gerowitt and Heitefuss, 1990; Zanin et al., 1993). Yield loss due to weed competition was modelled based on early observations of weed density and coverage (Cousens, 1985; Kropf and Spitters, 1991). Population dynamic models were developed to determine the long-term effects of weeds in arable fields and to estimate the spatial and temporal variations of weed populations (Pandey and Medd, 1991; Cousens and Mortimer, 1995; Jones and Medd, 1997). Dose-response studies were carried out to correlate herbicide efficacy with weed biomass (Streibig, 1988). The objective of this study was to develop a computerized decision model to control *A. fatua* in winter wheat. Weed control decisions were aimed to minimize yield losses due to weed competition and reduce weed seed input. For model parameterization, dose-response data, yield-loss data and population dynamic parameters were assessed in two-year field studies and greenhouse trials. The second aim was to use this data in a five-year simulation of four different weed control decision rules including an economic weed threshold model with adjusted dose-rates (OPT), an economic weed threshold model with constant dose-rates (ETH), a constant use of the recommended dose-rate (RA) and no treatment at all (NWC). We hope that weed control decision rules help reducing the negative side-effects of herbicides, such as crop injury, herbicide residues in the food chain, costs for weed control, contamination of the environment and the evolution of persistent weed populations.

3.3 Materials and Methods

Experimental sites and climatic conditions Winter wheat field experiments were conducted in Germany at the University of Hohenheim experimental station 'Ihinger Hof' (48º27´36˝ N, 8º33´36˝ E) during cropping seasons 2009/2010 and 2010/2011. The forty year average annual rainfall at the experimental site is 690 mm and the mean temperature is 7.0°C. Soil type is loam. Rainfall and average temperatures during the season 2009/2010 (Figure 3.1, A) were within the 40-year average range of the experimental site. The season 2010/2011 (Figure 3.1, B) was characterized by a dry and warm period between April and May resulting in moderate drought stress for both, crops and weeds.

Experimental design A complete randomized block design with four repetitions was selected for this study. Winter wheat cultivar 'Schamane' was sown at a density of 330 seeds m^{-2} and a row distance of 12 cm at the beginning of October in both years. Experimental plots had a size of 2 x 9 m divided into an area of 12 m^{-2} for grain yield assessment in the beginning of August and another area of 6 m^2 for measurements of weed- and crop biomass and weed population dynamic parameters during the cropping season. Different densities of *A. fatua* (*Avena fatua* L.) were sown between the winter wheat rows at the same time as experimental factors. Winter wheat was sown at a depth of 3 cm and *A. fatua* at 1 cm with a RTK-GPS controlled seed drill. Weed densities ranged from 1-25, 26-75, 76-125, 126-225 to 226-325 plants m^{-2}. One treatment was permanently weed-free. Other weed species were removed by hand every two weeks from sowing until harvest. There was no natural infestation of *A. fatua* in the trials.

Observations of yield loss and population dynamics *Avena fatua* density and biomass m^{-2} was assessed two times, at BBCH 12 (2-3 leaf stage) and shortly before flowering of winter wheat. A 50 x 50 cm frame was used to count *A. fatua* densities at four randomly selected positions per plot. A sample of 1 m^2 per plot was harvested and separated into winter wheat and weed. For dry matter determination, plant material was dried at 80°C for 48 h. For measurements of weed seed production, 20 *A. fatua* plants per plot were covered with Crispac® bags (Sealed Air Corporation, USA) after flowering, to prevent seed loss through seed rain and predation.

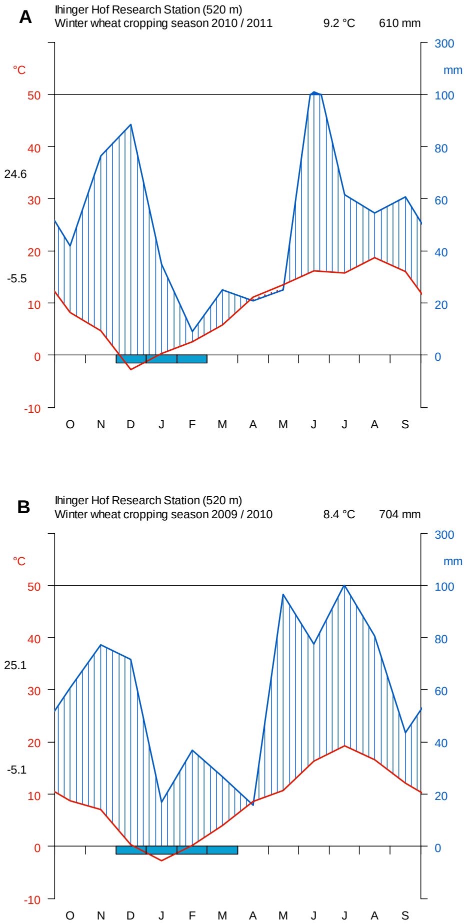

Figure 3.1: Climate diagram for the cropping season 2009/2010 (A) and 2010/2011 (B). Blue bars below the 0° line indicate frost events. Vertical blue lines between the temperature and rainfall curve indicates humid conditions. Red dots between the temperature and rainfall curve indicates arid conditions.

Before winter wheat harvest, covered *A. fatua* plants were cut at ground level and seeds were removed from plants with a laboratory thresher. Seeds were counted and weighed to determine seed production per plant. For winter wheat grain yield determination an area of 12 m^2 per plot was harvested with a plot combine harvester.

Dose-response studies *A. fatua* seeds were pre-germinated in vermiculite. After the cotyledon was fully developed, seedlings were transplanted into 8 x 8 cm paper pots to a density of two plants per pot. Plants were grown in a greenhouse at a temperature regime of 15°C day and 5°C night at a day/night cycle of 12 h. Herbicide treatment was carried out at 2-3 leaf stage (BBCH 12-13) with a precision application chamber (Aro Langenthal, Switzerland) and a flat fan nozzle (8004 EVS, Teejet® Spraying Systems Co., Wheaton, IL, USA). A volume of 400 L ha^{-1} was sprayed with a speed of 800 mm s^{-1}, a distance of the spray nozzle of 500 mm above sprayed surface and a spraying pressure of 300 kPa. Plants were treated with commercial formulations of pinoxaden (Axial 50, 50 g a.i. L^{-1}, Dow AgroSciences) and isoproturon (Arelon, 500 g a.i. L^{-1}, Stähler). Each treatment was repeated four times. Isoproturon dosages ranged from 3000 g a.i. ha^{-1} to 6 g a.i. ha^{-1}, and from 90 g a.i. ha^{-1} to 0.18 g a.i. ha^{-1} for pinoxaden. Residual dry biomass was measured 28 days after treatment for determination of herbicide efficacy.

Model structure The decision model presented in this paper is based on four interacting sub-models:

1. Crop yield loss model (Cousens, 1985)
2. Weed population dynamics model (Cousens et al., 1986)
3. Herbicide dose response model (Streibig, 1988)
4. Economics of weed control decisions model (Munier-Jolain et al., 2002)

The decision model is mainly based on the decision algorithm for patch spraying proposed by Christensen et al. (2003).

Weed seedling density to biomass transformation

Incorporation of a dose response sub-model into a decision model makes calculations based on weed biomass rather than on weed density necessary. A linear relationship between seedling density and cumulative seedling biomass m^{-2} is assumed for the two leaf growth stage of *A. fatua*, or rather for the time of weed control decision. The linear relationship is following equation 3.1:

$$SB_t = aSD_t \tag{3.1}$$

For cases where weed density exceeds the densities presented in this study, it is assumed that the relationship between seedling density and seedling biomass can be described by a hyperbolic function as proposed by Cousens (1985). Seedling biomass (SB_t) can be expressed as a function of *A. fatua* density (SD_t) and herbicide efficacy (γ_U), by extending equation 3.1:

$$SB^t_{\gamma_U} = aSD_t * (1 - \gamma_U) \tag{3.2}$$

Yield loss sub-model

Winter wheat yield in year t (Y_t) in dependency of herbicide dose dependent *A. fatua* biomass ($SB^t_{\gamma_U}$) can be calculated according to Cousens (1985) by the following the equations:

$$Y^t_{SB_{\gamma_U}} = Y_{wf}[1 - (I * SB^t_{\gamma_U})/(1 + I * SB^t_{\gamma_U}/A)] \tag{3.3}$$

with Y_{wf} = weed free winter wheat yield, I = yield per unit weed biomass as $SB^t_{\gamma_U} \to 0$, A = yield as $SB^t_{\gamma_U} \to \infty$.

Population dynamics sub-model

The number of *A. fatua* panicles m^{-2} in year t (reproduction units, RU_t) prior to winter wheat harvest shows a linear relationship with herbicide dose dependent *A. fatua* ($SB^t_{\gamma_U}$) which can be described by equation 3.4:

$$RU^t_{SB_{\gamma_U}} = aSB^t_{\gamma_U} \tag{3.4}$$

General assumption for this model approach is, that residual biomass which survives the herbicide treatment produces reproduction units ($RU^t_{SB^t_{\gamma_U}}$) according to equation 3.4.

The number of seeds per panicle ($FRU^t_{SB_{\gamma_U}}$) in dependency of the number of panicles m^{-2} can be described by a hyperbolic function according to Cousens (1985):

$$FRU^t_{SB_{\gamma_U}} = S * [1 - (J * RU^t_{SB\gamma_U})/(1 + J * RU^t_{SB\gamma_U}/Z) \tag{3.5}$$

for $RU^t_{SB_{\gamma_U}} \in N^*$. with S = estimated maximum number of seeds per panicle, J = number of seeds per panicle as $RU^t_{SB_{\gamma_U}} \to 0$, Z = number of seeds per panicle as $RU^t_{SB_{\gamma_U}} \to \infty$. Hereby the resulting annual weed biomass dependent seed input [seeds m^{-2}] can be described by the yield loss equation proposed by Cousens (1985):

$$SI^t_{\gamma_U} = (K * SB_{\gamma_U})/(1 + K * SB_{\gamma_U}/V) \tag{3.6}$$

The parameters K and V correspond to I and A of the yield loss function of Cousens (1985). Soil seed bank dynamics are described as proposed by Cousens et al. (1986):

$$SD_{t+1} = (v^{new} * SSB^{new}_{t-1}) + (v^{old} * SSB^{old}_{t-1}) \tag{3.7}$$

$$SSB^{new}_t = (1 - l)(1 - p)SI^t_{\gamma_U} \tag{3.8}$$

$$SSB^{old}_t = (1 - m^{old} - v^{old})SSB^{old}_{t-1} + (1 - m^{new} - v^{new})SSB^{new}_{t-1} \tag{3.9}$$

Seedling density in year t is described by soil seed bank content of newly produced seeds (SSB^{new}_{t-1}) and seeds from the previous seasons (SSB^{old}_{t-1}) and their respective germination rates ($v^{new/old}$). We assume a maximum seed survival time for *A. fatua* of two years. The respective soil seed bank input of newly produced seeds (SSB^{new}_t)is a function of seed losses via harvest (l) and seed losses via predation (p). Soil seed bank decline of seeds produced in the previous season are described by the seed mortality of new and old seeds ($m^{new/old}$), and losses through germination.

Economic sub-model

Net return in dependency of the residual weed biomass can be calculated by the equation:

$$NR^t_{SB_{\gamma_U}} = (P_y * Y^t_{SB_{\gamma_U}}) - P_uU - C_1 - C_2 \tag{3.10}$$

Where P_y is the price per crop unit, P_u is the per unit costs of weed control (U) or rather the variable costs for weed control, C_1 are the constant costs for weed control and C_2 are the costs for the remaining production factors.
According to Christensen et al. (2003), the economically optimal herbicide dosage can subsequently be found by differentiation of equation 3.10:

$$\frac{d}{dU} NR^t_{SB_{\gamma U}} = 0 \Longrightarrow 0 \leqslant U \leqslant N \tag{3.11}$$

where N is the maximum acceptable herbicide dose.

Statistical analysis of sub-models For investigating the effect of the year of the linear relationships (Equation 1 and 4) an analysis of variances of the full model was conducted according to equation 3.12:

$$r_{ij} = \mu + x_i + y_i + x_i y_i + e_{ij} \tag{3.12}$$

with r_{ij} = expected *A.fatua* biomass respectively the number of panicles, x_i = *A. fatua* density respectively biomass, y_j = year, $x_i y_j$ = interaction of both parameters and e_{ij} = residual effect. For both sub-models, neither the intercept, nor the main effect of the year (y_j) nor the interaction ($x_i y_j$) was significant, so the model was reduced to its simplest form. Coefficient of determination was calculated as well as the confidence intervals for the estimated parameter. To compare the effect of the year for non-linear relationships, models were fitted separately by year and for combined years. 95% confidence intervals of the model parameters were calculated and compared for significant differences. For assessing the quality of fit of the models to the data, root mean square error ($RMSE$) and relative root mean square error ($RRMSE$) were calculated. For statistical analysis of the dose-response relationships the three parameter log-logistic dose-response function by Streibig (1988) was fitted to the data, following the equation:

$$Y = \frac{D}{1 + e^{b * ln(\frac{U}{ED_{50}})}} \tag{3.13}$$

Herbicide efficacy (Y) was computed in dependency of the herbicide dosage (U), with D as the upper asymptote or rather efficacy at indefinitely large dosages , b as the rate of change at ED_{50} and ED_{50} as the dosage causing 50% of the total response. The quality of fit of the model was assessed by an *F-Test* for the lack-of-fit based on variance analysis at p=0.05 (Schabenberger et al., 1999).

Modelled decision strategies The four modelled decision rules are:

1. Herbicide dosage is adjusted to suppress weed infestations below the economic weed threshold and prevent increase of population densities (OPT). At weed infestation levels below the economic threshold, herbicide dosages will be reduced to a point were net profit is maximized. To avoid the evolution of herbicide resistant weed biotypes, herbicide mode of action will be rotated every two years. As a restriction we defined that herbicide dosages have to be high enough to avoid an increase of the soil weed-seed bank.

2. Herbicides are applied at the recommended field rate when the economic weed threshold is exceeded (ETH). The economic threshold for the respective herbicides at the recommended field rate was calculated according to Cousens (1987).

3. In the risk-averse decision strategy (RA) no weeds are tolerated. Herbicides were sprayed at the recommended dosage when weed density is higher than zero. This decision strategy represents the current farmers practice in intensive winter wheat growing areas.

4. No weed control methods were applied (NWC).

3.4 Results

Relationship between seedling density and seedling biomass A linear relationship between seedling density and seedling biomass was found at the 2-3 leaf stage (BBCH 12-13) of *A. fatua* with a R^2=0.98 (Figure 3.2). There was no significant difference between the two experimental years. Therefore, the model was fitted across both years. In total, seedling densities were lower in the season 2010/2011 due to the dry and warm weather conditions, which however did not affect the biomass per seedling.

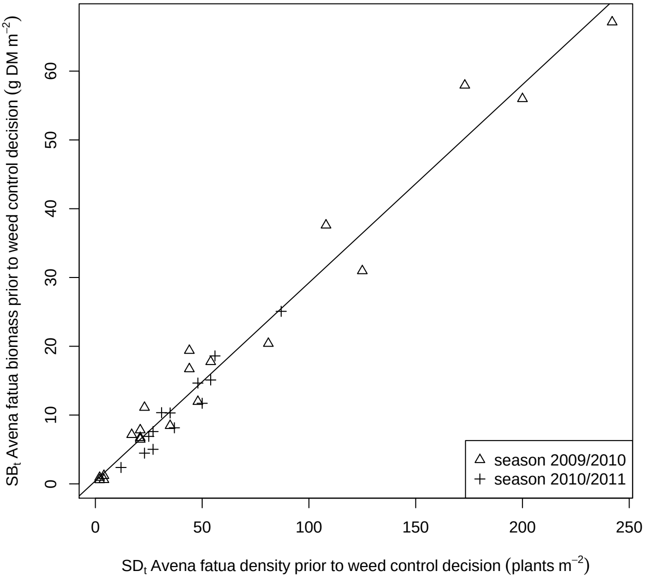

Figure 3.2: *A. fatua* seedling biomass m^{-2} (SB_t) in dependency of *A. fatua* seedling density m^{-2} (SD_t) at the 2 – 3 leaf stage. a=0.29, R^2=0.98.

Winter wheat yield loss due to *A. fatua* competition The relationship between *A. fatua* seedling biomass and grain yield can be described by a hyperbolic function) as proposed by Cousens (1985) (Figure 3.3). Maximum winter wheat yield loss was around 40%. Comparison of the 95% confidence intervals of the parameter estimates shows that there are no significant differences between the parameter estimates between the years. The function averaged across the two years described the data well with a $RMSE$ of 0.544 t equating to a $RRMSE$ of 8.5% (Table 3.1).

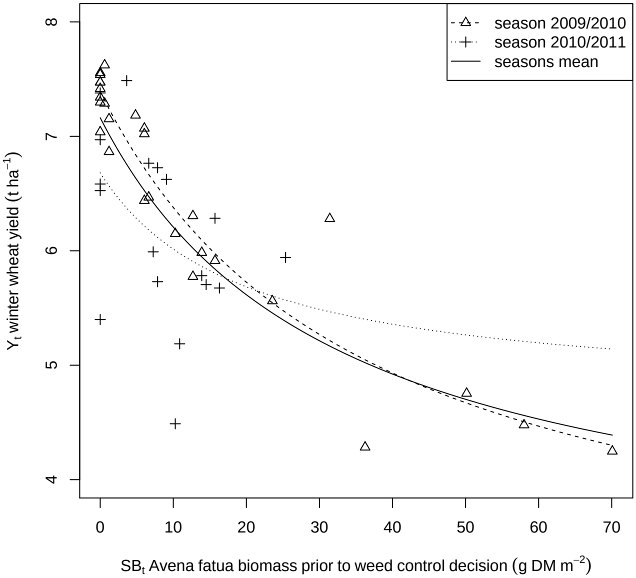

Figure 3.3: Winter wheat yield (t) (Y_t) in dependency of *A. fatua* seedling biomass m^{-2} (SB_t) at the 2 – 3 leaf stage.

Figure 3.4 shows the number of *A. fatua* panicles m^{-2} prior to winter wheat harvest in relation to *A. fatua* biomass at 2-3 leaf stage. A lin-

ear relationship between *A. fatua* biomass and *A. fatua* panicles could be observed with a R^2=0.78. Even if the number of panicles produced in season 2010/2011 was lower compared to season 2009/2010, the effect of the year was not significant.
A. fatua produced less seeds per panicle with increasing densities (Figure 3.5). Seed number per panicle was reduced due to the dry and warm weather in 2010/2011 compared to season 2009/2010. Comparing the 95% confidence intervals of the parameter estimates, the observed differences were not significantly different. The fitted function has a $RMSE$ of 14 panicles equating to a $RRMSE$ of 36%. Seed production reached a maximum of approximately 6000 seeds m^{-2} for the highest *A. fatua* densities (Table 3.1).

Thus total seed input was reduced in season 2010/2011 due to lower *A. fatua* densities on the one hand and reduced number of seeds per panicle on the other hand (Figure 3.6). However differences between the parameter estimates were again not significant. $RMSE$ for the seed production was 1040 seeds, equating to a relative error of 43% (Table 3.1).

Herbicide dose response experiments It was possible to fit the four parameter dose response model by Streibig (1988) for both tested herbicides. Therefore ED_{50} and ED_{90} values could be calculated. Pinoxaden and isoproturon were able to reduce *A. fatua* biomass by at least 90% compared to the untreated control at the maximum recommended field dosage. Parameter estimates can be found in Table 3.2.

Modelling approach Weed control decisions were modelled for a period of five years and for an initial *A. fatua* density of 15 plants m^{-2}. For modelling the economic threshold decision rule (ETH), an economic threshold of 7 *A. fatua* plants m^{-2} was calculated for isoproturon and of 9 *A. fatua* plants m^{-2} for pinoxaden. In the ETH decision rule, herbicides were applied in three out of five years at the maximum recommended dosage due to initial weed densities higher than the economic threshold. In the risk-averse decision strategy (RA) no weeds were tolerated and herbicides were used at the maximum recommended dosage every year. Parameter estimates used for the modelling approach can be obtained from Table 3.2.

All modelled decision strategies except of the untreated control resulted in equal accumulated grain yields of approximately 36 t ha-1 over the mod-

				Confidence interval (α=0.05)					
Equation	Relationship	Season	Parameter	Estimate	Lower	Upper	R²	RMSE	RRMSE [%]
1	$SD_t\,(SB_t)$		a	0.29	0.28	0.31	0.98		
3	$Y_{SB\gamma}{}^{t}\,(SB_{\gamma}{}^{t})$	2009/2010	Y_{wf}	7.39	7.19	7.59		0.32	4.91
			i	0.02	0.01	0.02			
			a	0.64	0.41	0.86			
		2010/2011	Y_{wf}	6.68	5.99	7.37		0.67	10.80
			i	0.02	-0.03	0.06			
			a	0.30	-0.79	1.38			
		seasons mean	Y_{wf}	7.16	6.89	7.44		0.54	8.51
			i	0.02	0.01	0.03			
			a	0.57	0.27	0.86			
4	$RU^{t}\,(SB_{\gamma}{}^{t})$		b	4.25	3.43	5.07	0.7839		
5	$FRU^{t}\,(Ru^{t})$	2009/2010	Y	62.09	49.01	75.17		11.84	24.13
			A	1.68	-5.41	8.77			
			I	0.003	-0.003	0.008			
		2010/2011	Y	52.49	-31.62	136.61		5.19	21.17
			A	0.85	0.38	1.35			
			I	0.02	-0.07	0.11			
		seasons mean	Y	68.34	49.37	87.31		13.69	36.05
			A	0.71	0.45	0.97			
			I	0.02	-0.01	0.05			
6	$SI_{SB\gamma}{}^{t}\,(SB_{\gamma}{}^{t})$	2009/2010	C	311.82	133.79	489.85		985.94	30.24
			D	9371.03	4014.90	14727.16			
		2010/2011	C	207.70	-138.78	554.18		518.92	54.71
			D	2660.60	-2142.44	7463.64			
		seasons mean	C	231.03	126.30	335.76		1039.58	42.94
			D	11329.16	3369.60	19288.72			

Table 3.1: 95% confidence intervals of the parameter estimates.

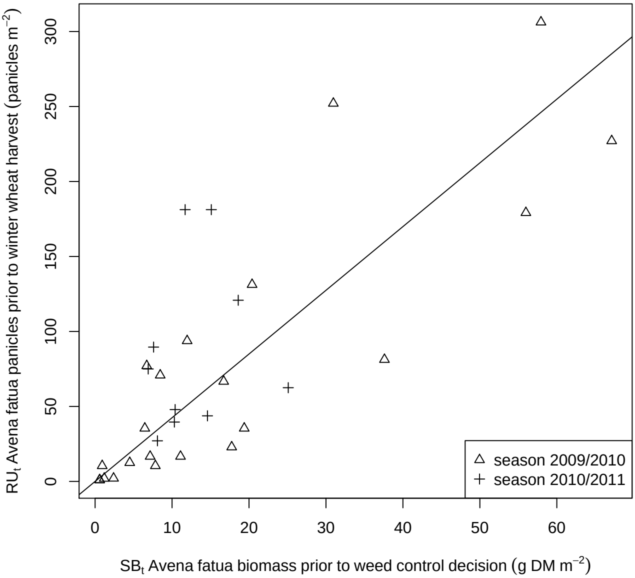

Figure 3.4: *A. fatua* panicles m^{-2} prior to winter wheat harvest (RU_t) in dependency of *A. fatua* seedling biomass m^{-2} (SB_t) at the 2 – 3 leaf stage. a=4.25, R^2=0.78.

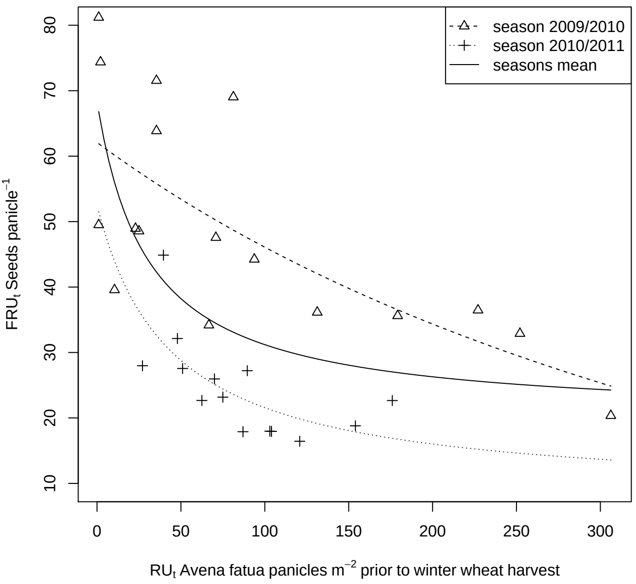

Figure 3.5: *A. fatua* seeds per panicle (FRU_t) in dependency of *A. fatua* number of panicles m^{-2} prior to winter wheat harvest (RU_t).

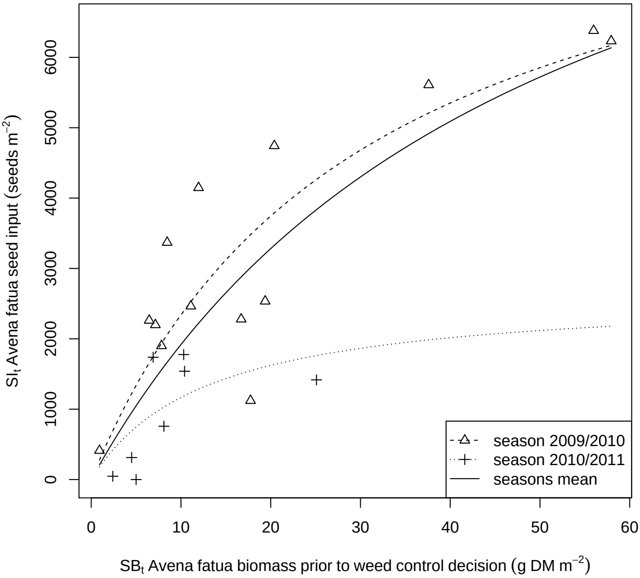

Figure 3.6: *A. fatua* seed input (seeds m^{-2}) in dependency of *A. fatua* seedling biomass m^{-2} (SB_t) at the 2 – 3 leaf stage.

Economic parameters	parameter	estimate	source
Grain price (Euros t^{-1})	P_y	190	
Weed free yield (t ha^{-1})	Y_{wf}	7.3	
Crop management costs (Euros ha^{-1})	C_2	550	
Costs for herbicide application (Euros ha-1)	C_1	10	
Yield loss parameters			
	I	0.02	own data
	A	0.558	own data
Population dynamic parameters			
Weed biomass calculation SB_t	a	0.292	own data
Reproduction unit calculation RU_t	a	4.25	own data
Seeds per panicle calculation FRU_t	S	68	own data
	J	0.02	own data
	Z	0.74	own data
Seed production calculation SI_t	K	231	own data
	V	11329.2	own data
New seed germination rate	v^{new}	0.1	Cousens et al. (1986)
Old seed germination rate	v^{old}	0.1	Cousens et al. (1986)
New seed mortality	m^{new}	0.57	Cousens et al. (1986)
Old seed mortality	m^{old}	0.65	Cousens et al. (1986)
Seed removal with harvest	l	0.2	estimate
Seed loss by predation	p	0.3	estimate
Dose response parameters for herbicide variable costs calculation			
pinoxaden	b	-1.03	own data
	D	96.43	own data
	ED_{50}	7.77	own data
Price per unit pinoxaden (Euros g a.i.$^{-1}$)	P_u	0.68	
isoprotuon	b	-0.74	own data
	D	93.67	own data
	ED_{50}	1.75	own data
Price per unit isoproturon (Euros g a.i.$^{-1}$)	P_u	0.016	

Table 3.2: Parameter estimates used for model parameterization

elled period of five years. In the untreated control (NWC), accumulated grain yields were reduced to 26 t ha^{-1} (Table 3.3). The optimized decision strategy (OPT) reduced the herbicide input by 50% compared to the RA decision rule and by 15% compared to the ETH decision rule.

With the OPT decision strategy it was possible to reduce the initial weed density from 15 plants m^{-2} to around 9 plants m^{-2} within the modelled period of five years. The ETH decision strategy resulted in an increase of the population density to around 21 plants m^{-2} after five years. The risk averse decision rule resulted in a density decrease to less than 0.5 *A. fatua* plants m^{-2}. The accumulated net-returns were only slightly different between the OPT, ETH and RA decision rule. The model evaluation has shown that *A. fatua* biomass has to be reduced by at least 73% to prevent an increase of the weed density in the following year. To achieve this aim a minimum dosage of isoproturon of 420 g a.i. ha^{-1}, or a minimum pinoxaden dosage of 30 g a.i. ha^{-1} would be necessary.

A)

			OPT			
Year	SD_t (plants m^{-2})	$NR_{(SBt,\gamma)}$ (€ ha^{-1})	herbicide	dosage (equivalent ha^{-1})	weed biomass reduction efficacy (%)	yield (t ha^{-1})
t	**15**	788	ipu	0.56	82%	7.17
t+1	10.03	796	ipu	0.40	78%	7.18
t+2	9.11	784	pin	0.50	67%	7.15
t+3	11.15	779	pin	0.60	71%	7.15
t+4	11.97	793	ipu	0.48	80%	7.18
t+5	**8.91**					
∑		3941		2.54		35.83

B)

			ETH			
Year	SD (plants m^{-2})	$NR_{(SBt,\gamma)}$ (€ ha^{-1})	herbicide	dosage (equivalent ha^{-1})	weed biomass reduction efficacy (%)	yield (t ha^{-1})
t	**15**	783	ipu	1.00	88%	7.20
t+1	6.72	782	-	-	0%	7.01
t+2	26.51	772	ipu	1.00	88%	7.15
t+3	11.78	786	ipu	1.00	88%	7.22
t+4	5.29	792	-	-	0%	7.06
t+5	**21.03**					
∑		3916		3.00		35.64

C)

			RA			
Year	SD (plants m^{-2})	$NR_{(SBt,\gamma)}$ (€ ha^{-1})	herbicide	dosage (equivalent ha^{-1})	weed biomass reduction efficacy (%)	yield (t ha^{-1})
t	**15**	783	ipu	1.00	88%	7.20
t+1	6.72	791	ipu	1.00	88%	7.25
t+2	1.54	796	ipu	1.00	88%	7.27
t+3	< 1	797	ipu	1.00	88%	7.28
t+4	< 0.5	797	ipu	1.00	88%	7.28
t+5	**< 0.5**					
∑		3964		5.00		36.28

D)

		NWC	
Year	SD (plants m^{-2})	$NR_{(SBt,\gamma)}$ (€ ha^{-1})	yield (t ha^{-1})
t	**15**	727	6.72
t+1	51.97	559	5.84
t+2	>100	399	4.50
t+3	>100	399	4.50
t+4	>100	399	4.50
t+5	**> 100**		
∑		2483	26.06

Table 3.3: Model output. OPT= optimized decision strategy, ETH= economic threshold decision strategy, RA=risk avoider decision strategy, NWC= no weed control, ipu=isoproturon, pin=pinoxaden.

3.5 Discussion

Avena fatua has been found to be a very competitive weed species in winter wheat. Yield losses of up to 40% were found for densities higher than 200 plants m^{-2} or respectively 60g weed DM m^{-2} prior to weed control decision. A linear relationship between *A. fatua* density and biomass was obeserved. The transformation of weed density into weed biomass appears to be reliable and negligible biased by weather conditions and enables the incorporation of weed biomass based dose-response models into yield-loss calculations.

Weed biomass dependent yield losses were equal in both years although weather conditions were extremely different. This confirms observations of Milberg and Hallgren (2004), who found no effect of the year when investigating yield loss caused by different weed species on several crops in more than 1,400 experiments. The presented yield loss sub-model gave a precise estimate of yield loss in both years although climate data were not included in the model. We therefore conclude for *A. fatua*, that eco-physiological models, as proposed e.g. by Benjamin et al. (2010), are not mandatory for decision support purposes. These eco-physiological models however have advantages investigating weed- and crop biomass in competition studies. We hypothesise that the presented yield loss parameters are transferable at least to sites with comparable growing conditions for winter wheat. For confirmation of this hypotheses, validation experiments under various agronomic and climatic conditions, e.g. in the North China Plain region, however will be necessary. Although differences were not statistically significant, we could observe the tendency that seed input under dry and warm weather conditions was reduced. This goes in line with the findings of Adkins et al. (1987), who found a decrease in *A. fatua* number of seeds per plant, when plants were exposed to high temperatures during development. Complementary to the results of Adkins et al. (1987) we found a reduced biomass production under dry and warm weather conditions resulting in a reduced number of panicles m^{-2}. Additionally the number of seeds per panicle was reduced as well. We can conclude that under dry and warm weather conditions the presented model will overestimate the seed input. According to Figure 3.6 this overestimation will increase with increased initial *A. fatua* biomass prior to the weed control decision.

General assumption for the presented model approach is, that residual biomass which survives the herbicide treatment produces reproduction units according to equation 3.4. Our assumption goes in line with the findings of O'Donovan et al. (2003a) on reduced rates of tralcoxydim on *A. fatua* seed production. The authors investigated an up to three times enhanced seed production when tralcoxydim rates were reduced to 50% of the recommended dose, although the variability of results was very high. Holm et al. (2000) found that efficacy of graminicides is influenced by the density of *A. fatua* infestation, were efficacies of reduced herbicide rates tended to be better at low infestation levels. Belles et al. (2000) emphasized the risk of returning large numbers of *A. fatua* seeds following reduced rates of tralcoxydim at *A. fatua* densities higher than 140 plants m^{-2}. Similar results were found by Wille et al. (1998) and O'Donovan et al. (2003b) for reduced rates of imazamethabenz and difenzoquat.

In contrast Travlos (2012) investigated the effect of reduced rates of iodosulfuron-methyl + mesosulfuron-methyl on efficacy and seed production of *Avena sterilis* and other weeds in competitive wheat cultivars. He could show that dosages of 50% of the recommended dosage resulted in equal weed control efficacy and weed seed production compared to label-recommended dosages. The discrepancies between the mentioned results indicate that dose dependent seed production is affected by combined effects of weed density and crop competitiveness as well as by the herbicide mode of action. The presented modelling approach of dose dependent seed production takes account of the findings mentioned above. However, up to now no data on isoproturon or fenoxaprop-ethyl dose depending weed population dynamics of *A. fatua* is available in literature and thus additional experiments have to be conducted.

Our modelling approach has shown that weed control decisions based on the optimal herbicide dosage (OPT) resulted in lowest amounts of applied herbicides while maintaining high level of weed control efficacy, low yield loss and no increase in weed seed bank. Compared to the economic threshold decision rule (ETH), weed density could even be reduced for the simulation period. Both strategies resulted in higher net returns and lower herbicide inputs. Our model is set up as a modular system allowing the model to be expanded by additional sub-models. For modeling of mixed weed species infestations we suggest the density equivalent respectively the recursive density equivalent method, as proposed by Berti and Zanin (1994) and Holst (2005) which can be easily incorporated into the presented modular modeling approach. Furthermore, sub-models calculating

seed emergence and time of removal, as proposed by Berti et al. (2008) would be able to further improve the prediction reliability.
A serious concern regarding reduced herbicide doses is the enhanced selection pressure towards herbicide resistant weed populations. Recently, Manalil et al. (2011) published his work on the influence of reduced rates of diclofop on *Lolium rigidum*. He observed a rapid resistance development due to surviving plants. This is a strong argument for high weed control efficacies in competitive weed populations.

The **third article** focuses on the development of a novel herbicide resistance screening method. Aim is to provide a cheap, time and space saving method which is ready to use in the NCP region. With the presented method it will be possible to monitor the herbicide efficacy status of the most abundant weed species and therefore to adapt the herbicide selection within the season. It would be possible to include the results of an annual herbicide resistance monitoring into the decision support approach presented in article two, and therefore to optimize the herbicide selection process.

Chlorophyll fluorescence imaging microscreening: a new method for rapid detection of herbicide resistance in weeds

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Submitted to:
Weed Research (2012)
Wiley-Blackwell, Hoboken, NJ

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4 Chlorophyll fluorescence imaging microscreening: a new method for rapid detection of herbicide resistance in weeds

4.1 Summary

Due to the steadily increasing number of suspicious herbicide resistant weed populations, the demand for rapid in-season tests is rising. In this study we introduce a new quantitative herbicide resistance test system based on chlorophyll fluorescence imaging of photosynthesis related parameters. Susceptible and herbicide resistant populations of *Alopecurus myosuroides* Huds. were cultivated in multiwell tissue culture plates containing nutrient agar and growth medium with different dosages of fenoxaprop-P-ethyl and mesosulfuron-methyl. The maximum quantum efficiency of the PSII was measured 3 hours after transplanting (HAT) and then for seven days every 24 hours. Data of maximum quantum efficiency of the PSII were compared with standard whole-plant pot test and molecular tests for target-site mutations. It was possible to fit dose-response curves and calculate corresponding resistance factors for ED_{90} for all populations tested using the chlorophyll-fluorescence micro-screening method. It was possible to distinguish between resistant and susceptible populations. The results of the chlorophyll-fluorescence micro-screening test corresponded well to the standard whole-plant pot test in the greenhouse. However, populations with proved target-site mutations did not differ from other herbicide resistant populations in the maximum quantum efficiency values of the PSII. We conclude that the chlorophyll-fluorescence micro-screening test provides reliable data on herbicide resistance for both modes of action tested in shorter time and using less space compared with standard whole-plant pot tests in the greenhouse. Since the chlorophyll fluorescence micro-screening test can be applied with small weed seedlings

it is assumed that it can be used in-season with seedlings directly taken from the field.

4.2 Introduction

On a global scale, weed competition causes yield losses of 40% when averaged of all major agricultural crops (Oerke, 2006). Therefore, weed control is an important measure in crop production. Manual and mechanical weed control strategies have largely been replaced by the use of herbicides over the past 40 years (Powles and Yu, 2010). The continuously repeated application of herbicides with the same mode of action has led to the selection of herbicide-resistant weed populations. During the past two decades more than 300 biotypes within 194 species of weeds became resistant to one or more of the major groups of herbicides (Powles and Yu, 2010). So far 114 dicotyledonous and 80 monocotyledonous weeds are affected on over 340 000 fields world-wide.

A. myosuroides is one of the most abundant grass weeds in Germany. It predominantly germinates in autumn at about the same time when winter annual cereals are sown (Gerhards, 2009). Approximately 200 seeds are produced plant^{-1} having a lifetime of 6-10 years in the soil (Moss, 1985). *A. myosuroides* prefers heavy and loamy soils. It is one of the most competitive grass weed in winter wheat causing grain yield losses of 20% at an average infestations level of 100 plant m^{-2} (Gerhards, 2009). Densities of *A. myosuroides* have increased in Europe in the past 3 decades probably due to a higher proportion of winter cereals in the crop rotation, earlier sowing dates of winter wheat (Melander, 1995) and a change to reduced tillage systems (Melander et al., 2008). These cropping practices have caused a greater reliance on herbicides, which can support the selection of herbicide resistant *A. myosuroides* populations. Many populations in Germany are resistant against herbicides inhibting acetolactate synthase (ALS) and acetyl CoA carboxylase (ACCase) (Hess et al., 2012). *A. myosuroides* was also classified as the most important herbicide resistant weed species in Europe (Moss et al., 2007).

Due to the steady increasing number of suspicious herbicide resistant weed populations the demand for new rapid resistance tests is rising. Conventional whole-plant-pot tests in the greenhouse are often used to screen for herbicide resistance. These tests are relatively expensive and require a lot of space and time. Furthermore they need to be done with seeds from suspicious plants in the field and therefore, do not provide results in the season when the resistance problem has been observed in the field. Various alternative tests have been developed to accelerate the detection of herbicide resistance. Kaundun et al. (2011) decribe a novel in-season method for detecting herbicide resistance in *Lolium rigidum* and *L. multiflorum.* Grasses were grown in agar, containing discriminating rates of herbicides (Syngenta 'Risq' Test). A visual assessment was carried out 10 days after application by recording the percentage of surviving plants. The results of this qualitative agar-based method correlated well with classical whole plant pot test. The objective of this paper is to further develop and improve the Syngenta 'Risq' Test using quantitative data of chlorophyll fluorescence imaging to measure the response of weed populations to different herbicides/dose of herbicide. Chlorophyll fluorescence imaging is a non-destructive sensor system that can be used as a very sensitive indicator of the physiological status of plants providing images of photosynthetic activity and its spatial and temporal variations (Schreiber, 2004). Riethmüller-Haage et al. (2006a) and Kempenaar et al. (2011) showed that herbicides with different modes of action including PSII-inhibitors, ALS inhibitors and auxin like herbicides, caused a rapid increase of the relative quantum efficiency of photosystem II and photosystem I electron transport in different weed species shortly after herbicide application. There are few publications in which chlorophyll fluorescence measurement was associated with resistance to PSII-inhibitors (Ahrens et al., 1981; Ali and Machado, 1981; Hensley, 1981; Vencill and Foy, 1988; OOrschot Van, J L P and Leeuwen Van, P H, 1992).

The hypothesis for this studies were that Chlorophyll fluorescence imaging is capable (1) for measuring effects of herbicides that interfere with amino acid and fatty acid synthesis, (2) for early detection of herbicide dose-response in weed species, (3) for differentiation of sensitive and resistant weed species to different herbicides and (4) that the chlorophyll-fluorescence micro-screening test corresponds well to the standard whole-plant pot experiment in the greenhouse.

4.3 Materials and Methods

Seed origin Six populations of *A. myosuroides* were examined in this study. Seeds of the sensitive reference standard (ALOMY-S) and the population Peldon with a metabolic-based herbicide resistance (ALOMY-PEL) were obtained from Herbiseed Ltd., Berkshire, UK. The population ALOMY-R1 originates from southern Germany. Seeds of the populations ALOMY-R2, ALOMY-R3 and ALOMY-R4 were collected on different fields in the south of Germany. All four *A. myosuroides* populations (ALOMY-R1-ALOMY-R4) were characterized with suspected lower sensitivity to herbicides.

Whole-plant pot test in the greenhouse and PCR-based sreening for target-site mutations Whole-plant pot tests were carried out in the greenhouse with all populations tested according to the protocol of Hess et al. (2012). The plants were grown in 8 x 8 cm paper pots at a temperature regime of 15°C day and 5°C night with a 12 h photoperiod. Herbicide treatment was carried out at 2-3 leaf stage (BBCH 12-13) with a precision application chamber using a Teejet nozzle (8002 EVS, Teejet® Spraying Systems Co., Wheaton, IL, USA). The application chamber was calibrated for a volume of 200 L ha^{-1}, at a speed of 800 mm s^{-1} , a distance of the spray nozzle of 500 mm above sprayed surface and a spraying pressure of 300 kPa. Depending on the experiment, plants were treated with 1.2 l ha^{-1} Puma® (Bayer CropScience) or RalonSuper® EW (Nufarm), both containing 69 g fenoxaprop-P-ethyl l^{-1} and 300 g ha^{-1} Atlantis® WG (BayerCropScience) containing 30 g mesosulfuron-methyl and 6 g iodosulfuron-methyl-sodium kg^{-1} together with 0.3 l ha^{-1} FHS®. Each treatment was repeated three to four times. Herbicide efficacy was evaluated between 10 and 30 days after herbicide treatment using visual rating of percent biomass reduction compared to the sensitive reference standard and the untreated control variation. Degrees of resistance were classified according to the R rating system of Moss et al. (1999). PCR assays and pyrosequencing procedures were conducted by IDENTXX GmbH (Stuttgart, Germany) and Hess et al. (2012), to get information about known target-site mutations in the populations.

Table 4.1: Tested herbicides for the chlorophyll fluorescence resistance microscreening

Trade name	Active ingredient (class)	Mode of action	Herbicide dose range (mM)
Ralon Super	fenoxaprop-P-ethyl	Inhibition of ACCase	4.59 - 0.002*
Atlantis WG	mesosulfuron-methyl	Inhibition of ALS	0.96 - 0.06*

*recommended field rate (in mM): Ralon Super EW, 1.14 , Atlantis WG, 0.12

Chlorophyll fluorescence microscreening test Seeds for the chlorophyll fluorescence microscreening test were treated similar to the procedure in Kaundun et al. (2011). First they were pre-grown on two folds of filter paper in 9 cm petri dishes. For germination 6.0 ml of nutrient solution (Pedas et al., 2005) was added. Petri dishes were placed in growth cabinets at a 12h-photoperiod and a temperature regime of 15/5°C. Seedlings were grown about 10 days in the growth cabinet until the cotyledons were fully developed and then transplanted into 24-well multiwell plates (Greiner bio-one GmbH, Germany). Multiwell plates were filled with 500 μl of herbicide solution in 6 (Experiment 2+3) to 12 (Experiment 1) descending dosages including an untreated control and filled up with 500 μl of sterilized 0.8% agar (50°C, pH 6, Micro Agar, Duchefa, Germany) containing the same nutrient composition used for the pre-growing. Tested herbicides and dosages can be found in Table 4.1. All herbicides were dissolved in water at the highest concentration as stock solution and diluted stepwise. Multiwell plates were placed in the growth cabinet and randomized. Chlorophyll fluorescence parameters were analyzed with an IMAGING-PAM M-Series Chlorophyll Fluorometer (Heinz Walz GmbH, Germany). For evaluation of herbicide efficacy, maximum quantum efficiency of PSII, defined as Fv/Fm, was measured. Fv/Fm is calculated according to the equation

$$Fv/Fm = (Fm - F0)/Fm \tag{4.1}$$

where Fm is the maximal fluorescence yield and $F0$ the dark fluorescence yield. For determination of $F0$, plants were dark adapted for the duration of 30 minutes prior to the measurement. After dark adaption, plants were illuminated with a light saturation pulse of 580 μM m^{-2} s^{-1} and a wavelength of 450 nm for Fv/Fm determination. Usually, all PS II reaction centers are open after dark adaptation and non-photochemical energy dissipation is minimal. During the saturation pulse fluorescence yield is maximal. The IMAGING-PAM Fluorometer measures also other parmeters related to chlorophyll fluorescence including effective quantum yield. The maximum quantum efficiency of PSII however was selected for this study because it remains unchanged until the next Fo, Fm-determination. In all experiments, the first measurement was carried out 3 hours after transplanting (HAT) and then for seven days every 24 hours. Measurents were taken with a CCD camera mounted above the multiwell

plates. The spatial resolution of the camera was 640 by 480 pixels and the field of view was 10 by 13 cm. Only the plants were measured. The background was removed from the images. This is a main advantage of using IMAGING-PAM. Fluorescence intensities were displayed in false colors. Light emitting diodes (LED) were placed around the lense of the camera. Blue (450 nm) LED light provides the pulsemodulated excitation light and at the same time serves for actinic illumination and saturation pulses. Red (660 nm) and near-infrared LED light (780 nm) were arranged in order to obtain homogenous illumination of the image. The red long-pass filter in front of the CCD-chip guaranteed that only red and a part of the infra-red light was remitted from the plants to the CCD camera.
Figure 4.1 gives an overview of the imaging system including multiwell plates containing the treated plants and the chlorophyll fluorescence imaging system during the measurement routine.

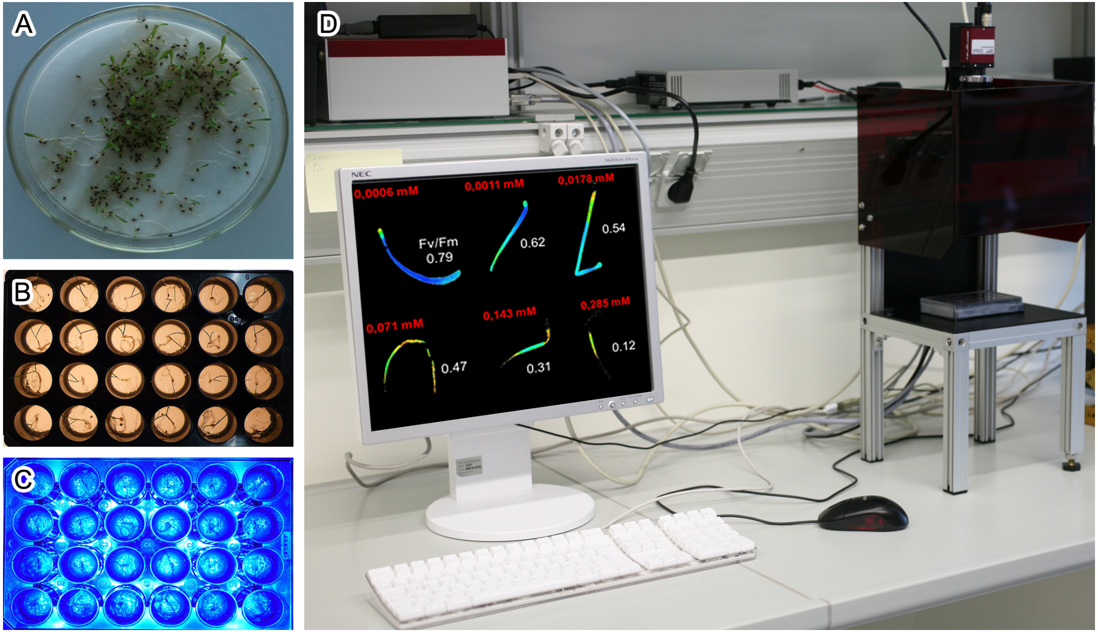

Figure 4.1: Overview of the chlorophyll fluorescence imaging microscreening. A) germinated weed seedlings, B) transplanted weed seedlings, C) multiwell plate blue illuminated during measuring process, D) PAM-IMAGING sensor system with chlorophyll fluorescence pictures

Statistical analysis Statistical analysis was carried out with the statistical software R (R Development Core Team 2011) and the R extension package *drc*. For the analysis of dose response relationships the non-linear model after Streibig (1988) was used. The model follows the equation:

$$Y = C + \frac{D - C}{1 + e^{b*ln[\frac{x}{ED_{50}}]}} \tag{4.2}$$

where y represents the plant response (Fv/Fm or $Inh.$), D the upper limit of the curve, C the lower limit, and b is proportional to the slope around $ED50$, the dose at which the plant response is reduced by 50%. Dose–response curves were compared by horizontal assessment (F-test, $\alpha = 0.05$) after data normalization according to Streibig et al. (1995). In cases were data showed a heterogeneity of variances a box-cox data transformation was carried out. In all evaluations, a model lack of fit test was performed according to Knezevic et al. (2007). Finally the herbicide resistance level was calculated according the equation:

$$RF = ED90_{resistant}/ED90_{susceptible} \tag{4.3}$$

where $ED90$ is the herbicide dosage causing 90% reduction of the plant response (Knezevic et al., 2007).

4.4 Results and Discussion

Detection of resistance against fenoxaprop-P-ethyl In all experiments Fv/Fm-values of the control plants were between 0.65 and 0.7 at all measurement times. The susceptible *A. myosuroides* population (ALOMY-S) treated with fenoxaprop-P-ethyl (Ralon Super® EW, Nufarm) showed a clear reduction in photosynthetic activity 96 hours after treatment (HAT). At a fenoxaprop-P-ethyl concentration of 0.57 mM the maximum quantum efficiency of PSII of the susceptible population tended towards zero. Maximum quantum efficiency of PSII of ALOMY-PEL tended towards zero at a fenoxaprop- P-ethyl concentration of 2.28 mM. The population ALOMY-R1 showed only a slight reduction in maximum quantum efficiency of PSII even at the highest fenoxaprop-P-ethyl concentration of 2.28 mM (Figure 4.2). It was possible to fit the three parameter dose-response model resulting in a resistance factor RF=7.57 for the ALOMY-PEL population and RF=29.86 for the ALOMY-R1 population. Both examined populations showed an increased tolerance to fenoxaprop-P-ethyl compared to the susceptible population, although the resistance factor for the ALOMY-R1 population is an estimation gained by extrapolation. There was no significant lack of fit test (p=0.99), suggesting that the model was describing the data appropriate. In Table 4.2, calculated resistance factors of the Chlorophyll fluorescence microscreening test are compared to the results of the standard whole-plant pot tests and the molecular background of the three populations. In the whole-plant pot test ALOMY-PEL and ALOMY-R1 were classified as RR and no mutation could be found in the ACCase gene, indicating a non-target- site-based resistance. The results of both tests corresponded well and a clear classification of sensitve and resistant populations could be made with both tests.

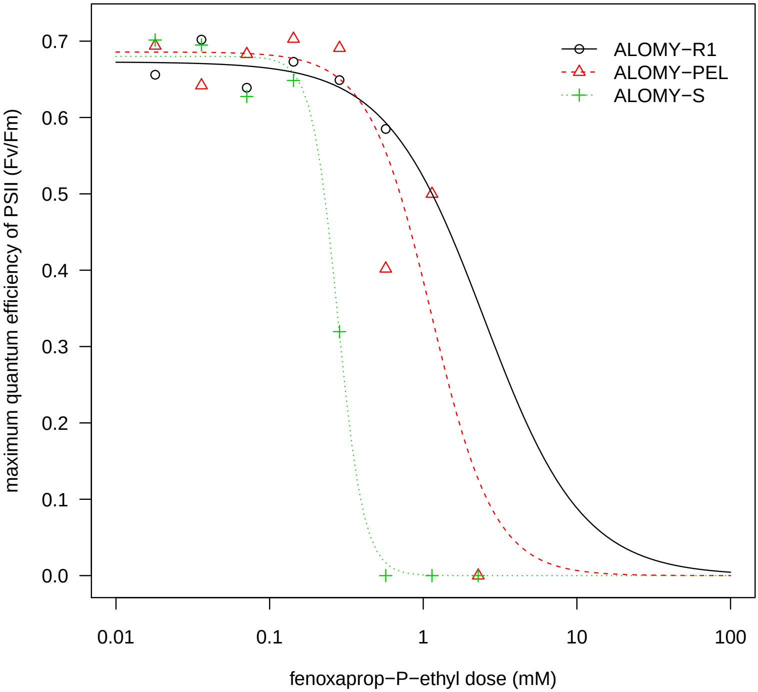

Figure 4.2: Fenoxaprop-P-ethyl dose-response curves for the *A. myosuroides* populations ALOMY-R1 and ALOMY-PEL compared to the susceptible ALOMY-S population 96 HAT. Each point represents the mean value of three replicates. (Lack of fit, p=0.99)

Table 4.2: Evaluation of resistance of the *A. myosuroides* populations ALOMY-S, ALOMY-PEL and ALOMY-R to fenoxaprop-P-ethyl in the chlorophyll fluorescence microscreening test, whole-plant pot greenhouse test and analysis of the molecular background; RF = resistance factor

	ALOMY-S	ALOMY-PEL	ALOMY-R1
Chlorophyll fluorescence microscreening test (RF)	-	7.57	29.86
Whole-plant pot greenhouse test (R rating system)	S	RR	RR
Molecular background	No mutation*	No mutation*	No mutation*

*ACCase loci tested: 1781, 2027, 2041, 2078, 2096

	ALOMY-S		ALOMY-R2		ALOMY-R3		ALOMY-R4	
	FPE	MSM	FPE	MSM	FPE	MSM	FPE	MSM
Chlorophyll fluorescence microscreening test (RF)	–	–	2.4	26.9	3.8	25.3	8	1.3
Whole-plant pot greenhouse test (R rating system)	S	S	RRR	R	R	R	RR	S
Molecular background	no mut.[1]	no mut.[2]	I1781L[1]	W574L[2]	I1781L , D2078G[1]	P197T[2]	no mut.[1]	no mut.[2]

mut., mutation; FPE, fenoxaprop-P-ethyl; MSM, mesosulfuron-methyl;

[1] ACCase loci tested: 1781, 2027, 2041, 2078, 2096, [2] ALS loci tested: 197, 574

Table 4.3: Evaluation of resistance of the *A. myosuroides* populations ALOMY-S, ALOMY-R2, ALOMY-R3 and ALOMY-R4 to fenoxaprop-P-ethyl and mesosulfuron-methyl in the chlorophyll fluorescence microscreening test, whole-plant pot greenhouse test and analysis of the molecular background; RF = resistance factor

In the second experiment, differences in photosynthetic activity of the investigated populations ALOMY-S, ALOMY-R2, ALOMY-R3 and ALOMY-4 treated with fenoxaprop- P-ethyl were visible 48 HAT. At this time of measurement, 2.28 mM of the active ingredient caused a reduction in maximum quantum efficiency of PSII to zero in population ALOMY-S. The examined populations R2, R3 and R4 showed an increased tolerance to fenoxaprop-P-ethyl compared to ALOMY-S. With the three parameter dose-response model a resistance factor of RF=2.4 could be calculated for R2, RF=3.8 for R3 and RF= 8.0 for R4. The test for lack of fit was not significant (p=0.21), indicating that data is well described by the selected model. In Table 4, results of the Chlorophyll fluorescence microscreening test, the standard whole-plant pot test and the molecular background of the populations are listed. The calculated resistance factor RF=2.4 for ALOMY-R2 seems low when regarding the standard whole-plant pot test and the classification in category RRR. For the populations ALOMY-R3 and ALOMY-R4 which are classified as R and RR in the standard whole-plant pot test, the calculated resistance factors of 3.8 and 8.0 correspond well. The molecular backround information for these populations was a modification of the target site ACCase in R2 (I1781L) and ALOMY-R3 (I1781L, D2078G) and no modification of the target site in ALOMY-R4.

The target for ACCase inhibitors is the enzyme ACCase which is essential for lipid biosynthesis, catalyzing the adenosine triphosphate–dependent carboxylation of acetyl-coenzyme A (CoA) to form malonyl-CoA (Vencill, 2002). Although this target is not directly affecting photosynthesis, Fv/Fm-value was reduced. As summarized by Abbaspoor et al. (2006) the effects on plants which are susceptible to AOPP herbicides (like fenoxaprop-P-ethyl) are:

1. an irreversible membrane potential depolarization and an enhanced permeability to protons, causing a collapse of the transmembrane proton gradient

2. a membrane disintegration and an accumulation of polyunsaturated fatty acids (PUFAs)

3. a peroxidation of PUFAs by lipoxygenase, which produces reactive oxygen species (ROS)

Due to the production of ROS numerous damaging reactions are initiated, leading to plant death. These reactions, collectively called oxidative

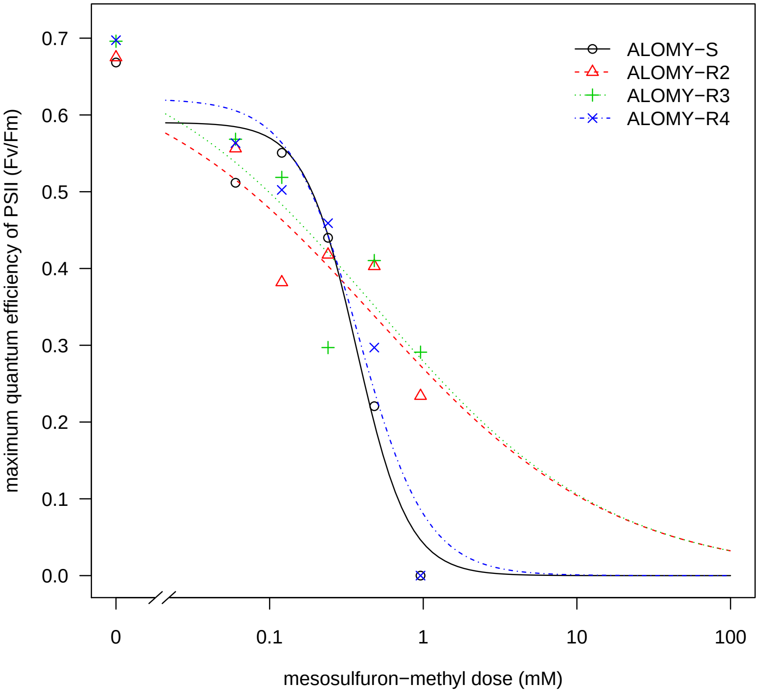

Figure 4.3: Fenoxaprop-P-ethyl dose-response curves for the *A. myosuroides* populations ALOMY-2 (significant, p=0.00), ALOMY-3 and ALOMY-4 compared to the susceptible ALOMY-S population 48 HAT. Each point represents the mean value of three replicates. (Lack of fit, p=0.21)

stress, cause an interruption of the electron transport chain from PSII to PSI. This interruption has an influence on chlorophyll fluorescence, probably enabling the detection of herbicide efficacy by measuring maximum quantum efficiency of PSII.

Detection of resistance against mesosulfuron-methyl In the chlorophyll fluorescence microscreening test of the populations ALOMY-S, ALOMY-R2, ALOMY-R3 and ALOMY-4 treated with mesosulfuron-methyl, the highest dosage (0.96 mM) caused a reduction in $FvFm$-value to zero in ALOMY-S 72 HAT. There was no significant lack of fit (p=0.32), suggesting that the model was appropriate for data. In comparison to ALOMY-S the dose-response curves of ALOMY-R2 and -R3 are shifted to the right indicating an increased tolerance to mesosulfuron-methyl compared to ALOMY-S. Resistance factors of 26.9 and 25.3 could be calculated for ALOMY-R2 and -R3 using the the three parameter dose-response model. As can be seen in Table 3, these populations were classified as R in the standard whole-plant pot test and the molecular background information verified a W574 mutation in R2 and a P197T mutation in ALOMY-R3. The course of the dose-response curve of R4 is very similar to that of ALOMY-S. The calculated resistance factor of RF=1.3, the classification in category S of the standard whole-plant pot test and also the molecular background information (Table 3) are in agreement. Our findings are in line with studies by Riethmüller-Haage et al. (2006b,a); Judy et al. (1990); Percival and Baker (1991). Up to now there is no sufficient explanation why ALS inhibitors affect photosynthesis. It seems likely that this effect is a controlled down regulation of the photosystem due to a sink limitation by a lack of the branched-chain amino acids amino acids valine, leucine and isoleucine whose synthesis is catalyzed by the ALS enzyme. Further research has to be done to explain this phenomenon.

Suitability of the Chlorophyll fluorescence microscreening test The hypothesis that the effect of both herbicides can be detected with the chlorophyll fluorescence microscreening test could be confirmed although fenoxaprop-P-ethyl and mesosulfuron-methyl are not directly affecting photosynthesis. For both herbicides all resistant populations could be identified with the new chlorophyll fluorescence microscreening test regardless if it was a target-site or a non-target-site-based resistance. It was shown that the chlorophyll fluorescence microscreening test corresponded

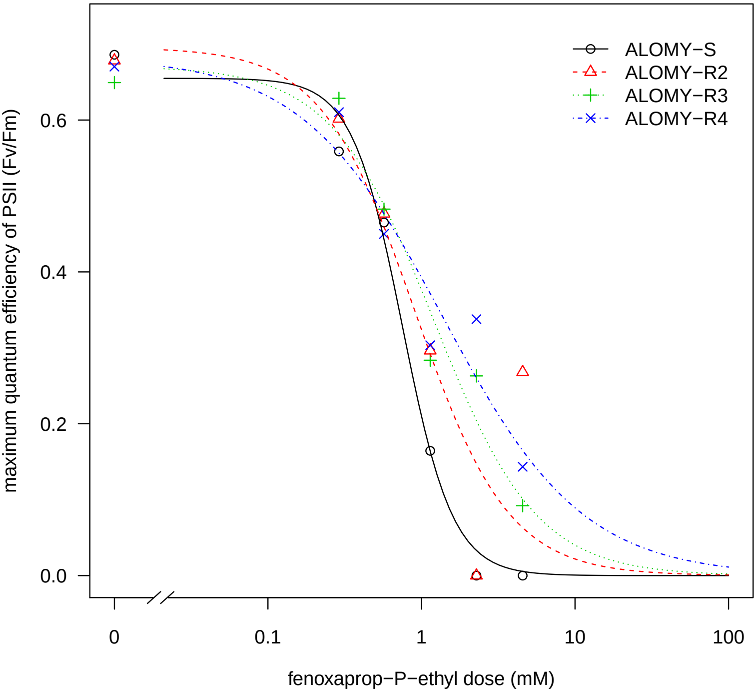

Figure 4.4: Mesosulfuron-methyl dose-response curves for the *A. myosuroides* populations ALOMY-2, ALOMY-3 and ALOMY-4 compared to the susceptible ALOMY-S population 72 HAT. Each point represents the mean value of three replicates. (Lack of fit, p=0.32)

well in most cases with the standard whole-plant pot test. However, the new test needed less time and space than for the standard test in the greenhouse. Additionally, no costs for greenhouse and precision track sprayer had to be spent. Results of the chlorophyll fluorescence microscreening test were available 96 hours after transplanting at the latest, depending on the herbicide mode of action and the dose. For better and automatic differentiation of sensitive and resitant population classification algorithms such as maximum likelehood classification, nearest neighbour classification or neural networks could be applied (Weis and Soekefeld, 2009).

The chlorophyll fluorescence microscreening test might also be used as an in-season field test. For this application, weed seedlings could be transplanted into multiwell plates treated with different herbicides and the response could be measured after 48-96 hours in relation to an untreated control. Alternatively, weed seedlings from the field that had been treated with herbicides could be measured directly in the field. Only few adaptions would be needed for the IMAGING-PAM system to make the chlorophyll fluorescence measurements in the field. The chlorophyll fluorescence microscreening test presented in this study could be a helpful tool to get reliable information on the response of weed populations to herbicides in short time. This could assist decision support system in integrated weed management.

5 General discussion

Aim of this study is, to develop a decision support system for weed management in North China Plain double cropping fields. For this purpose four working packages were defined (see chapter 1.4) and the results are presented in the form of three articles which are part of this thesis. Each article can be read independently and each article was already discussed independently.

5.1 Modelling of weed-crop interaction towards decision support systems

Mathematical modelling of weed-crop interactions became an inherent part of weed control decision making and weed research. Short term weed control tactics can be evaluated well by multifactorial field experiments, as shown in the second publication of this thesis. However, long term effects of weed control decisions have to be evaluated mathematically in conjunction with empirical observations (Holst et al., 2007).
Since the publication of Sagar and Mortimer (1976) about modelling the population dynamics of weeds, more than 100 weed-crop interaction modelling approaches have been published (Holst et al., 2007). Most published weed-crop interaction models are structured around the weed life cycle and consist of **three basic sub-models**, calculating crop yield loss, weed population dynamics and economics of weed control decisions:

1. Calculation of crop yield loss in dependency of weed density according to Cousens (1985)

2. Modelling of weed population dynamics, based on equations calculating the initial weed density as well as seed production per weed plant. According to observations by Cussans (1982) the soil seed bank can be divided in to two or more soil layers, depending on

the weed species dependent ability to germinate from different soil depths. Watkinson (1981) and Doyle et al. (1986) described the density dependent survival of weed seedlings. Furthermore Watkinson (1981) and Doyle et al. (1986) described the number of produced seeds per plant in dependency of weed density.

3. The economic profit as a function of weed control efficacy as proposed by Christensen et al. (2003), Munier-Jolain et al. (2002), Wilkerson et al. (1991) and Doyle et al. (1986).

Models predicting the population dynamics of weeds have been found as the major source of uncertainty in decision support systems for weed control. Weed seedling emergence can be affected by temperature, water availability, burial depth and soil type (Cao et al., 2011). According to Forcella et al. (2000) it seems that water availability and temperature are the main driving forces. Complex hydrothermal time (HTT) models were introduced in recent years for predicting the time of weed seed germination more precisely (Benjamin et al., 2010; Grundy, 2003; Bradford, 2002; Forcella et al., 2000). Dividing weed germination into several so called cohorts can improve weed control decisions substantially. Thus it becomes possible to differentiate between the first cohorts which contribute the most to the total weed biomass and weed seed production and later emerging cohorts which are less competitive and reproductive (Fernandez-Quintanilla et al., 1986). With this kind of models it becomes possible to predict the time of weed emergence and therefore decisions about weed control timing can be optimized (Leblanc et al., 2003; Izquierdo et al., 2009). Beneath the theoretical benefits of these models there are some drawbacks. Outside of reduced tillage systems the models loose their prediction accuracy due to seed burial and seed dormancy (Cao et al., 2011). Also questions occur in which depth temperature and water availability should be measured, because differences between soil layers can be enormous. Apart from that, the general question arise how this method can be implemented into practical agriculture ore rather how farmers can measure soil temperature and water availability for HTT calculation on field scale? Due to these drawbacks HTT is of minor importance for practical decision making rather than for research purposes.

Beside the effect of extrinsic factors on the population dynamics of weeds, the effect of extrinsic factors on weed-crop competition in general has to considered. Several approaches were published in recent years trying to find a practical solution for this problem. Jame and Cutforth (1996) and Deen et al. (2003) discussed the use of crop-weed competition models in this context. There are a number of eco-physiological models existing whereof ALMANAC, APSIM, CROPSIM and INTERCOM are the most frequently used. The comparative evaluation of these four models by Deen et al. (2003) showed that relatively simple algorithms were quite capable to simulate the major competition responses. Increased model complexity did not significantly improve the model accuracy. It can be stated that eco-physiological models are valuable tools for research purposes to deepen our understanding about the underlying mechanisms of crop-weed interaction. On the other hand such models are not recommendable for practice oriented decision support systems, because complex models need complex and difficult to assess background data.

Numerous decision support system for weed management have been published, like PALWEED:WHEAT (Kwon et al., 1995), WeedSOFT (Neeser et al., 2004), GESTINF (Berti and Zanin, 1997), HERB (Wilkerson et al., 1991), to mention only a few. All decision support systems have in common that their source code is not freely available, that different programming languages were used and that they are parametrized to specific agronomic and environmental conditions. This makes it difficult to transfer and regionalize these models into the NCP cropping system.

5.2 Continuation of the research project

Studies by Chen et al. (2006b), Qiu et al. (2011) and Yin et al. (2005) demonstrated the high potential for nitrogen fertilizer input reduction in the NCP cropping system and their results are in line with the results presented in in the first paper of this thesis. It can be assumed that in future the fertilizer consumption will significantly decrease. This process will be encouraged by rising fertilizer costs and massive environmental problems due to overfertilization for the last decades. The results in the first paper demonstrate that reduced fertilization intensity will increase weed competitiveness, at least in the short term and at least for the investigated species. With increased winter wheat seeding rates this negative side-effect can be reduced without increasing the use of herbicides. For the development of a decision support system these results are of major interest. It turned out, that the agronomic preconditions have to be considered and thus have to be incorporated into the model algorithm. In the case of the presented decision support system approach of the second paper, an underestimation of weed competitiveness under reduced fertilization intensities has to be avoided. It seems to be realistic to incorporate the additional information on fertilization practice and agronomic preconditions into the yield loss sub model. Therefore additional field experiments will be necessary in the future to estimate crop yield loss in dependency of crop density at constant weed infestation levels. Certainly the chosen crop cultivar plays an important role too. Additional field experiments would be necessary to test different cultivars on their competitiveness against weeds. New introduced wheat cultivars in the North China Plain region show a reduced growth hight. These cultivars are supposed to have a less weed suppressive effect than tall growing cultivars (Zwerger and Ammon, 2002). Aim of the presented decision support system is to give reliable weed management suggestion based on a minimum of input variables. The following input variables will be necessary to operate the decision support system:

1. Major weed species and their density at the time of weed control decision, normally BBCH 11-13 for grass weeds and BBCH 12-14 for broad leafed weeds)
2. Crop cultivar
3. Crop seeding rate (row distance as well as total seeding rate)
4. Estimated yield
5. Fertilization strategy or rather intensity
6. Tillage system

In paper two the possibility of reduced herbicide dosages was discussed. Unfortunately data on herbicide dose dependent population dynamics of weeds is lacking. To improve the predictive capability of the model approach this data will be indispensable and thus has to be investigated in further field experiments too.

Beside the incorporation of agronomic preconditions into the DSS, mechanical weed control methods have to be considered. Harrowing for instance, seems be a promising method for the North China Plain cropping system. In 2012 the first field experiments were performed to test the feasibility of this method under the given agronomic conditions.

5.3 Herbicide efficacy monitoring as additional tool for weed control decision making

The incorporation of information on the herbicide efficacy status of weed populations into a decision support system for weed management was not thought possible so far. The assessment of herbicide efficacy was limited only to suspicious herbicide resistant weed populations because herbicide efficacy tests are expensive as well as time, space and labour intensive. The herbicide resistance quick test presented in the third paper of this thesis provides a cheap and fast method to assess the herbicide efficacy status of weed populations. This method enables the extension service in the NCP region as well as researchers the annual extensive screening of weed biotypes on their herbicide efficacy status. Considering this information in herbicide selection and dosage decisions would significantly reduce the risk of herbicide resistance development and the risk of wrong herbicide selections. So far herbicide resistance is not a widespread phenomenon in the North China Plain region and this method would be able to conserve this condition. In cases of herbicide resistant weed populations the presented method can also be used to find alternative herbicides.

5.4 Chances of integrated weed control measures for the North China Plain cropping system

Beside chemical and mechanical weed management strategies, the implementation of integrated weed control measures (IWM) has to be considered. The objective of IWM is to reduce weed infestations while minimizing the reliance on herbicides. In Europe, IWM strategies are under intensive investigation, forced by problems with herbicide resistant weed populations and an increasing concerns about the environmental impacts of herbicides (Chikowo et al., 2009). The tools of IWM comprise:

- Diverse crop rotations with diverse sowing dates
- Soil tillage either to bury weed seeds (deep tillage) or to stimulate weed emergence flushes (shallow tillage)
- Adapted sowing dates to escape weed emergence flushes
- Selection of competitive crops and cultivars

- Optimized seeding rates and row distances
- Undersown crops and mulch to reduce weed emergence
- Mechanical weed control methods (hoeing, harrowing)
- Intercropping systems

The adoption of IWM strategies imply substantial changes in crop management as well as farm and labour organization (Munier-Jolain et al., 2008). Furthermore detailed crop and weed management knowledge as well as suitable machinery is necessary to implement IWM successfully. The importance of the double cropping system for the Chinese national food supply would probably complicate the IWM implementation for several reasons: Diversifying the crop rotation would be aligned with a production decline of wheat and maize. The acquisition of diverse soil tillage machinery is not affordable for small scale farmers. The choice of different winter wheat cultivars is limited. Finally the necessary agricultural knowledge and know how of the farmers in the North China Plain is limited.

The economic consequences for farmers and food prices caused by the implementation of IWM strategies in Europe is presently under investigation.

Intercropping systems are already part of the NCP cropping system (Feike et al., 2010), however the effect of intercropping on weed suppression and weed species composition is not evaluated yet. It can be concluded that beneath the already suggested adjustment of fertilization, seeding rate and crop cultivar room for IWM strategies is very limited.

5.5 Possible distribution channels for decision support systems in the North China Plain

The distribution of the decision support system in the North China Plain region will be the last step of this project. Farmers are not well equipped with information technology which makes the distribution of a decision support system as computer software difficult. So far, farmers receive their knowledge on weed control measures, or rather herbicide selection, from the agricultural extension service. For this purpose the agricultural extension service broadcasts recommendations on herbicide selection, timing and dosage via the governmental television channels. These recommendations are neither specific nor based on scientific knowledge on crop-weed competition. In the first instance, the decision support system should be used to train agricultural extension service workers. Subsequently the system could be used as teaching tool in agricultural training centres. First training centres are tested in the county area of Beijing and may be introduced in every county in the North China Plain. An internet-based version of the decision support system would be beneficial for large scale farmers, or state owned farms.

Holst et al. (2007) criticized the poor availability of validated model approaches and the poor model documentation. Model validation is the most critical part in developing a decision support system, because several sites and years will be necessary. In this project a two year model validation phase should be planned. Therefore several sites in the North China Plain region could be selected where, in cooperation with the Chinese agricultural extension service, the model will be validated. For research purposes the presented decision support system approach will be available as *R* add-on package. *R* is a widespread open source statistical software and statistical programming environment with growing importance in the scientific world. Thus, for the first time it would become possible for other research groups to further develop the presented modelling approach and additionally model validation and regionalization would be simplified.

6 Summary

The North China Plain region is on eof the major production regions for wheat and maize in China.Weed control practice in the North China Plain has changed from hand weeding towards chemical methods. This change in weed management practice is caused by a shift of labour towards the fast growing industrial sector and by steadily increasing yields which made herbicides affordable even for small scale farmers. Agriculture in the North China Plain region is characterised by a double cropping system of winter wheat followed by summer maize in one year. Due to the continuous overuse of chemical fertilizers, irrigation water and pesticides severe problems are aligned with this intensive cropping system. Especially the accumulation of pesticide residues in the food chain as well as in environmental resources becomes an increasing problem.

Objective of this study is to develop a decision support system for weed management for the North China Plain winter wheat production system. Examples in Europe showed that herbicide input can significantly be reduced by implementing decision support systems. Herbicide selection, dosage and timing of application is calculated on basis of knowledge on weed-crop interaction and dose-response relationships of herbicides and weeds. The decision support systems aims to provide reliable decisions under consideration of economic and ecologic effects of herbicide use.

To achieve this objectives this thesis was structured in four interacting work packages:

1. Collection of expert knowledge and information on the most abundant weed species and their spatial distribution

2. Evaluation of integrated weed control measures

3. Development and evaluation of a decision support system prototype

4. Development of rapid screening method for the in-season detection of herbicide resistance in weeds

Weed surveys in more than 100 winter wheat fields in the North China Plain region showed that winter wheat fields are heavily infested by mostly broadleafed weed species, whereof the most abundant are *Descurainia sophia* L., *Capsella bursa pastoris* L. and *Calystegia hederacea* WALL. Beneath the dependency of species distribution on environmental contraints, multivariate analysis of the survey data showed a clear dependency of species abundance and competitiveness on crop density and nitrogen fertilization intensity. Subsequent field experiments were conducted for deeper investigation of the mentioned variables on weed competitiveness. It turned out that fertilization adjusted to soil mineral nitrogen content has a promoting effect on the competitiveness of *C. hederacea*. On the other hand It could be shown that increased winter wheat seeding rates are an efficient measure to reduce the competitiveness of the investigated species. To enhance the predictive accuracy of a decision support system under varying agronomic conditions, the presented results are of great value.

In the second step of this thesis a decision support system prototype was developed and evaluated. Data for model parametrization was gained from a two year field experiment for estimation of crop yield loss and population dynamics in dependency of weed species density. Additionally herbicide dose response studies were carried out for major weed species found in the North China Plain. Crop yield loss, weed population dynamics and herbicide dose response models were combined towards a first decision support model approach. For model evaluation four different decision strategies were simulated over a time period of five years and two initial weed infestation levels. It turned out that herbicide input can be significantly reduced by up to 50% compared to the farmers practice weed control strategy by economically optimized decision rules while winter wheat yield was not negatively affected.

Due to the steady increasing number of weed populations which are suspicious to be herbicide resistant, the demand for rapid in-season resistance tests is rising. The novel rapid herbicide resistance test presented in the third article of this thesis is based on chlorophyll fluorescence imaging measurement. For all tested herbicides and modes of action effects on maximum quantum efficiency of PSII were measurable. It was possible to distinguish between resistant populations and to calculate corresponding resistance factors. The experiments demonstrate the potential of the presented method for accelerated herbicide resistance detection. Beyond

herbicide resistance detection this method could be of interest for the early screening of newly developed herbicides as well. A combination of preventive and direct weed control methods is considered as an important measure to prevent a further development and distribution of herbicide resistant weed populations within and between fields. The microscreening system presented in the study could be a helpful tool to test if the herbicide is still effective to control the present vegetation before it is sprayed.
The articles presented in this thesis highlight the chances by the implementation of a decision support system for weed control in the North China Plain region. Several novel approaches were presented like the incorporation of agronomic preconditions into the decision process as well as the incorporation of herbicide efficacy data.
The presented decision support system can be of use for teaching the agricultural extension service in the North China Plain. The presented results showed that through the use of a decision support system herbicide use can be reduced to a minimum and thus negative side effects can be reduced.

7 Zusammenfassung

Die Nordchinesische Tiefebene zählt zu den wichtigsten Anbaugebieten für Weizen und Mais in China. Unkrautkontrollmaßnahmen in der Nordchinesischen Tiefebene haben sich von manuellen Methoden hin zu rein chemischen Methoden verändert. Diese Veränderung der Unkrautregulierungsmaßnahmen wurde einerseits verursacht durch die Abwanderung von Arbeitskräften in den ständig wachsenden chinesischen Industriesektor und andererseits durch konstant steigende Erträge welche Herbizide auch für Kleinbauern erschwinglich gemacht haben. Die landwirtschaftliche Praxis in dieser Region ist charakterisiert durch eine Doppelfruchtfolge von Winterweizen gefolgt von Mais in einem Jahr. Überdüngung, Bewässerung und der massive Einsatz von Pestiziden führten zu weitreichenden Umweltproblemen.

Ziel dieser Arbeit ist es, ein Entscheidungsmodel zur Unkrautkontrolle für das Weizenanbausystem der Nordchinesischen Tiefebene zu entwickeln. Zahlreiche Beispiele aus Europa haben gezeigt, dass der Einsatz von Herbiziden durch die Einführung von Entscheidungsmodelle signifikant reduziert werden konnte. Die Wahl des Wirkstoffes, der Dosis und des Einsatzzeitpunktes wird hierbei auf Basis von Interferenzmodellen und Dosis-Wirkung Modellen getroffen. Das vorgestellte Entscheidungsmodel hat zum Ziel, unter Berücksichtigung ökonomischer und ökologischer Aspekte der Unkrautregulierung, verlässliche Entscheidungen hinsichtlich der Durchführung von Unkrautkontrollmaßnahmen zu treffen. Um dieses Ziel zu erreichen ist die vorliegende Forschungsarbeit in vier Arbeitspakete gegliedert:

1. Das Sammeln von Informationen über die Hauptunkrautarten und deren Verbreitung

2. Evaluierung von integrierten Unkrautkontrollstrategien

3. Entwicklung und Evaluation eines ersten Prototyps eines Entscheidungsmodels

4. Entwicklung einer Methode zur Detektion von Herbizidresistenz in Unkrautpopulationen

Untersuchungen in mehr als 100 Winterweizenfeldern in der Nordchinesischen Tiefebene haben ergeben dass zweikeimblättrige Unkrautarten wie *Descurainia sophia* L., *Capsella bursa pastoris* L. und *Calystegia hederacea* WALL. die Artenzusammensetzung dominieren. Neben dem generellen Einfluss von Umweltfaktoren auf das Vorkommen und die Konkurrenzkraft einzelner Arten haben multivariate Datenanalysen ergeben, dass die Konkurrenzkraft einzelner Arten stark mit der Intensität der Stickstoffdüngung sowie der Saatstärke von Winterweizen korreliert. Zur näheren Untersuchung der genannten Variablen wurden Feldversuche durchgeführt. Es konnte gezeigt werden, dass Düngestrategien basierend auf der N_{min} Methode die Konkurrenzkraft von *C. hederacea* steigert. Eine Erhöhung der gängigen Saatstärke von Winterweizen hingegen hat sich als geeignete Maßnahme zur Unterdrückung der genannten Arten herausgestellt. Um die Vorhersagegenauigkeit des geplanten Entscheidungsmodells unter sich ständig verändernden agronomischen Rahmenbedingungen zu verbessern, sollten diese Ergebnisse berücksichtigt werden.

Im nächsten Schritt dieser Arbeit wurde ein erster Ansatz für ein Entscheidungsmodell konzipiert und evaluiert. Die für die Parametrisierung des Modells notwendigen Daten wurden durch zweijährige Feldversuche gewonnen, welche die Abschätzung von Ertragsverlusten und der Populationsdynamik von Unkräutern zum Ziel hatten. Zusätzlich wurden Herbizid Dosis-Wirkungs Untersuchungen für die Hauptunkrautarten des genannten Weizenanbausystems durchgeführt. Modelle zur Berechnung von Ertragsverlusten und der Populationsdynamik von Unkräutern als auch zur Kalkulation von Herbizid Dosis- Wirkungsbeziehungen wurden zu einem ersten Entscheidungsmodell kombiniert. Es wurden vier unterschiedliche Entscheidungsstrategien zu zwei unterschiedlichen Ausgangverunkrautungen über einen Zeitraum von fünf Jahren modelliert. Im Vergleich zur derzeit gängigen Unkrautkontrollstrategie hat sich gezeigt, dass unter Anwendung ökonomisch optimierter Entscheidungsstrategien die eingesetzten Herbizidmengen um bis zu 50% reduziert werden können. Die Simulationen haben weiterhin gezeigt, dass der Winterweizenertrag hierdurch nicht negativ beeinträchtigt wurde.

Auf Grund der wachsenden Zahl von Unkrautpopulationen mit Verdacht auf Herbizidresistenz wächst die Nachfrage nach Resistenzschnelltests, welche innerhalb einer Saison anwendbar sind, stetig. Für alle getesteten

Herbizidgruppen war es möglich die Effekte auf die maximale Quantenausbeute des Photosytem II zu quantifizieren. Hierdurch ist es möglich zwischen resistenten und sensitiven Populationen zu unterscheiden. Die Experimente haben gezeigt dass die vorgestellte Methode sehr gut geeignet ist für eine beschleunigte Detektion von Herbizidresistenz. Über die Detektion von Herbizidresistenz hinaus könnte die vorgestellte Technologie auch für das Testen neuer Wirkstoffe zu Einsatz kommen. Eine Kombination aus vorbeugenden und direkten Unkrautkontrollmaßnahmen wird als wichtigste Maßnahme zur Verhinderung der Entwicklung und Ausbreitung von herbizidtolleranten Unkrautpopulationen angesehen. Durch die Einbindung der Daten, welche mit Hilfe dieses neuen Testsystems gewonnen werden können, kann der Entscheidungsprozess des vorgestellten Entscheidungsmodells hinsichtlich Herbizidwahl und Dosierung nachhaltig verbessert werden.

Die in dieser Arbeit präsentierten Studien geben einen ersten Eindruck über die Chancen welche mit der Einführung eines Entscheidungssystems zur Unkrautkontrolle in der Nordchinesischen Tiefebene verbunden sind. Mehrere Neuerungen für Entscheidungsmodelle wurden präsentiert, wie die Einbindung agronomischer Variablen als auch die Verwendung von Daten zur Herbizidwirkung.

Das vorgestellte Entscheidungsmodell soll zukünftig für die Schulung von landwirtschaftlichen Beratern in der Nordchinesischen Tiefebene zum Einsatz kommen. Die vorgestellten Ergebnisse haben gezeigt, dass durch die Anwendung eines solchen Modells der Herbizideinsatz auf ein Minimum reduziert werden kann und damit die negativen Auswirkungen auf Mensch und Umwelt reduziert werden können.

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