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Integrated Weed Management in Intensive Cropping Systems - Towards Reduction of Herbicide Input

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Abbreviations and acronyms

%	percent
∞	infinity
$^{\circ}C$	degree centigrade
A	fraction winter wheat yield loss as $SB_{U_i} \rightarrow \infty$
a	yield loss per unit *A. fatua* (for $x \rightarrow \infty$)
$a.i.$	active ingredient
$ACCase$	Acetyl Coenzym A Carboxylase
ALS	Acetolactate synthase
b	slope around e
C	*A. fatua* seed input per unit residual *A. fatua* biomass as $SB_{U_i} \rightarrow 0$
C_1	fixed production costs
C_2	fixed costs for herbicide application
D	*A. fatua* seed input as $SB_{U_i} \rightarrow \infty$
e	ED_{50}
ED_{50}	effective dose, causing 50 % efficacy
g	gramm
h	hour
ha	hectar

I	fraction winter wheat yield loss per unit residual *A. fatua* biomass as $SB_{U_i} \to 0$
i	yield loss per unit *A. fatua* (for $x \to 0$)
L	liter
m	meter
m^2	square meter
$m_{new/old}$	seed mortality of newly produced *A. fatua* seeds/seed from the previous season
MSO	Methylated seed oil
N	nitrogen
N_{min}	soil mineral nitrogen
$NR_{SB_{U\,i}}$	net return in dependency of the herbicide dose dependent residual *A. fatua* biomass
p	*A. fatua* seed losses due to predation
P_U	price per unit herbicide
P_y	price per unit crop yield
s	*A. fatua* seed losses via harvest
SB	*A. fatua* seedling biomass
SB_{U_i}	residual *A. fatua* biomass in dependency of herbicide dosage
SD	*A. fatua* seedling density
$SI_{SB_{U\,i}}$	*A. fatua* seed input in dependency of the herbicide dose dependent residual biomass
SSB_{new}	soil seed bank content of newly produced *A. fatua* seeds
SSB_{old}	soil seed bank content of *A. fatua* seeds from the previous season

t	ton
U	herbicide dosage
$v_{new/old}$	germination rate of newly produced *A. fatua* seeds/seed from the previous season
x	*A. fatua* density / biomass / relative biomass
$Y_{SB_{Ui}}$	Winter wheat yield in dependency of herbicide dose dependent *A. fatua* biomass
Y_{wf}	weed-free winter wheat yield
YL	yield loss
€	euro
N	nitrogen
NH_4^+	ammonium
NO_3^-	nitrate

1 General Introduction

Among the biotic factors affecting crop yields, weeds cause the highest yield losses if not controlled. They especially are important in maize and wheat, where they cause potential yield losses of 40 % and 23 % worldwide (Oerke, 2006).

In conventional farming, weeds are usually controlled by herbicides. However, herbicides can have negative environmental impact, such as contamination of ground- and surface water (Annett et al., 2014) and negative impacts on non-target organisms (Freemark and Boutin, 1995).

This thesis deals with the potential of reducing herbicide input in intensive cropping systems. Experiments were carried out in two regions, i.e. North China Plain with a highly intensive double cropping system consisting of winter wheat and summer maize, and Germany.

1.1 Structure of the Thesis

The thesis is structured in six sections.

Section 1 gives an short introduction into the topic, describes the structure and states the objectives of the thesis. At the end of this section a list of the publications being included in this thesis as well as those not being considered in this thesis is given.

Section 2 introduces a method to screen for herbicide efficacy in a rapid and objective way using bi-spectral imaging.

Section 3 focuses on the potential of reducing herbicide input in maize. This section includes two publications, dealing with the efficacy of reduced herbicide dosages in summer maize and the mechanism of methylated seed oil, an additive, to enhance herbicide efficacy of topramezone, a maize herbicide.

Section 4 deals with the efficacy of reduced herbicide dosages in winter wheat at the example of *A. fatua* and how reduced dosages influence seed production and other population dynamics paramaters. Furthermore, yield loss potential of *A. fatua* in winter wheat is handled.

Section 5 mainly deals with non-chemical weed management. The first publication in this section is about the influence of winter wheat seeding rate and nitrogen fertilization on *Calystegia hederacea* competitiveness and control. The second publication in this chapter investigates the effect of cover crops on crop and weed growth.
In section 6 the potential of reducing herbicide dosages in intesive cropping systems is being discussed. This section contains a further manuscript (section 6.1) examining the long-term effects of reduced dosages on weed population development, total herbicide input and net return at the example of *A. fatua* in winter wheat by using a simulation approach.

1.2 Objectives of the Thesis

The objectives of the thesis are, to

1. develop a method for fast and objective screening of herbicide efficacy
2. investigate the potential of reduced herbicide dosages in maize cropping
3. examine the mechanism of enhancing herbicide efficacy by methylated seed oil adjuvant
4. test the yield loss potential of *A. fatua* in winter wheat
5. test the influence of reduced herbicide dosages on control of *A. fatua* and their influence on seed production
6. investigate how agronomic factors influence *Calystegia hederacea* competitiveness and control
7. investigate the influence of cover crops on weeds and crops
8. to examine how reduced herbicide dosages influence long-term weed population development, yield and net return at the example of*A. fatua* in winter wheat.

1.3 Publications

The thesis includes following publications and manuscripts that have been submitted:

Jäck, O., A. Menegat, M. Weis, H. Ni and R. Gerhards. 2012. Introduction of a non-destructive method for the investigation of herbicide efficacy in greenhouse bioassays based on image analysis. Pakistan Journal of Weed Science Research 18: 239-247.

Zhang, J., **O. Jäck**, A. Menegat, Z. Zhang, R. Gerhards and H. Ni. 2013 b. The Mechanism of Methylated Seed Oil on Enhancing Biological Efficacy of Topramezone on Weeds. PLoS ONE 8(9).

Zhang, J., L. Zheng, **O. Jäck**, D. Yan, Z. Zhang, R. Gerhards and H. Ni. 2013 a. Effcacy of four post-emergence herbicide applied at reduced doses on weeds in summer maize (Zea mays L.) fields in North China Plain. Crop Protection 52: 26-32.

Menegat, A., **O. Jäck**, J. Zhang, K. Kleinknecht, B. U. Müller, H.-P. Piepho, H. Ni and R. Gerhards. 2013. Japanese Bindweed (*Calystegia hederacea*) Abundance and Response to Winter Wheat Seeding Rate and Nitrogen Fertilization in the North China Plain. Weed Technology 27(4): 768-777.

Rueda-Ayala, V., **O. Jäck** and R. Gerhards. 2015. Investigation of biochemical and competitive effects of cover crops on crops and weeds. Crop Protection 71: 79-87.

Menegat, A., **O. Jäck** and R. Gerhards. 2015. Long-term simulation of herbicide saving weed control strategies in intensive winter wheat cropping systems. Weed Research (submitted).

Jäck, O. and R. Gerhards. 2015. Winter wheat yield losses due to *Avena fatua* competition and effect of reduced herbicide dosages on population dynamic parameters of *Avena fatua*. Journal of Plant Diseases and Protection (submitted)

Parts of the work had been presented at national and international conferences:

Zhang, J., **O. Jäck**, H. Ni and R. Gerhards. 2012. The spread, evaporation, penetration of topramezone in giant foxtails (*Setaria faberi* HERRM) affected by two different mode adjuvants and effeicacy test. Proceedings of the 6^{th} International Weed Science Congress, Hangzhou, China.

Jäck, O., A. Menegat, J. Zhang, H. Ni and R. Gerhards. 2013. R-based simulation model for longterm management of *Avena fatua* L. in winter wheat. Proceedings of the $16^{t}h$ EWRS Symposium, Samsun, Turkey.

Jäck, O., A. Menegat, J. Zhang, H. Ni and R. Gerhards. 2014. Simulation model for longterm management of *A. fatua* in winter wheat. 26. Deutsche Arbeitsbesprechung über Fragen der Unkrautbiologie und -bekämpfung, Braunschweig, Germany.

2 Introduction of a non-destructive method for determination of herbicide efficacy in greenhouse bioassays

To screen on herbicide efficacy for estimating the potential of reducing herbicide dosages, various dose-response experiments are necessary. These experiments are usually time and labour intensive, since estimation of herbicide efficacy is done by visual rating or by measurement of weed dry weight. Aim of the first article was to enhance the process of herbicide efficacy determination by using bi-spectral imaging for determination of soil coverage of weeds. By taking images in the red and near-infrared wavelength range it is possible to separate weeds from soil and thus measuring soil coverage of weeds exactly. Experiment were carried out with *Bromus japonicus* biotypes from the North China Plain. Analysis showed that weed dry weight and soil coverage correlated well. With this method it is possible to objectively determine herbicide efficacy in a rapid and easy way.

Introduction of a non-destructive method for determination of herbicide efficacy in greenhouse bioassays

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Abstract *Bromus japonicus* is an important grass weed in North China Plain winter wheat cropping, that causes yield losses and is difficult to control due to lack of efficient herbicides. Therefore, dose-response studies were conducted to investigate the efficacy of different herbicides on *B. japonicus*. Herbicide efficacy was determined by biomass assessment and by leaf coverage measurements using a bi-spectral camera system. Among the tested herbicides were ACCase-inhibitors, ALS-inhibitors ans PS(II)-inhibitors. Of those, only the tested ALS-inhibitors showed sufficient efficacies for control of *B. japonicus*. Leaf coverage measured with the bi-spectral camera system correlated well with biomass data and thus can serve as rapid and non-destructive method to assess herbicide efficacy.

3 Efficacy of reduced herbicide dosages end enhancing herbicide efficacies in intensive maize cropping

3.1 Efficacy of four post-emergence herbicide applied at reduced doses on weeds (*Zea mays* L.) in summer maize fields in North China Plain

The first publication in this chapter investigates the possibilities of reducing herbicide dosages in summer maize fields in the North China Plain. A two-year field experiment was conducted testing three registered herbicides and a mixture of two of those. Variable dosages were applied to different weed growth stages. The results highlight the potential for reducing herbicide dosages for weed control in North China Plain maize cropping systems without having negative impact on weed control efficacy or maize grain yield. But they also show that the potential for dosage reduction is dependent on the herbicide used and the present weed flora.

Efficacy of four post-emergence herbicide applied at reduced doses on weeds in summer maize (*Zea mays* L.) fields in North China Plain

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Abstract The efficacy of our post-emergence herbicides applied at reduced dosages and to different weed growth stages was tested in field experiments in the North China Plain in 2010 and 2011. Tested herbicides were nicosulfuron, topramezone, mesotrione and a mixture of mesotrione and nicosulfuron. Nicosulfuron, topramezone and the mixture of nicosulfuron and mesotrione revealed higher weed control efficacies at the 2- to 3-leaf stage and 4- to 5-leaf stage of the weeds at their label recommended doses than mesotrione. Topramezone dose could be reduced to 33 % of label recommended dosage and nicosulfuron alone or in combination with mesosulfuron could be reduced to 67 % of the label recommended dosage without reducing total weed control efficacy or maize grain yield. Both, grass and broadleaved weeds were sufficiently controlled by 33 % of the label recommended dosage of topramezone and by 67 % of the label reommended dosage of nicosulfuron applied alone and in mixture with mesotrione. In contrast, mesotrione efficacy against grass weeds was low even at recommended dosage. None of the tested herbicides affected maize grain yield.

(Zhang et al., 2013 a), Crop Protection 11

3.2 The mechanism of methylated seed oil on enhancing biological efficacy of topramezone on weeds

A crucial point for reducing herbicide dosages is that the herbicide reveals high efficacy also at lower dosages. To enhance herbicide efficacy, additives are often added to spray mixtures. Those affect for example adhesion of the spray droplet on the plant surface or penetration of the herbicide's active ingredient through the cuticle into the leaf. There are many different additives available on the market belonging to different chemical classes. However, their mechanisms of enhancing herbicide efficacy are often still not clear, yet. In the first article we showed, that topramezone efficacy was throughout high, even at reduced dosages. This herbicide is commonly tank-mixed with methylated seed oil adjuvant. Therefore we investigated in which way methylated seed oil adjuvant affects parameters of topramezone spray-mixture properties and behavior on the leaf surface and within the plant. The results show that methylated seed oil decreases the surface tension of the spray mixture which results in a decreased contact angle on leaf surfaces. Uptake of topramezone was enhanced, because less crystallized compound was found on leaf surfaces, while tompramezone content in the leaf tissue was increased. Furthermore, translocation of topramazone was increased. Those findings mostly explain why methylated seed oil adjuvant increases the efficacy of topramezone.

The mechanism of methylated seed oil on enhancing biological efficacy of topramezone on weeds

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Abstract Topramezone, a newly registered herbicide in China, is recommended to be applied in combination with a methylated seed oil (MSO) adjuvant. However, its mechanism for enhancing efficacy of topramezone is not known, yet. Experiments were carried out to investigate the effect of MSO on topramezone efficacy, physical properties of the spraying mixture, behaviour of the spraying mixture on the leaf surface as well as on absorption and translocation of topramezone. Experiments were conducted using the monocotyledonous weed giant foxtail (*Setaria faberi* Herrm.) and the dicotyledonous weed velevetleaf (*Abutilon thephrasti* Medic.). 0.3 % MSO in the spraying solution increased efficacy of topramezone in giant foxtail by 1.5-fold and in velvetleaf by 1.0-fold. MSO decreased surface tension of topramezone spraying mixture as well as its contact angle on leaf surfaces of giant foxtail and velvetleaf, and its spread area on leaf surfaces was increased. Wetting time of the leaf surfaces was decreased on giant foxtail leaves, but not in leaves of velvetleaf. Additin of MSO further decreased topramzone crystals on treated leaf surfaces and increased the absorption of topramezone by around 69 % into giant foxtail leaves and by around 46 % into velvetleaf leaves 24 hours after treatment. Translocation of topramezone was increased by addition of MSO.

4 Efficacy of reduced herbicide dosages in winter wheat - influence on weed seed production at the example of *Avena fatua* L.

Reducing herbicide dosages below the recommended dosage bears the risk of unwanted weed seed input. Weeds can produce seeds after herbicide application either due to efficacy failure of the herbicide or because dosages are reduced to a point where yield loss caused by the residual weed biomass equates economic yield loss at the expense of efficacy. Residual weed biomass, however, still can produce seeds. Thus, weed population may increase in the long-run. To investigate the effect of reduced herbicide dosages on efficacy and weed seed production in winter wheat as well as yield loss potential, field trials were conducted with *A. fatua* in winter wheat. Four herbicides were tested at various dosages. Results show, that *A. fatua* causes yield losses up to 40 percent in winter wheat. Tested herbicide revealed high efficacies, also at reduced dosages. Seed production of *A. fatua* was not directly related to residual biomass or herbicide efficacy and competition of winter wheat decreased *A. fatua* seed onset. This study on the one handsite highlights the potential of reducing herbicide dosages in controlling *A. fatua* in winter wheat, but shows on the other handsite, that decision on dosage reduction should not only be met with respect to herbicide efficacy but also to its effect on seed production.

Winter wheat yield losses due to *Avena fatua* competition and effect of reduced herbicide dosages on population dynamic parameters of *Avena fatua*

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4.1 Abstract

Avena fatua is a very abundant and competitive grass weed in spring cereals. Recently, it has been observed in German winter wheat fields. Five yield loss experiments were conducted over five years to investigate the impact of *A.fatua* on winter wheat yield. Two additional field studies were conducted to assess the effect of four herbicides at variable doses on biomass and seed production of *A. fatua* as weed in winter wheat. *A. fatua* caused significant winter wheat yield losses of up to 40 % at densities of approximately 250 plants m^{-2} or 60 g m^{-2} with a high variability between experiments and years. All herbicides showed high efficacies even at reduced dosages and efficacy (biomass) was not influenced by experimental site. However, *A. fatua* produced more seeds after application of reduced rates of fenoxaprop-P and pinoxaden compared to reduced rates of iodosulfuron+mesosufuron and florasulam+pyroxsulam suggesting that higher rates of both ACCase-inhibitors were needed for sustainable control of *A. fatua* compared to the ALS-inhibitors tested. The results show, that *A. fatua* is a serious grass weed in German winter wheat fields leading to high yield losses. However, there is a potential for effectively controlling this *A. fatua* at reduced herbicide doses.

Key words: Yield loss, ACCase-inhibitors, ALS-inhibitors, dose-response, seed production, wild oat

4.2 Introduction

Avena fatua L. belongs to the 10 world's worst weeds, causing high yield losses of up to 70 % in cereals (Holm et al., 1991; Beckie et al., 2012 a). It is the second most abundant weed and most abundant grass weed in spring cereals, but also occurs in winter cereals (Schroeder et al., 1993). The abundance of *A. fatua* in winter cereals in Germany has increased during recent years. Seedlings emerged in autumn can survive if the temperatures during the winter are not far below 0° C. and then strongly compete with the crop. It has been found for *Avena spp.* and other weeds such as *Papaver rhoeas* L. and *Phalaris minor* RETZ., that reduction of herbicide rates did not significantly reduce efficacy and crop yield (O'Donovan et al., 2003 a,b; Gonzales-Andujar et al., 2010; Travlos, 2012). However, *Avena sterilis* was completely controlled only at full recommended herbicide doses. At reduced herbicide doses, some plants survived and produced viable seeds (Gonzales-Andujar et al., 2010). This might cause a shift in weed population towards less sensitive individuals and reduced efficacy in the following generations (Manalil et al., 2011; Kudsk, 2014). Thus, dose-response studies are needed to determine the optimal rate of herbicides. Since *A. fatua* has only recently been found in winter wheat in Germany, data characterizing yield loss potential of *A. fatua* and herbicide efficacy in winter wheat are missing. For this reason, we investigated the yield response of winter wheat to different densities of *A. fatua*. We hypothesized that *A. fatua* causes higher yield losses than *Alopecurus myosuroides* HUDS. due to its tall growing habitus. Effects of four herbicides commonly applied in winter wheat to control grass-weeds were tested on textitA. fatua biomass production, tillering and seed production. We assumed that efficacy will be high even at reduced dosages as a selection towards less tolerant populations has not yet taken place for those herbicides in *A. fatua*.

4.3 Materials and Methods

4.3.1 Yield loss experiments

Five yield loss experiments were established at Ihinger Hof research station in southern Germany between 2009 and 2013. Winter wheat cultivar Shamane (I.G. Pflanzenzucht GmbH, München, Germany) was sown at a density of 300 to 330 seeds m^{-2}, depending on the experiment, and a depth of 3 cm in all experiments (Table 4.1). Winter wheat was sown from end of September until end of October, depending on the harvest time of the previous crop and weather conditions. Row distance was 12 cm in all years. *A. fatua* seeds were derived from Herbiseed (Twyford,UK. Seeds were sown with a RTK-GPS equipped precision seed drill (Deppe, Bad Lauterberg, Germany) between the winter wheat rows at a depth of 1.5 cm. *A. fatua* sowing density was targeted to reach different plant density levels. Intended levels were 0, 1-25, 26-75, 76-125, 126-225 and 226-325 plants m^{-2} in the experimental seasons 2009/2010 and 2010/2011 and 0, 1-50, 51-100, 101-200 and 201-300 in season 2012/2013. A germination test was carried out to calculate the densitiy of *A. fatua* seeds. In seasons 2009/2010 and 2010/2011, 150 g ha^{-1} fluroxypyr, 3.75 g ha^{-1} florasulam, 120 g ha^{-1} clopyralid (Ariane C, EC, Dow AgroScience) were sprayed against the broad-leaved weeds. In season 2012/2013, 750 g MCPA ha^{-1} (U 46 M-Fluid, SL, Nufarm) were sprayed against the broad-leaved weeds. Grass weeds other than *A. fatua* and broadleaved weeds that survived the herbicide treatments were removed manually. The weed-free control plots were continuously weeded by hand. Crop management was performed according to the common practice in this region. Total nitrogen fertilizer amount was dependent on residuals soil nitrogen (Nmin) and was 150 kg N ha^{-1} in seasons 2009/2010 and 2010/2011 and 170 kg N ha^{-1} in season 2012/2013 split into three applications. A growth regulator (Trinexapac-ethyl (0.2 l ha^{-1} Moddus, 250 g a.i. L^{-1}, ME, Syngenta Agro GmbH, Maintal, Germany) was applied during stem elongation of winter wheat. Fungicide and insecticide treatments were conducted if necessary. The experiments were set up as completely randomized plot design with three replications of each infestation level. Experimental plots had a size of 2 x 9 m divided into two parts. The larger part of size 2 x 6 m^2 was used for grain yield assessment using a combine plot harvester. In the smaller part of 2 x 3 m^2, destructive measurements of weed and crop biomass were performed. At the two-leaf-stage of *A. fatua*, an area 0.5 m^2 was cut shortly above ground in each plot. Biomass of *A. fatua* and winter wheat was separated and shoots of *A. fatua* were counted (except for experiment 3). The samples were dried in an oven at 80 ºC for 48 hours to assess dry biomass.

Table 4.1: Experimental details yield loss experiments

Season	Experiment	Sowing date	Sowing density (seeds m^{-2})	Weed-free winter wheat yield (t ha^{-1})
2009/2010	1	7th Oct	330	7.4
2010/2011	2	11th Oct	330	6.4
2010/2011	3	11th Oct	330	7.3
2012/2013	4	22nd Nov	300	4.7
2012/2013	4	24th Oct	300	7.7

4.3.2 Herbicide dose-response experiments

Two dose-response experiments were carried out in the season 2012/2013. The two sites, Kirrlay and Katzenloch, differed in soil type, crop rotations and sowing date. Kirrlay is a low yielding site with a loamy clay soil and average winter wheat yields of 5.5 t ha^{-1}. Previous crop was maize, resulting in a later winter wheat sowing date at this site. Katzenloch is characterized by a loamy soil with average winter wheat yields of approximately 8 t ha^{-1}. Previous crop on this site was durum wheat. Winter wheat cultivar, sowing dates and density as well as crop management was the same as in the yield loss experiments. Sowing density of *A. fatua* was calculated according to targeted seedling density of 50 plants m^{-2}. At the experimental site Kirrlay, one herbicide treatment was conducted with 750 g MCPA ha^{-1} (U 46 M-Fluid, 500 g a.i. L^{-1}, SL, Nufarm) against the broad-leaved weeds. At Katzenloch, this was not necessary. Grass weeds other than *A. fatua* and new emerging broad-leaved weeds were continuously removed manually at both sites. The experimental layout was a split-plot design with 3 replications on each site. Herbicides were randomized as main factor and the dosages were randomized within the herbicide blocks. Plots were 2 m wide and 2.5 m long.

Application Details Iodosulfuron+ mesofulfuron (Atlantis WG, 5.6 g kg^{-1} iodosulfuron + 29.2 g kg^{-1} mesosulfuron, WG, Bayer CropScience), florasulam + pyroxsulam (Broadway, 22.8 g kg^{-1} florasulam + 68.3 g kg^{-1} pyroxsulam, WG, Dow AgroSciences), pinoxaden (Axial 50, 50 g L^{-1}, EC, Syngenta) and fenoxaprop-P (Ralon Super Power Plus, 63.6 g L^{-1}, EW, Nufarm) were applied at 7 dosages each, (100 %, 75 %, 50 %, 37.5 %, 25 %, 12.5 % and 0 % of the recommended field rate on the label. If recommended by the manufacture the corresponding additive was added to the spray solution. Application rate of additives was kept constant in relation to the total application volume. Herbicide application rates equate to 10.44, 7.83, 5.22, 3.915, 2.61, 1.305, 0 g a.i. ha^{-1} for iodosulfuron + mesosulfuron, 11.84, 8.88, 5.92, 4.44, 2.96, 1.48, 0 g a.i. ha^{-1} for florasulam + pyroxsulam, 45, 33.75, 22.5, 16.875, 11.25,5.625, 0 g a.i. ha^{-1} for pinoxaden and 63.6, 47.7, 31.8, 23.85, 15.9, 7.95, 0 g a.i. ha^{-1} for fenoxaprop-P. Herbicides were applied at May 14, 2013, when *A. fatua* was at 2-3-leaf growth stage (BBCH 12-13) (Hess et al., 1997). Winter wheat was in growth stage BBCH 25 at Kirrlay and in growth stage 31 at

Katzenloch. Herbicide application was conducted with a hand-driven plot sprayer equipped with air-injector flat-van nozzles (IDK 120-02, Lechler, Germany), at a pressure of 320 kPa and a water volume of 200 L ha^{-1}. Weather conditions after herbicide application were characterized by a drop of maximum day temperature as well as minimum temperature for a period of around two weeks, before temperatures started to rise again. Average minimum and maximum temperatures within two weeks before application were 6.4 and 22.2 °C, which dropped to 3.7 and 18.5 °C within the two weeks after application. Occasional light rainfalls occured.

Assessments Four weeks after application, *A. fatua* plants were counted in an area of 0.5 m^{-2} in each plot. After counting, shoot biomass of wheat and *A. fatua* was harvested in the same area of 0.5 m^{-2}. At this time, winter wheat was in BBCH 47 at Kirrlay and in BBCH 55 at Katzenloch site. The plant material was oven-dried at 80°C for 48h and weighted, to assess the dry biomass. At the beginning of seed ripening of *A. fatua*, number of panicles per plant was assessed on five randomly chosen plants per plot, which were harvested to count number of seeds per panicle. Total number of panicles per plot was counted. If there were less than five plants per plot due to high herbicide efficacy, the abovementioned assessments were conducted on the remaining plants. The number of seeds per plant was then calculated for each plant as well as the total seed input m^{-2}.

4.3.3 Statistical Analysis

Yield data of winter wheat were transformed into relative yield loss with respect to the corresponding control treatment. The yield-loss function according to (Cousens, 1985) was fitted to the relative yield loss data, using following equation:

$$YL = (i * x)/(1 + i * x/a) \tag{4.1}$$

YL is the relative yield loss, x is the independent variable. In our study, we used relative *A. fatua* biomass, i.e. proportion of *A. fatua* biomass to total biomass m^2 (winter wheat plus *A. fatua*), absolute *A. fatua* biomass and *A. fatua* density. The parameter i is the initial yield loss per unit x for $x \to 0$ and a is the maximum yield loss (asymptote) for $x \to \infty$. Data were first fit separately for each experiments and then the model was stepwise reduced on common parameters for all experiments. The reduced models were compared via F-test (α=0.05) to the full model. If the models were not significantly different, common parameters were used for the experiments.

A. fatua data from dose-response experiments were analysed separately for each herbicide. Two-factorial analyses of variance were performed including a block-effect with experimental site and herbicide dosage as factors. Residuals of the models were tested on normal distribution with the Shapiro-Wilk test and homogeneity of variance was controlled visually. If the prerequisite of normal distribution and homogeneity of variance was not given, data were square-root transformed. Afterwards, multiple comparison of means was performed using Tukey's honestly significant difference at α=0.05. Back-transformed data are displayed in the figures. Herbicide efficacy was calculated from data of *A. fatua* residual biomass 28 days after herbicide treatment relative to untreated *A. fatua* biomass. Data of winter wheat were first analysed separately by herbicides to test if there were effects of dosages on biomass, number of tillers and yield. Analysis of variance models included a block effect and effects for the factors experimental site and dosage as well as their interaction. Since effects of dosages and interaction with the experimental site were not significant for all herbicides, this factor was dropped from further analysis, in which a block effect and effects for the factors experimental site and herbicide were included. Analysis of variance was performed and significant factors were compared with Fisher's Least Significant Differences test ($alpha$=0.05). Statistical analyses were performed using R version 3.1.1 and the package agricolae for calculating Tukey's honestly significant differences (de Mendiburu, 2014; R Core Team, 2014).

4.4 Results

4.4.1 Winter wheat yield losses caused by *A. fatua*

A. fatua caused significant yield losses in winter wheat in all experiments, except for experiment 5 (Figure 4.1 ($a - c$), Table 4.2). For the data of *A. fatua* density, the yield loss function could only be fitted to the combined dataset, but not separately for experiments. Initial yield loss per *A. fatua* plant m^{-2} was 0.38 % and maximum winter wheat yield loss was estimated to around 77 % (Figure 4.1 (a), Table 4.2). There were significant differences for the initial yield loss for low *A. fatua* biomass between the experiments (p=0.04), but maximum potential yield loss was the same across all experiments (p=0.50) (Figure 4.1 (b)). Initial yield losses ranged from 0.4 to 7.6 % per g *A. fatua* biomass m^{-2}. Maximum potential yield loss of winter wheat caused by *A. fatua* was estimated to be 57 % (Table 4.2). Maximum *A. fatua* biomass was established in experiment 1 with 67 g m^{-2}. When *A. fatua* biomass was converted into relative biomass, its relationship to winter wheat yield loss did not differ between the experiments (p=0.25) (Figure 4.1 (c)). Initial yield loss of winter wheat was estimated to 5.7 % per percent relative *A. fatua* biomass and maximum yield loss 51 %.

Though estimation of maximum potential yield loss was significant in our analysis, we did not achieve this value in our experiments. In the experiments,we did not measure yield losses higher than 40 %.

Table 4.2: Parameter estimates with corresponding standard errors and p-values for winter wheat yield loss in dependency of *A. fatua* density, *A. fatua* biomass and relative *A. fatua* biomass.

	Parameter	Estimate	Standard error	p-value
A. fatua density	i	0.375	0.0815	<0.001
	a	76.639	30.1942	0.014
A. fatua biomass	i1	1.707	0.7309	0.023
	i2	0.970	0.4251	0.026
	i3	0.364	0.2599	0.166
	i4	7.617	3.5053	0.033
	a	57.430	23.7491	0.018
Relative *A. fatua* biomass	i	5.659	1.818	0.003
	a	51.203	21.203	0.018

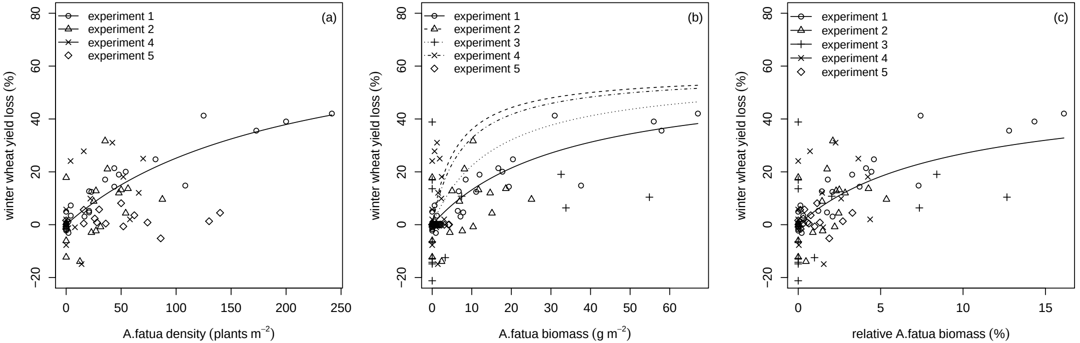

Figure 4.1: Relative winter wheat yield loss in relation to *A. fatua* density (*a*), *A. fatua* biomass (*b*) and relative *A. fatua* biomass (*c*).

4.4.2 Dose-response experiments

Influence of the experimental site on winter wheat and *A. fatua* growth Herbicides and dosages didn't have an influence on winter wheat tillers, biomass and yield in the dose-response experiments. But winter wheat parameters differed significantly between the two experimental sites. Winter wheat density was 412 tillers m^{-2} at Katzenloch and significantly higher than at Kirrlay, where density was only at 280 tillers m^{-2}. Consequently, winter wheat biomass was also higher at Katzenloch. Winter wheat grain yield was around 8.7 t ha^{-1} at Katzenloch, whereas at Kirrlay grain yield reached only at 5.9 t ha^{-1}. *A. fatua* densities differed between the experimental sites. Average *A. fatua* density was 34 plants m^{-2} at Kirrlay and 18 plants m^{-2} at Katzenloch. Average *A. fatua* biomass in the untreated plots was 30.0 g m^{-2} at Kirrlay and 17 g m^{-2} at Katzenloch four weeks after treament. Average number of seeds per plant of untreated *A. fatua* was 71 at Katzenloch and 110 at Kirrlay. Total seed input m^{-2} measured at the end of the season was 1700 seeds m^{-2} at Katzenloch and 5300 seeds m^{-2} at Kirrlay.

Efficacy of herbicides on *A. fatua* control and seed production Iodosulfuron + mesosulfuron showed high efficacy on *A. fatua*, irrespectively of the dosage applied or the experimental site (Figure 4.2 (a)). Residual *A. fatua* biomass was the same for all tested dosages, but complete control was never achieved, also not by full dosage. The influence of iodosulfuron + mesosulfuron dosages on average amount of panicles per *A. fatua* plant differed between the two sites (Figure 4.2 (b)). At Kirrlay, the number of panicles per plant was reduced at dosages of 50 % of the recommended rate or higher. Only at full recommended dosage, panicle production was completely inhibited. At Katzenloch, *A. fatua* panicle production was completely inhibited at dosages of 37.5 % of the recommended dosage and higher. Number of seeds $panicle^{-1}$ was not significantly reduced at Katzenloch site (Figure 4.2 (c)). Only at dosages of 37.5 % of the recommended rate and higher, no seeds were produced, since panicle production was also inhibited. At Kirrlay, all dosages significantly reduced number of seeds $panicle^{-1}$, but the effects of dosages did not differ between each other. Seed production by plants was highly dependent on iodosulfuron + mesosulfuron dosage (Figure 4.2 (d)). 12.5 % and 25 % of recommended dosage led to significantly higher seed onset as higher dosages, though seed production was reduced to 20 seeds plant^{-1} compared to untreated control. Complete inhibition of seed production was only achieved at full dosage. Though there was no statistical difference between the sites, seed onset happened only at dosages lower than 37.5 % of the full dosage at Katzenloch, whereas at Kirrlay seed production already happened when dosages were reduced below the recommended dosage.

Efficacy of florasulam + pyroxsulam was constant over all tested dosages but efficacy was lower compared to iodosulfuron + mesosulfuron and complete control was not achieved (Figure 4.3 (a)). At lowest tested dosage, i.e. 12.5 % of recommend, florasulam + pyroxsulam did not significantly decrease *A. fatua* biomass at site Kirrlay. Florasulam + pyroxsulam did not have an influence on panicle production of *A. fatua*. The average amount of *A. fatua* panicles plant^{-1} differed only between the two experimental sites ($p<0.001$) (Figure 4.3 (b)). At Katzenloch, *A. fatua* produced less than one panicle plant^{-1}, whereas at the less competitive site Kirrlay, *A. fatua* produced 2.3 panicles plant^{-1} in average. The amount of seeds per *A. fatua* panicle was significantly reduced by all florasulam + pyroxsulam dosages (Figure 4.3 (c)) and was generally lower at Katzenloch site ($p<0.001$). *A. fatua* seed onset was generally lower at Katzenloch site ($p<0.001$), but effect of dosages did not differ (Figure 4.3 (d)). At Kirrlay, there were more than 20 seeds per *A. fatua* plant produced even at recommended dosage. 12.5 % of recommended dosage did not significantly reduce seed production compared to untreated control, but dosages above did. However, even at recommended dosage, *A. fatua* seed production and input was not completely inhibited.

Fenoxaprop-P showed the same efficacy on *A. fatua* at both sites (Figure 4.4 (a)). All dosages except 12.5 % of recommended significantly reduced *A. fatua* biomass. Efficacy of the remaining dosages did not differ among each other and were constantly high with almost full control of *A. fatua* at dosages between 37.5 and 100 % of the recommended dosage. At fenoxaprop-P dosages of 37.5 % of the recommended dosage and higher, panicle production was significantly reduced (Figure 4.4 (b)). There was no difference between the two sites. At both sites panicle production of *A. fatua* was completely inhibited at dosages higher than 75 % of the recommended fenoxaprop-P dosage. The relationship of seeds per *A. fatua* panicle and fenoxprop-P dosage was similar to the one of panicle

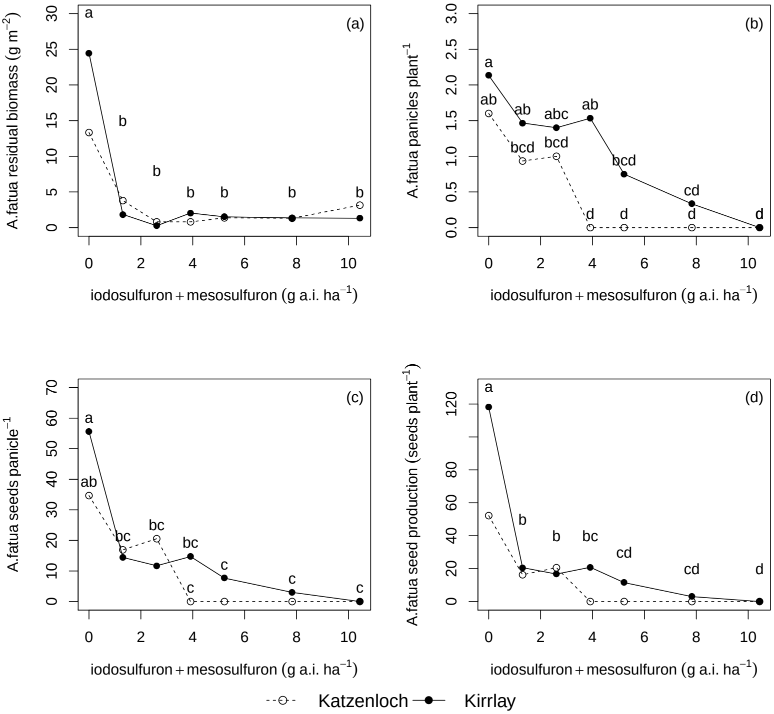

Figure 4.2: Influence of variable dosage of iodosulfuron + mesosulfuron on *A. fatua* biomass (a), *A. fatua* panicle production (b), number of seeds per panicle (c) and *A. fatua* seed production (d) at the two experimental sites Katzenloch and Kirrlay. Different letters indicate significant differences at α=0.05.

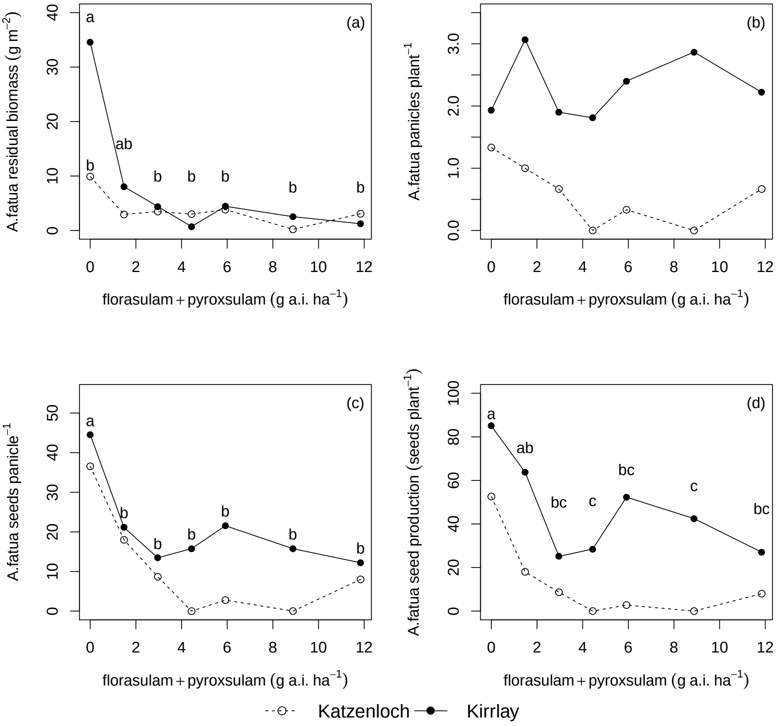

Figure 4.3: Influence of variable dosage of florasulam + pyroxsulam on *A. fatua* biomass (a), *A. fatua* panicle production (b), number of seeds per panicle (c) and *A. fatua* seed production (d) at the two experimental sites Katzenloch and Kirrlay. Different letters indicate significant differences at α=0.05.

production (Figure 4.4 (c)). At dosages higher than 37.5 % of the recommended dosage, amount of seeds panicle^{-1} was significantly reduced and at dosages higher than 75 %, no panicles and thus no seeds were produced. Up to a dosage of 25 % of the recommended, seed production per *A. fatua* plant was not significantly reduced (Figure 4.4 (d)). The influence of fenoxaprop-P dosages between 37.5 % to 100 % of recommended dosage on *A. fatua* seed production was the same. *A. fatua* didn't produce seeds at all at dosages as high as 75 % of the recommended dosage and higher. At Katzenloch, there occurred no seed production at rates as low as 37.5 % of recommended, whereas at Kirrlay, *A. fatua* produced up to 20 seeds plant^{-1} at dosages below 75 %.

Pinoxaden dosages of 37.5 % to 100 % all showed high efficacy though not complete control, whereas efficacy of lower dosages was significantly reduced (Figure 4.5 (c)). There was no difference in efficacy between the two sites, but *A. fatua* biomass was generally higher at Kirrlay ($p=0.01$). Average number of panicles plant^{-1} was significantly reduced at dosages of 37.5 % of the recommended and higher (Figure 4.5 (b)). At dosages of 75 % of the recommended pinoxaden dosage, no panicle production occurred. Though the effect of dosages on panicle production was the same at both sites, it was completely inhibited at dosages higher than 37.5 % at Katzenloch. Number of seeds panicle^{-1} was significantly reduced at Katzenloch site at 25 % of the recommended pinoxaden dosage and at Kirrlay at dosages higher than 37.5 % (Figure 4.5 (c). Similar to the efficacy, also seed production was significantly reduced for dosages as low as 37.5 % and higher and lower dosages led to increased seed production (Figure 4.5 (d)). Though the difference between the higher dosages was not significant, *A. fatua* treated with 37.5 % and 50 % of recommended pinoxaden dosage, produced up to 20 seeds plant^{-1} at the experimental site Kirrlay. In contrast no seed onset occurred as dosages down to 37.5 % of the recommended pinoxaden dosage.

Efficacy variability of the two ALS-inhibitors iodosulfuron + mesosulfuron and florasulam + pyroxsulam was constant for all tested dosages at both sites (Figure 4.6). For the ACCase-inhibitors, this was true only for dosages ranging from 25 % to 100 % of the recommended dosages showing only little variability in this range. A further reduction to 12.5 % of the

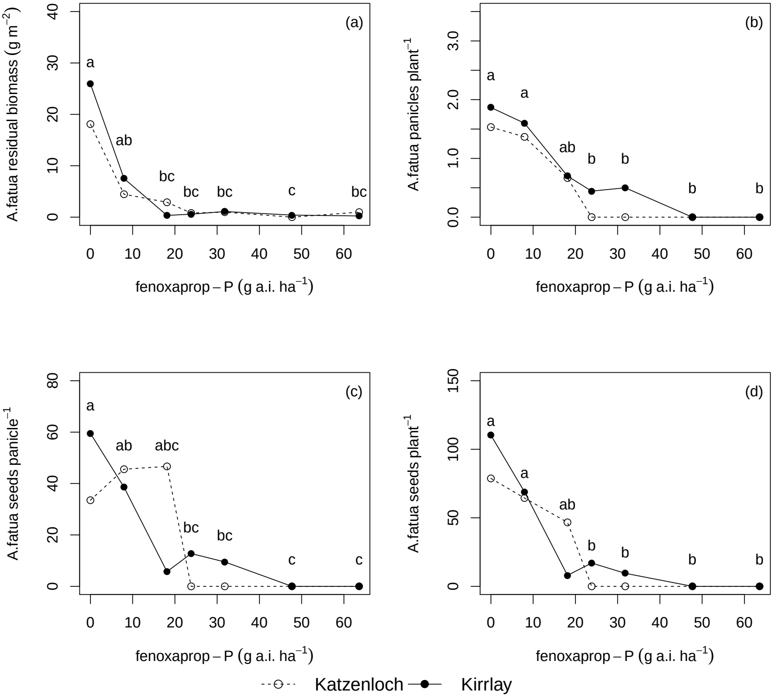

Figure 4.4: Influence of variable dosage of fenoxaprop-P on *A. fatua* biomass (a), *A. fatua* panicle production (b), number of seeds per panicle (c) and *A. fatua* seed production (d) at the two experimental sites Katzenloch and Kirrlay. Different letters indicate significant differences at α=0.05.

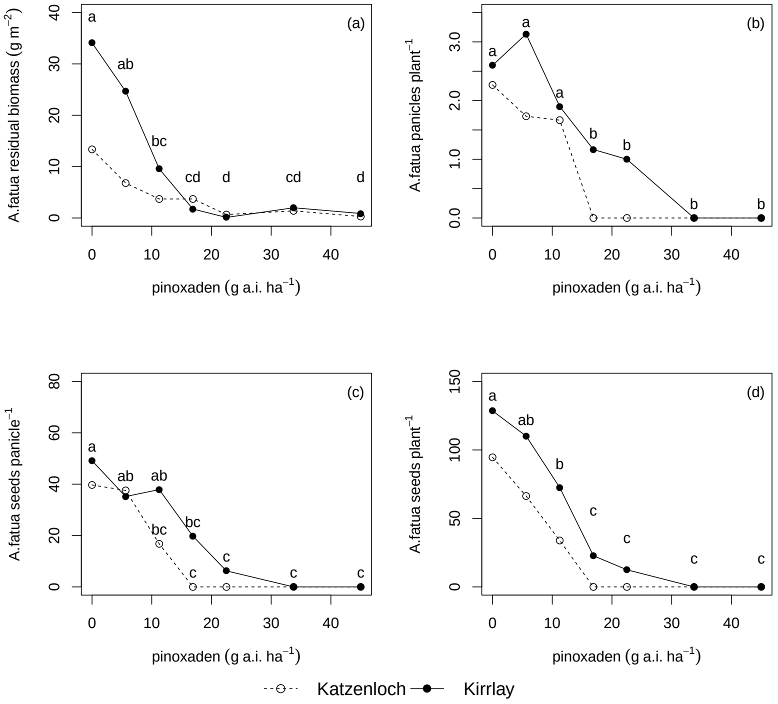

Figure 4.5: Influence of variable dosage of pinoxaden on *A. fatua* biomass (a), *A. fatua* panicle production (b), number of seeds per panicle (c) and *A. fatua* seed production (d) at the two experimental sites Katzenloch and Kirrlay. Different letters indicate significant differences at α=0.05.

recommended dosages led to a tremendous increase of efficacy variability at both sites coupled to reduced efficacy in terms of residual *A. fatua* biomass.

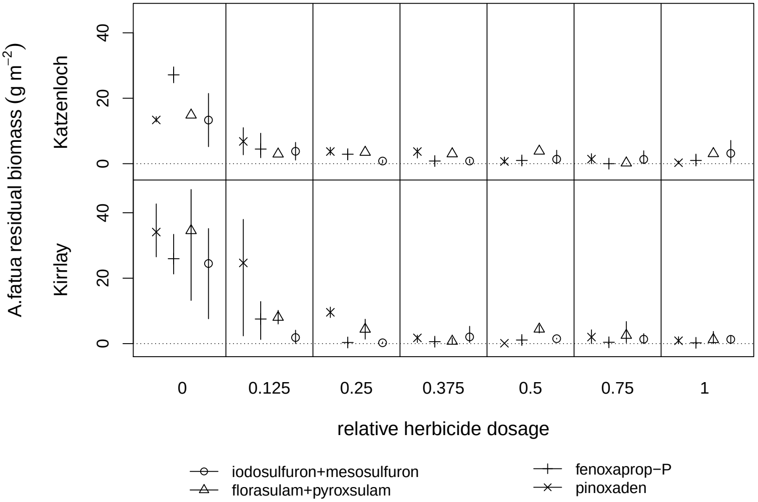

Figure 4.6: Efficacy variability in terms of residual *A. fatua* biomass in relation to herbicide dose at both experimental sites. Bars represent the range of residual biomass (i.e. min and max observed value).

The influence of herbicide efficacy on *A. fatua* seed production differed between the two experimental sites (Figure 4.7 (a)). At Kirrlay, the less competitive winter wheat site, seed production clearly increased with decreasing herbicide efficacy, whereas this trend was not so obvious at Katzenloch. There were only small differences in *A. fatua* seed production at herbicide efficacies above 50 %. The influence of herbicide efficacy on seed production also differed between the two tested groups of herbicides, i.e. ALS-inhibitors and ACCase-inhibitors (Figure 4.7 (b)). ALS-inhibitors tremendously reduced *A. fatua* seed production at all efficacy levels and seed production was not efficacy-dependent, but even at highest efficacy levels (> 98 %) *A. fatua* produced seeds. The influence of ACCase-inhibitors on *A. fatua* seed production was efficacy-dependent. Efficacy-levels above 80 % revealed high suppression of seed onset with medians at 0, but at lower efficacy-levels seed production increased. Below 50 % efficacy of ACCase-inhibitors, seed production was similar to that of the untreated control treatment.

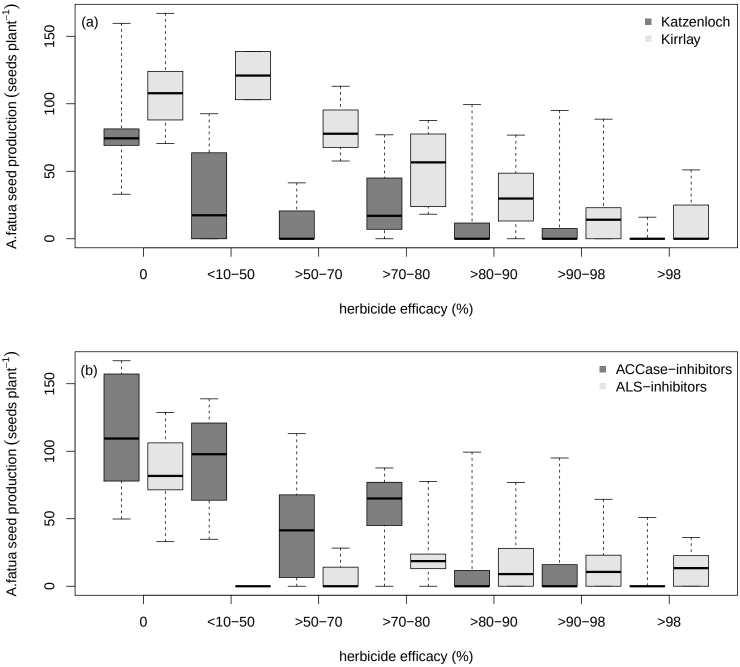

Figure 4.7: *A. fatua* seed production for different herbicide efficacy classes averaged across herbicides for both experimental sites (a), and averaged across sites for the two tested herbicide groups (ALS-inhibitors, ACCase-inhibitors) (b).

4.5 Discussion

A. fatua led to significant yield losses in winter wheat in four experiments out of five. Densities of 5, 10, 15, 30 *A. fatua* plants m^{-2} led to estimated yield losses of 1.8, 3.6, 5.2 and 9.8 %. Menan et al. (2003) found the economic threshold of *A. fatua* in winter wheat field in Turkey ranging between 12 and 15 plants m^{-2}. Assuming winter wheat prices of 180 to 200 €t^{-1} and a weed-free yield of 7 t ha^{-1}, economic yield losses are in the range of 45 €to 73 €for *A. fatua* densities of 10-15 plants m^{-2} for our experiments and thus comparable to what Menan et al. (2003) found.
The results indicate that the yield loss potential of *A. fatua* did not differ between the experiments and years, but is dependent on the ratio of winter wheat and *A. fatua* biomass. This goes in line with previous findings about crop-weed competition. It has been shown that crop yield loss related to weed density varies a lot, mainly being associated with different emergence times of weeds and thus their size and competitiveness relative to the crop. Lotz et al. (1996) have shown that relative weed leaf area better describes yield loss than weed density, because weed competitiveness is taken into account. Similarly, Lutman et al. (1996) found relative weed biomass being a much more precise predictor for crop yield loss than weed density, which showed high variation between experiments. We cannot draw this conclusion directly from our data, because it was not possible to fit the yield loss function separately for each experiment's *A.fatua* density. We could not explain all winter wheat yield loss. No yield loss function could be fitted to data of experiment 5, though *A. fatua* density was up to 150 plants m^{-2}. However, relative *A. fatua* biomass achieved in this experiment was low compared to the other experiments arising from advanced winter wheat growth.
The experimental sites of dose-response experiments differed significantly regarding winter wheat yield and competitiveness. This was partly due to the different sowing dates, giving winter wheat at Katzenloch more time for biomass development before winter. Alternatively, Katzenloch is a much more favourable site for cropping with generally higher yields. At the time of herbicide application winter wheat at Katzenloch was already at the beginning of stem elongation phase, while at Kirrlay, wheat was still in the tillering phase. Lower winter wheat density and competitiveness could also explain why *A. fatua* densities were twice as high at Kirrlay than at Katzenloch.

Lemerle et al. (1996) showed that herbicide efficacy is not influenced by wheat cultivars differing in competitiveness in seasons where herbicide efficacy is generally high, whereas in seasons with reduced herbicide efficacy, biomass reduction of *Lolium rigidum* was higher in more competitive wheat cultivars at equivalent doses than in less competitive ones. Similarly, O'Donovan et al. (2006) showed that both ALS- and ACCase-inhibitors' efficacy on *A. fatua* increased with higher spring wheat seeding rate. This effect of crop competitiveness on herbicide efficacy could not be found in our experiments, where effect on *A. fatua* residual biomass was the same at both sites. Efficacy of the tested herbicides was high even at reduced dosages, so that the effect of wheat competitiveness might not have come into effect.

As reported by Kudsk (2014) efficacy profiles varied between herbicides. Experiments showed, that mesosulfuron revealed very high efficacy throughout all tested dosages and florasulam + pyroxsulam showed constant efficacy over all tested dosages, whereas efficacy of both ACCase-inhibitors decreased at lower dosages. Consequently, there is higher potential to reduce dosages of tested ALS-inhibitors as of ACCase-inhibitors, since almost no efficacy reduction at dosages as low as 25 % of the recommended dosage occurred and according to Kudsk (2014), efficacy variability and thus risk of efficacy failure is inversely correlated with herbicide efficacy. This relationship was also observed for the two ACCase-inhibitors fenoxaprop-P and pinoxaden, which showed increased efficacy variability at lowest dosages.

Though not always significant, *A. fatua* seed production was lower at Katzenloch where winter wheat was more competitive. This goes in line with findings of reduced *A. fatua* soil seed bank at higher wheat seeding rates, implying reduced seed input (O'Donovan et al., 2006). It has been shown for other weeds too, that crop competition reduces weed seed production (Wilson et al., 1988).

Beside the experimental site, also the mode of action of the herbicides influenced the dependency of *A. fatua* seed production on herbicide efficacy. Seed production was not influenced by the efficacy of the tested ALS-inhibitors, where it was constantly low, even at low efficacies. In contrast, *A. fatua* seed production increased with decreasing ACCase-inhibitors' efficacy. These findings go in line with those of Fletcher et al. (1996), who found tremendous reduction of canola and soybean yield to 8 and 1 % compared to control when treated with low dosages of chlorsulfuron without having effects on vegetative growth beforehand, whereas for other herbicide modes of action this effect was not observed.

It has been shown for several plant species and herbicides that low dosages reduce seed production. But also that herbicide efficacy may be underestimated when taking into account only short-term observations on biomass, because damage to plant reproduction often is higher than damage observed in plant biomass (Carpenter and Boutin, 2010; Carpenter et al., 2013; Boutin et al., 2014; Rotchés-Ribalta et al., 2015). This effect of higher damage to reproduction, i.e. seed production per plant, as to biomass was also found in our experiments with *A. fatua* for all herbicides, but only at the site where winter wheat was more competitive. At the less competitive site, we observed the contrary effect, i.e. higher seed production at the same efficacy level, which was probably due to recovery of *A. fatua* plants. These results show that *A. fatua* seed production was not directly related to residual biomass and thus herbicide efficacy, but dependent on interaction with the crop and herbicide mode of action.

Allowing *A. fatua* treated with below-labelled dosages to produce seeds may bear the risk of non-target-site resistance development. Busi et al. (2013) and Manalil et al. (2011) have shown for *Lolium rigidum* that selection with reduced dosages favours the evolution of non-target-site resistance not being limited to a single herbicide or mode of action but to a broad range of active ingredients. This mechanism of resistance is thought to be of polygenic quantitative nature involving several gene loci and to require some generations of sexual reproduction for enrichment of resistance alleles in single plants (Petit et al., 2010; Délye et al., 2013). In contrast to *L. rigidum*, *A. fatua* is mainly self-pollinating. Outcrossing rates are only between 0.05 to 0.08 % in wheat and hence contribution of outcrossing to evolution of resistance is assumed to be low (Murray et al., 2002). However, Beckie et al. (2012 b) found evidence for non-target-site-based resistance in *A. fatua* biotypes from Canada to ALS- and ACCase-inhibitors.

Our results highlight, that *A. fatu*a is a competitive weed in winter wheat leading to high yield losses if not controlled. Furthermore, the results show that making decision on using reduced herbicide dosages for weed control should not only be made on herbicide efficacy data but also on their effect on seed production, since this was not directly related to each other. Otherwise, the risk of unwanted seed input rises as possibly the risk for evolution of polygenic resistance especially in outcrossing weed species. However, since *A. fatua* is mainly self-pollinating and this risk is small, dosages of the tested herbicides could be reduced for control of *A. fatua* in winter wheat, especially in competitive winter wheat stands. Taking into account the high *A. fatua* seed mortality rates of 15 % - 88 % (Mickelson and Grey, 2006) in combination with the low seed input even at reduced dosages, reduction of herbicide dosages to below-labelled still can provide efficient long-term control of *A. fatua* in winter wheat.

5 Integrated weed management

5.1 Japanese bindweed (*Calystegia hederacea*) abundance and response to winter wheat seeding rate and nitrogen fertilization in the North China Plain

In the previous manuscripts possibilities of reducing herbicide input based on dosage reduction were discussed. In the following two publications, two aspects of non-chemical weed control will be treated. The first publication deals with the influence of winter wheat sowing density and nitrogen fertilization level on the abundance and competitiveness of *Calystegia hedereacea* are investigated. *C. hedereacea* is a perennial weed, which is difficult to control with herbicides. This paper highlights the potential of integrated weed management strategies to suppress *C. hedereacea* and promote herbicide efficacy in winter wheat. On the other hand, it also shows that adjusting nitrogen fertilization can promote weed growth.

Japanese Bindweed (*Calystegia hederacea*) Abundance and Response to Winter Wheat Seeding Rate and Nitrogen Fertilization in the North China Plain

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Abstract Surveys conducted in the North China Plain in 2009 and 2010 showed that Japanese bindweed is one of the most abundant weed species in winter wheat fields which, in addition, is difficult to control. Analysis of survey data showed that it is most abundant at sites with low nitrogen (N) fertilization and low winter wheat densities. To confirm these findings and to better understand the competitive ability of Japanese bindweed in winter wheat, field experiments were carried out in 2010/2011 and 2011/2012 to investigate the influence of N fertilization intensities, winter wheat seeding rate, the herbicides tribenuron-methyl and 2,4-D as well as their interactions. In nonfertilized plots, tribenuron-methyl and 2,4-D reduced Japanese bindweed shoot density by 25 % and 22 %, respectively. In plots fertilized according to N_{min} (N demand based on expected crop yield minus soil mineral nitrogen, NH_4^+ - N + NO_3^- - N) efficacy was 34 % for tribenuron-methyl and 32 % for 2,4-D. Herbicide efficacy was highest in plots fertilized according to farmer's practice, where 2,4-D reduced Japanese bindweed shoots by 72 % and tribenuron-methyl by 64 %. Increased winter wheat seeding rates improved 2,4-D efficacy by at least 44 % and tribenuron-methyl efficacy by at least 39 %. N_{min}-based fertilization lead to a significant reduction of winter wheat yield at low and medium seeding rates, compared to farmer's practice fertilization. At high seeding rate winter wheat yield did not differ between N_{min}-based fertilization and farmer's practice.

(Menegat et al., 2013), Weed Technology 43

5.2 Investigation of biochemical and competitive effects of cover crops on crops and weeds

In the previous publication it was shown that cropping parameters as sowing density and nitrogen level can suppress or promote weed competitiveness and abundance. Another possibility to influence weed growth is the use of allelopathic active plant species either sown as cover crops in between main crops or as undersown crops within a crop stand. The following paper shows how commonly used or new cover crop species influence crop and weed growth. Pot and lab experiments show that extracts of tested cover crop species affect weed growth, whereas effects can be growth-promoting or -inhibiting. Effects differed between cover crop species, extraction times and extract concentrations. Also the plant organ extracts were derived from influenced their effect on weed growth. This paper highlights the potential of using allelopathic active plant species as cover crops or undersown crops to suppress weed growth. However it also shows that a lot about allelopathic interactions between plants and compounds is still unclear and needs further investigation.

Investigation of biochemical and competitive effects of cover crops on crops and weeds

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Abstract Seventeen cover crop and undersown crop species were tested in eleven pot and laboratory experiment on growth and weed suppression. Mulched cover crops revealed higher weed suppression ability than undersown crops. Furthermore, they did not influence biomass production of *Hordeum vulgare* whereas undersown crops lead to a reduction of *Triticum aestivum* biomass in pot experiments. The influence of aqueous cover crop root- and shoot-extracts on root growth of *Lactuca sativa*, *Setaria viridis*, *Amaranthus retroflexus* and *Zea mays* was tested in laboratory experiments. Hormetic and inhibitory effects were observed, as well as a combination of both. At higher concentration of the extracts, effects were more pronounced. Most pronounced inhibitory effects showed extracts of *Festuca rubra*, *Avena strigosa* and *Cannabis sativa* on *L. sativa*, maize and weeds. However, the exact mode of action and the responsible compounds still remain unclear and further investigation in field experiments is required.

6 General Discussion

6.1 Long-term simulation of herbicide saving weed control strategies in intensive winter wheat cropping systems

In section 4 it was shown at the example of *A. fatua* in winter wheat that herbicide dosages could be reduced, while still achieving high control efficacy and low seed input. In the following section, the influence of reduced herbicide dosages on the long-term development of *A. fatua* in a winter wheat - winter wheat - oilseed rape rotation is being discussed. Therefore, the influence of three weed control strategies on *A. fatua* population development, herbicide input, winter wheat yield and net return had been simulated. The reults show, that long-term control of *A. fatua* is possible while remarkably reducing total herbicide input. Herbicide dosage reduction did not lead to changes in cumulative winter wheat yield and net return.

Long-term simulation of herbicide saving weed control strategies in intensive winter wheat cropping systems

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6.1.1 Summary

Weeds are causing significant losses in intensive winter wheat cropping systems worldwide. Prospective weed control strategies aim to reduce herbicide inputs to its absolute minimum in order to reduce environmental, food safety and operator risks. The objective of this study is to make a long-term simulation and comparison of herbicide saving weed control strategies in intensive winter wheat cropping systems. The simulation approach was based on existing models for calculation of crop yield loss, herbicide dose-response, weed seed bank development and economic net return. Three herbicide saving weed control strategies were compared, namely the economic threshold strategy as well as two reduced herbicide dosage strategies. The two reduced dosage strategies differed in their intensity of dosage reduction and thus in their risk for potential efficacy failure. The simulation was calibrated for *Avena fatua* in winter wheat, based on a two-year experimental data set. The simulation results could show that, depending on the risk level, reduced dosage strategies decreased the herbicide inputs between 27 % and 46 %, compared to the economic threshold method. Differences in yield and economic net returns were negligible. From the consumer and environmental safety point of view, the high potential for herbicide input reduction makes the reduced dosage methods favourable. However, due to the absence of an actual economic benefit and the enhanced risk of efficacy failure and herbicide resistance development, the true benefit for farmers is questionable.

6.1.2 Introduction

In Europe and other areas with temperate climate, winter wheat (*Triticum aestivum* L.) is a major crop and often rotated with other cereal crops or oilseed rape (textitBrassica napus L.). Weeds are the most yield limiting biotic factor in those cropping systems and therefore, effective weed control is very important (Oerke, 2006). However in recent years political and social pressure has increased aiming the overall reduction of pesticide inputs into the environment. According to the directive 2009/128/EG of the European Parliament on the sustainable use of pesticides within the European Union, the use of pesticides is aimed to be reduced to its necessary minimum by the implementation of integrated pest management methods (Parliament and of the European Union, 2009).

Beneath the use of site-specific weed control methods as proposed e.g. by Christensen et al. (2003) or the replacing of herbicides by non-chemical weed control measures (Rueda et al., 2010) there are two practical strategies for the reduction of herbicide inputs conceivable:

1. The use of economic thresholds as proposed by Niemann (1986), Cousens et al. (1986), Gerowitt and Heitefuss (1990), Pallut (1992) and Zanin et al. (1993).
2. The reduction of the herbicide dosage as proposed by Rasmussen (1993), Brain et al. (1999), Rydahl (1999), Schroeder et al. (2007) and Travlos (2012).

The objective of this study is to compare three herbicide saving weed control strategies, namely the economic threshold method and two reduced herbicide dosage approaches regarding their long term effects on crop yield, weed population development, herbicide input and economic net return. Analysis and discussion will be done with respect to two contrary perspectives; the farmer's perspective with main focus on production risks and an economically optimized production process. The second perspective is on consumer and environmental safety with focus on the reduction of pesticide input to its necessary minimum. Since the study of long term effects of herbicide saving weed control strategies would be necessarily based on long term experiments under multiple environmental conditions, a simulation approach was chosen in order to evaluate the general effects.

The presented simulation is based on a combination of existing models for crop yield loss calculation in dependency of weed density (Cousens, 1985), soil seed bank development (Cousens et al., 1986), herbicide dose-response (Streibig, 1988) and calculation of the economic net return of the production system (Christensen et al., 2003). The simulation was carried out with *Avena fatua* (L.) in winter wheat. Data were gathered in two-year field experiments. *A. fatua* belongs to the top 10 worst weed species of temperate agricultural regions worldwide (Beckie et al., 2012 a). Beneath its typical occurrence in spring cereals, *A. fatua* is also abundant in winter cereals and oilseed rape (Schroeder et al., 1993). Depending on crop density and relative time of emergence, *A. fatua* is able to reduce yields by up to 70 % (Beckie et al., 2012 a).

6.1.3 Materials and Methods

Mechanistic structure of the simulation approach The comparison of the three herbicide saving weed control strategies was set up as a modular model. First, seedling density of *A. fatua* was related to weed biomass, since the calculations of the dose-response sub-model are based on weed biomass rather than on weed density. A linear relationship between seedling density (SD) and weed biomass m^{-2} (SB) is assumed for the period of weed control from two leaf growth stage of *A. fatua* until early tillering. The linear relationship is following Eqn. 6.1:

$$SB = a * SD \tag{6.1}$$

For calculation of the normalized herbicide dose dependent residual *A. fatua* biomass (SB_{U_i}), the two-parametric log-logistic dose-response function according to Streibig (1988) was used with the upper limit set to 1 and the lower limit set to 0 (Eqn. 6.2). The parameter e_i denotes the ED50 value of herbicide i, the dose at which herbicide efficacy is at 50 %, and b_i denotes the slope around e_i. U stands for the dosage of herbicide i.

$$SB_{U_i} = SB * (1/(1 + exp(b_i * log(U_i/e_i)))) \tag{6.2}$$

Seed production per m^{-2} in year t ($SI_{SB_{U\,i}}$) of the herbicide dose dependent residual *A. fatua* biomass (SB_{U_i}) follows a hyperbolic function. C = seed input per unit residual *A. fatua* biomass as $SB_{U_i} \rightarrow 0$ and D = seed input as $SB_{U_i} \rightarrow \infty$.

$$SI_{SB_{U}i} = C * SB_{U_i}/(1 + C * SB_{U_i}/D) \tag{6.3}$$

Seedling density in year t+1 ($SD_{(t+1)}$) is described by soil seed bank content of newly produced seeds (SSB_{new}) and seeds from the previous seasons (SSB_{old}) and their respective germination rates ($v_{new/old}$). The respective soil seed bank input of newly produced seeds (SSB_{new}) is a function of seed losses via harvest (s) 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 (Eqn. 6.4-6.6).

$$SSB_{new} = SI_{SB_{U}i} * (1 - p) * (1 - s) \tag{6.4}$$

$$SSB_{old} = (1 - m_{old} - v_{old}) * SSB_{old}^{(t-1)} + (1 - m_{new} - v_{new}) * SSB_{new}^{(t-1)} \tag{6.5}$$

$$SD_{(t+1)} = (v_{new} * SSB_{new}) + (v_{old} * SSB_{old}) \tag{6.6}$$

Winter wheat yield ($Y_{SB_{U}i}$) in dependency of herbicide dose dependent *A. fatua* residual biomass (SB_{U_i}) can be calculated by replacing seedling density by seedling biomass of the yield loss function proposed by Cousens (1985):

$$Y_{SB_{U}i} = Y_{wf} * (1 - I * SB_{U_i}/(1 + I * SB_{U_i}/A)) \tag{6.7}$$

with Y_{wf} = weed free winter wheat yield, I = fraction yield loss per unit weed biomass density as $SB_{U_i} \to 0$ and A = fraction yield loss per unit weed biomass as $SB_{U_i} \to \infty$.
The final economic net return can be calculated by Eqn. 6.8:

$$NR_{SB_{U}i} = P_y * Y_{SB_{U}i} - P_u U - C_1 - C_2 \tag{6.8}$$

Where P_y is the price per crop unit, P_u is the per unit costs of the respective herbicide (U) or rather the variable costs for weed control, C_1 are fixed production costs and C_2 are the fixed costs for herbicide application.
According to Christensen et al. (2003), the economically optimal herbicide dosage can be found by differentiation of Eqn. 6.9:

$$\frac{d}{dU} NR_{SB_{U}i} = 0 \quad for \quad 0 < U < N \tag{6.9}$$

where N is the maximum acceptable herbicide dose. Table **??** shows the parameters for Eqn. 6.1-6.9.

Table 6.1: Parameters used for the simulation approach. Herbicide details: Atlantis WG, 5.6 g a.i. kg^{-1} iodosulfuron + 29.2 g a.i. kg^{-1} mesosulfuron, Bayer CropScience. Broadway, 22.8 g a.i. kg^{-1} florasulam + 68.3 g a.i. kg^{-1} pyroxsulam, Dow AgroScience. Axial 50, 50 g a.i. L^{-1} pinoxaden, Dow AgroScience. Ralon Super, 63.6 g a.i. L^{-1} fenoxaprop-P, Nufarm.

Submodel	Equation		Parameter	Value	Unit
A. fatua seedling density to biomass transformation	1)		a	0.292	g DM m^{-2} / plants m^{-2}
Herbicide efficacy	2)	Mesosulfuron (Atlantis WG)	U	0-11.68	g a.i. ha^{-1}
			b	0.83	
			e	0.061	g a.i. ha^{-1}
		Pyroxsulam (Broadway)	U	0-15.03	g a.i. ha^{-1}
			b	2.08	
			e	0.94	g a.i. ha^{-1}
		Pinoxaden (Axial 50)	U	0-25.0	g a.i. ha^{-1}
			b	2.04	
			e	7.09	g a.i. ha^{-1}
		Fenoxaprop-P (Ralon Super)	U	0-63.3	g a.i. ha^{-1}
			b	1.87	
			e	4.12	g a.i. ha^{-1}
A. fatua biomass dependent seed production	3)		C	782.7	Seeds m^{-2}
			D	21338	Seeds m^{-2}
	4)		p	0.3	
			s	0.2	
Soil seedbank development (parameters adopted from Cousens, 1986)	5)		v_{old}	0.1	
			v_{new}	0.1	
			m_{old}	0.65	
			m_{new}	0.57	

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Table 6.1 – continued from previous page

Submodel	Equation		Parameter	Value	Unit
Winter wheat yield	7)		Y_{wf}	7	t ha^{-1}
			I	0.059	t ha^{-1} / g DM m^{-1}
			A	0.508	t ha^{-1}
Economics of weed control	8)		P_y	190	€t^{-1}
			C_1	550	€ha^{-1}
			C_2	10	€ha^{-1}
		Mesosulfuron	P_U	4.45	€g^{-1} a.i.
		Pyroxsulam	P_U	4.05	€g^{-1} a.i.
		Pinoxaden	P_U	0.73	€g^{-1} a.i.
		Fenoxaprop-P	P_U	0.28	€g^{-1} a.i.

Statistical Analysis The relationships between *A.fatua* seedling biomass (SB) and seedling density (SD), seed input (SI) and seedling biomass (SB) as well as winter wheat yield (Y) and seedling biomass (SB) were tested on differences between experimental datasets. Therefore full models were set up in which all parameters were estimated separately by dataset. Subsequently the models were reduced to common parameters and compared with Fishers F-test (α=0.05) on significant differences. Analysis was performed with the statistical software SAS 9.3 (SAS Institute Inc., Cary, NC, USA), using *proc glm* and *proc nlin*.
For statistical analysis of the dose-response relationships the tow parameter log-logistic dose-response function by Streibig (1988) was fitted to the data (Eqn. 6.10):

$$\gamma = 1/(1 + exp(blog(U/ED50))) \tag{6.10}$$

giving the herbicide efficacy (γ) in dependency of the herbicide dosage (U), 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).

Experimental sites and climatic conditions All field experiments were conducted in Germany at the University of Hohenheim experimental station 'Ihinger Hof' (48°27'36" N, 8°33'36" E) from 2009 until 2011. The average annual rainfall at Ihinger Hof is 688 mm and the mean temperature is 8.8 °C. Soil type is loam.

Winter wheat yield loss and *A. fatua* seed production experiments The density dependent winter wheat yield loss and *A. fatua* seed production experiments were carried out over two years. A complete randomized block design was selected for this study with five replicates in season 2009/2010 and at two sites with four replicates per variant in cropping season 2010/2011. In the beginning of October, winter wheat cultivar 'Schamane' was sown at a density of 330 seeds m^{-2} and at a depth of 3 cm with a row distance of 12 cm. The experimental plots had a size of 2 x 9 m, divided into an area of 12 m^2 for grain yield assessment at time of harvest and an area of 6 m^2 for weed- and crop biomass assessments as well as for assessment of *A. fatua* seed production. Grain yield was measured in the centre of the plots at a length of 8 m and width of 1 m with a plot combine harvester. After winter wheat sowing, *A. fatua* was sown at a depth of 1 cm with a RTK-GPS controlled seed drill between the winter wheat rows. Five *A. fatua* density classes were realised ranging from 1-25, 26-75, 76-125, 126-225 and 226-325 plants m^{-2}. One treatment was kept permanently weed-free by hand weeding. In plots sown with *A. fatua*, 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.

Avena fatua density and biomass m^{-2} was assessed at 2-3 leaf stage. A 50 x 50 cm frame was used to count *A. fatua* densities at four randomly selected positions per plot. For relative weed biomass determination, a sample of 1 m^2 out of the centre of each plot was harvested and separated into winter wheat and weed. Plant material was dried at 80 °C for 48 h. For determination 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. 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 to determine seed production per plant.

Due to partial poor germination of *A. fatua* seeds in season 2009/2010 and partial winter wheat logging in season 2010/2011, several plots were removed from the dataset.

Field dose-response studies Dose-response experiments were realized in the field during cropping season 2012/2013. *A. fatua* seeds were sown to a target density of 25 plants m^{-2} into the winter wheat plots as described previously. At 2-3 leaf-stage of *A. fatua* herbicides were applied at seven descending dosages, namely 100%, 75%, 50%, 37.5%, 25%, 12.5% and 0% of the recommended field rate. Herbicides were applied with a plot sprayer at a volume of 200 l ha^{-1} and a pressure of 320 kPa (Flatfan Nozzle, LU120-02, Lechler GmbH, Germany). Four weeks after herbicide application 0.5 m^2 were harvested out of the centre of each plot to determine the residual *A. fatua* biomass. Herbicides used and their recommended field rates are listed in Table **??**.

Simulated weed control strategies The following herbicide saving weed control strategies were simulated over a time period of 15 years, an initial

A. fatua seedling density of 100 plants m^{-2} and a crop rotation of winter wheat - winter wheat - oilseed rape.

1. Herbicides are applied at the recommended field rate if the economic weed density threshold is exceeded (Economic Threshold Strategy, abbreviated as ET). The economic threshold is reached when the costs for weed control equal the expected monetary yield loss.

2. Herbicides are applied at a predefined minimum dose rate if the economic threshold for the respective minimum dose rate is exceeded (Low Risk Reduced Dosage Strategy, abbreviated as RED-LR).

3. Herbicides are applied when the economic threshold for the full dosage is exceeded. The dosage of the respective herbicide is then reduced to its economic optimum according to Eqn. 6.9 (High Risk Reduced Dosage Strategy, abbreviated as RED-HR).

The following general assumptions were defined for the simulation:

1. Residual *A. fatua* biomass after herbicide treatment will produce seeds according to Eqn. 6.3.

2. No additional seed input other than by the plants which survive the herbicide treatment is assumed.

3. Constant germination rates of *A. fatua*, seed predation and seed mortality rates are assumed excluding eco-physiological relationships.

4. A reduced tillage system is assumed, where no deep burial of *A. fatua* seeds takes place.

5. A herbicide dosage equivalent of 1 will be used in years where oilseed rape is grown assuming a herbicide efficacy of 90%.

6.1.4 Results

Rainfall and average temperatures during the season 2009/2010 were within the 40-year average range of the experimental site. The season 2010/2011 was characterized by a dry and warm period between April and May resulting in moderate drought stress for both, crops and weeds.

Herbicide dose-response experiments It was possible to fit the two parameter dose-response model by Streibig (1988) for all tested herbicides. Therefore parameter estimates could be calculated given in Table **??**. The minimum dose rate for the low risk reduced dosage approach (RED-LR) was estimated visually according to the dose-response curve of the respective herbicide (Fig. 6.1). Decisive for the selection of the minimum dosage was that dosages are still above the linear part of the respective dose-response curve, where only marginal effects on efficacy and variability due to dose reduction can be expected (Kudsk, 2014). Mesosulfuron appeared to be the most flexible compound tested, since the dosage can be reduced by up to 50% of the maximum recommended field rate without major efficacy decline. The minimum dosages for pyroxsulam and fenoxaprop-P were both set to 75% of the recommended field rate, since their dose-response curves showed comparable shapes. Pinoxaden appeared to be the weakest compound tested, since dosage reductions showed pronounced effects on herbicide performance. Therefore the minimum dosage for pinoxaden was set to 90% of the recommended field rate.

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 (Fig. 6.2). There was no significant difference between the two experimental years. Thus, the model was fitted across both years (Table 6.2). 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.

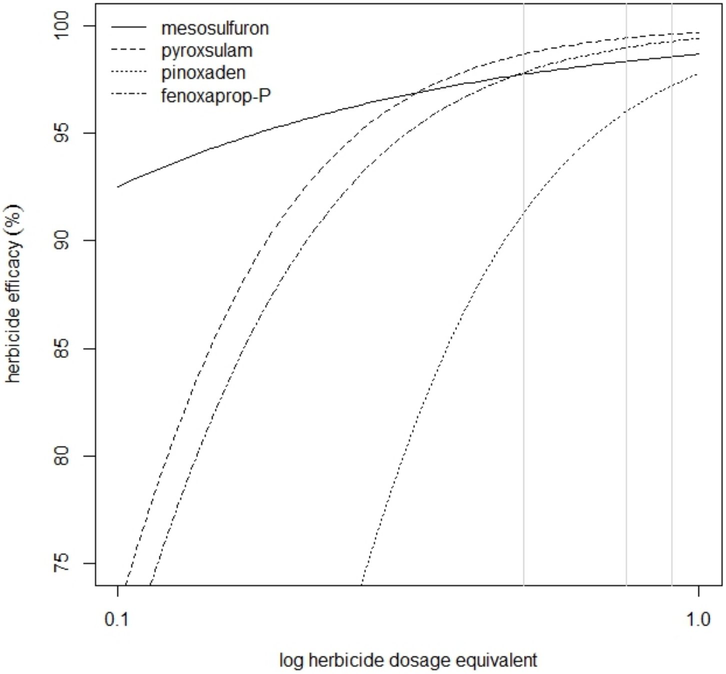

Figure 6.1: 1 Dose-response curves for mesosulfuron, pyroxsulam, pinoxaden and fenoxaprop-P for herbicide dosage equivalents ranging from 0.1 to 1. Vertical lines mark the estimated minimum recommended dosage equivalent, from left to right 0.5 for mesosulfuron, 0.75 for fenoxaprop-P and pyroxsulam and 0.9 for pinoxaden.

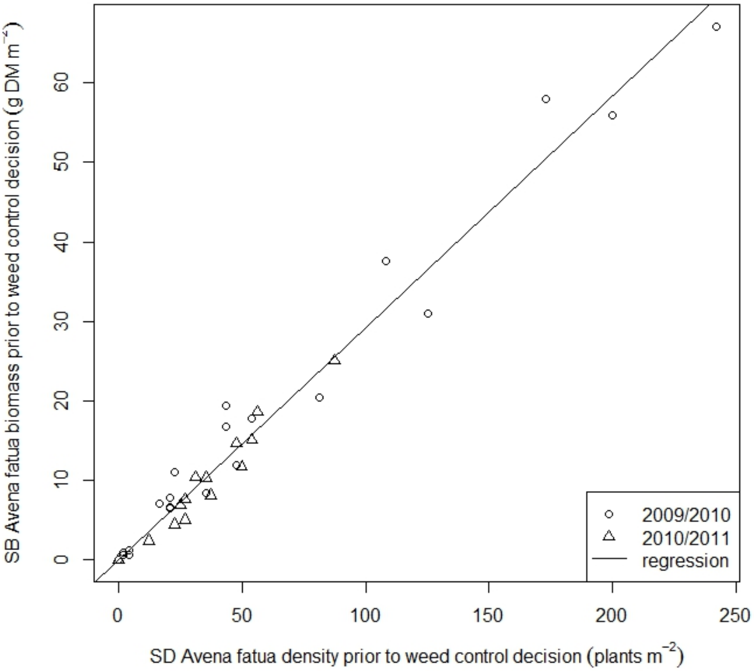

Figure 6.2: *A. fatua* seedling biomass m^{-2} (SB) in dependency of *A. fatua* seedling density m^{-2} (SD) at the 2 – 3 leaf stage. a=0.29, R^2=0.98.

Table 6.2: Results of the statistical analysis of empirical datasets from field experiments. Y_{SB} is the winter wheat yield in dependency of *A. fatua* seedling biomass (SB), SI gives the *A. fatua* seed input in dependency of seedling biomass and SB is the *A. fatua* seedling biomass in dependency of the seedling density. The index i describes that parameters were fitted separately by experiments. SSE is the residual sum of squares and DF the degrees of freedom of the respective model. The corresponding F-value is given as well as the p-value of model comparison.

Model		SSE	DF	F-value	p-value
$Y_{SB_{U_{rel}}}(SB_{U_{rel}})$	$Y_{SB_{U_{rel_i}}}=Y_{wf}{}^{t}{}_{i}*(1-I_i*SB_{U_{rel_i}}/(1+I_i*SB_{U_{rel_i}}/A_i))$	20.01	51	2.4303	0.0594
	$Y_{SB_{U_{rel_i}}}=Y_{wf}{}^{t}{}_{i}*(1-I*SB_{U_{rel}}/(1+I*SB_{U_{rel}}/A))$	23.83	55		
$SI_{SB_{U_{rel}}}(SB_{U_{rel}})$	$SI_{SB_{U_{rel_i}}}=C_i*SB_{U_{rel_i}}/(1+C_i*SB_{U_{rel_i}}/D_i))$	162920000	36	1.4263	0.2451
	$SI_{SB_{U_{rel}}}=C*SB_{U_{rel}}/(1+C*SB_{U_{rel}}/D))$	188740000	40		
SB-SD	$SB_i=b_i*SD_i$	284.62	44	0.6127	0.438
	$SB=b*SD$	288.58	45		

i=ith experiment

Winter wheat yield in relation to *A. fatua* relative biomass The relationship between relative *A. fatua* seedling biomass m^{-2} and winter wheat grain yield can be described by a hyperbolic function (Eqn.6.7 and Fig.

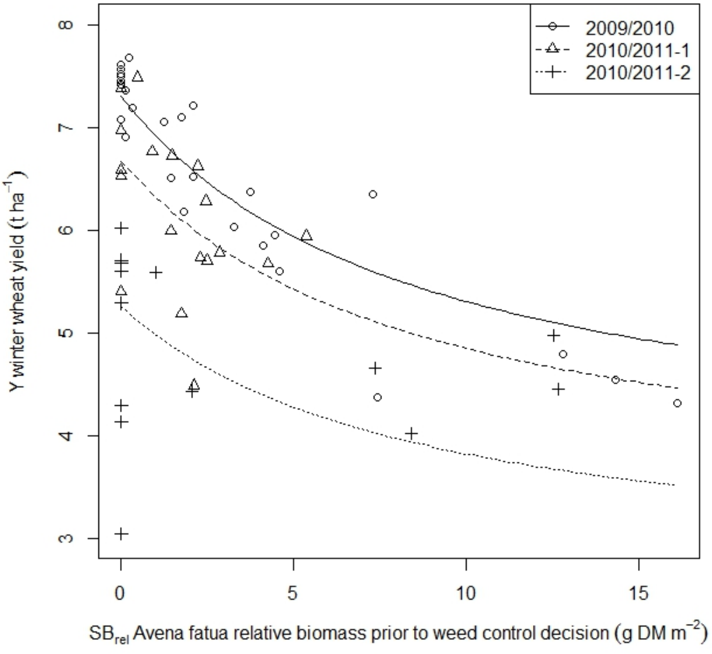

Figure 6.3: Winter wheat yield (t ha^{-1}) in dependency of *A. fatua* seedling biomass m^{-2} (SB)

Table 6.3: Parameter estimates of the empirical models from field experiments, with corresponding standard errors, confidence intervals and measures of fit of the model. RMSE=root mean squared error, RRMSE=relative root mean squared error. Y_{wf_1} = weed free yield in season 2009/2010. Y_{wf_2} = weed free yield in season 2010/2011 at site 1. Y_{wf_3} = weed free yield in season 2010/2011 at site 2.

					2*confidence intervals (95 %)					
Equation		Parameter	Estimate	Std. error	lower	upper	R^2	RMSE	RRMSE[%]	Bias
1)	SB(SD)	b	0.292	0.006	0.280	0.303	0.98			
3)	$SI_{SB_{Urel}}(SB_{Urel})$	C	782.7	255.9	265.5	1299.9		2119.8	78.02	492.1
		D	21338	18078.3	-15199.5	57875.5				
		I	0.0591	0.023	0.013	0.105				
		A	0.5081	0.182	0.143	0.874				
7	$Y_{SB_{Urel}}(SB_{Urel})$	Y_{wf_1}	7.3006	0.172	6.956	7.646				
		Y_{wf_2}	6.6738	0.206	6.262	7.086				
		Y_{wf_3}	5.2571	0.198	4.861	5.654				

Seed input in relation to *A. fatua* relative biomass prior to weed control decision The observed *A. fatua* seed production in relation to the relative biomass prior to the weed control decision varied between the experimental years and sites (Fig. 6.4, Table 6.2). Although, the data variation was high no significant difference could be found, neither between the years nor between the different experimental sites of the second year. Therefore, the parameter estimates of the reduced model were used for the simulation approach as given in Table **??**. A RRMSE of 78% as well as a bias of 492.1 was calculated, indicating that seed production calculation based on weed biomass determination prior to the weed control decision is highly biased (Table 6.3). The calculated bias indicates that the seed production is highly overestimated.

Simulation results Weed control strategies were simulated over a period of 15 years and for an initial *A. fatua* density of 100 plants $m^{-2)}$. The calculated economic thresholds for the ET and RED-HR strategy were 7 plants m^{-2} for mesosulfuron, 5 plants m^{-2} for pyroxsulam, 4 plants m^{-2} for pinoxaden and 13 plants m^{-2} for fenoxaprop. The economic thresholds for the RED-LR strategy, calculated for the herbicide dependent minimum dosages mentioned before, were 4 plants m^{-2} for mesosulfuron, 4 plants m^{-2} for pyroxsulam, 4 plants m^{-2} for pinoxaden and 10 plants m^{-2} for fenoxaprop. For direct comparison of the simulation results, herbicide rates were transformed into herbicide dosage equivalent (HDE), ranging from 0 (no herbicide application) to 1 (maximum recommended dosage). Simulation results for the economic threshold scenario are given in Table 6.4. In year 5 the seedling density was reduced from initially 100 plants m^{-2} to 7 plants m^{-2}. Therefore, the fenoxaprop-P treatment was postponed to year 7. Consequently, the seedling density in year 7 increased to 49 plants m^{-2}. For decreasing the seedling density again to a level below the economic threshold, three consecutive years of herbicide treatment were necessary. In year 11 seedling density was below the economic threshold for the scheduled pyroxsulam treatment. A cumulative dosage equivalent of 12 was used over the simulated time period of 15 years, whereof a dosage equivalent of 5 was used for oilseed rape and a dosage equivalent of 7 for winter wheat.

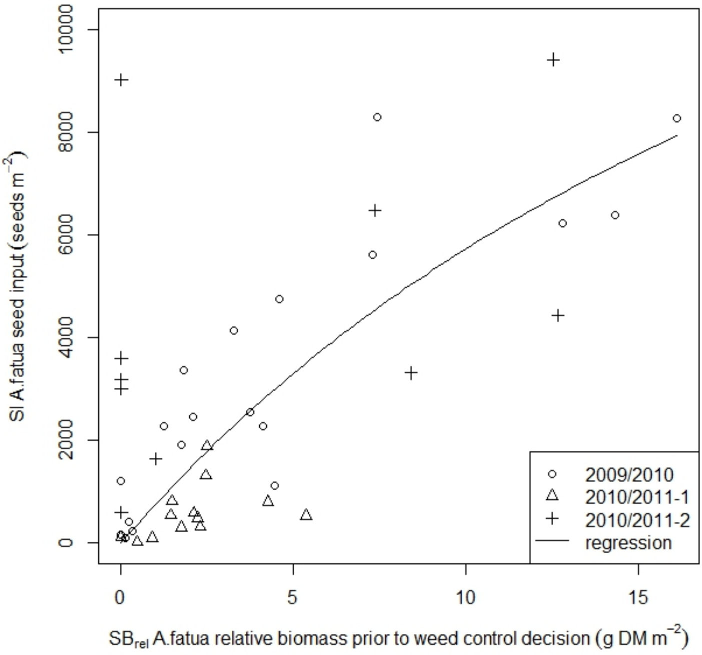

Figure 6.4: *A. fatua* seed input (seeds m^{-2}) in dependency of herbicide dose dependent *A. fatua* biomass m^{-2} (SB).

Table 6.4: Simulation results for the **Economic Threshold strategy** (ET). SI = calculated *A. fatua* seed input, NR= calculated net return, SD = *A. fatua* seedling density, WW = winter wheat, OR = oilseed rape, HDE = herbicide dose equivalent.

		ET						
Year	Crop	SD plants m^{-2}	Scheduled herbicide	Dose (g a.i. ha^{-1})	HDE	Yield (t ha^{-1})	NR (€ha^{-1})	SI (seeds m^{-1})
1	WW	100	mesosulfuron	11.68	1.00	6.8	702	22
2	WW	29	pinoxaden	45.00	1.00	7.0	756	1
3	OR	7	alternative MOA		1.00			168
4	WW	15	pyroxsulam	15.03	1.00	7.0	752	32
5	WW	7	fenoxaprop-P	0.00	0.00	6.8	743	379
6	OR	23	alternative MOA		1.00			514
7	WW	49	fenoxaprop-P	63.60	1.00	7.0	714	0
8	WW	16	mesosulfuron	11.68	1.00	7.0	739	4
9	OR	4	alternative MOA		1.00			94
10	WW	9	pinoxaden	45.00	1.00	7.0	759	0
11	WW	3	pyroxsulam	0.00	0.00	6.9	764	159
12	OR	10	alternative MOA		1.00			218
13	WW	21	pyroxsulam	15.03	1.00	7.0	750	43
14	WW	9	fenoxaprop-P	0.00	0.00	6.7	732	502
15	OR	31	alternative MOA		1.00			676
$\sum$		22			12.0	69.1	7411	2813

Simulation results for the RED-LR scenario are given in Table 6.5. After four years *A. fatua* density could be reduced from initial 100 plants m^{-2} to 8 plants m^{-2} in year 5, which was below the economic threshold for the scheduled fenoxaprop-P treatment. Since after the oilseed rape season in year 6 the *A. fatua* density in year 7 was still below the economic threshold for fenoxaprop-P, the treatment was postponed to year 8. Between year 8 and 13 the seedling densities varied between 2 and 28 plants m^{-2}. Winter wheat yields remained stable between 6.74 and 6.99 tons ha^{-1}. In total a herbicide dosage equivalent of 10.05 was used in 15 years, whereof a dosage equivalent of 5.0 was used for oilseed rape and 5.05 was used for winter wheat. Cumulative yield was 0.08 t lower compared to the economic threshold strategy, while the cumulative net return was around 30€higher.

Table 6.5: Simulation results for the **Low Risk Reduced Dosage** Strategy RED-LR. SI = calculated *A. fatua* seed input, NR= calculated net return, SD = *A. fatua* seedling density, WW = winter wheat, OR = oilseed rape, HDE = herbicide dose equivalent.

RED-LR								
Year	Crop	SD plants m^{-2}	Scheduled herbicide	Dose (g a.i. ha^{-1})	HDE	Yield (t ha^{-1})	NR (€ha^{-1})	SI (seeds m^{-1})
1	WW	100	mesosulfuron	5.84	0.50	6.74	709	64
2	WW	31	pinoxaden	40.50	0.90	6.97	756	2
3	OR	8	alternative MOA		1.00			186
4	WW	17	pyroxsulam	11.27	0.75	6.77	754	48
5	WW	8	fenoxaprop-P	0.00	0.00	6.77	736	457
6	OR	28	alternative MOA		1.00			618
7	WW	8	fenoxaprop-P	0.00	0.00	6.77	736	457
8	WW	28	fenoxaprop-P	47.70	0.75	6.99	727	1
9	OR	9	alternative MOA		1.00			205
10	WW	19	mesosulfuron	5.84	0.50	6.95	748	14
11	WW	7	pinoxaden	40.50	0.90	6.99	760	1
12	OR	2	alternative MOA		1.00			41
13	WW	4	pyroxsulam	0.00	0.00	6.89	759	214
14	WW	13	pyroxsulam	0.00	0.00	6.98	755	37
15	OR	6	alternative MOA		1.00			144
$\sum$		19			10.1	69.0	7441	2488

Simulation results for the RED-HR scenario are given in Table 6.6. After four years *A. fatua* density could be reduced from initial 100 plants m^{-2} to 11 plants m^{-2}. Since the economic threshold for fenoxaprop-P was not exceeded in year 5 the treatment was postponed to year 7. Between year 7 and 13 *A. fatua* density was ranging between 5 and 82 plants m^{-2}. In year 13 *A. fatua* desity was again below the economic threshold for fenoxaprop-P why the treatment was postponed to year 14. Cumulative yield was around 0.3 t lower compared to the ET strategy and around 0.2 t lower compared to the RED-LR strategy. Cumulative net return was only marginal different compared to the ET strategy and around 30€lower compared to the RED-LR strategy. In total, a herbicide dose equivalent of 8.8 was used in 15 years, whereof a dosage equivalent of 5.0 was used for oilseed rape and 3.8 was used for winter wheat.

Table 6.6: Simulation results for the **High Risk Reduced Dosage** Strategy RED-HR. SI = calculated *A. fatua* seed input, NR= calculated net return, SD = *A. fatua* seedling density, WW = winter wheat, OR = oilseed rape, HDE = herbicide dose equivalent.

RED-HR								
Year	Crop	SD plants m^{-2}	Scheduled herbicide	Dose (g a.i. ha^{-1})	HDE	Yield (t ha^{-1})	NR (€ha^{-1})	SI (seeds m^{-1})
1	WW	100	mesosulfuron	4.84	0.41	6.7	709	85
2	WW	32	pinoxaden	41.68	0.93	7.0	756	2
3	OR	9	alternative MOA		1.00			195
4	WW	18	pyroxsulam	5.42	0.36	7.0	757	102
5	WW	11	fenoxaprop-P	0.00	0.00	6.7	720	636
6	OR	39	alternative MOA		1.00			854
7	WW	82	fenoxaprop-P	27.16	0.43	6.9	734	15
8	WW	27	mesosulfuron	2.44	0.21	6.9	748	76
9	OR	11	alternative MOA		1.00			249
10	WW	23	pinoxaden	37.23	0.83	7.0	757	2
11	WW	8	pyroxsulam	4.06	0.27	7.0	762	58
12	OR	5	alternative MOA		1.00			117
13	WW	11	fenoxaprop-P	0.00	0.00	6.7	722	612
14	WW	38	fenoxaprop-P	20.53	0.32	6.9	742	24
15	OR	14	alternative MOA		1.00			304
$\sum$		28			8.8	68.8	7408	3331

6.1.5 Discussion

Simulation approach The assumed linear relationship between *A. fatua* density and biomass could be confirmed. The transformation of weed density into weed biomass appears to be reliable and negligible biased by weather conditions and therefore enables the incorporation of dose-response models into yield loss calculations. For weed densities exceeding the densities presented in this study, a hyperbolic relationship between seedling density and seedling biomass is necessary, taking account of intra- and interspecific competition.

The calculation of *A. fatua* seed production in dependency of *A. fatua* biomass prior to the weed control decision in spring was found to be highly biased. The results make clear that the use of an eco-physiological modelling approach, based on herbicide dose dependent seed production data, is inevitable for the forecast of seed production (e.g. for decision support systems). The presented approach assumes, that even at herbicide efficacy levels of around 90%, the surviving residual biomass will produce seeds. This leads to an overestimation of the seed production. However, for the presented simulation approach, the overestimation was accepted since the main focus was on the comparison of different management strategies rather than on the exact forecast of the population development.

Although the observed yields without *A. fatua* competition were significantly different between years and sites, no significant differences could be found for the model parameters I and A. This result indicates that yield losses in dependency of the relative *A. fatua* biomass are following the same dynamics even though eco-physiological factors were excluded. The low bias and RRMSE values are supporting this hypotheses. However, yield loss studies by Milberg and Hallgren (2004) in more than 1600 field trials demonstrated that residual variation in yield loss data is highly affected by the geographic region as well as by the crop itself whereas the factor year alone was unable to explain the variation.

Despite the fact that the presented simulation approach was based on a single weed species, the reduced dosage method can be adjusted for mixed weed species situations by slight modifications. We suggest the density equivalent respectively the recursive density equivalent method, as proposed by Berti and Zanin (1994) and Holst (2005) for crop yield loss calculation. Herbicide dosage selection should be based on the weed species showing the highest ED_{90} value for the respective chosen herbicide and exceeding the economic threshold for the upcoming season without herbicide treatment. Furthermore, sub-models calculating seed emergence and time of removal, as proposed by Berti et al. (2008), would be able to further improve the simulation reliability.

The results of the field dose-response experiments could demonstrate the different herbicide specific potentials for dose reductions. As demonstrated by Kudsk (2014), variability in herbicide performance is not necessarily correlated with herbicide dosage. Due to the asymptotic properties of dose-response curves, an increase or decrease of dose rates at very high or low dose levels might have only marginal effects on herbicide performance (Kudsk, 2014).

The presented results could show that mesosulfuron is offering a comparatively high potential for dose reductions, since the efficacy remains above 90% until dosage of 10% and less of the recommended field rate. This confirms the result of Travlos (2012) who pointed out that dosages of 50% of the recommended dose rate of iodosulfuron-methyl + mesosulfuron-methyl resulted in equal weed control efficacy and weed seed production of *Avena sterilis* compared to label-recommended dosages.

Pinoxaden in contrast offers almost no flexibility for dosage variation, since efficacy seems to be directly correlated with herbicide dose, even at very high dosages around the maximum recommended field rate. Holm et al. (2000) found that efficacy of graminicides is influenced by the density of *A. fatua*, where efficacies of reduced herbicide rates tended to be higher 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. (2003 a) for reduced rates of imazamethabenz and difenzoquat. The discrepancies between the mentioned results indicate that dose dependent seed production is affected by combined effects of weed density, crop competitiveness as well as by the herbicidal compound itself.

Simulation results The simulation results could show that the RED-LR strategy is able to decrease the herbicide input in winter wheat by around 27% compared to the ET strategy. The economic optimization of the reduced dosage strategy (RED-HR) could further decrease the herbicide input in winter wheat by around 25% compared to the RED-LR strategy. Compared to the ET strategy, herbicide input appeared to be reduced by around 46%. Differences in cumulative yield and cumulative net return appeared to be negligible. Cumulative *A. fatua* seed input was lowest for the RED-LR strategy which can be explained by the significant lower economic thresholds compared to the ET and RED-HR strategy.

From a farmer point of view, both reduced dose strategies are not favourable compared to the ET strategy. Both reduced dose strategies do not provide a significant increase in cumulative net return and especially the RED-HR strategy is bearing a high risk of herbicide efficacy failure. From a consumer and environmental safety point of view, the reduced dosage methods are favourable due to the high potential of further reduction of herbicide inputs.

According to studies by Neve and Powles (2005) and Manalil et al. (2011) reduced herbicide dosages favour the development of herbicide resistance in *Lolium rigidum* by the selection of individuals with increased metabolic activity. Even by the rotation of modes of action and chemical classes within the modes of action, this effect can't be excluded. This is especially true, when other weed management tools are ignored, like the use of competitive crop cultivars, high crop seeding rates as well as non-chemical weed control measures (Kirkland et al., 2000; O'Donovan et al., 2003 a). A combination of the proposed reduced dosage method with non-chemical weed control methods and agronomic practices aiming maximum competitive crop stands could minimize the risk for herbicide resistance evolution as well as compensate the possible production risks. However, form a farmer point of view the benefit of reduced dosage methods is questionable in case of absence of a true economic benefit.

6.2 Potential of reducing herbicide input and dosages in intensive cropping systems

In section 3 it was shown that there is potential for reducing herbicide dosages in maize while still maintaining high control efficacies and maize yields. What was not included in this study, is, how reduced dosages would influence weed seed production in maize crop. As shown at the example of *A. fatua* in winter wheat (section 4, reduced dosages may lead to increased seed input, depending on the herbicide used and the crop competitiveness, thus leading to an increasing weed population in the long run. Sikkema et al. (2008) have shown that herbicide dosages could be reduced by 50 % in maize without increase in weed seed input. Contrary, Simard et al. (2011) found increased soil seed bank of weeds when lowering herbicide rates. In general, herbicide efficacy is dependent on environmental conditions (Kudsk and Kristensen). Thus it is difficult to derive general recommendations for the required dosage. As already described in section 6.1, there is higher risk of efficacy failure at decreasing dosages, where efficacy is decreasing exponentially (Kudsk, 2014). To prevent efficacy failure and increasing weed populations in the long-run, follow-up studies have to be conducted, to investigate how dosage reduction would influence weed seed production in maize cropping.

Maize is not a highly competitive crop, especially in its juvenile stage. The sowing pattern of maize gives weeds favourable growth conditions, providing a lot of space between the rows in the early development of maize. In section 5 it was highlighted, how increased sowing density of winter wheat can increase its competitiveness against *C. hedereacea*. Similarly, decreasing row spacing of maize can enhance its competitiveness against weeds, as shown for several environments (Tollenaar et al., 1994; Mashingaidze et al., 2009; Fanadzo et al., 2010). Furthermore, seed onset by weeds may also be reduced (Mashingaidze et al., 2009). Increased competitiveness of the maize crops at narrower row spacing can allow to reduce herbicide dosage while achieving same control efficacy (Tresdale, 1995; Kegode et al., 1999).

Beside chemical weed control, several studies have been conducted by using the effect of cover crops, or their extracts, on weeds. In section 5 it was shown how cover crops and their extracts influence weed growth. These experiments, however, cannot be easily transferred into the field, because allelopathic active compounds show strong interaction with their environment, e.g. by adsorption to soil particles or degradation. Others have investigated the effect of cover crops on weed suppression and crop plants in field experiments. Malik et al. (2008) could show that wild radish and rye used as cover crop in maize reduced weed density by up to 50 %. Khan et al. (2012) showed with their study that plant extracts of different allelopathic species added to the spray solution could remarkably reduce the required amount of atrazine for efficient weed control in maize. Also in cereals, cover crops or undersown crops can efficiently suppress weed growth (Brust et al., 2011).

The above-mentioned examples show how herbicide input could be reduced, also by combining herbicides with agronomic weed control measures or by extending conventional weed control to allelopathic plant species. Agronomic weed control options are often site-specific and furthermore need to meet the requirements of the farmers. However, there are a lot of different tools available, ranging from adapting the crop rotation, soil cultivation and selection of cultivars, to fertilization and sowing density, as described in section 5.

The articles in this thesis highlight the potential of reducing herbicide input in intensive cropping systems, while still achieving high control efficacies. This can be achieved on the one hand by reducing the applied herbicide dosage. Therefore, extensive dose-response experiments including various crop and weed species are necessary providing information on minimum required dosages. On the other hand, herbicide input can be reduced by enhancing integrated weed management measures.

7 Summary

Weed control in conventional cropping is commonly done using herbicides. Those, however, can have negative side-effects on the environment.
The objective of this thesis is to investigate the potential of reducing herbicide input into cropping systems with a focus on two of the most important staple crops, maize and winter wheat. The thesis is divided into five main sections, dealing with different topics, i.e.:

1. Determination of herbicide efficacy
2. Efficacy of reduced herbicide dosages in maize
3. Efficacy of reduced herbicide dosages in winter wheat
4. Integrated weed management
5. Long-term effect of reduced herbicide dosages

To examine herbicide efficacy at reduced dosages it is necessary to conduct a wide range of dose-reponse experiments. They are usually time and labour consuming and the assessment of herbicide efficacy is often not objective. To overcome these issues, a novel method for assessing herbicide efficacy using bi-spectral imaging was tested. The results show at the example of *Bromus japonicus* that weed coverage assessed with the bi-spectral camera system can serve as a non-destructive, rapid and objective method to assess herbicide efficacy.
In field experiments the potential for reducing herbicide dosages in summer maize was investigated with several common herbicides and herbicide mixtures. These experiments show that it is possible to reduce herbicide dosages for weed control in maize without influencing weed control efficacy and crop yield. However, the extent to which dosages can be reduced without loss in efficacy is dependent on the herbicide used and the weed growth stage. One of the herbicide tested in the field (topramezone) is usually applied together with a methylated seed oil (MSO) adjuvant. Adjuvants play an important role for herbicide efficacy, but the mechanism

for enhancing herbicide efficacy is often not clear, yet. To examine the mechanism of MSO in enhancing efficacy of topramezone, several experiments were conducted. Efficacy of topramzone was significantly increased by addition of MSO. The results show that MSO enhances the uptake and translocation of topramezone in the two tested weed species. Furthermore, physical properties of the spray solution were altered. More precisely, surface tension and thus the contact angle on the leaf was decreased. These results can explain why MSO adjuvant enhances topramezone efficacy.

To investigate the potential of reducing herbicide dosages in winter wheat and its impact on weed seed production, experiments were conducted using *A. fatua* as weed. The results show, that dosages of the four tested herbicides could be tremendously reduced without loss in efficacy. However, *A. fatua* seed production was influenced by winter wheat competitiveness and herbicide mode of action and did not necessarily follow herbicide efficacy. These results on the one hand highlight the potential of herbicide dosage reduction for controlling *A. fatua* in winter wheat. But on the other hand, the results point out that decision on herbicide dosage reduction should not only be made on basis of herbicide efficacy data but also on its influence on weed seed production.

Reduction of herbicide input cannot only be achieved by reducing herbicide dosages, but also by applying non-chemical weed control methods. These methods may not be able to fully replace herbicide usage, but they can serve as tool to reduce weed pressure and competitiveness. Field experiments were carried out to investigate the effect of adjusted winter wheat seeding rate and nitrogen fertilization on *Calystegia hederacea* abundance and herbicide control efficacy. The results show that increased seeding rate reduces density of this weed while enhancing herbicide efficacy. Lowering nitrogen fertilization rate towards N_{min} based fertilization increased density of *C. hederacea*. This study points out how adjustment of agronomic parameters can influence weed competitiveness and can serve in enhancing weed control efficacy by herbicides. It had been shown in several studies that cover crops or undersown crops can effectively suppress weed growth. This suppression may not only be due to competition for resources, but also by chemical interaction via allelopathic active compounds. To examine the allelopathic effect of several cover crops, pot and laboratory experiments were carried out. These experiments show, that effects of the tested cover crops can be growth promoting or inhibiting, and are dependent on the species and extract concentration. Furthermore, cover crops can also affect growth of the crop.

To discuss the long-term effect of reduced herbicide dosages on weed population development, a simulation model was set-up at the example of winter wheat and *A. fatua.* Different strategies for herbicide input reduction were simulated. This paper highlights the potential of reducing total herbicide input without population increase, while keeping grain yield and net return at high level.

The presented articles work out the risks and potential for herbicide dosage reduction and point out the possibilities of using integrated weed management options for enhancing weed suppression.

8 Zusammenfassung

Im konventionellen Landbau werden Unkräuter in der Regel mit Herbiziden kontrolliert. Dies kann negative Auswirkungen auf die Umwelt haben.
Ziel dieser Arbeit ist es Möglichkeiten zur Reduktion des Herbizideintrags in intensiven Anbausystemen zu untersuchen. Der Fokus liegt hierbei auf zwei der bedeutendsten Nutzpflanzen: Mais und Winterweizen, Die Arbeit ist in fünf Themenbereiche gegliedert, welche folgende Punkte abhandeln:

1. Bestimmung von Herbizidwirkung
2. Wirkung reduzierter Herbizidaufwandmengen in Mais
3. Wirkung reduzierter Herbizidaufwandmengen in Winterweizen
4. Integrierte Unkrautkontrolle
5. Langfristige Auswirkung reduzierter Herbizidaufwandmengen

Um die Herbizidwikrung von reduzierten Aufwandmengen festzustellen, müssen breit angelegte Dosis-Wikrungsversuche durchgeführt werden. Diese sind in der Regal arbeits- und zeitintensiv und die Messung der Herbzidwirkung ist oftmals nicht objektiv. Um das Verfahren zur Herbizidmessung zu verbessern, wurde eine neue Methode getestet, welche die Herbizidwirkung anhand von bi-spektralen Bildaufnahmen bestimmt. Die Ergebnisse zeigen anhand von *Bromus japonicus*, dass der mit der bi-spektral Kamera gemessene Unkrautdeckungsgrad ein geeigneter Parameter ist, um Herbizidwirkung schnell, nicht desttruktiv sowie objektiv zu bestimmen.
In Feldversuchen wurden unterschiedliche Herbizide einzeln und in Mischungen hinsichtlich ihres Potentials für Aufwandmengenreduktion in Mais getestet. Diese Versuche machen deutlich, dass eine Herbizidaufwandmengenreduktion zur Unkrautkontrolle in Mais möglich ist ohne dabei die Herbizidwirkung und den Maisertrag negativ zu beeinflussen. Inwieweit die Herbizidaufwandmenge ohne Wirkungsverlust reduziert werden kann

hängt jedoch von dem jeweiligen Herbizid sowie des Wachstumsstadiums des Unkrauts ab. Eines der in Feldversuchen getesteten Herbizid (Topramzone) wird in Kombination mit einem Adjuvans appliziert. Adjuvantien spielen für die Herbizidwirkung eine wichtige Rolle. Die Mechanismen, mit denen Adjuvantien die Herbizidwirkung steigern können sind allerdings oftmals nicht bekannt. Um die Wirkunsgweise von methylierten Samenöl (MSO) auf die Wirkung von Topramezone zu untersuchen, wurden verschiedene Versuche durchgeführt. Die Ergebnisse ergaben, dass MSO die Aufnahme und Translokation von Topramezone in den zwei untersuchten Unkrautarten steigert. Zudem beinflusst es die physikalischen Eigenschaften der Applikationslösung. Die Oberflächenspannung der Applikationslösung war herabgesetzt und dadurch verringerte sich der Kontaktwinkel der Applikationslösung auf dem Blatt. Die Ergebnisse können die Wirkungssteigerung von Topramezone durch Zugabe von MSO weitgehend erklären.

Um das Potential zur Herbizidaufwandmengenreduktion in Winterweizen, sowie die Auswirkung auf Unkrautsamenproduktion zu untersuchen wurden Feldversuche mit *Avena fatua* durchgefgührt. Die Ergbenisse zeigen, dass die Aufwandmengen der vier getesteten Herbizide ohne Wirkungseinbußen stark vermindert werden können. Jedoch war die Samenprouktion von *A. fatua* abhängig von der Konkurrenzkraft des Winterweizens sowie des Wirkmechanismus' der Herbizide und nicht zwangläufig abhängig von der Herbizidwirkung. Diese Ergbnisse verdeutlichen einerseits das Potential der Herbizidaufwandmengenreduktion zur Kontrolle von *A. fatua* in Winterweizen. Andereseits zeigen die Ergebnisse, dass eine Entscheidung zur Aufwandmengenreduktion nicht nur anhand der Herbizidwirkung getroffen werden sollte, sondern dass der Einfluss auf die Samenproduktion der Unkräuter für die Entscheidung berücksichtigt werden sollte.

Der Herbizideintrag kann nicht nur durch Aufwandmengenreduktion vermindert werden, sondern auch durch Anwendung nicht-chemischer Unkrautkontrollmaßnahmen. Diese Maßnahmen mögen den Herbizideinsatz nicht vollständig ersetzen können, aber sie dienen als Instrument um Unkrautdruck und -konkurrenzkraft zu reduzieren. Feldversuche wurden durchgeführt, um den Einfluss von Winterweizensaatstärke und Stickstoffdüngung auf die Konkurrenzkraft von und die Herbizidwirkung auf *Calystegia hederacea* zu untersuchen. Die Ergbenisse zeigen, dass eine erhöhte Saatstärke die Konkurrenzkraft dieses Unkrauts verringert und gleichzeitig die Herbizidwirkung steigert. Eine Verminderung der applizierten Stickstoffmenge auf N_{min}-basierte Stickstoffmengen förderte die Konkurrenzkraft von *C. hederacea*. Diese Versuche machen deutlich, inwieweit eine Anpassung von agronomischen Parametern die Konkurrenzkraft von Unkräutern beeinflussen kann und den Grad der Unkrautkontrolle durch Herbizide steigern kann. In einigen Arbeiten wurde gezeigt, dass Zwischenfrüchte und Untersaaten wirkungsvoll Unkraut unterdrücken können, wobei die Unterdrückung nicht nur durch Konkurrenz um Ressourcen hervorgerufen wird, sondern auch durch chemische Interaktionen über alleolpathisch wirksame Substanzen. Um die allelopathische Wirkung einiger Zwischenfrüchte zu untersuchen wurden Topf- und Laborversuche durchgeführt. Die Ergebnisse zeigen, dass die Wirkung von Zwischenfrüchten sowohl wuchsfördernd als auch wuchshemmend sein kann und dass die Wirkung artspezifisch ist sowie von der Konzentration der Stoffe abhängt. Außerdem können Zwischenfrüchte nicht nur das Wachstum der Unkräuter beeinflussen, sonder auch das der Kulturpflanze. Um den langfristigen Einfluss von reduzierten Herbizidaufwandmengen auf die Populationsentwicklung von Unkräutern am Beispiel von *A. fatua* in Winterweizen zu untersuchen, wurde ein Simulationsmodell aufgestellt. Verschiedene Strategien zur Herbizidaufwandmengenreduktion wurden simuliert. Dieses Manuskript hebt das Potential hervor, Herbizidaufwandmengen bei gleichbleibendem Kornetrag und Erlös zu reduzieren, ohne dass die Unkrautpopulation ansteigt.

Die in dieser Arbeit vorgestellten Manuskripte und Veröffentlichungen arbeiten die Risiken und Potentiale von Herbizidaufwandmengenreduktion aus und zeigen die Möglichkeiten auf, wie integrierte Unkrautkontrolle helfen kann, Unkräuter zu unterdrücken.

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