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“Evaluation of weed populations under the influence of site-specific weed control to derive decision rules for a sustainable weed management”

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Man muss seine Ideen verwirklichen, sonst wuchert Unkraut darüber.

Johann Paul Friedrich Richter (1763 - 1825)

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Chapter I

General Introduction

1. General Introduction

Agricultural productivity is geared to a high yield and quality level, but pests and diseases can compromise these objectives; therefore plant protection is needed.

Weeds especially cause heavy losses. They compete for water, light, and nutrients (Wilson and Wright 1990) and decrease quality and quantity of yield. Weeds cause an increase in moisture in the field and grain, implicating non-uniform ripening. They hinder harvest techniques and lead to contamination of harvest grain with weed seeds resulting in cleaning costs (Koch and Hurle 1978).

Nowadays chemical plant protection is established because of the convenient handling and the high degree of efficiency. The commencement of chemical weed control goes back to the 18th century, at that time it was discovered that several chemicals cause a damaging effect on plants (Hock *et al.* 1995). The first herbicides 2,4-D and MCPA were developed in the 1940s for weed control in cereals. Herbicides increasingly replaced the labour–intensive mechanical weed control. Today around 34 % of worldwide yield is saved due to chemical weed control (Oerke 2006). However, herbicides represent about 50 % of the globally used plant protection products (Berger 2002). Pesticide use in European countries is strictly regulated to minimize any negative side effects for the environment and pesticide residues in the food chain. In context of the German reduction program for chemical plant protection, herbicide use needs to be strictly controlled in the future and reduced to the absolute necessary extent (BMVEL, 2005). Additionally, herbicide resistance must be prevented, thus sustainable technologies for weed control are needed.

1.1 State of knowledge

1.1.1 Weed distribution in agricultural fields

It is generally known, that the weed seedlings distribution within agricultural fields is spatially and temporally heterogeneous, weeds often occur in patches of varying size, whereas other areas in the field are less infested or weed free (Marshall 1988, Thornton *et al.* 1990; Wiles *et al.* 1992; Mortensen *et al.* 1993; Cardina *et al.* 1995; Johnson *et al.* 1996, Gerhards *et al.* 1997a, b; Christensen and Heisel 1998; Dieleman and Mortensen 1999; Perry *et al.* 2002; Nordmeyer and Zuk 2002; Dicke *et al.* 2007). This heterogeneity is conditional on numerous factors. Seedlings emergence varied depending on crop, soil cultivation, crop rotation, and weather conditions in the current year (Gerowitt and Heitefuss 1990). Dunker and Nordmeyer (2000) found out that the occurrence of A. myosuroides is positively correlated with clay and total nitrogen content in the soil at those locations. Cardina *et al.* (2002) analysed the effects of crop rotation and tillage on weed seedbanks. They determined vertical distribution, weed species abundance and composition in response to crop and soil management. Cousens and Moss (1990) analysed the effects of different soil cultivation methods on the vertical distribution of *Alopecurus myosuroides* seeds in the soil, and found that vertical distribution was reached sooner under ploughing than under rigid tine cultivation. Additionally, the growth rate and development of a population is depending on density of the species involved, the cropping system, soil type, and climate (Mortimer 1987; Fernandez-Quintanilla 1988; Mortimer *et al.* 1989).

1.1.2 Population dynamics

Population dynamics are the modification in frequency, distribution and genetic structure of the entirety of individuals of one species that are present in a natural habitat (Koch and Hurle 1978). Compared to single weed plants, weed populations have different characteristics due to community interactions (Koch and Hurle 1978). Weed population dynamics in arable fields are mainly influenced by intrinsic parameters, such as population density and longevity of the seeds. Additionally, several extrinsic factors, such as soil characteristics, weather conditions, soil cultivation and management (above-mentioned), are affecting population dynamics.

Studies on weed population dynamics permit recognition and identification of parameters and factors of influence (Zwerger and Eggers 2004) and help to understand the interactions of these parameters, to compile prognoses and formulate hypotheses (Koch and Hurle 1978). Kropff (1996) declared that an insight into the population dynamics of weeds and the interactions between crop and weeds is needed in order to develop improved weed management systems, to effectively control weeds with a reduced dependency on herbicides, and to prevent colonisation of new areas.

Profound knowledge of weed population dynamics is the basis for all weed management systems, thus population dynamic models are strongly needed in order to study, or rather simulate long-term effects of weed populations in agricultural fields, and to ensure precise weed management.

Since the seminal paper of Sagar and Mortimer (1976) several computerized models were developed to help farmers to define the need for herbicide application and to support an optimal assortment and dosage of herbicides. Most of these models are based on the lifecycle of weed populations (Figure 1).

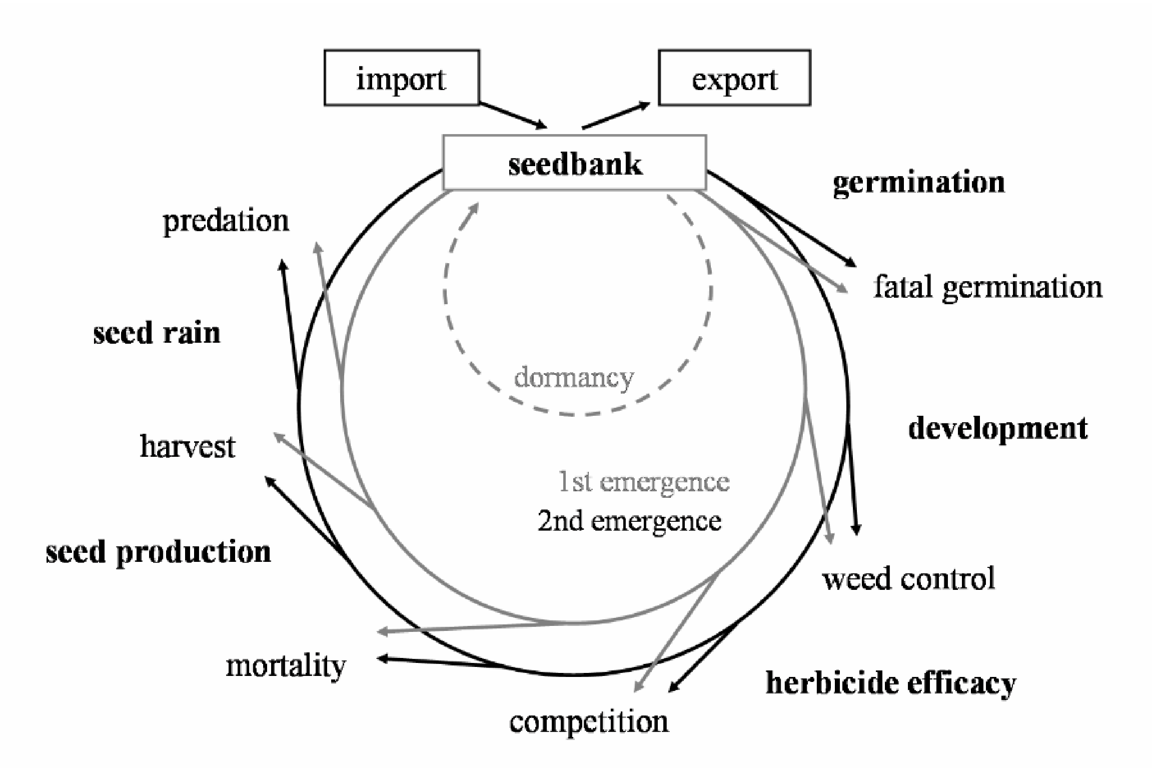

Figure 1: Life cycle of an annual weed population [Cousens & Mortimer 1995, modified]

The seedbank is the central point of the model, it is updated in one year steps by subtracting the emerging seedlings, fatal germinated and died seeds and adding the new produced seeds. During growth and development the population is influenced by inter- and intra-specific competition, mortality due to competition, weed management induced mortality, diseases, fungal decay, aging and predation due to rodents, snails, beetles and birds (Cousens and Mortimer 1995).

The models describe the interactions of several parameters within a population. By changing a variable or an intrinsic or extrinsic factors (mentioned above) of influence the consequence of this change can be simulated. In such a way processes can be qualified and prognoses can be derived. The output of the model is the generated optimal combination of weed management strategies. The models differ in the life stages that are included (Holst *et al.* 2005).

Some models are only valid for one single weed species, and other approaches model particular population parameters in detail. Colbach *et al.* (2006 a, b) modelled germination and emergence of *Alopecurus myosuroides* HUDS. The model from Aarts (1986) allegorised the complete life cycle of *Galium aparine* L. The model of Pacala and Silander (1990) accurately predicts growth, fecundity, survivorship, germination, seed dormancy, and dispersal of *Abutilon theophrasti* and *Amaranthus retroflexus*. The model from

Cousens *et al.* (1992) dealt with the weed competition in cropping systems, and Grundy (2003) modelled the weed seedlings emergence. Van der Weide and Groenendael (1990) tested the complexity of a demographic model on the example of *Galium aparine* in consideration of several management practices. They found that changes in sowing time or time of herbicide application can cause enormous differences in population dynamics. Additionally, they showed that weed density and spatial weed distribution have bearing on population dynamics. Van Groenendael (1988) found that a patchy distribution of weeds can influence its population dynamics. Mortimer *et al.* (1989) hypothesised a relationship in-between weed biomass and fecundity. Further research on these parameters is needed to evaluate the models.

1.1.3 Site-specific weed control

The uniform application of herbicides is still the standard method of weed control, and spatial variation has often been ignored in weed management decisions. However, the use of field-scale mean weed density estimates in spatially heterogeneous weed populations results in under-prediction of yield loss at locations where weed density is high and in over-prediction in areas of the field where the weed density is low or absent; thus weed distribution must be considered in the development of economic weed thresholds (Lindquist *et al.*, 1998; Brain and Cousens 1990).

Based on the awareness that weeds are distributed heterogeneously, first spatially variable herbicide application has been tried and tested in the 1990's (Gerhards *et al.* 1996, 1997a)

Site-specific weed control is managing weeds with respects to their spatial and temporal variability (Mortensen *et al.* 1998). The site-specific weed management is based on the use of weed thresholds. That means to implement an appropriate post-emergence herbicide application only at infested locations in the field. Thompson *et al.* 1991 proved that spatially variable herbicide application based on map information has potential. Johnson *et al.* 1995 verified that herbicide use could be reduced, if information on spatial weed distribution would be used for threshold adjustment. Gerhards and Christensen (2003) saved 60 % of the herbicides against broad leaf weeds and 90 % of grass weed herbicides in winter cereals, due to site-specific herbicide application. In maize they saved 78 % of grass weed herbicides and 11% of grass weed targeting herbicides. In sugar beet 36 % of herbicides against grass weeds and 41 % of broad leaf weed targeting herbicides were saved, respectively. Gerhards and Oebel (2006) tested a system for site-specific weed management in various crops resulting in herbicide reduction by 6 up to 81 %. The efficacy of weed control varied in between 85 % and 98 %, thus the system appears to be effective. Site-specific weed control is reasonable, and it has been applied successfully to various crops, resulting in a considerable reduction of herbicide use and treatment costs.

1.1.4 Weed thresholds

In order to minimise herbicides, the German plant protection law from 1986, modified in 1990, requires the use of economic weed thresholds. The economic weed threshold is the critical value above which an herbicide treatment is economically required (Warmhoff 1986). Herbicide application will not be carried out under the economic threshold (Swanton and Murphy 1996; Buhler *et al.* 2000). It is not arguable to spray without the certainty that economic threshold is exceeded (Gerhards and Kühbauch 1993). In combination with weed thresholds, it makes sense to use selective herbicides. In the past a couple of studies were made to derive weed thresholds.

The thresholds for cereal grain crops vary depending on weed species, their competitiveness, crop, and treatment costs. Meinert and Mittnacht (1992) found weed thresholds for *Galium aparine* L. ranged from 0.1 up to 2 plants m^{-2}. For *Alopecurus myosuroides* HUDS. thresholds of 25-35 plants m^{-2} were detected by Wellmann and Feucht (2002). For *Apera spica-venti* (L.) BEAUV. threshold densities of 10-20 plants m^{-2} were obtained (Warmhoff and Heitefuss, 1985). Börner (1995) determined thresholds of 1-2 plants m^{-2} for *Cirsium arvense* (L.) SCOP. and *Polygonum convolvulus* L., whereas for the most broad leaf weed species, the thresholds are closer to 40-90 plants m^{-2} (Zanin *et al.* 1993). These thresholds for weed control have not consequently been changed in relation to changes in the price of grain and the costs of weed control, and therefore, they need to be used as an approximate guide to decide on weed control methods (Gerhards *et al.* 2005). Additionally, implementation of the estimated weed thresholds into practice showed some problems that resulted first and foremost from the heterogeneous weed distribution in the fields (Warmhoff 1986). The heterogeneity clearly impedes the treatment decision clearly.

Decision support systems that perform calculations on the cost-effectiveness of weed management under the given circumstances, offering an appropriate management solution were developed. So for example Cousens (1985) applied a model to relate yield loss to weed density, and Gerowitt and Heitefuss (1990) developed an economic threshold model to derive weed thresholds; therein an estimated value for weed density was used. Gerhards and Kühbauch (1993) established and tested a model to predict yield loss caused by weed competition. Results of this work showed that the degree of weed coverage, the weed density, the development stage, and the degree of crop coverage need to be objectively measured and considered in order to evaluate precise weed control thresholds. Christensen *et al.* 2003 developed a decision support system for patch spraying that is suitable for a wide range of cereals. It is based on current crop state and weed infestation and helps farmers to decide which control treatments are necessary during the growing season. They determined the economic optimal herbicide dose with respect to the spatial heterogeneous weed distribution, weed competition, and population dynamics. This strategy was tested in a five-year experiment and resulted in highest crop yields, lowest soil seed banks, and equal weed control costs compared to conventional decision models. Effective decision rules for site-specific weed control are not available at present, but they urgently required (Dicke and Kühbauch 2006).

In order to derive valid decision rules for site-specific management, the heterogeneity of factors that affect productivity need to be considered. Therefore a new experimental design, often described as on-farm research, is needed (Luschei *et al.* 2001; Leithold and Traphan 2006; Dicke and Gebhardt 2007).

Recently, sensors to measure within-field variation of factors that affect crop yield such as soil properties (Corwin and Lesch 2005; Sudduth *et al.* 2003) and to detect weeds (below-mentioned) have been developed to provide spatially referenced information. With such techniques quantitative thematic information on arable fields can be obtained with high spatial resolution. This information layers need to be overlaid and spatially joined in order to explain where yield variability comes from. The influences of the co-variables weed and soil on yield need to be assessed. Out of this information yield losses due to weed and herbicide injury can be defined and valid decision rules for site-specific weed management can be ascertained.

1.1.5 Weed mapping

Site-specific weed management requires accurate information on weed infestation and distribution within agricultural fields. Thus weed distribution needs to be mapped in order to know where it makes sense to spray and where herbicide application is not reasonable (Warmhoff and Heitefuss 1985). In the following several methods of manual and sensor-based weed detection are described.

1.1.6.1. Manual mapping

In the most studies up to this day the weed distribution was mapped manually by means of global positioning system (GPS) and geographical information system (GIS) software. Several authors used irregular sampling at random successfully (Chauvel *et al.* 1998). Punctual mapping is convenient for a precise detection of weed patches e.g. *Cirsium* *arvense* (L.) SCOP., *Galium aparine* L., and *Avena fatua* L. (Colliver *et al.* 1996). However, grid sampling is the most frequently used method. Usually a regular grid is established in the experimental field, and the spatial distribution and density of emerged weed seedlings is assessed by counting the weeds at each grid intersection point (Gerhards *et al.* 1996, 1997a, 2005; Gerhards and Oebel 2006; Dicke *et al.* 2007; Krohmann *et al.* 2006). Different resolutions of sampling grids have been applied. The sampling size is determined by cost and is not based on any prior knowledge. In the literature, sampling intensities from a few meters up to 50 x 50 m were used, depending on the width of the spray boom used for herbicide application (Wilson and Brain 1991; Christensen and Heisel 1998; Hamouz *et al.* 2004). Backes and Plümer (2004) showed that heterogeneity on a small scale could not be assessed with any of the so far used sampling grids, weed patches that are smaller than the grid size may remain undetected (Backes and Plümer 2005). Rew and Cousens (2001) and Wyse-Pester *et al.* (2002) showed also that interpolation methods may fail to detect patches that are smaller than the distance between the sampling points. Independently of the used method of weed mapping, interpolation is always necessary to estimate the weed seedlings density in-between the sampling points. Out of sparely distributed observations continuous surfaces can be calculated by the use of deterministic or geostatistic methods. Several interpolation methods are used to calculate weed density at unsampled locations (e g. Johnson *et al.* 1995, 1996; Cardina *et al.* 1996, Gerhards *et al.* 1997a, Colbach *et al.* 2000; Goudy *et al.* 2001). All interpolation methods are based on the assumption that similarity occurs between spatially neighbouring points in the field, thus unknown values can be calculated out of the information of surrounding sampling points. The Nearest-Neighbour interpolation performs segmentation of the field into polygons, each polygon get the same value like the nearest measured point has. It is a local accurate interpolation method but not close to reality. Gerhards *et al.* 1997a used linear triangulation, while the absent values are calculated by triangle creation out of the three adjacent support points. This interpolation method is local accurate, but very abrupt. Inverse-Distance-Weighting considers all support points weighted according to their distance to the unknown positions. This is a constant approximative method (Streit 2007). Kriging is the generic term for several geostatistic interpolation methods. Kriging interpolations are based on linear estimation procedures with spatially weighted average determination (Goovaerts 1997). Johnson et al. (1995) and Colbach *et al.* (2000) used kriging to estimate weed distribution at unsampled positions. Heisel *et al.* (1996) showed that kriging based on seedling counts in a sampling grid of 10 x 10 m resulted in a good agreement with actual field situation, but reducing the sampling intensity to 20 x 30 m gave a poor agreement. Generally the methodology of manual weed mapping serves the purpose of creating weed distribution maps, but is very labour-intensive, time consuming, and expensive (Wiles and Schweizer 1999). Additionally interpolations always implicate inaccuracies and will never accurately express the reality Backes and Plümer (2004).

1.1.6.2 Sensor-based weed detection

In order to determine the weed distribution more detailed and more effective, automatic sensors for weed detection and imaging technologies for weed identification were developed. Brown and Noble (2005) assumed that the absence of an automatic image acquisition and analysis technology is the reason why site-specific weed management is not yet introduction into practice. Ground based detection technologies using cameras or sensors and remote sensing technologies are introduced in the following.

Lamb *et al.* 1999 used a remote sensing technique to detected *Avena* spp. patches in agricultural fields with multi-spectral images, Lamb and Brown (2001) ascertained that satellite systems at that time were not able to offer the required spatial resolution and mission flexibility for practical weed identification. Hyper spectral scanner systems are suitable, but they will only be economic on a large scale. Only lower cost multi-spectral systems based on digital and video camera technique are affordable. Several approaches for image acquisition for automatic weed identification used CCD (charge-couple device) cameras for aerial photography. Medlin *et al.* (2000) applied this technique to map weeds in soybean fields, but only high density weed patches could be recognised, which was insufficient for any site-specific weed management decision. Another approach was taking pictures with a colour camera from a drone, which was flying in-between 10 and 100 meters high (Vioix *et al.* 2001), but because of bad light conditions and poor picture quality weed species could not be identified with this technique. Rew and Maxwell (2002) analysed satellite images and aerial pictures in conjunction with farmers' information on weed occurrence, in order to find appropriate site-specific management decisions. This methodology was very time consuming and there was a lack of evaluation algorithms, thus no precise management decision could be derived.

Promising technologies are near-range sensor technologies. Optoelectronic sensors for weed detection against a soil or crop residue background were developed by Vrindts and de Baedemaeker (1997) and Biller (1998). The different light reflection properties of plants and soil are used to discriminate soil, crop and weeds. Reflection intensity of plants depends on water and nutrient conditions, so that the system needed to be calibrated prior to every use. Additionally, the optoelectronic sensors are not able to distinguish between weed species; they are suitable for weed management at rail tracks but unqualified for weed management in agricultural fields.

Gerhards *et al.* (1993); Gerhards and Kühbauch (1993); Chapron *et al.* (1999); Sökefeld *et al.* (2000); Oebel (2004) and Gerhards and Oebel (2006) used digital image analysis for automatic weed identification based on shape, colour and texture analysis.

Several systems are based on CCD colour cameras in boxes with internal illumination (Hemming 2000; Downey *et al.* 2004), the images provided good segmentation of plants and background, but the large dimension of the system prohibits the practical exertion. Images taken from colour or monochrome cameras without boxes, under natural light conditions, were used for shape analysis techniques by Pérez *et al.* (2000) and Gerhards and Sökefeld (2001). Direct solar radiation impaired image quality, thus this techniques for weed identification was applicable only to a limited degree. Sökefeld *et al.* (2007) created a mobile bi-spectral camera technique for image acquisition at a speed of up to 10 km h^{-1}, providing images largely free of background information and a sufficient sample size with a spatial resolution of 1 x 3 m in the field. In addition to camera systems creating high images with strong contrast between plants and background, fast and robust image analysis algorithms to classify the weed species are needed. Gebhardt and Kühbauch (2007) developed an algorithm for automatic *Rumex obtusifolius* L. detection within digital images by using colour and texture features and the influence of image resolution. The image classification procedure leads to large detection rates (up to 95 %) and only few misclassifications.

Weis and Gerhards (2007) enhanced the weed species identification in digital images by using feature extraction with shape features based on skeleton operation, leading to a more precise identification of crop and weed, and weed species among each other. Camera technology and automatic image analysis are being developed and will be implemented into practice soon (Weis and Gerhards 2007). The objective is to establish an intelligent sensor system that provides online weed detection, classification, and site-specific herbicide application based on economic weed thresholds (Sökefeld *et al.* 2000).

1.1.6 Site-specific herbicide application technique

For this thesis a site-specific herbicide application technique, developed since 1996 and built by a working group of the Bonn University in collaboration with *Kverneland Group* (Sökefeld *et al.* 2000; Dicke *et al.* 2007) was used, in order to apply herbicides site-specifically with varying mixture and dosage. An automated 21 m wide sprayer, divided into seven sections of 3 m, was A Differential Global Positioning System (DGPS) provides real time location of the sprayer. The sprayer integrates three separated hydraulic circuits including tank, spray line and regulation system, allowing it to realise three different application maps at the same time. Thus the weeds can be grouped into three target classes; for example, grass weeds, broad leaf weeds and a special weed such as *Galium aparine* L. or *Cirsium arvense* (L.) SCOP., and sprayed with an appropriate selective herbicides. Different volume rates, depending on weed density, can be applied by changing the pressure in the system. Thus up to three weed thresholds can be set for each target weed group. A spray control system is connected to an on-board computer with the application maps for the three weed classes. Herbicide mixture can be varied in composition and dosage during the application based on the weed thresholds and map information (Gerhards and Oebel 2006). This sprayer was used for all experiments of this thesis.

1.2 Thesis objectives

The overall aims of this research were to test the site-specific weed management over time, to study the spatial and temporal dynamics of weed populations, to evaluate the population dynamics of weeds and the interactions between crop and weeds under the site-specific weed management. Additionally an experimental approach to create precise decision algorithms for site-specific weed management was needed. Three publications resulted out of this study.

The first one deals with the population dynamics of two dominant weed species with high importance throughout Western Europe: *Galium aparine* L. and *Alopecurus myosuroides* HUDS. The aim was to ascertain the effects of the site-specific weed management on the population dynamics in order to provide more information for population dynamic models in order to make them more precise, to predict weed performance under different management practices, and to warrant an appropriate decision. The active life cycle from emerging to seed production was studied under the influence of the site-specific weed control; weed seedling emergence, competition, mortality, biomass, seed production and seeds viability were examined. It was hypothesised that the weed density has a considerable impact on population dynamics and that fecundity is related to weed biomass.

The objective of the second article was to detect the long term effects of site-specific weed management, if site-specific weed management leads to an increase in weed density, and if weed patches remain stable in density and location over time. Furthermore, to determine whether these short-term effects are persistent or if herbicide use reductions in one year result in increased use and costs in subsequent years. Data of an eight year study, which consists of two full crop rotation cycles, allowed the examination of long-term effects.

The purpose of the third paper was to design an experimental on-farm approach in order to explain yield variation caused by within-field heterogeneity of weed density, soil quality and herbicide application. The effects of the co-variables needed to be quantified separately in order to know where yield variability comes from. Out of this information yield losses due to weed and herbicide injury can be defined and valid decision rules for site-specific weed management can be ascertained.

Chapter II

Population dynamics of *Galium aparine* L. and *Alopecurus myosuroides* HUDS. under the influence of site-specific weed management

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2. Population dynamics of *Galium aparine* L. and *Alopecurus myosuroides* HUDS. under the influence of site-specific weed management

Abstract – In order to study weed population dynamics under the influence of site-specific weed management, data on population dynamics of Catchweed bedstraw (*Galium aparine* L.) and Blackgrass (*Alopecurus myosuroides* HUDS.) were collected from 2005 to 2007 in maize, sugar beet, winter and spring cereals. Assessed parameters were weed seedling emergence, crop-weed competition, seedlings mortality, herbicide efficacy, seed production and viability. It was found that most of the tested population parameters were weed density dependent. With increasing weed density weed biomass and fecundity increased in this study. Seed viability showed no correlation to density biomass or seed production rate. All findings support that weed density has to be considered in weed management strategies.

Keywords: competition · emergence · mortality · population dynamic model · seed bank · seed production · viability

2.1 Introduction

The basis for a successful practical weed management is a comprehensive understanding of weed biology and the interactions in a cropping system. Information on spatial and temporal dynamics of weeds is needed to control weeds effectively, and to prevent colonisation of new areas. Weed population dynamics in arable fields are mainly influenced by intrinsic parameters such as population density and longevity of the seeds. Additionally, several extrinsic factors such as soil characteristics, weather conditions, soil cultivation and management are affecting population dynamics. In the recent past several population dynamic models have been developed to describe population dynamics, and study or rather simulate long-term effects of weed populations in agricultural fields (Holst *et al.* 2007). These models are strongly needed to precise weed management. In general they are describing the weed populations quite well, but the agreement between simulation and the measurement in the field was not sufficient (Zwerger and Hurle 1990) and there is still a lack of knowledge on some population parameters (Cousens 1995; Kropff *et al.* 1996).

The aim of this study was to provide more information for population dynamic models for two dominant weed species widespread throughout Western Europe: *Galium aparine* L. and *Alopecurus myosuroides* HUDS. Already low densities of *G. aparine* are causing crop-weed competition for water, light, and nutrients (Wilson and Wright 1990) and an increase in moisture in field and grain implicating non-uniform maturation. Additionally the prickly stems, leaves and fruits are hindering harvest techniques and leading to contamination of harvest grain with weed seeds resulting in cleaning costs. *Alopecurus myosuroides* is the dominant monocot weed across agricultural fields in Western Europe. It primarily occurs in winter cereals. The plants are competing for resources and are plant disease vectors (e.g. *Septoria tritici* is transmitted by *A. myosuroides*). The seeds of *A. myosuroides* are viable up to eight years in the soil seed bank. Usually *A. myosuroides* is managed by preventive tillage and chemical weed control. But in recent years less effect of herbicides was reported and the first herbicide resistant *A. myosuroides* biotypes were identified in Germany (Cocker *et al.* 1999).

Weeds life cycle can be separated into the active lifecycle (growing plants) and the passive (dormant seeds and underground buds) lifecycle (Fernandez-Quintanilla 1988). Information on the passive life cycle that includes the seed losses in the seed bank and the proportion of seedlings emergence are already well studied for *A. myosuroides* and *G. aparine* (Kemmer *et al.* 1980, Röttele 1980, Zwerger and Hurle 1988; 1990, Amann 1991). This research focuses on the active life cycle, from emerging to seed production, faced with environmental conditions, diseases, competition, and herbicide application.

2.2 Materials and methods

2.2.1 Study site

Field trails were carried out from 2005 to 2007 at two Hohenheim University research stations. Field 1 (1.8 ha) and 2 (1.6 ha) were located at Heidfeldhof (48°42`N; 9°11`E), about 400 m above sea level, with an average temperature of 8.5°C and an annual precipitation of 685 mm. Field 3 (6.3 ha) was located at Ihinger Hof (48°44`N; 8°55`E), 481 m above sea level, with an average temperature of 7.9°C and average rainfall about 690 mm, respectively. The soil texture at both study sites is a silty clay loam.

2.2.2 Weed mapping

The population dynamic parameters were estimated in the three arable fields (crop rotation, sowing and herbicide application date are shown in Table 1). In 2006 field 2 was separated in two fields and sugar beet and maize was grown. The weeds were manually counted along a permanent 8 x 8 meter raster, using four 0.1 m^2 quadrants, abutted next to each other (135 sampling points per ha). During metering a GPS with real time kinematical satellite navigation provided a typical nominal accuracy of 1 centimetre ± 2 ppm horizontally and 2 centimetres ± 2 ppm vertically, thus a high repeatability was secured. In every year the weed distribution and density were assessed prior to herbicide application, and about three weeks after herbicide application. The sampled weed densities from 0.4 m^2 were extrapolated to 1 m^2. Based on these data weed distribution and herbicide application maps were created using linear triangulation interpolation (Gerhards *et al.* 1997a) and a geographical information system (ArcGIS by ESRI).

Table 1: Overview of crop rotation, sowing and herbicide application dates in the experimental fields.

		2005	***2006***		***2007***
field 1	crop	winter wheat	winter barley		sugar beet
	sowing date	10/06/04	09/19/05		04/03/07
	herbicide application date	04/05/05	10/25/05		04/27/07
field 2	crop	spring barley	sugar beet	maize	winter wheat
	sowing date	03/22/05	04/19/06	05/04/06	10/16/06
	herbicide application date	05/02/05	04/24/06	05/24/06	03/28/07
field 3	crop	maize	maize		maize
	sowing date	05/02/05	04/26/06		04/24/07
	herbicide application date	06/02/05	06/06/06		05/31/07

2.2.3 Herbicide application

The date of herbicide application depended on weather conditions, crop, and herbicide; at the optimal date for the best effect of the herbicides for the most part weeds were in between seedling stage and the begin of tillering. Herbicide application was done site-specifically with a DGPS-controlled sprayer (Gerhards and Oebel 2006), based on the map information. The used active ingredients are shown in Table 2. The fields were treated with the herbicide doses: no herbicides at all 200 l ha^{-1}, 245 l ha^{-1} or 290 l ha^{-1}. For weed control thresholds based on regional guidelines and farmers former experience were set. If the threshold weed densities were exceeded, herbicide application was made. In maize the thresholds 1/5/10 were set against broad leaf weeds as well as for grass weeds. That means that it was not sprayed if the threshold of 1 plant m^{-2} was not exceeded, if there were more than one plant m^{-2} 200 l ha^{-1} were sprayed, from > 5 plants m^{-2} 245 l ha^{-1} were applied and from > 10 plants per m^2 the full dose of 290 l ha^{-1} were sprayed. In winter wheat the grass weed thresholds were set at 10/25/40 and for broad leaf weeds 10/30/50. In sugar beet the first application was made for the whole field; and in further applications grasses were sprayed from 1/5/10 and broad leaf weeds if 1 plant per m^2 was exceeded. In sugar beet in some years an additional treatment with a third herbicide against *Cirsium arvense* (active ingredient Clopyralid) was needed (threshold: 1 plant m^{-2}). In winter- and spring barley no weed thresholds were used.

Table 2: Active ingredients used for site specific weed control in the three experimental fields from 2005-2007.

crop	***active ingredients***
maize	nicosulfuron
	sulcotrione + bromoxynil
winter wheat	clodinafop-propargyl + cloquintocet-mexyl
	fluroxypyr + florasulam + metsulfuron + carfentrazone *or*
	thifensulfuron + metsulfuron-methyl + florasulam
sugar beet	haloxyfop-R
	phenmedipham, ethofumesat, desmedipham
	clopyralid
winter barley	flufenacet + diflufenican
spring barley	tribenuron methyl

2.2.4 Population dynamic parameter estimation

Seedlings mortality is defined as the seedlings that died after emerging due to diseases, competition and environmental conditions; it was estimated at sampling locations where no herbicide application was done. The herbicide efficacy was assessed by calculating the difference between the weed density before herbicide application and the density of surviving weeds, about three weeks after spraying, at all sampling points where chemical weed control was performed. New weed seedlings emergence after herbicide application was not considered. In order to estimate the seed production whole weed plants were harvested during maturation and their densities of growth were listed. Since weed seeds do not ripe simultaneously, not all seeds are mature at the same time. Whole plants were harvested when most of the seeds were mature and before they started to drop off. To prevent the fall off of the *A. myosuroides* seeds flimsy envelopes were imposed on the seed heads during maturation. Biomass of the weeds was measured after drying the whole plants at 40°C for two weeks. Seed production per plant was assessed and their viability was measured by tetrazolium test (after ISTA Rules, Leist and Krämer 2003).

2.2.5 Data analysis

Weed seedlings emergence and weed distribution was monitored over the period of three years. Seed production was correlated with weed density and weed biomass. Additionally, it was tested if seed viability is correlated with the seed production as well, if fecundity is increasing or rather decreasing with rising seed production. The statistical analysis was made with SPSS. Regression analysis was used to examine the relation of the population dynamic parameters, and the coefficient of determination (r^2) was estimated to explain the correlation between the observer population dynamic parameters.

2.3 Results and discussion

Weed distribution was spatially heterogeneous in all fields. Besides the two observed weeds other weed species such as *Lamium purpureum* L., *Matricaria chamomilla* aut. non L., *Chenopodium album* L., *Thlaspi arvense* L., *Amaranthus retroflexus* L., *Viola arvensis* MURR. *Veronica persica* POIRET, *Stellaria media* (L.) VILL., *Capsella bursa-pastoris* (L.) MED. and *Cirsium arvense* (L.) SCOP. were present in lower densities in the experimental fields. Average weed densities over the three years are shown in Figure 2 and 3.

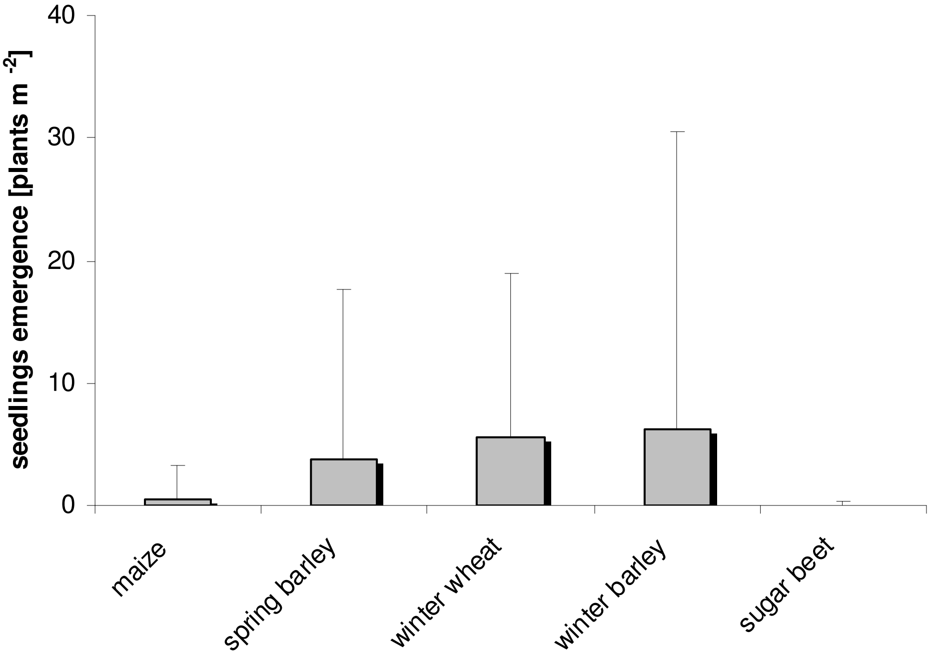


Figure 2: Seedlings emergence of *Galium aparine* in the years 2005-2007 (error bars indicate standard deviation).

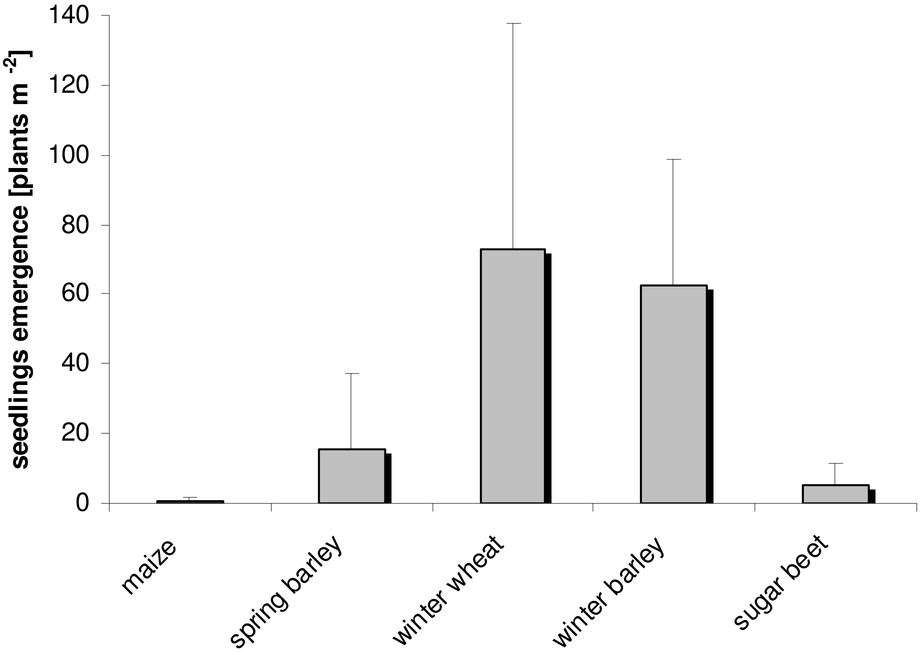


Figure 3: Seedlings emergence of *Alopecurus myosuroides* in the years 2005-2007 (error bars indicate standard deviation).

In all three fields the weed seedlings emergence of *A. myosuroides* was higher than the one of *G. aparine*. The weed seedling emergence ranged up to 228 *G. aparine* seedlings m^{-2} in winter barley and the maximum density for *A. myosuroides* was 358 seedlings m^{-2} in winter wheat. The weed seedling emergence is a function of the seed density in the soil seed bank (Moray 2005). According to Leguizamón and Roberts (1982) 3 % of the apparently viable seeds in the 0-10 cm soil layer emerge in spring, independently of crop. Roberts and Ricketts (1979) found that the weed seedlings represented 3-6 % of the number of seeds in the top 10 cm of soil, and Zhang *et al.* 1998 estimated 3-7 % seedling emergence from the active soil seed bank. Granted that 3-6 % of the viable soil seed bank germinates, the soil seed bank in field 1 counted from 100 up to 2500 seeds, in field 2 around 300 to 500 seeds and in field 3 about 3-8 *A. myosuroides* seeds per m^2 in the top 10 cm of soil. For *G. aparine* it varied in between 100 and 250 seeds m^{-2} in field 1, around 30-20 seeds m^{-2} in field 2 and about 5-14 seeds m^{-2} in field 3. These differences are explainable by the history of crop rotation and field management. Due to common weed management field 1 and 2 show an ordinary weed appearance; field 3 is known to be slightly infested because of an intensive weed management in the past.

The seedlings mortality was assessed when no herbicide application was done. According to the weed threshold, most of the fields were already sprayed when low weed densities occur. In such a way the natural mortality could just be evaluated in winter wheat where the thresholds were set higher and sufficient sampling points were not treated. Average mortality of *A. myosuroides* in winter wheat was 35 % and 26 % for *G. aparine*, respectively (Table 3 and 4).

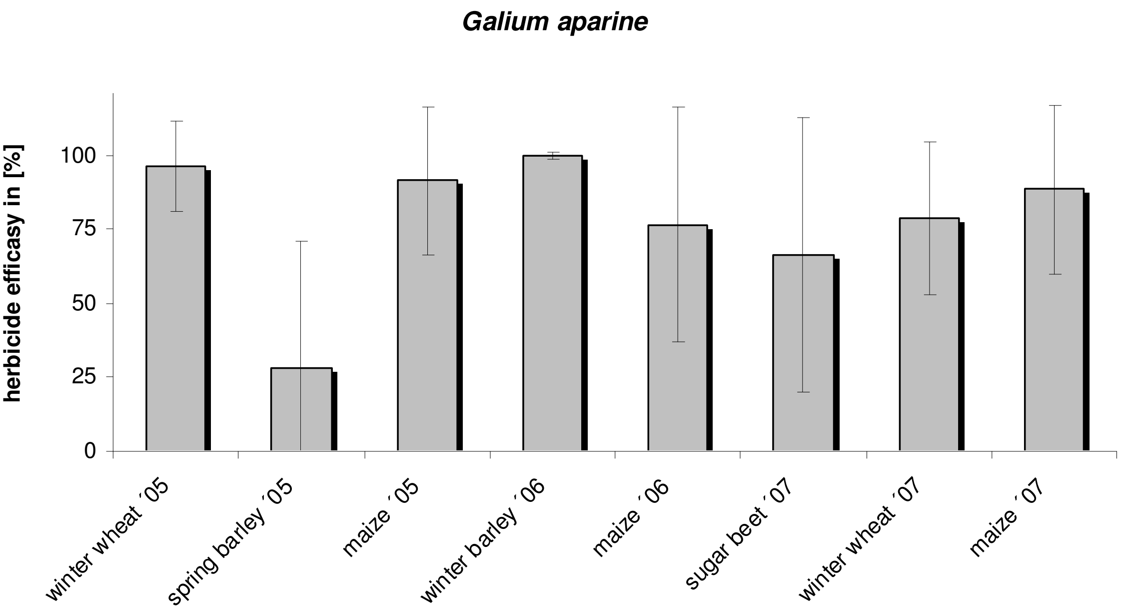
Table 3: Seedlings mortality, herbicide efficacy and seed production of *Galium aparine* (GALAP).

	seedlings mortality	***herbicide efficacy***	***seed production*** [*seeds/plant*]	
			single plant	patch >5 GALAP m^{-2}
winter cereals	0.26	0.93	356	430
spring cereals	-	0.28	59	89
maize	-	0.58	-	-
sugar beet	-	0.66	168	683

Table 4: Seedlings mortality, herbicide efficacy and seed production of *Alopecurus myosuroides* (ALOMY).

	seedlings mortality	***herbicide efficacy***	***seed production* [*seeds/plant*]**	
			single plant	patch >5 ALOMY m^{-2}
winter cereals	0.35	0.96	149	651
spring cereals	-	0.67	218	294
maize	-	0.72	2,536	-
sugar beet	-	0.50	3,640	4,230

Kemmer *et al.* (1980) estimated an average mortality rate for *A. myosuroides* of 26 %. Röttele (1980) found that the seedling mortality of *G. aparine* goes up to 52 % and it is highly depending on crop and weed density. Zwerger and Hurle (1988, 1990) found for *G. aparine* a mortality of 23-66 % depending on crop. Generally seedlings mortality depends on the crop because of higher suppression; in cereals it is higher than in row crops (Röttele 1980). Mortality of *G. aparine* due to competition seems to be lower in winter cereals. The herbicide efficacy of the site specific weed management against *G. aparine* and *A. myosuroides,* over the three years in the three fields, is detailed shown in Figure 4.



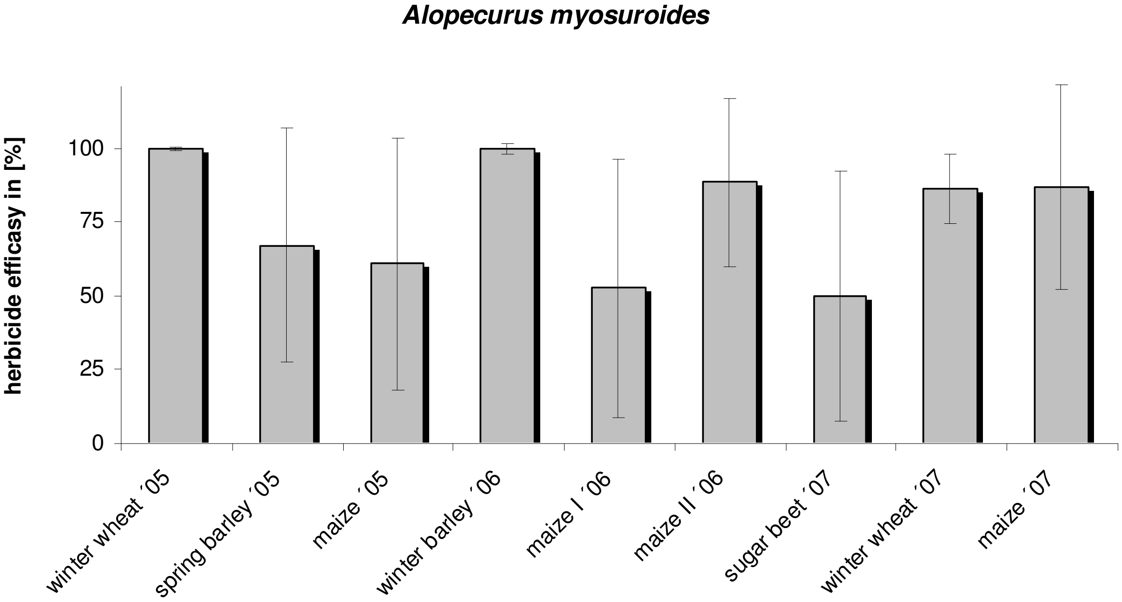


Figure 4: Herbicide efficacy rates in various crops against *Galium aparine* and *Alopecurus myosuroides* in the years 2005-2007 (error bars indicate standard deviation).

In this research the herbicide efficacy increased in decreased from year to year in between 28 and 96 %. It is evident, that herbicide efficacy is depending on several factors, such as weed density, weed threshold used, herbicides spectrum of activity and weather conditions. Averaged the efficacy of site-specific weed management was quite satisfying over the three years of study. Mean values of all estimated data on population dynamics for each crop are shown in Table 3 and 4. In this research herbicide efficacy was higher in cereals than in row crop. Herbicide efficacy is density-dependent, too. Kemmer *et al.* (1980), Weidenhamer *et al.* (1989) and Weidenhamer (1996) found that more weeds survived the herbicide application the higher weed density was, and obtained lower herbicide efficacies with increasing weed densities. Herbicide efficacy is conditioned by a number of factors such as the development stage of the weeds, soil, weather, and growth conditions. At very high weed densities it could happen, that an insufficient amount of active ingredient hits the target weed plants, in this case more herbicide is required to obtain equivalent fresh weight reductions (Winkle *et al.* 1981). Seed production went up to 2,638 *G. aparine* seeds per plant and 16,258 seeds per *A. myosuroides* plant (Figure 5).

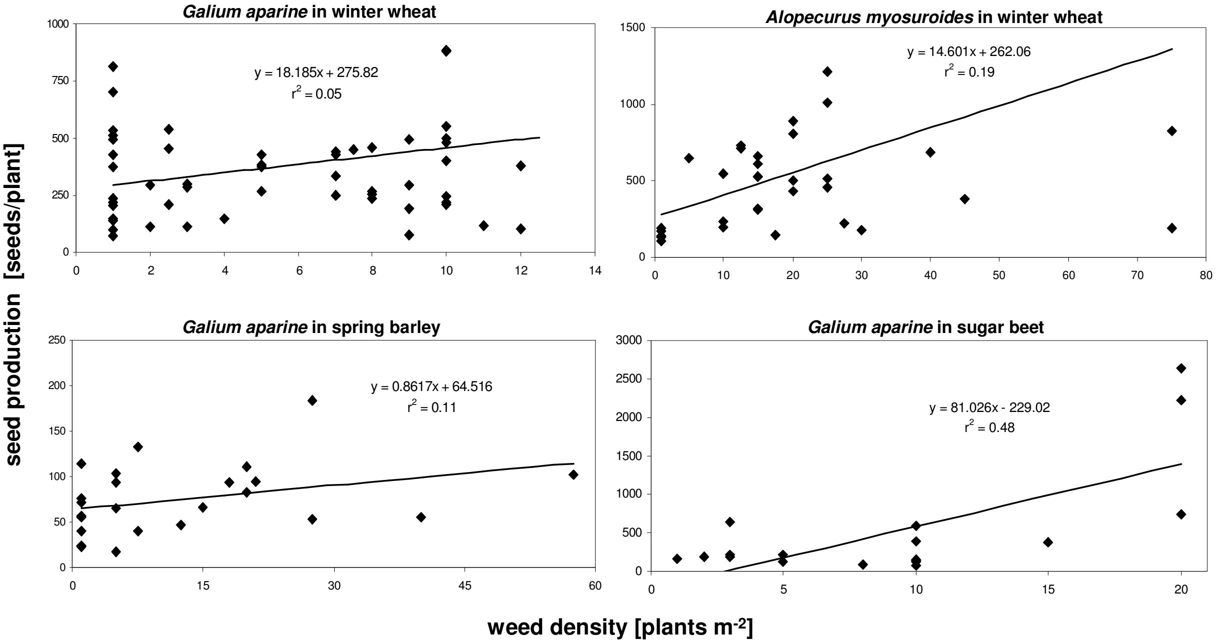


Figure 5: Weed density and seed production of *Galium aparine* and *Alopecurus myosuroides* in various crops.

It was presumed, that individual weeds without competition evolve better and produce more seeds but this study showed opposed results. The coefficient of determination (r^2) for weed density and seed production was 0.05 for *G. aparine*, 0.19 for *A. myosuroides* in winter wheat (Figure 6), and 0.11 for *G. aparine* in spring barley, and the highest coefficient of determination achieved *G. aparine* in sugar beet (0.48). Statistical analysis achieved no significant positive correlation, but there is a slight indication that the weeds in higher growth densities rank and benefit themselves reciprocative; and they might need each other to entwine around themselves or support one another. Further studies should provide more experimental data on this issue in order to survey this result. Seed production increased with increasing biomass (r^2 = 0.73) (Figure 6).

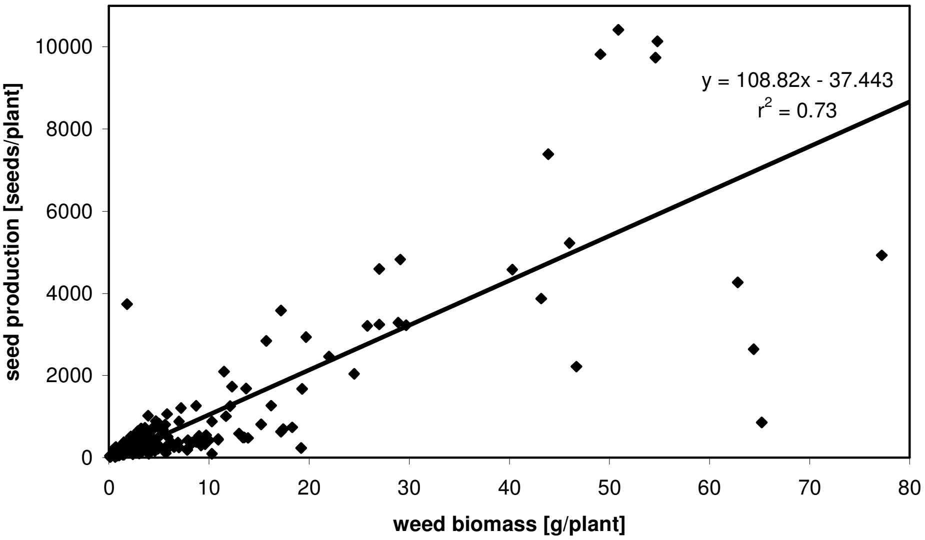


Figure 6: Correlation of weed biomass and seed production of *Galium aparine* and *Alopecurus myosuroides* over all crops**.**

The stronger the weeds the more fecund they were and the more seeds were produced. Weed seed viability of *G. aparine* and *A. myosuroides* is shown in Figure 7. Seeds viability was rather good in this study; it varied from zero, in one singular case, up to 100 %; averaged it was 78 % for *G. aparine* and 86 % for *A. myosuroides*. Data showed no correlation to weed density or seed production, so that this study could not prove that seeds viability is decreasing with increasing seed production.

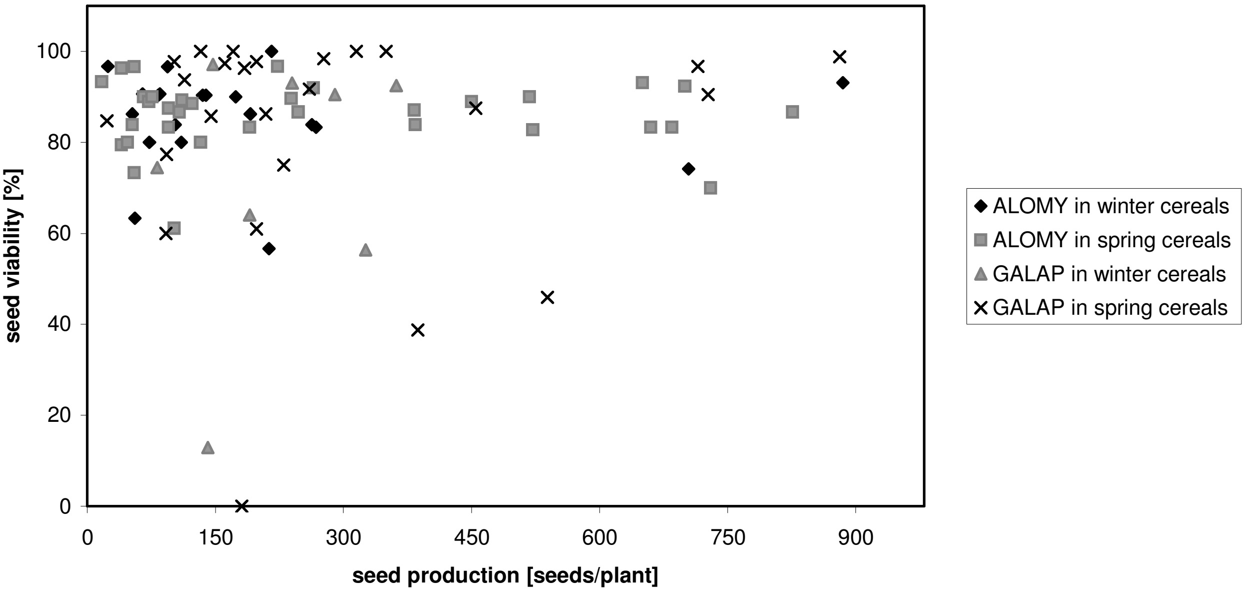


Figure 7: Seed viability of *Galium aparine* (GALAP) and *Alopecurus myosuroides* (ALOMY) in winter and spring cereals.

Obtained weed data can be integrated into computer models providing valuable insights that are needed to understand dynamics of weed populations and the effects of a cropping system on the demography of weeds; in order to manage weed populations sustainable. The results of this research showed the high influence of weed density on the population dynamic parameters, seedlings emergence, mortality, herbicide efficacy, and seed production. Up to this day, variation in weed density was not considered in weed population models, but it should be considered to precise decision support systems to warrant an economical and ecological sensibly herbicide application.

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Chapter III

Can short-term gains in site-specific weed management be sustained over multiple years?

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3. Can short-term gains in site-specific weed management be sustained over multiple years?

Abstract – In order to test long-term effects of site-specific weed management on population dynamics of blackgrass (*Alopecurus myosuroides* HUDS.) three arable fields were studied over a period of eight years. Emergence of *A. myosuroides* was assessed from 1999 until 2006 in a crop rotation of winter wheat, winter barley, maize and sugar beet at the Bonn University Research Station Dikopshof, in Germany. Herbicides were applied site-specifically with a DGPS-controlled patch sprayer based on weed distribution and density maps. Weed distribution was spatially and temporally heterogeneous from year to year. In two of the observed fields, the average weed density remained relatively stable through the eight years of study and in one field it even decreased. Site-specific weed management including competitive small annual grains in the crop rotation appears to be effective for long term control of *A. myosuroides.*

Keywords: crop rotation · weed distribution · *Alopecurus myosuroides* HUDS. · patch spraying · long-term data

3.1 Introduction

Weed control has proved to save around 34 % of worldwide yield (Oerke, 2006). Among all strategies of weed control herbicides play an important role. However, herbicide application leads to economic costs and environmental risks. Therefore, site-specific weed management is a promising approach to minimize these shortcomings. Over the past years several studies of site-specific weed control found that this practice is reasonable and has been successfully implemented in research experiments resulting in a significant reduction of herbicide use, satisfying efficiencies and environmental benefits (Cousens, 1987; Thompson *et al.* 1991; Johnson *et al.* 1995; Gerhards *et al.* 1997a; Dammer *et al.* 2003; Timmermann *et al.* 2003). Currently, sensors for precise and powerful weed detection are under way (Gerhards and Christensen, 2003), that site-specific weed control will be ready for implementation in the field soon. Gerhards and Oebel (2006) found that herbicide use following a map-based approach can be reduced in winter cereals by 20-79 %. Timmermann *et al.* (2003) achieved herbicide reduction of up to 90 % for grass weed herbicides in winter cereals and Gerhards and Christensen (2003) realised herbicide savings of 78 % in maize and 41 % in sugar beet. Most of these studies are based on short-term data, studies in which current year infestations guided herbicide use and subsequent savings.

To test the profitability of the site-specific weed management a dataset consisting out of three fields and eight years was consulted for this study. This work focuses on blackgrass (*Alopecurus myosuroides* Huds.), the dominant monocot weed in agricultural fields across Western Europe. Blackgrass exhibits similar germination requirements like winter cereals; it primarily germinates in winter crops in autumn, but as well in spring. It germinates between 10°C and 15°C out of the top ten centimetres of soil. Narrow winter cereal based crop rotations, that offer ideal evolution potentials for grasses, are common. Blackgrass is competing for resources and plant disease vector (e.g. *Septoria tritici*). Blackgrass seeds are viable up to eight years in soil seed bank. Seed production of blackgrass occurs during maturation and before harvest of winter wheat, maize and sugar beet, in winter barley blackgrass seeds were produced contemporaneously with crop harvest. Typically blackgrass is managed using soil tillage and chemical weed control (IPU, ALS- and ACCase-Inhibitors), but in recent years less effect of herbicides towards blackgrass was reported and the first herbicide resistant biotypes were identified in Germany (Cocker *et al.* 1999).

Objective of this study was to detect if site-specific weed management does lead to an increase in weed density at locations where no herbicides or reduced rates were applied and if high density patches are remain stable in density and location overtime and if so, for how long. Furthermore, to make aware whether these short-term effects are persistent or herbicide use reductions in one year result in increased use and costs in subsequent years. Since the extent of herbicide use is dictated by the distribution and abundance of the target weed, blackgrass; the answer to the question of short vs. long-term benefits of site-specific management is driven by the population dynamics. This eight year study, which consists of two full crop rotation cycles, allows examining long-term effects.

3.2 Material and Methods

3.2.1 Study site

The studies were initiated in 1999 on three arable fields at the Bonn University Research Station Dikopshof in Germany (50°48`N; 6°57`E). Winter wheat (*Triticum aestivum* L.), winter barley (*Hordeum vulgare* L.), maize (*Zea mays* L.) and sugar beet (*Beta vulgaris* L.) were rotated in the experimental fields (Table 5). The soil type at the study site is a silty loam, the average temperature is 9.7°C and the average rainfall is 630 mm. Prior to the onset of the experiment in 1999 these three fields had been managed for bulk production in the two years preceding the initiation of the study and had weed infestations typical of fields managed with this crop rotation. The experimental fields were ploughed every year.

3.2.2 Data collection

The spatial distribution and the density of emerged blackgrass seedlings were manually sampled along a 7.5 x 15 meter grid, this means about 97 sampling locations per ha. The same locations were sampled in each year from 1999 to 2006. The weed density was assessed immediately prior and about three weeks after herbicide treatment, using four 0.1 m^2 quadrates abutted next to each other and centred on each grid intersection. Data were converted into plants per m^2 for data analysis. Inverse Distance Weighting (IDW) was used to estimate weed seedling density at unsampled positions. Weed patches in this study are defined as clear visual weed aggregations with densities higher than 25 plants per m^2.

3.2.3 Herbicide application

Due to the spatially-heterogeneous nature of the blackgrass infestation site-specific herbicide application was implemented. Decision rules were based on regional guidelines and an economic weed control threshold model depending on field crop, weed infestation and weather conditions. Weed control thresholds were set (Table 5) and herbicide dose was reduced depending on weed density. Linear triangulation was used to create application maps out of the weed distribution and density data. A 21 m wide Differential Global Positioning System (DGPS)-controlled multiple boom sprayer (*Kverneland Group*) was used for herbicide application. This sprayer is guided by the application map and varies the herbicide mixture and dosage during application based on map information. Rates were regulated by varying pressure and volume delivered by the sprayer. Broadleaf weeds were managed according to custom, using an appropriate herbicide group.

Table 5: Experimental fields, field size, crop rotation and weed control thresholds (in plants m^{-2}) for *A. myosuroides* used in the experimental fields from 1999 until 2006 at the Bonn University Research Station Dikopshof, Germany.

	Year	*Crop*	*Low*	*Medium*	*Full*
Field A	1999	Winter barley	15	25	50
5.3 ha	2000	Maize	3	6	25
	2001	Sugar beet	10	24	49
	2002	Winter wheat	10	20	30
	2003	Winter barley	10	15	20
	2004	Sugar beet	3	10	25
	2005	Winter wheat	10	20	30
	2006	Winter barley			1
Field B	1999	Winter wheat		20	50
2.4 ha	2000	Winter barley	15	30	50
	2001	Maize	4	10	20
	2002	Sugar beet			1
	2003	Winter wheat	3	5	15
	2004	Maize	5	10	25
	2005	Spring barley	10	25	40
Field C	1999	Sugar beet	15	30	50
5.8 ha	2000	Winter wheat	19	35	50
	2001	Winter barley	15	30	50
	2002	Maize			5
	2003	Sugar beet			1
	2004	Winter wheat	3	5	15
	2005	Winter barley	10	20	30
	2006	Maize			1

The target weed blackgrass was sprayed separately with adequate herbicides (Table 6). Herbicide selection was made based on weed infestation, stage of development, compatibility of the crop, atmospheric conditions and farmers’ former experiences (Gerowitt *et al.* 1988). Unless the threshold weed density was exceeded no herbicide was applied. Three different volume rates were sprayed against blackgrass.

Until 2003 300 l ha^{-1} was the full dose, the medium label was 240 l ha^{-1} and the low dose 180 l ha^{-1}. Normally, winter barley was sprayed in autumn; the other crops were sprayed in spring or early summer. Since autumn 2003, by reason of the development of a new sprayer, lower rates were used. The full dose was 290 l ha^{-1}, medium 245 l ha^{-1}, and the lowest 200 l ha^{-1}.

Table 6: Application date and grass weed herbicides (active ingredient ha^{-1} by full dose) used in the experimental fields (A, B, and C) from 1999 until 2006 at the Bonn University Research Station Dikopshof in Germany.

	Crop	*Date*	*Herbicide (active ingredient ha^{-1})*
A	Winter barley	03/16/1999	750 g Bifenox + 924 g Mecoprop-P + 1500 g Isoproturon
	Maize	05/26/2000	600 g Bentazon + 600 g Terbuthylazin + 12.5 g Rimsulfuron
	Sugar beet	05/22/2001	78 g Haloxyfop-R
	Winter wheat	03/12/2002	1500 g Isoproturon +14 g Carfentrazone-ethyl + 600.3 g Mecoprop-P
	Winter barley	10/24/2003	1200 g Isoproturon + 156.25 g Diflufenican + 1500 g Isoproturon
	Sugar beet	04/29/2004	120.95 g Clethodim
	Winter wheat	11/02/2004	1500 g Isoproturon
	Winter barley	10/21/2005	1500 g Isoproturon
		04/06/2006	60 g Pinoxaden und 15 g Cloquintocet-mexyl
B	Winter wheat	04/23/1999	500 g Bifenox + 616 g Mecoprop-P + 1400 g Isoproturon
		05/12/1999	90 g Mefenpyr + 76.32 g Fenoxaprop-P (only in weed patches)
	Winter barley	03/22/2000	1400 g Isoproturon
	Maize	05/30/2001	7.5 g Rimsulfuron + 15 g Prosulfuron + 300 g Bromoxinil
	Sugar beet	04/30/2002	187.5 g Fluazifop-p-butyl
	Winter wheat	03/10/2003	1250 g Isoproturon + 14 g Carfentrazone-ethyl + 600.3 g Mecoprop-P
	Maize	05/25/2004	7.5 g Rimsulfuron
	Spring barley	04/22/2005	75g Mefenpyr + 63.6 g Fenoxaprop-P
C	Sugar beet	04/30/1999	52 g Haloxyfop-R
	Winter wheat	03/20/2000	1050 g Isoproturon + 25 g Diflufenican + 187.5 g Ioxinyl + 234 g Mecoprop-P
	Winter barley	11/15/2001	100 g Diflufenican + 250 g Flurtamone + 1250 g Isoproturon
	Maize	05/30/2002	12.5 g Rimsulfuron + 666 g Terbuthylazin + 300 g Bromoxinyl
	Sugar beet	05/13/2003	187.5 g Fluazifob-p-buthyl
	Winter wheat	03/15/2004	1500 g Isoproturon
	Winter barley	11/02/2004	1500 g Isoproturon
	Maize	06/05/2006	10 g Rimsulfuron

3.2.4 Data analysis

Scale for the success of site-specific weed control in this work was the weed density in the fields. Out of the weed seedling data, weed distribution and density maps were created using ESRI ArcGIS Software. In order to test the stability of the weed patterns and to determine whether short-term effects are persistent the weed distribution and herbicide application decisions were monitored over eight years. A difference map approach was used to quantify the degree of stability of the weed aggregations. Weed patches were observed in order to analyse their change in density and location under the influence of site-specific weed control. The maps identify how often high density patches remain high and low density patches remain low, disappear or increase. Furthermore herbicide savings were estimated in comprehensive analysis in order to calculate the economic and environmental effects of the site-specific weed control.

3.3 Results

The spatial distribution of *A. myosuroides* seedlings in the experimental fields was always heterogeneous and varied depending on crop and weather conditions. Figures 7, 8, and 9 show the blackgrass density in the three fields immediately before (T_1) and about three weeks after herbicide application (T_2). The weed density increased and decreased from year to year depending on crop and their competitiveness. The density varied from 2.5 weeds per m^2 to 280 in winter cereals, 800 in sugar beet and up to 2500 in maize. The blackgrass density in row crop and subsequent years was always higher than in winter cereals.

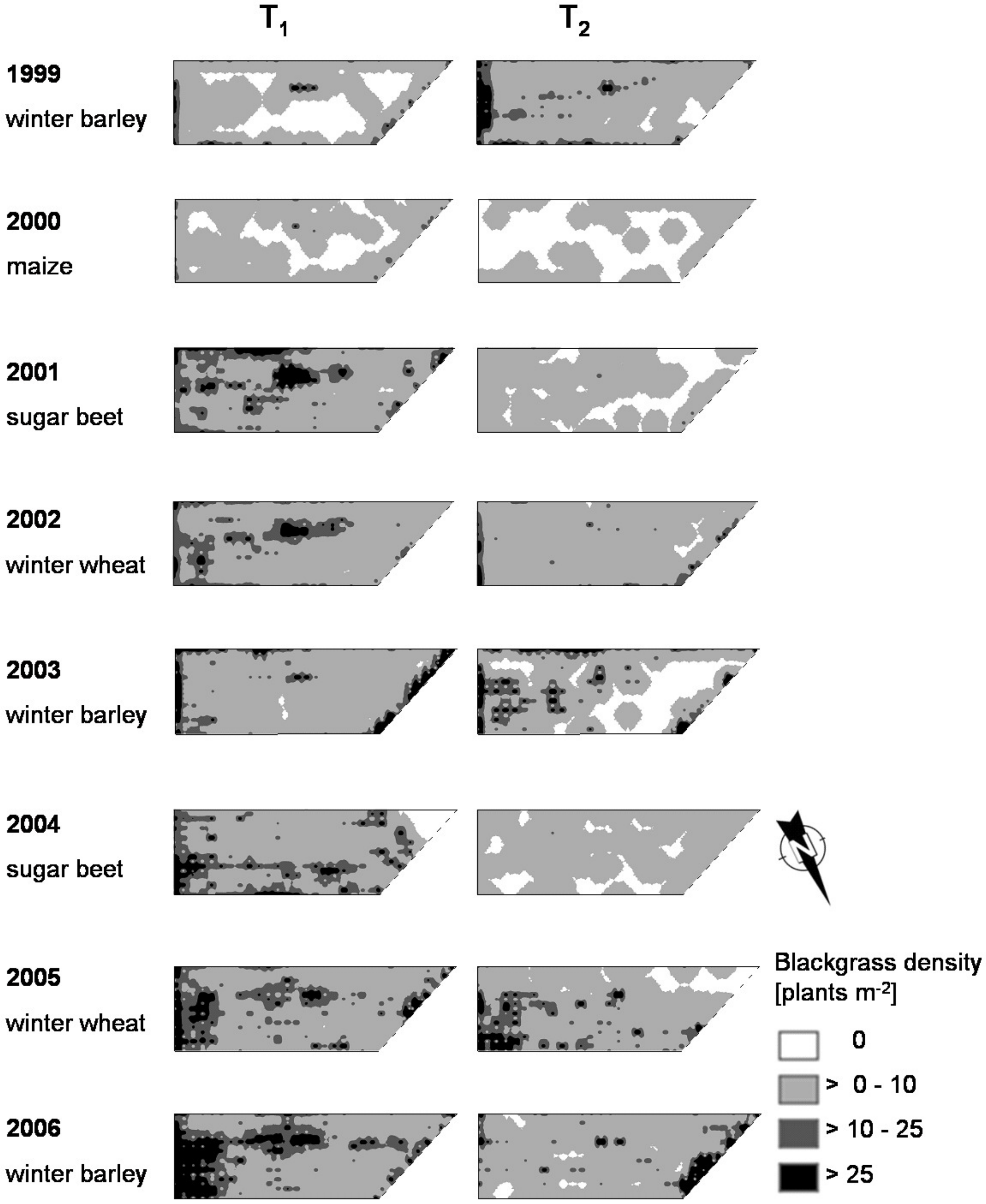

Figure 8: Blackgrass distribution and density (in plants m^{-2}) in field A before (T_1) and about 3 weeks after herbicide application (T_2) from 1999 until 2006.

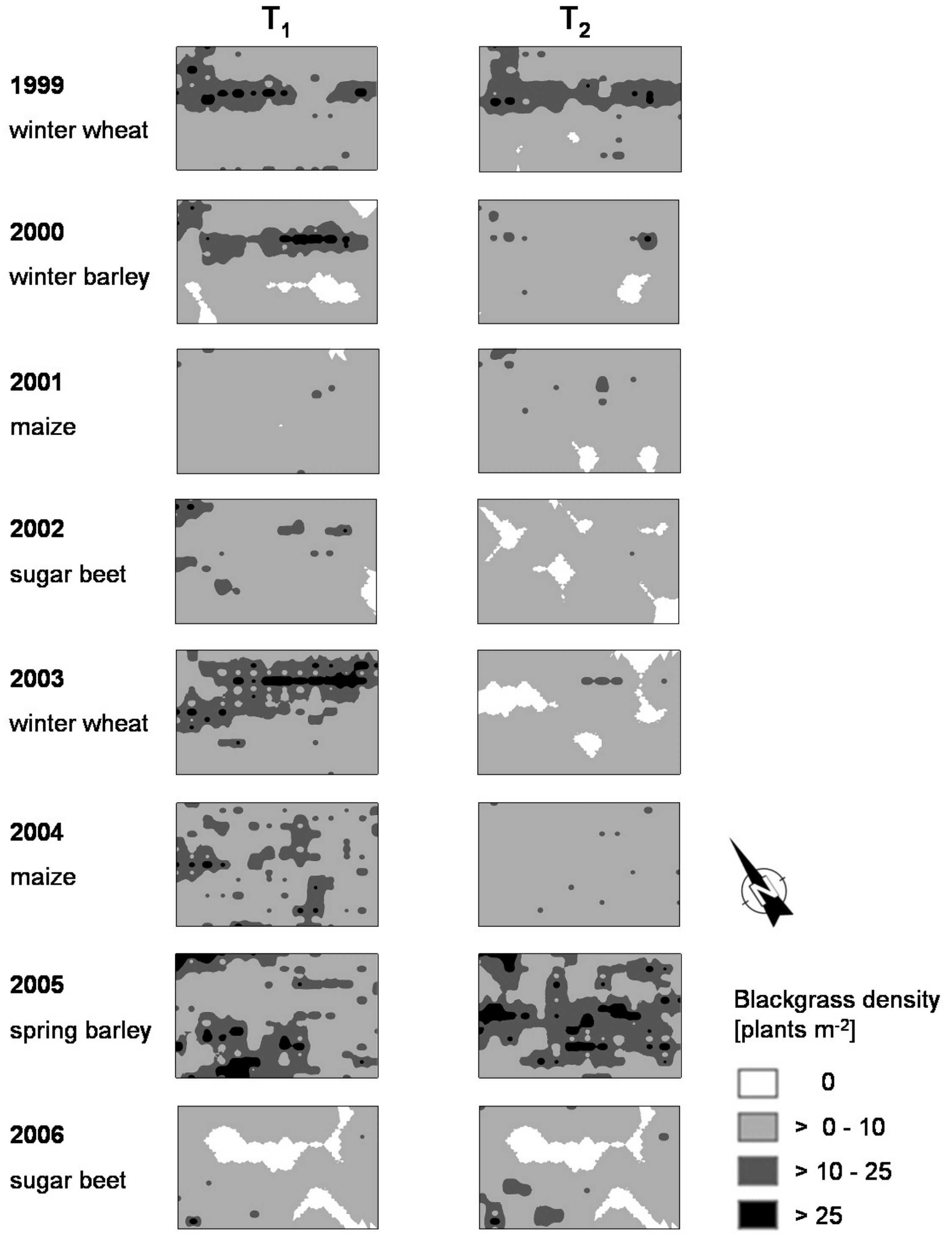

Figure 9: Blackgrass distribution and density (in plants m^{-2}) in field B before (T_1) and about 3 weeks after herbicide application (T_2) from 1999 until 2006.

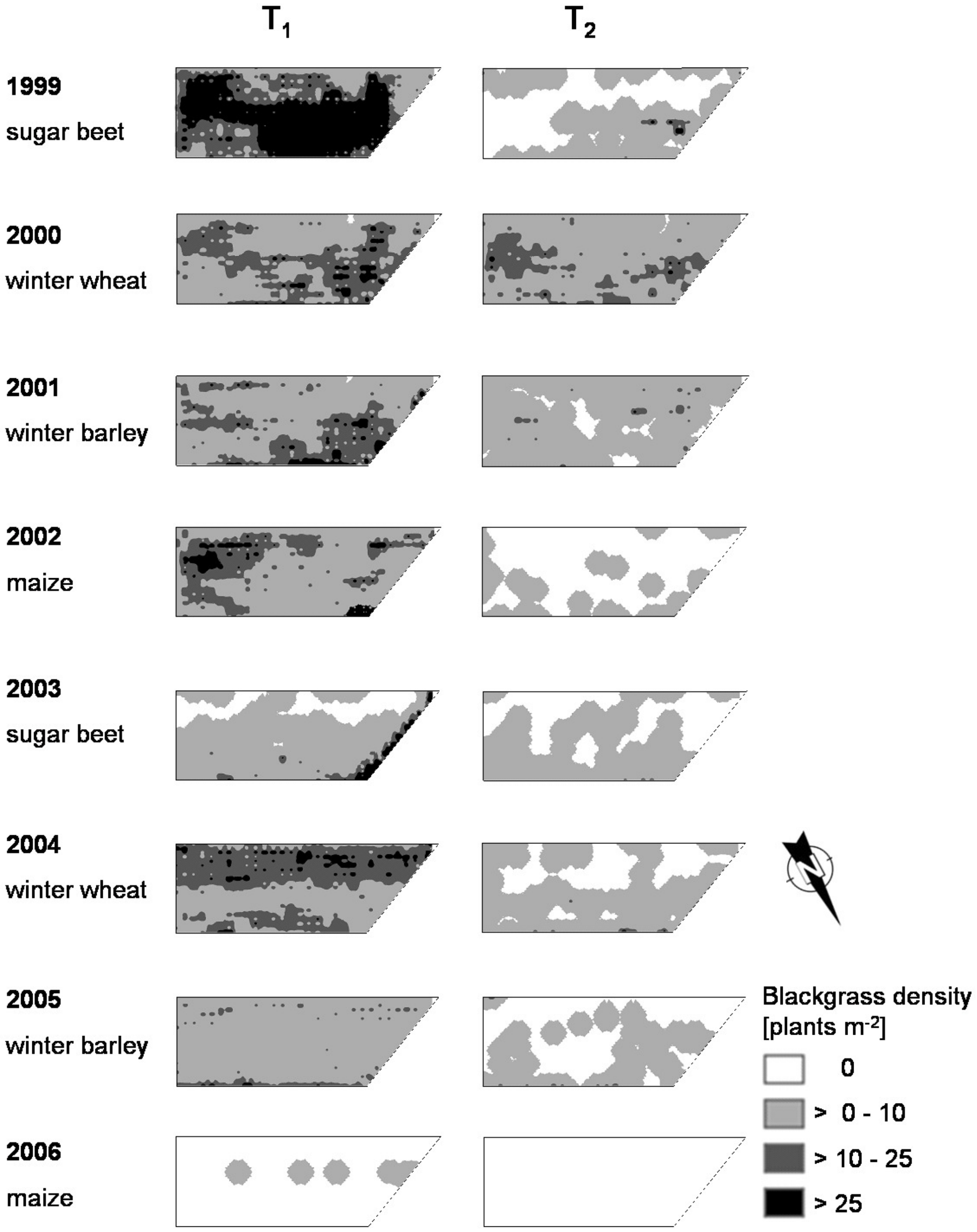

Figure 10: Blackgrass distribution and density (in plants m^{-2}) in field C before (T_1) and about 3 weeks after herbicide application (T_2) from 1999 until 2006.

In field A and B the average weed density remains relatively stable from year to year (Figure 11); in field C the mean of the weed density even decreases. During the eight years studied, the mean density of *A. myosuroides* remains in between 3 and 15 plants per m^2.

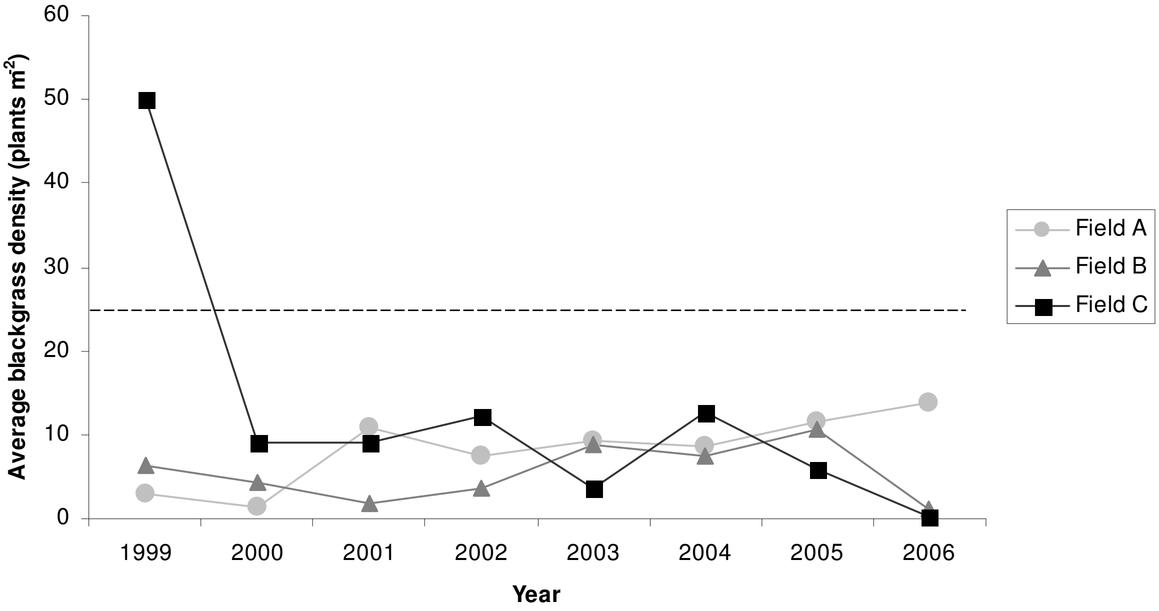

Figure 11: Blackgrass density from 1999 until 2006 compared in the three fields [dotted line indicates the ecological threshold of 25 *A. myosuroides* plants m^{-2}].

High density weed patches, with densities higher than 25 plants per m^2, consistently recur over the years at the same areas in the experimental fields (Figure 8, 9, and 10); they were mostly stable in density and location. Within the weed patches high pixels remain high and low pixels remain low or disappear. Total area of *A. myosuroides* aggregations in the three fields remains in between 0-16 % expanse (Table 7).

Table 7: Number of blackgrass plants in the fields, relative patch area (%), mean, standard error and maximum blackgrass abundance in the patches (plants m^{-2}).

		1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Field A	**Total field**	1,453	715	5,513	3,808	4,783	4,396	5,925	7,068
	Patch area %	3.54	0.39	10.61	5.30	7.86	10.81	9.63	16.70
	Patch mean	39	31	56	42	90	44	75	59
	SE	2.66	1.25	8.86	2.87	8.28	2.19	9.49	3.31
	Patch max.	75	33	500	83	280	90	253	145
Field B	**Total field**	1,485	1,048	448	870	2,110	1,776	2,538	290
	Patch area %	4.20	3.78	-	1.26	8.82	3.36	10.08	-
	Patch mean	42	39	-	33	46	35	47	-
	SE	3.80	4.60	-	1.67	4.65	2.24	4.08	-
	Patch max.	58	65	-	35	113	48	100	-
Field C	**Total field**	27,720	4,978	5,030	6,783	1,965	6,995	3,240	13
	Patch area %	41.98	6.67	7.93	7.21	3.06	10.81	0.72	-
	Patch mean	107	41	42	97	61	34	49	-
	SE	6.95	2.05	2.53	61.63	7.92	1.06	11.93	-
	Patch max.	800	70	108	2500	125	80	84	-

The herbicide efficacy or rather the weed reduction from T_1 to T_2 was satisfying in each year. Weed density did not increase at locations where no herbicides or reduced rates were applied. Herbicide use (Table 8) and costs did not increase in subsequent years. The site-specific weed control resulted in high herbicide saving rates.

Table 8: Percentage area sprayed in the experimental fields.

	Threshold	1999	2000	2001	2002	2003	2004	2005	2006	Total
Field A	full	0	0	4	3	10	11	7	63	
	medium	3	7	8	6	1	13	5	0	
	low	3	4	13	11	4	22	12	0	
	Total	**6**	**11**	**26**	**21**	**14**	**46**	**24**	**63**	**26**
Field B	Full	1	1	0	57	15	3	0	-	
	Medium	5	1	2	0	23	27	3	-	
	Low	0	6	13	0	16	18	27	-	
	Total	**6**	**8**	**15**	**57**	**54**	**48**	**30**	**-**	**31**
Field C	Full	26	1	2	41	33	28	1	1	
	Medium	12	3	4	0	0	39	1	0	
	Low	15	10	11	0	0	12	9	0	
	Total	**54**	**14**	**16**	**41**	**33**	**80**	**10**	**1**	**35**

In winter barley 84 %, winter wheat 75 %, maize 80 % and sugar beet 61 % on average were saved due to site-specific weed control (Figure 12). In average over the long run about 26-35 % of the experimental fields were sprayed.

Figure 12: Herbicide savings average over eight years in four fields [error bars indicate standard deviation].

3.4 Discussion

The results of this study restate that weeds are heterogeneously distributed in agricultural fields and confirm the need of site-specific weed control (Gerhards *et al.* 1997b). Marshall (1988) proved that an amount of at least 18 sampling points per ha is required to warrant precise estimations of the mean grass weed density in the field, so that the sampling intensity in this research (97 sampling points ha^{-1}) was quite sufficient.

The weed germination and density in this research varied depending on weather and crop conditions. So for example in 2001 in early summer there were low rainfall and high temperatures, so that the weed germination in field B in maize was low, and in spring 1999 reigned optimal weather conditions for *A. myosuroides* germination. Weed abundance in row crops such as sugar beet and maize was always higher than in winter wheat and winter barley. Due to the wider spacing between crop rows, weed competition is higher thus sugar beet and maize are less competitive than winter cereals. The higher weed occurrence in and after row crops was embanked by suppression of cereals in the following years. Primarily the buffering effect from winter cereals drove weed density down again (Legacy effect). This fact clarifies the need of adequate crop rotations. Weed thresholds have to be varied with the competitiveness of the crop; in less competitive crops such as sugar beet and maize they were set lower than in cereals in this experiment.

Estimation of the profitability of the weed management was made on the basis of weed seedlings emergence: at some locations the situation remains stable, ameliorated or was getting worse. In two of the observed fields, the average weed density remained stable over the eight years of the study, while in the third field the mean blackgrass density declined. Out of this data consequences for further decision algorithms for the site-specific weed control could be drawn. In the long run the average *A. myosuroides* density remained under 25 plants m^{-2}, Warmhoff and Heitefuss (1984) obtained a weed threshold of 25 plants per square meter up to this level *A.myosuroides* can be tolerated without a significant yield loss.

Earlier than this study started persistent weed patches already existed. Some *A. myosuroides* populations persisted in the experimental fields, even through effective herbicide rates were sprayed every year. These patches were increasing and decreasing in weed density and their spread shifts from year to year. These patches occur in elliptic pattern, were increasing and decreasing in weed density and their spread shifts from year to year.

The weed patch centres were rather stable in this study, but the in-patch densities and the patch frames were spatially varying over the years, similar results obtained Mortensen and Dieleman (1998) and Dieleman and Mortensen (1999). Wilson and Brain (1991) monitored the incidence of seed heads for ten years. Blackgrass weed patches were persistent in cereal fields during 10 years, although effective herbicides were applied every year.

The success of the site-specific weed control was always satisfying. The weed reduction in between T_1 and T_2 is not really a measures value for the herbicide efficacy, because in T_2 it was not distinguished in between weeds that survived the herbicide application and new emerging weeds, so that the real measurement of herbicide efficacy might be higher than the weed reduction from T_1 to T_2 was.

Locations in the field where reduced rates or no herbicides were applied according to the thresholds did not increase in weed populations within the eight years of study. But already existing weed patches could not be extinguished due to site-specific weed control, the high density patches were persistent overtime. This is a deficit of the site-specific weed management. But it might be more important that no new patches arose during the eight years of study.

Enormous herbicide savings were obtained during this study so that the site-specific weed control was profitable. Only 26-35 % of the fields were sprayed over the years. The highest herbicide savings were realised in cereals. Maize and sugar beets are less competitive so that lower but nevertheless appreciable herbicide savings could be realized. At locations where no or reduced herbicide rates were sprayed, the population density did not increase so that a purposeful site-specific weed management can tolerate a marginal weed emergence. The actual seedlings emergence depends on annual weather conditions (Gerowitt *et al.* 1988), soil cultivation and crop rotation in the current year.

By reason of the aggregation performance of weeds, the knowledge of weed density and distribution in the one year can be used for herbicide treatment decisions in the following years with regard to the competitiveness of the crop. However, site-specific management coupled with competitive cereal grain crops in the rotation provided a buffering effect that reduced weed density. The site-specific weed control appears to be effective and sustainable. The site-specific weed management offers a great potential for herbicide reduction in agricultural crops. Additionally, the change of active ingredient and the combination of herbicides with different modes of action are essential for herbicide resistance prevention. Throughout this study no negative long-term effects from the site-specific weed control on weed population dynamics were found. The profitability of the site-specific weed management remains stable over years.

3.5 Conclusions

The site-specific weed management remained successful over multiple years. High weed control efficacy and enormous herbicide savings and can be achieved. In the long run, weed density remained relatively stable and no new weed patches were generated. But already existing high density blackgrass patches could not be eliminated through the eight years of study, since from a specific weed density patches remain stable under common and site-specific herbicide measure.

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Chapter IV

An on-farm approach to quantify yield variation and to derive decision rules for site-specific weed management

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4. An on-farm approach to quantify yield variation and to derive decision rules for site-specific weed management

Abstract – Grain yield often varies within agricultural fields as a result of the variation in soil characteristics, competition from weeds, management practices, and their causal interactions. To implement appropriate management decisions yield variability needs to be explained and quantified. A new experimental design was established and tested in a field experiment to detect yield variation in relation to the variation in soil quality, the heterogeneity of weed distribution, and weed control within a field. Weed seedling distribution and density, apparent soil electrical conductivity (EC_a) and grain yield were recorded and mapped in a 3.5 ha winter wheat field during 2005/2006. A linear mixed model with an anisotropic spatial correlation structure was used to estimate the effect of soil characteristics, weed competition and herbicide treatment on crop yield. The results showed that all properties had a strong effect on grain yield. By adding herbicide costs and current grain price into the model, thresholds of weed density were derived for site-specific weed control. This experimental approach enables the variation of yield within agricultural fields to be explained, and an understanding of the effects on yield of the factors that affect it and their causal interactions to be gained. The approach can be applied to improve decision algorithms for the patch spraying of weeds.

Keywords: Weed distribution · Soil variation · Weed control thresholds · Herbicide injury · Geostatistics

Chapter V

General Discussion

5. General Discussion

In this study the site specific weed management was tested in the field, long term effects were examined, population dynamics under the influence of site-specific weed control were analysed and a model approach to derive management decision was approved. The main outcomes of these experiments are summarised, and discussed, and future prospects are given in this chapter.

Population dynamics

Over the past years several authors proved the spatially heterogeneous distribution of weed in agricultural fields (Marshall 1988; Thornton *et al.* 1990; Wiles *et al.* 1992; Mortensen *et al.* 1993; Cardina *et al.* 1995, Johnson *et al.* 1996). This heterogeneity was once again proved with this work and confirms the need of site-specific weed control. In this study the dynamics of weed seedlings distribution was monitored in winter and spring cereals, sugar beet and maize in several fields over different periods of time (three up to eight years). Various weed species were dominating in the different fields. Characteristic weed associations for region and crop rotation were found during this study: *Alopecurus myosuroides* HUDS., *Poa annua* L., *Galium aparine* L., *Lamium purpureum* L., *Matricaria chamomilla* aut. non L., *Chenopodium album* L., *Thlaspi arvense* L., *Amaranthus retroflexus* L., *Viola arvensis* MURR. *Veronica persica* POIRET, *Stellaria media* (L.) VILL., *Capsella bursa-pastoris* (L.) MED. and *Cirsium arvense* (L.) SCOP. The weeds were controlled site-specifically based on weed distribution maps and an economic weed control threshold model.

It was proved that the weed seedlings emergence varied depending on crop, soil cultivation, crop rotation, and weather conditions in the current year (Gerowitt and Heitefuss 1990). In row crops such as sugar beet and maize weed germination was always higher than in cereal grains. The higher weed occurrence in and after row crops was embanked by suppression of cereals in the following years. Primarily the buffering effect from winter cereals drove weed density down again. This fact clarifies the need of adequate crop rotations. The results showed that low rainfall and high temperatures caused low germination and optimal weather conditions lead to higher germination. Bouwmeester (1990) showed that germination performance depends on seed dormancy. Differences in soil moisture and light requirements for germination are result of the dormancy state of the seeds, which is determined by temperature during seed ripening.

Spectrum of germinating weed seedlings varied depending on the soil seed bank and this varied depending on the history of crop rotation and field management. However a weed seed bank of zero is unattainable. In the same manner competition and mortality are depending on crop. In row crops occurs less competition due to the wider spacing between crop rows. Thus weed thresholds have to be varied with the competitiveness of the crop; in less competitive crops have to be set lower than in cereal grains.

A clear result was the hypothesised relation between weed biomass and fecundity (Mortimer *et al.* 1989). In this study it was proved that the seed production rate increased with increasing and biomass. Another explicit result was the density dependence of the observed population dynamic parameters. First and foremost the seed production increased with increasing weed density. Weeds in higher growth densities rank and benefit themselves reciprocative; and they might need each other to entwine around themselves or support one another. It was rather presumed, that individual weeds without competition evolve better and produce more seeds. However, seed viability showed no correlation to density biomass or seed production rate. However, up to this day variation in weed density was not considered in weed population models, but it should be considered to precise decision support systems to warrant an economical and ecological sensibly herbicide application.

Weed mapping

Weed mapping was the basis of all experiments of this work. Therefore sampling grids from an 8 x 8 m up to 7.5 x 15 m were used in this study, depending on the width of the spray boom for herbicide application. Marshall (1988) proved that an amount of at least 18 sampling points per ha is required to warrant precise, thus the sampling intensities in this research was quite sufficient and Heisel *et al.* (1996) showed that a sampling grid of 10 x 10 m resulted in a good agreement with actual field situation. Linear triangulation and Inverse-Distance-Weighting interpolation were used and served the purpose of estimating weed seedlings densities in-between the sampling points in order to generate continuous weed distribution maps. Backes and Plümer (2004) studied the differences between the weed distribution maps with respects to the interpolation methods. They found, that the lacking aberration is also conditional on the sampling grid used for mapping and not only based on the used interpolation method, since interpolation methods is only as good as its underlying data. With the use of new automatic sensors for weed detection and identification that are under way, interpolation will not be much important anymore. Weed mapping will be faster and more effective. Smaller sampling grids will be used providing higher density of data. Information will be more detailed and the real infestation situation in the field will more accurately be assessed. Small scale heterogeneity could be assessed and weed patches will not remain undetected anymore.

Site specific weed management

Site-specific weed management was effective over the eight years of study. Herbicides use was significantly reduced due to spatially variable herbicide application site specific herbicide application without loosing performance. The highest savings were realised in cereals. In average in winter barley 84 % and in winter wheat 75 % of herbicides were saved compared to uniform application of herbicides that is still the standard method of weed control. Maize and sugar beets are less competitive crops, so that lower but nevertheless appreciable herbicide savings could be realized. In maize 80 % and sugar beet 61 % of herbicides were saved. In average only 26-35 % of the fields were sprayed over the years.

For the purpose of calculating the herbicide efficacy the weed reduction from T_1 (before herbicide application) to T_2 (about three weeks after herbicide application) was consulted in this study. However, in T_2 it was not distinguished in between weeds that survived the herbicide application and new emerging weeds, so that the real measurement of herbicide efficacy might be higher than the weed reduction from T_1 to T_2 was. In further studies this fact should be considered for better evidence. However, the weed reduction was satisfying over the eight years of study, even if it was higher in cereals than in row crops. KEMMER *et al.* 1980 found that herbicide efficacy intensely varies from year to year and is conditioned by a number of factors such as the development stage of the weeds, soil, weather, and growth conditions. WEIDENHAMER *et al.* 1989 ascertained that phytotoxicity decreased as plant density increased. In this thesis similar results were obtained, it was proved that herbicide efficacy is density-dependent. In high density weed patches the herbicide efficacy decreases, since an insufficient amount of active ingredient hits the target weed plants. In such a way always a few weed plants survive the herbicide application and re-import seeds into soil seed bank, thus the patches are self-preservative.

The spatially variable herbicide application should not lead to an increase in weed infestation in following years. This concern was also studied in this work by analysing data from three fields which were managed site-specifically over a period of eight years. The site-specific weed control was sustainable over the eight years of study. In the long run the average weed density remained under a level that can be tolerated without significant yield losses. A purposeful site-specific weed management can tolerate a marginal number of weeds.

Weed aggregation

Weed densities in the fields were variable during the eight years of study. At some locations the situation remains stable, ameliorated or was rarely getting worse. Locations in the field where reduced rates or no herbicides were applied, by reason of low weed infestation and according to the thresholds, did not increase in weed populations and weed density.

A question in dispute is still what a ’weed patch’ is. A plurality of approaches to define weed patches can be found in the literature. For this study weed patches were defined as clear visual weed aggregations; with densities higher than the weed thresholds in the literature is.

In the past several studies attempt to quantify the spatial stability of weed patches in agricultural fields. High density patches were persistent over time, even through effective herbicide doses were sprayed at these locations every year, they were increasing and decreasing in weed density and their spread shifts from year to year. The weed patch centres were rather stable, but the in-patch densities and the patch frames were spatially varying over the years. Similar results summarised Mortensen and Dieleman (1998). Wilson and Brain (1991) found, that *A. myosuroides* weed patches were persistent in cereal fields over a period of 10 years, even with effective herbicide doses sprayed in every year.

In this study already existing high density weed patches could also not be eliminated due to site-specific weed control in the eight years of study. Stability of weed patches is a general problem that could be solved by site-specific weed control combining chemical, physical and preventive methods of weed management. In addition to that, it is more important that no new weed patches emerge over time.

Due to the aggregation performance of weeds, the weed density and distribution maps from previous years could be used to make herbicide application plans for site-specific weed management in subsequent years (Goudy *et al*. 2001; Barroso *et al*. 2003).

Decision rules

For a worthwhile site-specific weed management appropriate decision rules are essential. Especially for weed management strategies geared to long-term profitability the influence of population dynamics needs to be considered. Several computerised population dynamic models are available (Holst *et al.* 2007). Aim of these models is to simulate the effects of management decision, in order to find appropriate management decisions. In order to understand the interactions of weeds with the cropping system the population dynamics under the influence of the site specific weed management were observed over three years, using the examples of two weed species. The results of this work showed high variation even within a species. Meaning that population dynamic parameters can hardly be universalised and measured values can heavily be investigated. However they can be monitored in order to get more information on weed dynamics and interactions within a cropping system.

All in this study obtained data on population dynamics can be integrated into computer models providing valuable insights that are needed to understand dynamics of weed populations and the effects within a cropping system on the demography of weeds. An all-embracing understanding of fundamental weed population biology will improve our ability to develop expedient site-specific management decisions. In general the models are describing the weed populations quite well, and deliver valuable information for the development of sustainable management strategies. However, they are always afflicted with uncertainties since adequate comprehensive typal data sets on population dynamics are limited available and there is still a lack of knowledge on some population parameters (Cousens 1995; Kropff *et al.* 1996). Additionally, the agreement between simulation and the measurement in the field was not sufficient (Zwerger and Hurle 1990). Independent from the complexity that these models they will ever achieve, they will always reproduce the reality only fractional.

In order to quantify yield variation caused by within-field heterogeneity a linear mixed model was developed. In the model repeated measurements are incorporated into the analysis by using the spatial correlation structure. The effects of soil characteristics, weed competition and herbicide treatment could be quantified separately. The results showed that all factors had a significant effect on grain yield and must be considered for management decisions. At all locations where no application was required, because of the low weed occurrence (under the economical threshold), the costs for herbicides and application could be saved. An additional yield surplus was realised by means of the absence yield decrease due to the negative side effects of herbicides on crop. For the first time the injury to the crop due to herbicide application could be numeralised, a yield loss from about 0.7 t ha^{-1}, in this case 6 % of the average yield was revealed with this model. This large loss of yield can be avoided and considerable reductions in herbicide rates can be achieved by site-specific management based on weed thresholds. However, further investigations are needed on other fields, other cropping systems, and for more weed species to confirm these findings.

Prospects

The outcomes of this research are valuable for precision farming and help to create decision algorithms for precise weed management. With the development of sensors for weed detection, infestations of weeds can be recorded more detailed and effective. New sensors for weed detection will improve weed sampling thus it will be less time consuming compared to visual methods that are still the standard method of weed mapping.

The developed experimental approach described above enabled decision rules to be formulated for precise weed management. A site-specific management coupled with competitive cereal grain crops in the crop rotation provides a buffering effect that reduced weed density. Additionally, the change of active ingredient and the combination of herbicides with different modes of action are essential for herbicide resistance prevention. In consideration of the results of this work, large reductions in herbicide use can be achieved to meet the requirements of pesticide reduction programmes and for sustainable long-term weed management strategies.

Summary

Zusammenfassung

6. Summary

Weeds occur in agricultural land all over the world, causing decrease in yield quantity and quality. However, weeds can successfully be suppressed by the use of herbicides. Today, herbicides represent about the half of the globally used plant protection products. In context of reduction programs for chemical plant protection, herbicide use needs to be strictly controlled and reduced to the absolute necessary extent in order to minimise negative side effects for the environment and pesticide residues in the food chain. The site specific weed management is a promising way to reduce herbicide use. It aims at managing weeds with respects to their spatial and temporal variability. Post-emergence herbicides are only applied at highly infested locations in the fields. Several studies on site-specific weed control have shown that this practice is reasonable, and it has been successfully implemented in various crops, resulting in a considerable reduction of herbicide use, treatment costs, and consequently benefits to the environment. However, there is still lack of knowledge on the population dynamics of weeds and the interactions between crop and weeds under the site-specific weed management. Long term effects of the site-specific weed control have not been studied in detail yet. Additionally, an experimental approach was needed to create precise decision algorithms for site-specific weed management.

Therefore the applied scientific objective of this research was:
- to analyse the spatial and temporal distribution of weeds,
- to provide information on weed population dynamics under the influence of the site-specific weed control,
- to detect if site-specific weed management leads to an increase in weed density, and if weed patches remain stable in density and location over time,
- to determine herbicide savings and efficacy of the site specific weed management,
- to design an experimental on-farm approach to explain yield variation caused by within-field heterogeneity of weed density, soil quality and herbicide application, in order to derive decision rules for site-specific weed control.

During the course of this work site specific weed management tested in field trails, long term effects were examined, population dynamics were analysed and a model approach to derive management decision was approved.

It was proved that weed distribution was heterogeneous in all experimental fields. The average weed density remained stable when economical weed thresholds were applied. The application of effective herbicides in every year did not reduce density in high density weed patches. The patches were persistent over eight years, with slight variations in density from year to year. It is suggested that a combination of chemical, mechanical, and cultural weed management strategies would be necessary to effectively control weeds in high density locations. However, the knowledge about the spatial stability of weed patches of individual species offers possibilities to use this information for weed management strategies.

Population dynamic parameters such as weed seedling emergence, crop-weed competition, seedlings mortality, herbicide efficacy, seed production and viability were found to be weed density dependent. With increasing weed density weed biomass and fecundity increased. These findings support that weed density has to be considered in weed management strategies. Site-specific weed management was effective over time. The amount of herbicides used could be decreased significantly due to site specific herbicide application, without loosing performance. Only 26-35 % of herbicides were sprayed compared to uniform application of herbicides that is still the standard method of weed control. Additionally, a new experimental design based on an anisotropic exponential model with nugget effect was established. The influences of the co-variables weed and soil on yield and the side-effects of herbicides were quantified separately with this model, by overlaying and spatially joining all data. Out of this information, yield losses due to weed and herbicide injury could be defined, and valid decision rules for site-specific weed management could be ascertained. For the first time the injury to the crop due to herbicide application could be numeralised with this experimental design. A yield loss from about 0.7 t ha^{-1}, in this case 6 % of the average yield, was revealed with the model. This large loss of yield can be avoided and considerable reductions in herbicide rates can be achieved by site-specific weed management based on weed thresholds. This experimental approach enables to explain the variation of yield within agricultural fields, and an understanding of the effects on yield of the factors and their causal interactions. This work is seen as a mayor step forward in order to precisely manage weeds with respect to their spatial and temporal dynamics.

7. Zusammenfassung

Unkräuter verursachen weltweit auf landwirtschaftlich genutzten Flächen Ertragseinbußen sowie Quantitätsverluste. Durch Herbizide können Unkräuter erfolgreich bekämpft und Erträge gesichert werden. Herbizide stellen heute ungefähr die Hälfte aller weltweit eingesetzten Pflanzenschutzmittel dar. Um negative Auswirkungen auf die Umwelt und Pflanzenschutzmittelrückstände in der Nahrungskette zu minimieren, muss der Herbizideinsatz im Rahmen von Reduktionsprogrammen für den chemischen Pflanzenschutz grundsätzlich geregelt und auf das notwendige Maß begrenzt werden. Die teilflächenspezifische Unkrautbekämpfung ist ein richtungweisender Ansatz, um diesen Anforderungen gerecht zu werden. Bei der teilflächenspezifischen Unkrautbekämpfung werden die Unkräuter unter Berücksichtigung ihrer räumlichen und zeitlichen Variabilität und unter Verwendung von ökonomischen Schadschwellen kontrolliert. Eine Herbizidapplikation im Nachauflaufverfahren findet nur beim Auftreten von Unkräutern statt. Durch Studien zur teilflächenspezifischen Unkrautkontrolle konnte gezeigt werden, dass dieses Verfahren erfolgreich angewendet werden kann, mit beachtlichen Herbizideinsparungen sowie signifikanten ökonomische und ökologische Vorteilen.

Neben diesen sehr positiven Ergebnissen mangelt es bisher noch an Kenntnissen über die Populationsdynamik von Unkräutern und den Wechselbeziehungen zwischen Kulturpflanze und Unkraut unter dem Einfluss der teilflächenspezifischen Unkrautbekämpfung. Die Langzeitwirkungen der teilflächenspezifischen Unkrautkontrolle wurden bisher nicht eingehend untersucht. Darüber hinaus war bislang keine Versuchsmethodik verfügbar um präzise Entscheidungsalgorithmen für die teilflächenspezifische Unkrautkontrolle abzuleiten.

Aus diesen Prämissen ergab sich die Zielsetzung dieser Arbeit:

- die Analyse der räumlichen und zeitlichen Verteilung von Unkräutern,
- die Bereitstellung von Informationen über die Populationsdynamik von Unkräutern unter dem Einfluss der teilflächenspezifischen Unkrautbekämpfung,
- zu untersuchen ob die teilflächenspezifische Unkrautkontrolle zu einem Anstieg der Unkrautdichte führt und ob Unkrautnester in ihrer Lage und Dichte stabil sind,
- Ermittlung von realistischer Herbizideinsparungen und Bekämpfungserfolge,

- Erarbeitung eines Modells zur Ermittlung von Entscheidungsalgorithmen für die teilflächen-spezifische Unkrautbekämpfung unter Berücksichtigung der Ertragsvariabilität.

Im Verlauf dieser Arbeit wurde die teilflächenspezifische Unkrautbekämpfung erprobt und ihre Langzeitwirkungen untersucht, die Populationsdynamik der Unkräuter unter dem Einfluss teilflächenspezifische Unkrautkontrolle analysiert und ein Modellansatz zur Ermittlung von Entscheidungsalgorithmen entwickelt.

Die Ergebnisse dieser Arbeit belegen die heterogene Verteilung von Unkräutern in Ackerflächen. Die durchschnittliche Unkrautdichte in den Ackerflächen blieb unter der Verwendung von ökonomischen Schadschwellen über den untersuchten Zeitraum stabil. Die Lage bestehender Unkrautnester war mit leichten Dichteschwankungen gleich bleibend. Um diese Nester wirkungsvoll zu kontrollieren empfiehlt es sich chemische, mechanische und kulturelle Unkrautbekämpfungsmaßnahmen zu kombinieren. Die populationsdynamischen Parameter: Keimung, Konkurrenz, Mortalität, Bekämpfungserfolg, Samenproduktion sowie Lebensfähigkeit zeigten sich abhängig von der Unkrautdichte. Mit zunehmender Unkrautdichte stiegen auch die Biomasse der Unkräuter und deren Samenproduktionsrate an. Diese Ergebnisse belegen, dass die Unkrautdichte im Unkrautmanagement berücksichtigt werden muss. Auch über einen längeren Zeitraum war die teilflächenspezifische Unkrautbekämpfung erfolgreich. Der Herbizideinsatz konnte ohne Verlust an Bekämpfungserfolg signifikant gesenkt werden. Im Vergleich zur ganzflächigen Herbizidapplikation, die immer noch die Standardmethode in der Unkrautbekämpfung darstellt, wurden in diesen Versuchen nur 26-35 % der Herbizidmenge ausgebracht.

Des Weiteren wurde ein geostatistischer Ansatz mit einem linearen gemischten Model und anisotropher räumlicher Korrelationsstruktur als Grundlage erarbeitet. Die Ertragswirkungen von Bodenqualität, Unkrautkonkurrenz und Herbizidapplikation können getrennt voneinander analysiert werden, indem die verschiedenen Informationsebenen übereinander gelegt und miteinander verschnitten wurden. Aus diesen Informationen konnten Ertragsverluste durch Unkrautkonkurrenz und Herbizidschäden definiert und zuverlässige Entscheidungsalgorithmen für die teilflächenspezifische Unkrautkontrolle ermittelt werden. Hierdurch war es erstmalig möglich Herbizidschäden an Kulturpflanzen zu beziffern. Mit Hilfe des Modells konnte ein Verlust durch Herbizidschäden von 0,7 t/ha, in diesem Fall 6 % des Durchschnittsertrages des Winterweizens, ermittelt werden. Durch die dargelegte teilflächenspezifische Unkrautkontrolle können deutliche Ertragsverluste vermieden und beachtliche Herbizideinsparungen realisiert werden.

Mit dem erarbeiteten geostatistischen Ansatz sind Ertragsvariabilität erklärbar und angepasste Entscheidungsalgorithmen können ermitteln werden. Die Ergebnisse dieser Arbeit bilden die Grundlage für zukünftige Entwicklungen um Unkräuter, unter der Berücksichtigung ihrer räumlichen und zeitlichen Dynamik, nachhaltig zu kontrollieren.

General References

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9. List of Figures

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