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Precision farming for weed management: techniques

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Abstract Site-specific weed control techniques have gained interest in the precision farming community over the last years. Managing weeds on a subfield level requires measuring the varying density of weeds within a field. Decision models aid in the selection and adjustment of the treatments, depending on the weed infestation. The weed control can be done either with herbicides or mechanically. A site-specific herbicide application technology can save large amounts of herbicides. Mechanical weed control techniques adapting to the weed situation in the field are applicable to a wide spectrum of crops.

Site-specific techniques for the detection and management of weeds are presented. A system for the discrimination of different weed species and crops from images is described, which generates weed maps automatically. Models for the yield effect of weeds are developed and applied in on-farm-research experimental setups. Economic weed thresholds are derived and used for a herbicide application with a patch sprayer.

Keywords Site-specific weed control · Weed mapping · Chemical control · Mechanical control · Expert systems for weed control

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Präzisionslandwirtschaft zur Unkrautbekämpfung: Techniken

Zusammenfassung Teilschlagspezifische Unkrautbekämpfung hat in den letzten Jahren zunehmendes Interesse im Bereich der Präzisionslandwirtschaft gefunden. Die Bekämpfung von Unkräutern auf Teilflächen innerhalb eines Schlages erfordert die Messung der unterschiedlichen Unkrautdichten. Entscheidungsmodelle helfen bei der Auswahl und der Steuerung der Maßnahmen abhängig von der tatsächlichen Unkrautsituation. Die Unkrautbekämpfung kann entweder mittels Herbiziden oder mechanisch erfolgen. Eine teilschlagspezifische Herbizidapplikation kann einen Großteil der Herbize einsparen. Mechanische Unkrautbekämpfungstechnik, die auf die Verunkrautungsituation abgestellt ist, kann in einem weiten Spektrum an Kulturen angewendet werden.

Teilschlagspezifische Techniken für die Identifizierung und Bekämpfung von Unkräutern werden vorgestellt. Ein System für die Differenzierung von Unkräutern und Kulturpflanzen mittels Bildanalyse kann Unkrautkarten automatisch erstellen. Modelle zur Beschreibung der Auswirkungen der Unkräuter auf den Ertrag werden entwickelt und in On-Farm-Research-Versuchen angewendet. Ökonomische Schadschwellen werden abgeleitet und können für eine Herbizidapplikation mit einer auf Teilflächen steuerbaren Spritze umgesetzt werden.

Schlüsselwörter Teilschlagspezifische Unkrautkontrolle · Unkrautkartierung · Chemische Unkrautbekämpfung · Mechanische Unkrautbekämpfung · Expertensysteme

Introduction

Pesticide use in European countries is strictly regulated in order to minimize negative side effects for the environment and pesticide residues in the food chain. For chemical weed control, the German plant protection law of 1986, which was modified in 1990 (PflSchG 1986), requires the use of economic weed thresholds. The economic weed thresholds for small annual grains such as wheat vary considerably in the literature. For *Galium aparine* the threshold ranges from 0.1–2 plants m^{-2} (Bartels et al. 1983; Meinert and Mittnacht 1992), for *Cirsium arvense* and for *Polygonum aviculare L.* 1–2 plants m^{-2} (Börner 1995), whereas for most broad-leaved weed species it is closer to 40–90 plants m^{-2} (Bartels et al. 1983). For *Alopecurus myosuroides* threshold densities of 25–35 plants m^{-2} have been determined (Wellmann and Feucht 2002) compared with 10–20 plants m^{-2} for *Alopecurus myosuroides* (Wahmhoff and Heitefuss 1985; Niemann 1986). The economic thresholds have not been consistently adjusted to the grain price and weed control costs. Therefore, they can only be used as an approximate value in deciding about weed control methods.

Computerised decision models help farmers to define the need for weed control and support an optimal choice of herbicides and doses (Wiles et al. 1996). The first group of models (efficacy-based models) includes large and updated databases with herbicide performances in different crops, as well as prices to select the most efficient herbicides with the lowest costs. The second group of models (population-based models) uses biological data to determine the relationship between weed control and yield increase (Kropff and Spitters 1991) and estimate changes in the soil seed-bank.

However, none of these decision rules have considered the spatial variation of weed populations within a field. The use of field-scale mean density estimates in spatially heterogeneous weed populations results in underestimation of yield loss at locations where weed density is high and overestimation in parts of the field where weed densities are low or weeds are absent. Spatial variation in weed density must thus be considered in the development of economic weed thresholds (Lindquist et al. 1998; Brain and Cousens 1990; Holst et al. 2007). Christensen et al. 2003 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.

Weed populations have been found to be distributed heterogeneously in time and space within agricultural fields (Dieleman and Mortensen 1999; Perry et al. 2002; Nordmeyer and Zuk 2002; Gerhards and Christensen 2003). They often occur in aggregated patches of varying size or in stripes along the direction of cultivation. The spatial distribution of weeds has often been ignored in weed management and weed science. With a large within-field variation in weed occurrence, patch spraying may reduce treatment costs as well as herbicidal loading to the environment. A major step towards a practical solution for site-specific weed management was the development of precise and powerful sampling techniques to automatically and continuously determine in-field variation of crop cover and weed seedling populations (Lamb and Brown 2001; Vrindts and de Baerdemaeker 1997; Biller 1998; Sökefeld et al. 2000; Søgaard and Heisel 2002; Gerhards and Oebel 2006).

Weed–crop interactions have usually been studied in small scale experiments in pots or small replicated field plots. This experimental design allowed relating yield variations to different weed infestation levels or weed control methods. Other factors influencing crop yield such as soil type and soil water content, side-effects of herbicides on the crop and variations in crop density could not be separated from effects of weed competition. These were also variable in small-scale plot experiments. Uncertainties of weed control decisions also arose from large variations in weed infestation within small-scale randomised plots (Hamouz et al. 2006) complicating the statistical analysis of the data.

Therefore, a different experimental approach that takes into account the temporal and spatial heterogeneity of weed populations was needed. This approach has been described as on-farm research and was applied by Leithold and Traphan (2006) to study the effect of different N-applications in large fields with heterogeneous soils. Strips with different N-levels were achieved across the total field including all soil classes. A yield map was created using a GPS-controlled yield monitor. Data was autocorrelated using geostatistical methods and analyzed using GIS-software and regression models. This approach allowed separating yield variability caused by heterogeneity of soil characteristics and N-levels.

The objective of this paper is to adopt precision farming technologies and expert systems for site-specific weed management. Decision algorithms and application technologies are investigated for chemical and mechanical weed control methods in cereals, sugar beet and maize.

Precision farming in weed control

Precision farming techniques involve the identification of changes within a field. To be able to work on a sub-field level, sensors and application technology that are able to detect differences and to change the intensity of an application must be available. Two different approaches can be distinguished: online procedures, using the sensor measurements directly to vary the application, and offline procedures, where the location information is already available for the whole field before application takes place.

Since the differences are spatially located, positioning plays an important role. The global navigation satellite system GPS (global positioning system) is mainly used for determination of the absolute position in precision agriculture.

Weed detection techniques

The weed infestation can be measured manually, which is affordable for research purposes, but due to the effort involved this is not suitable for a wider practice. More research is necessary to determine the optimal sampling rate and interpolation algorithms (Dille et al. 2003).

Automation of weed detection has the potential to increase the sampling point density. There are different approaches to detect the location of weeds automatically: based on biological morphology (shape), spectral characteristics or visual texture. Slaughter et al. (2008) give an overview of the research in the field and identify robust weed detection as a primary obstacle for robotic weed control technology.

Weed detection from images

For automatic weed detection, three digital bi-spectral cameras (IR-VIS) were developed and mounted on a vehicle. With each bi-spectral camera, two images were taken at the same time in the near-infrared spectrum (770–1.150 nm) and in the red spectrum (610–670 nm). The images of both cameras were adjusted in brightness and subtracted (IR-VIS) in real-time (Fig. 1). With this camera, a strong contrast between green plants and soil, mulch and stones was achieved even under variable illumination and soil moisture conditions; artificial illumination was not necessary. The cameras were triggered with an exposure time of 1/4,000 s to get well focused images at a speed of 7–8 km/h.

A grey level threshold was set automatically and all white objects in the picture are extracted. Objects, defined as a connected set of foreground pixels (segments), that are smaller or bigger than plants are automatically removed from the image. The region generation in the image can be improved using morphological image processing operators, erosion and dilation, that shrink and/or blow the regions. A morphological opening operator combines erosion and dilation in reverse order and separates regions at thin connections. A subsequent combination of dilation and erosion leads to a closing, whereby adjacent regions are merged.

The remaining objects are analysed with image processing and classification algorithms. The features of the shape of each object in the images are calculated and stored in a database. These features can be grouped into three categories: region based, contour based and skeleton features (Weis and Gerhards 2007). The region based features are computed from the set of pixels of the object. The contour based features are derived from the border of the object, Fourier features and a curvature scale space representation are derived. For the skeleton features a combination of a distance transform and a skeletonization of the object are used. These basically represent the thickness and elongatedness of a region. A subset of these is invariant to translation, rotation and scale and are suitable for a shape comparison, since they are normalised and can be compared directly to each other. A vector of the shape features represents the shape of the object, which can be used for discrimination of different species.

For classification purposes different weed species have to be trained by selecting prototypes from the set of objects. The classes indicate the plant species (denoted by the EPPO code) and growth stage (via BBCH code), since the shape

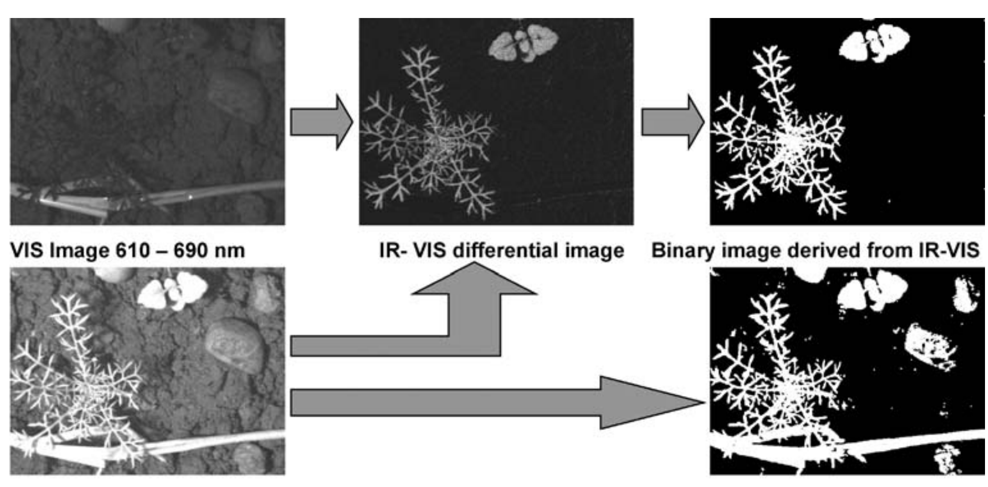

Fig. 1 Functionality of a bi-spectral camera for weed identification

changes for each species over the time of growth. A prototype definition consists of a region (segment) in an image, the corresponding shape features and a class association. A classifier can be trained based on the prototypes and then be used to classify all objects, assigning classes to them (Fig. 2). The results are the counts of each class in every image. In combination with the GPS position weed maps are generated, which contain the class counts for the different weed species in an attribute table of points.

Management decisions

In large field experiments randomization is often limiting. Therefore alternative statistical approaches with less randomization were investigated using spatial models. The datasets contain information about soil quality (Fig. 3a), weed species density (plants m^{-2}) (Fig. 3b), weed and crop coverage and crop yield (Fig. 3e). Covariate information is incorporated using geostatistics, including semivariogram analysis, autocorrelation and multiple linear regression approaches to determine the effects of soil characteristics, herbicide treatment (Figs. 3c and 3d) and yield loss on grain yield separately (Fig. 4). Biological and economic weed thresholds were quantified for each grid cell and yield loss per weed was calculated. The biological weed threshold is defined as the point where yield in the herbicide treated and untreated weedy cell are equal.

An experimental design was set up to analyse decision rules for site-specific weed control. In 2006, the weed seedling distribution in an 8.19 ha winter wheat field was assessed prior to and after post-emergence herbicide application and integrated into a geographical information system (GIS). The herbicide treatment was carried out using a differential global positioning system (DGPS) controlled multiple-boom sprayer. Two herbicide rates were used: the full label (100%) and no herbicide. In order to test their efficacy three weed density thresholds were set for each herbicide mixture targeting: broadleaves, grasses, and a combination of *Galium aparine* and *Matricaria chamomilla*. During harvest, yield was mapped using a DGPS-connected, combine-mounted yield monitor system. An EM 38-sensor was used for the mobile acquisition and mapping of soil apparent electrical conductivity (ECa) after crop harvest. The EM 38 value is a cardinal measurement of soil quality (texture, clay content and soil organic matter). A polygon grid with an 8×8 m grid size was created and combined with the following map layers: soil, weed distribution, plot position, treatment maps and crop yield. For each of the grid cells, the statistics (mean, standard deviation) of underlying maps were calculated.

For the determination of yield effects of the various factors a mixed linear model was developed with anisotropic spatial correlation structure. The calculations were carried out with PROC MIXED in SAS (Ritter et al. 2008).

GPS-controlled patch spraying

Application maps were created based on interpolated maps of weed distribution and economic weed thresholds. Three different application maps could be used at the same time using a multiple sprayer with three separated hydraulic circuits (Fig. 5). The sprayer was developed at the University of Bonn in cooperation with Kverneland Group. It allows varying the herbicide mixture on-the-go. Each of the three sprayer circuits had a boom width of 21 m, divided into seven sections of 3 m. Each sprayer circuit and each section were separately turned on and off by a control unit via solenoid valves. The herbicide dose for the full spray

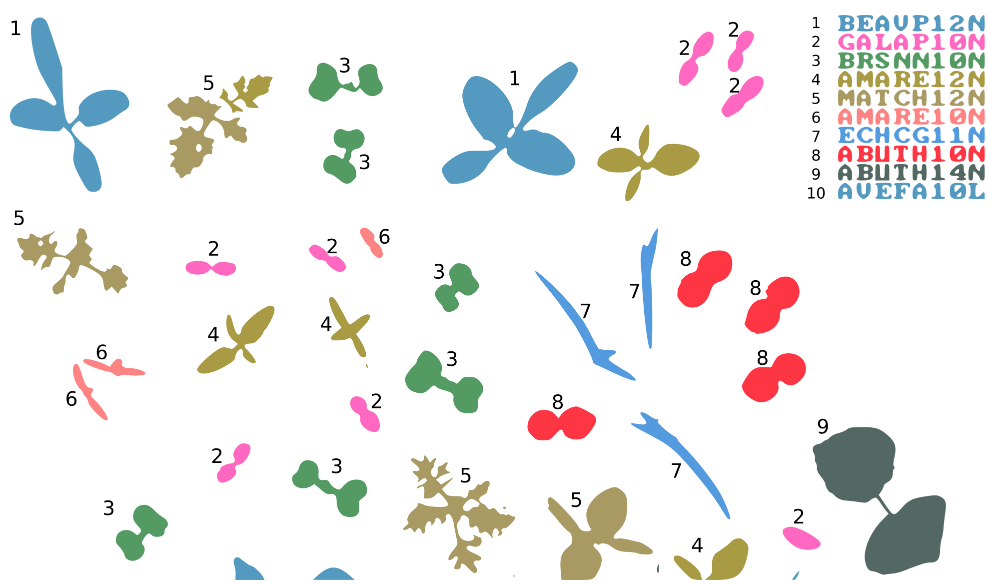

Fig. 2 Classification examples: each classified region is denoted by a color and a number for the class

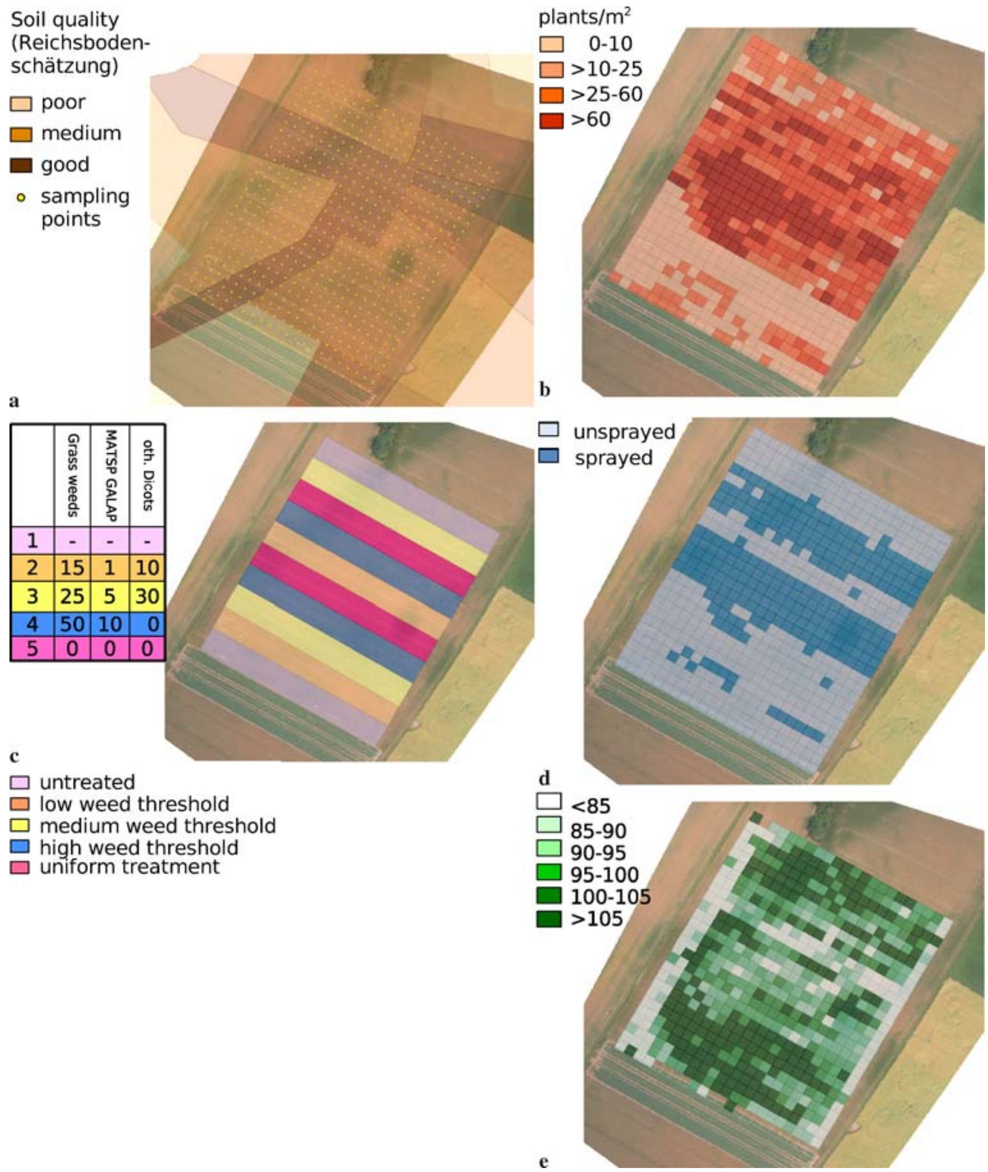

Fig. 3 a–e **a** Soil classification and sampling points; **b** weed distribution map; **c** weed control treatments; **d** application map; **e** yield map

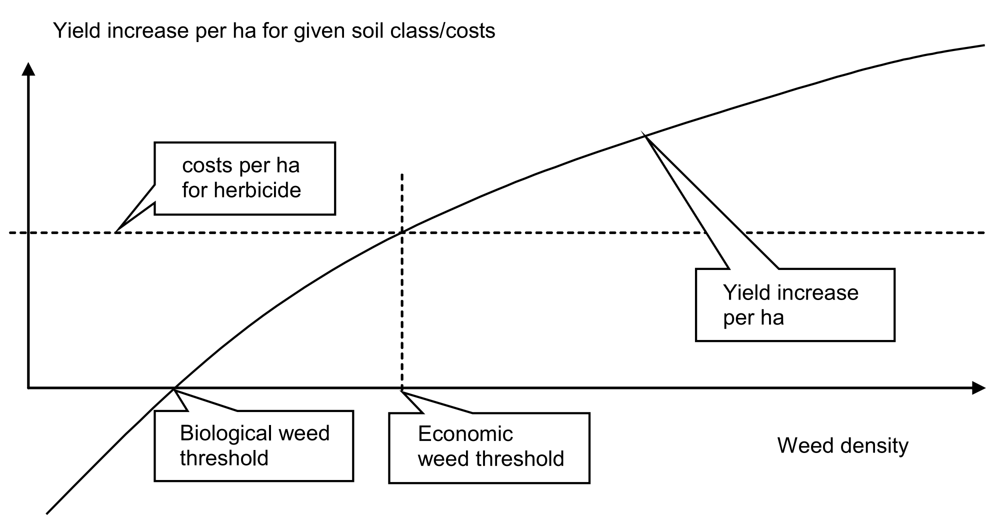

Fig. 4 Autocorrelation and multiple mixed (non-linear) regression

Fig. 5 GPS-controlled patch sprayer with three separated hydraulic circuits

boom was regulated by the same control unit via a spray computer. Three different volume rates could be applied by changing the pressure in the system ranging from 200 l ha^{-1} (herbicide doses of 70%) to 290 l ha^{-1} (herbicide doses of 100%). The main hydraulic circuit of each of the three sprayer circuits was similar to that on a conventional sprayer with an output from the main pump fed to a pressure control valve, which regulated the concentration that was set by the spray computer. During the herbicide application, the spray control system was linked to an on-board computer loaded with the weed treatment maps. A differential mode GPS was used for real-time location of the patch sprayer. The on-board computer compared the actual position of the sprayer with the information in the weed treatment maps, and signals were transmitted to the control unit via a data bus to open each individual solenoid valve when herbicide application was warranted. In the same way, the herbicide dose was adjusted to the recommended rate in the treatment map.

Mechanical weed control

Direct (physical) weed control can be successful only when it is considered as a part of a holistic management strategy. Three parts have to be integrated within this plan: preventive cultural methods, crop and weed ecology and mechanical control of weeds.

The aim of physical weeding is to maintain the weed populations to a manageable level; therefore a range of implements has been developed as mechanical weeders: hoes, harrows, tines and brush weeders, mowers, strimmers, and thistle-bars. A broad description of these implements is given by Bond et al. (2007) and Melander (2006).

Weed control in cereals involves whole crop cultivation and thus crop injury. Different flexible tine harrow types have been used for pre-emergence and early post-emergence weeding operations. Control at later growth stages has been more effective when the parameter of selectivity is considered. Selectivity is defined as the ratio between weed control and crop burial in soil as a result of post-emergence harrowing (Rasmussen and Rasmussen 2000). This theory includes the aspects: plant uprooting, tearing the plants into pieces and a soil covering mechanism, i. e. burying of plants (Rasmussen and Svenningsen 1995). Associated crop damage may be neglected. Harrowing can control about 40% of the weeds; with the use of selective weed harrowing a good result was achieved in spring cereals with up to 80% efficacy.

The timing of weed harrowing tends to be severely constrained by soil moisture and soil compaction, particularly after periods of frost (winter) or rain (spring) (Rasmussen and Nørremark 2006). To counteract this problem, it is suggested that the intensity of harrowing be increased (Cirujeda et al. 2003; Rasmussen and Nørremark 2006; Mouazen et al. 2007). More aggressive harrowing can be obtained by reducing the angle of the flexible tine, by increasing the number of passes of the harrow or by increasing the driving speed of the vehicle. Although, for the last option, speeds higher than 8 km/h have not shown more soil cover of weeds or uprooting (Cirujeda et al. 2003; Rasmussen et al. 2008).

Precision mechanical weed control

Projects and methods of mechanical intra-row weed control that require a constant distance between the plants of a row or information about the current distance for steering and control are the rotary hoe of the Institute of Agricultural Engineering of University of Bonn (Gobor 2007) and the rotating discs with gaps for crop plants of Cranfield University (O'Dogherty et al. 2006). One project that examines steering by image analysis was engineered in Sweden at Halmstad University. An autonomous vehicle with a camera detects weed plants and a fitted tool for weed control removes the plant (Åstrand and Baerveldt 2002).

The University of Wageningen developed a prototype for mechanical weed control that uses a disc, mounted and rotating in lateral direction to the row and the driving direction. Crop plants are detected by light barriers. If a crop plant is detected, the rotational speed of 850 rpm is reduced, and springs switch the mounted knifes to the disc at decreased centrifugal power (Dedousis 2007). These systems require the online detection of plant position with optical sensors.

If precise positioning is available, the relative or absolute positions of plants can be adjusted. A plant formation can be seeded that is adjusted to the requirements of mechanical weeding. Using position information of the seeding procedure as approximate coordinates and refining the current position in a second step by image analysis, detection of an individual plant was implemented by Griepentrog et al. (2004).

Another possibility is the generation of a previously defined formation of seeds, generating a rectangular formation, which can also be adjusted for diagonal hoeing directions (Rothmund et al. 2007; Schmittmann and Schulze Lammers 2004). Weeds that have been not removed in the first run of hoeing in the intra-row areas are removed in a second run, lateral or diagonal to the first run.

In the DFG-project "Position Steered Seed Deposition by High Accuracy for the Generation of Longitudinal and Lateral Rows", the plant positions are determined with an accuracy of 2 cm according to the rectangular formation. The standard deviation of the seed deposition position is determined with 1 cm at a driving velocity of 1–2 m/sec. A geodetic multi-sensor-system calculates steering information (position, velocity) for a precision seeder, powered by a step motor (Siemes and Kuhlmann 2007).

Experiments on selective harrowing are being carried out in Hohenheim University's experimental fields under the sensor based mechanical weed control approach. The intention is to combine real-time sensors for weed detection, positioning and measuring soil compactness with different instruments for mechanical weeding. Two experiments for winter cereals and two for summer cereals have been established. In Fig. 6 the setup of the experimentation to automatically control the intensity of harrowing operations is shown. All measuring and weeding tools are attached to the tractor (t). With a bi-spectral camera (bc) images of the crop and weeds are taken in order to compute the plant coverage as a percentage before and after harrowing operations. A soil sensor (ss) will measure the soil compaction (resistance to mechanical action). Positions are detected with a real time kinematics differential global positioning system (RTK-DGPS). All data are received, stored and computed within a control unit (cu) in order to generate the appropriate algorithm to automatically set up the mechanism. A more aggressive (strong) or less aggressive (light) treatment should be directed through a motor (m), which changes the angle of the harrow tines (ht). This adjustment is to be defined by the crop and weed soil coverage that generates the highest weed control with the least crop damage.

The data from the soil sensor are measured to generate a function that will control how many soil resistance force units should define either a smaller or a greater angle of the tines. The images taken with the bi-spectral cameras are used to determine the total plant coverage in percent (crop and weed plants), then the soil coverage can be calculated by simple subtraction from the 100 percent. Image classification procedures allow creation of weed maps to identify patches where the harrow should be set up to perform with higher intensity. Image based weed maps are used to define the increasing harrowing frequency.

Weed density and crop plant reductions are variables under measurement by hand; crop yield is assessed as grain yield. By using regression analysis, the selectivity curves, the recovery of the crop, the effect on competition and the yield response of the grain crop to different intensities of harrowing at different crop growth stages (timing) are defined and plotted. The analysis procedure was developed by Rasmussen et al. (2008). The models describe the percentage of weed control or yield loss relative to crop soil cover and are deduced from models on absolute values of leaf cover and weed density or leaf cover and grain yield. Timing and frequency of harrowing are analysed separately. Timing is determined by the models and intensity is ana-

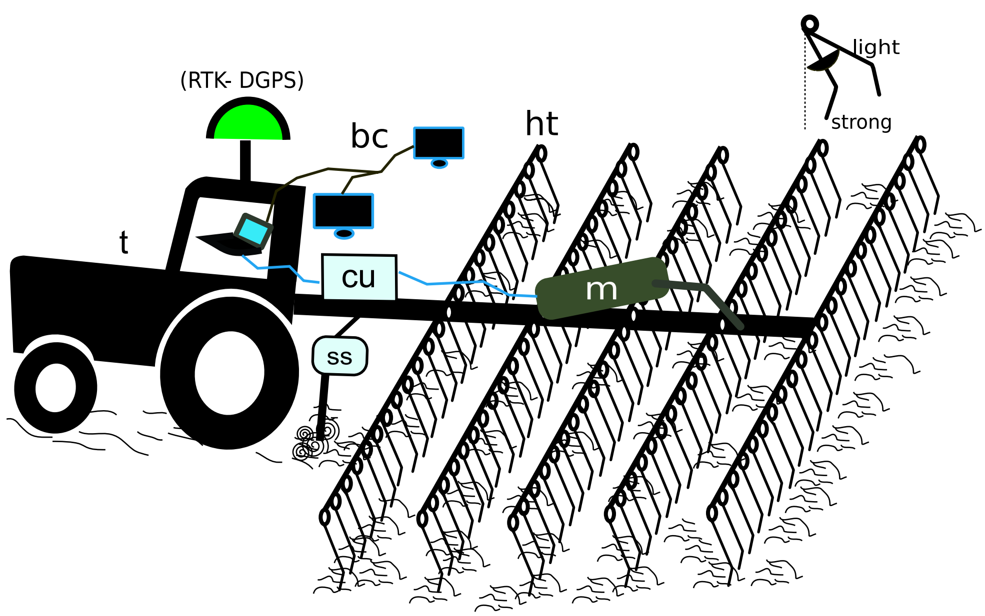

Fig. 6 Scheme of an automatically controlled real-time finger weeder

lysed by calculations of percentage of weed control, yield loss and crop soil cover.

Results

Examples for the results of the image based weed detection and site-specific application of herbicides are presented in the following.

Image based classification

A set of plants was used to determine the rate of identification based on different classification algorithms. The average identification rate was between 85 and 98% when plant species were grouped into five different classes (Table 1). Weed distribution maps using manual sampling and automatic camera weed identification were compared (Fig. 7).

On-farm-research

In the growing season 2007 such a field experiment was been done on corn. The distribution of weeds was relatively homogeneous with an average density of 28.1 weeds m^{-2}. There was no weed-free part on the field. In some regions of the field there were up to 150 weeds m^{-2}. The weed flora was mainly composed of *Chenopodium album*, *Polygonum aviculare L.*, *Veronica persica*, *Lamium purpureum*, *Galium aparine* and *Capsella bursa-pastoris*. The average density of grass weeds was 15.8 plants m^{-2}, while its distribution was concentrated in nests with up to 70 grass weeds m^{-2}, while the main grass weed was *Echinochloa crus-galli*.

Due to the uniform density of weeds, the weed control thresholds for site specific weed control had been outreached, therefore the herbicide use could not be reduced. For grass weeds a reduction in herbicide use was possible. The lower threshold led to a reduction of 26%, the higher threshold to savings of 42%.

Adaptation of economic thresholds

Due to the homogeneity of the soil, it was possible to ignore its effect on the yield. The interference of yield by weeds and grass were –0.028, or –0.047 kg ha^{-1} $plant^{-1}$. Since there were no sites in the field with no weeds and no Certrol B ap-

Table 1 Automatic classification of plant species in winter wheat (*Triticum aestivum L.*) using digital image analysis; data of 2,100 images

% identification	*T. aestivum*	Grass weeds	*G. aparine*	*M. chamomilla*	Other broad-leaves
T. aestivum	80	13	7	0	0
Grass weeds	0	100	0	0	0
G. aparine	0	0	92	0	8
M. chamomilla	0	0	0	100	0
Other broad-leaves	0	0	20	0	80
Total					86

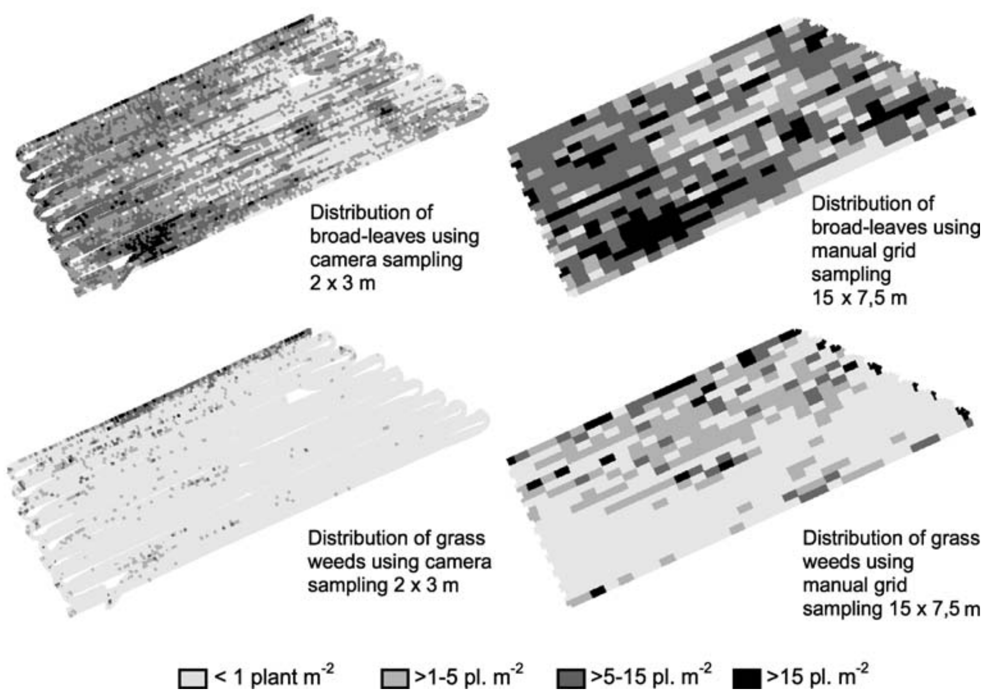

Fig. 7 Distribution maps for broad-leaved and grass weeds in a sugar beet field of 5.8 ha at Dikopshof Research Station

plication, the impact of Certrol B on the corn yield could not be determined. The effect of the application of Cato in areas without grass weeds was –0.341 kg ha^{-1}.

Table 2 shows the economic effect of the different weed control strategies. The economic yield of the conventional herbicide application is used as reference point. In this case an herbicide application, according to the average weed and grass weed density (28.1 weeds m^{-2}, 15.8 grass weeds m^{-2}), should be done on the entire field.

Fixed thresholds

With a site specific herbicide application and the use of fixed control thresholds (8 weeds m^{-2}, 3 grass weeds m^{-2}), due to the homogeneous weed distribution there would be a need to control weeds on 100% of the area. In the control of grass weeds, however, on 26% of the area a herbicide application can be omitted. Taking into account the economical effect of the remaining 1.1 grass weeds m^{-2} on 26% of the area (–0.013 t ha $plant^{-1}$), the lack of yield reduction of Cato on the same area (+0.089 t ha^{-1}) and the herbicide-saving, this herbicide application strategy would result in an economic benefit of 17.20 € ha^{-1}.

Adapted economic thresholds

For the adaptation of economic thresholds 29 € ha^{-1} for the application of Certrol B and 7,80 € ha^{-1} for the application of Cato were assumed, the price of corn was set to 200 € t^{-1}. The application costs have not been considered.

Since the yield effect of Certrol B could not be determined, the calculation of adjusted thresholds for weeds is not possible. For the grass weeds a threshold of 8 grasses m^{-2} was derived. On 42% of the area an application of Cato was not necessary. The interference of an average of 3 grass weeds m^{-2}, which would remain on this surface, would be –0.059 t ha^{-1}. On the other site the waiver of the application of Cato on 42% would lead to reduction of the negative yield effect of Cato on this area (+0.143 t ha^{-1}) and to herbicide savings. Thus, the site specific herbicide application using adapted economic thresholds leads to an economic benefit of 20.10 € ha^{-1}.

The achieved herbicide savings in the described experiments using the site specific herbicide application are in line with the results of other studies (Nordmeyer et al. 1997; Gerhards and Christensen 2003; Timmermann et al. 2003). Because of this the site specific herbicide application with its enormous herbicide savings potential fulfils social and political demands for a sustainable land management, water protection and conservation of biodiversity (Zwerger et al. 2004). It also offers the possibility to implement the demands of herbicide reduction programmes (BMVEL 2005). For the introduction of a site specific herbicide application in agriculture, however, the environmental benefits are not enough. There is also a need for economic benefits for farmers, at least to balance the additional financial expenses caused by this technique (Ackermann and Schwarz 1999). The previously known economic advantage of the site specific herbicide application consists only of the savings in herbicides. In the case of an application of a favourable herbicide, such as IPU (12 € ha^{-1}), a large herbicide saving potential is not able to equalise the added financial burden of a site specific herbicide application. This means that economic benefits, which are based on the savings of herbicide alone, are a very uncertain quantity of an economically successful site specific herbicide application.

In experiments, Deike et al. (2005) found that a low weed density in combination with a reduced herbicide application rate leads to a significant increase in the N-efficiency. Oebel (2006) found that a site specific herbicide application tends to result in increased cereal yields. In combination with the described statistical model the approach design used in the described trials, also called on-farm-research (Leithold and Traphan 2006), is able to quantify the yield effect of each variable parameter. It is possible to quantify the effect of the soil, weeds and the herbicide application on the yield.

The results of the described experiments on wheat and corn show that in areas without weeds application of herbicides causes yield losses. In wheat as well as in corn yield depressions of the herbicide application were observed. Based on the results of these experiments, different strategies for a herbicide application have been calculated. The calculations show that the economic benefits of a site specific herbicide application exceed the herbicide saving.

Table 2 Effect of weed control strategy on net return for maize, full application and patch spraying using economic thresholds

Application strategy	% herbicide savings Broad-leaved	Grass	Costs [€/ha]	Effect on yield [kg/ha] Broad-leaved	Grass	Herb. broadleaved	Herb. grass	Corn yield [kg/ha]	Net return [€/ha]
Fully	0	0	36.8	0	0	–	–	11,218	0
Fully, fixed thres.	0	0	36.8	0	0	–	–	11,218	0
Patch, fixed thres.	0	26	34.8	0	−13	–	89	11,294	17.2
Patch, adapted thres.	0	42	33.5	0	−59	–	143	11,302	20.1

The site specific herbicide application offers the possibility to avoid the negative yield effect of the herbicides in areas with low weed densities. In the corn experiment an application of Cato would be necessary only on 42% of the area due to the adapted economic threshold of 8 grass weeds m^{-2}. Thus the negative yield effect of –0.341 t ha^{-1} could be avoided on 58% of the area. Table 2 shows the different gains of several herbicide application strategies. An economically optimal use of this technology is only possible, if the site specific herbicide application is done by using an economically optimised threshold concept.

Therefore, this technology will play a critical role in decision support systems for site-specific weed control. The GIS-based analysing methodology is suitable for on-farm research, provides more information compared to classical experimental designs and thus potentially reduces costs in field trial operations.

Conclusions

The recent advances in technology allow site-specific chemical or mechanical weed control. Ongoing research is needed to improve sensors and application technology, but the general feasibility of these approaches has been shown. The required high accuracy in the detection of weeds and precise positioning demand new solutions. The combination of sensors and application technology to real-time systems, which are widely available and robust, will be the main driving force in the near future. To gain economic benefits from site-specific techniques detailed knowledge about the interactions of weeds and crop must be gathered. Criteria for the evaluation of the performance have to be developed. The on-farm-research approach using multi-variate models for the complex interactions of different influences can be used to identify the most important factors for successful weed management. Long-term experience guarding the population dynamics of weeds and the effect of reduced herbicide applications can be achieved with this technique. The site-specific use of herbicide can lead to an increased yield and improve the quality of the production.

The creation of weed maps from images has the potential to improve the accuracy and sampling rate of weed infestation measurements in the field. GIS are used to combine and analyse the information of different sensors and help develop new approaches as well as they become more and more an integral part of the instruments on the field. The information can be used to reduce the amount of herbicide and to improve the management decisions on a sub-field level. The gathered precision farming data is generally suitable to document the actions taken and review their benefits.

Mechanical weed control can be done on a plant level, if the discrimination of crop plants and weeds with a high positional accuracy is possible. Imaging sensors and RTK-DGPS solutions are the core technology for this. Several robotic seeding and weeding systems are the test bed for the combination of these sensors.

Many factors influencing the success of the weed management have to be studied and considered. Future decision support systems will incorporate the results of the research results achieved with these techniques.

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