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Patchy weed distribution and site-specific weed control in winter cereals

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Abstract Site-specific weed control in winter cereals was performed on the same fields every year over a 5-year period (1999–2003). The most common weeds (*Apera spica-venti, Galium aparine, Veronica hederifolia, Viola arvensis*) were counted by species, at grid points which were georeferenced and the data were analysed spatially. For weed control, weeds were grouped into three classes: grass, broad-leaved weeds (without *Galium aparine*), and *Galium aparine*. Based on weed distribution maps generated by the spatial analyses, herbicide application maps were created and site-specific herbicide application was carried out for grouped and or single weed species. This resulted in a significant reduction in herbicide use. Averaging the results for all fields and years, the total field area treated with herbicides was 39% for grass weeds, 44% for broad-leaved weeds (without *Galium aparine*) and 49% for *Galium aparine.* Therefore, site-specific weed control has the potential to reduce herbicide use compared to broadcast application, thus giving environmental and economic benefits.

Keywords Weed occurrence · Patches · Weed maps · Site-specific weed control

Introduction

Most farmers use herbicides based on the assumption of homogeneity within fields and of weed infestation. Weeds are never distributed uniformly throughout a field. Patchy weed distribution is the normal situation (e.g. Cousens and Woolcock 1997; Gerhards et al. 1997; Nordmeyer et al. 1997). There are many reasons for the occurrence of weed patches in fields (e.g. seed pools, dispersal, site heterogeneity and suitability, management). Herbicides were normally used at the same application rate throughout the whole field. Therefore, it can be assumed that

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herbicides were sprayed on areas with no weeds or with weed densities below economic threshold values. Critical analysis of risks and benefits of chemical weed control during the last decade and economic pressures have led to new considerations for herbicide reduction. Weed control adapted to the spatial distribution in weeds of agricultural fields is a way to gain economic and ecological benefits. Large savings in herbicide use are possible (e.g. Christensen et al. 1999). Herbicide use with a map-based approach was reduced in winter cereals by 60% for broad-leaved weeds and 90% for grass weeds (Gerhards and Christensen 2003).

Site-specific weed control requires detailed information about the spatial distribution of weeds. Weed distribution maps can be generated by discrete or continuous sampling techniques (Rew and Cousens 2001). Counting weeds in quadrats at the nodes of a grid is widely used for research purposes (e.g. Häusler and Nordmeyer 1999; Goudy et al. 1999). Methods of interpolation are needed to estimate weeds in unsampled areas. A commonly used method of interpolation is kriging, though Rew et al. (2001) have suggested that this might not be the most suitable method for estimating weed densities. Kriging has been used to interpolate data and to create weed and treatment maps (e.g. Heisel et al. 1996).

The main problem with site-specific weed control is how to map the spatial weed distribution at the required spatial resolution in a short time and at low cost. Automatic systems with high accuracy in weed detection are needed (e.g. optoelectronic sensors or digital cameras). Some systems developed for special applications (e.g. row crops and railways) have been successfully implemented. For weed detection in cereals, there are some promising developments (Oebel and Gerhards 2005; Gerhards and Christensen 2003; Gerhards and Sökefeld 2001).

Patch spraying can be carried out using different herbicides or no herbicides at all according to the spatial distribution of weeds and economic thresholds (i.e. the spray or no spray approach). The use of variable dosage is an additional concept (i.e. the low dose or high dose approach). In this study, site-specific weed control in winter cereals was carried out based on the weed-mapping concept. Weed maps and field specific threshold values were used to generate herbicide application maps. The objective was to show the possibilities of site-specific weed control in agricultural practice according to the spray or no spray approach.

Materials and methods

Field sites

Field studies were done over a 5-year period from 1999 to 2003. The farm ''Domäne St. Ludgeri'' with 440 ha of arable land is in the south-east of Lower Saxony, Germany (latitude 52°10′48″N; longitude 10°57′36″E). The mean annual rainfall is approximately 560 mm and the mean annual temperature is 8.4°C with a winter mean (December–February) of 0.3°C, and summer mean (June–August) of 16.4°C. The soil at the farm varies from loamy sand to clayey loam. The main crops in the crop rotation are winter wheat (WW), winter barley (WB), sugar beet (SB) and potatoes (P). Eight fields, with a total area of 106 ha, were chosen for the investigation (Table 1). Site-specific weed control was done in cereal crops only. In sugar beet and potato fields conventional uniform herbicide treatments were applied.

Table 1 Field characteristics, crop rotation, main weed species

Field code	Size [ha]	Number of grid points	Crop rotation 1999–2003	Main weed species in cereals
B244	11.8	122	WW-SB-WW-P-WW	*Apera spica-venti* (APESV*) *Veronica hederifolia* (VERHE) *Galium aparine* (GALAP)
GRW	14.1	136	WW-WW-SB-WW-WW	*Apera spica-venti* (APESV) *Galium aparine* (GALAP)
SF	17.8	168	WB-SB-WW-WW-WW	*Apera spica-venti* (APESV) *Galium aparine* (GALAP)
GM	11.6	150	WB-SB-WW-WW-SB	*Viola arvensis* (VIOAR) *Polygonum spp.* (POLSS)
MB	9.2	74	WW-WB-SB-WW-WW	*Apera spica-venti* (APESV)
SW	14.0	139	SB-WW-WW-WW-WW	Apera spica-venti *(APESV)* *Galium aparine* (GALAP)
GE	18.5	186	SB-WW-WW-WB-SB	*Apera spica-venti* (APESV) *Galium aparine* (GALAP)
OB	9.1	76	WW-WW-WW-SB-WW	*Apera spica-venti* (APESV)

* Codes according to the BAYER Code System (EPPO 2002)

Weed estimation

Weed species and their densities were counted at each grid point, located with Differential Global Positioning System (DGPS; model Leica GS50), using a square frame. For each field the grid spacing was 25 × 36 m, although a spacing of half the dimensions of the sprayer is the rule of the thumb (Cousens et al. 2002). This spacing was not practicable for our fields because of their size (9.1–8.5 ha). The grid spacing perpendicular to the direction of travel was twice that of the sprayer (36 m), that in the direction of travel was 25 m. For spraying a grid spacing of 18 × 18 m was chosen because the sprayer software allowed only a square grid spacing for herbicide spraying. The grid was orientated along the tramlines. Weeds were counted in two plots with an area of 0.1 m^2 at each grid point. The same grid points were used every year.

Weed densities were estimated in early spring before post-emergence herbicide application when cereals were at growth stages BBCH 13 (3-leaf stage) to BBCH 23 (tillering), and again 6–8 weeks after herbicide application.

Weed and herbicide application maps and data analysis

Experimental variograms were computed and modelled using GS^+ software (Gamma Design Software, Version 3.1). The variogram model parameters were used with the data for kriging to interpolate the weed data (GS^+ software). Weed maps were generated by SURFER 7.0. Based on these maps and according to threshold values given below for grouped weed species (broad-leaved weeds (BROWE), grass weeds (GRAWE)) and single weed species (*Galium aparine* (GALAP)), herbicide application maps were created with patch spraying software (AgroSat 2.0). The fields were divided into subunits of 18 × 18 m based on the tramline positions, and each subunit was marked as to whether it was to be sprayed or not. For decision making the following threshold values were used: GRAWE: 30 plants m^{-2}, BROWE: 40 plants m^{-2} and GALAP: 0.2 plants m^{-2}. These values are generally accepted for winter cereals in Germany (e.g. Gerowitt, 2002). For spraying, separate herbicide application maps were created for GRAWE, BROWE and GALAP. Patch spraying was undertaken using a commercial boom sprayer with a boom width of 18 m. The tractor was equipped with real-time DGPS (GPS 2100, Ag Leader Technology, Omnistar-Sat) and the on/off control of the sprayer was used. The process was repeated three times for each field.

To characterise patchy weed distribution the following indices were calculated: Lloyd's index of patchiness (Lloyd 1967) and Green's index (Ludwig and Reynolds 1988).

Lloyd's index of patchiness (PI) is given by

$$\mathrm{PI} = \frac{\bar{x} + \left(\frac{s^2}{\bar{x}} - 1\right)}{\bar{x}}, \tag{1}$$

where $\bar{x}$ is the mean and s^2 is the variance

If PI > 1, the weed population is described as an aggregated or patchy distribution across the field. An increasing PI index indicates an increase in patchiness.

Green's index (GI) is given by

$$\mathrm{GI} = \frac{\frac{s^2}{\bar{x}} - 1}{\sum x - 1} \tag{2}$$

If GI is $0 < \mathrm{GI} \leq 1$, the weed population is described as having an aggregated or patchy distribution.

Lloyd's (1967) and Green's (Ludwig and Reynolds 1988) indices are independent of the mean values. Therefore, a comparison of different samples with different plant densities and sample sizes is possible.

The temporal stability (patch stability) of weeds was described by Spearman's (r_s) rank correlation coefficient. It was used to determine the strength of relation between data from different years. Spearman's correlation coefficient is given by

$$r_s = \frac{6\sum_{j=1}^{n}(D)^2}{n(n^2 - 1)}, \tag{3}$$

where D is the difference between the ranks of corresponding values of X and Y, and n is the number of pairs of values.

The closer r_s is to +1 or –1, the stronger is the likely correlation. A perfect positive correlation is +1 and a perfect negative correlation is –1 ($-1 \leq r_s \leq +1$).

Results

Summary statistics of the weed groups GRAWE and BROWE at GRW field are shown in Table 2. The mean density of GRAWE was clearly higher in 2002 compared with the other years. The highest mean value for GRAWE and BROWE were estimated in 2002 and 1999. The maximum weed density was 435 plants m^{-2} for GRAWE (2000) and 250 plants m^{-2} for BROWE (1999). The variance to mean ratio

Table 2 Mean, variance, minimum and maximum density of grouped weed species at the GRW field in 1999 (n = 136), 2000 (n = 135), 2002 (n = 130) and 2003 (n = 133)

Weed group	Year	Mean (plants m^{-2})	Minimum (plants m^{-2})	Maximum (plants m^{-2})	Variance	Variance to mean ratio
GRAWE	1999	11.0	0	195	564.3	51.3
BROWE	1999	44.4	0	250	1143.1	25.7
GRAWE	2000	23.6	0	435	2431.6	103.0
BROWE	2000	23.2	0	120	437.1	18.8
GRAWE	2002	84.2	5	325	4254.1	50.5
BROWE	2002	11.6	0	72	270.6	23.3
GRAWE	2003	40.3	0	100	812.0	20.1
BROWE	2003	25.0	0	95	367.5	14.7

exceeded 1 for all weed groups and years. This indicates that the species are aggregated rather than randomly distributed.

Variograms were calculated from pairs of values in the four principal directions (Fig. 1). For GRAWE the shape of the variograms was similar for 2002 and 2003. However, the sill variance was much smaller in 2003 indicating that the spatial variation was less in 2003 than 2002. This is a result of lower weed density and less variation in 2003. For BROWE 2000, 2002 and 2003 the sill variances of the variograms (Fig. 1) are smaller than those of GRAWE, but the reverse is so for 1999.

Models were fitted to the omnidirectional experimental variograms and their parameters are given in Table 3. The nugget variance (c_0), sill variance ($c_0 + c$), and range provide quantitative measures of spatial dependence (Table 3 and Fig. 1). A nugget effect was present in most of the models. The largest nugget variances were for GRAWE 1999, 2000 and BROWE 1999, 2003. The isotropic spherical model adequately described the variation of GRAWE and BROWE for each year. The longest range of spatial dependence was approximately 272 m (BROWE 2003). The model parameters were used for kriging and the kriged predictions of the weeds were mapped.

The weed infestations in cereals were dominated by grass (*Apera spica-venti*) and broad-leaved weeds (*Veronica hederifolia, Viola arvensis, Galium aparine*). Figure 2 shows the maps of weed occurrence in field GRW for a period of 4 years. For all years, a clumped weed distribution with varying densities was observed. The highest mean densities for GRAWE occurred in 2002 and for BROWE in 1999. The size of weed-free areas differed from year to year. Based on the kriged maps of weed distribution and field specific threshold values, herbicide application maps were created. The success of site-specific weed control was assessed by counting weeds 6–8 weeks after herbicide application on sprayed and unsprayed areas.

Figure 3 shows the occurrence of GRAWE, BROWE and GALAP in field SW for 2001. Grass weeds occur in the middle of the field, broad-leaved ones are near the northern border and *Galium aparine* is near the southern border.

Figure 4 shows the herbicide application map and the weed distribution for field GRW two months after herbicide application. The horizontal and vertical lines divide the fields into sub-units (18 × 18 m) that receive the same treatment (Fig. 4b). Formerly unsprayed areas are nearly weed-free (<10 plants m^{-2}). Sprayed areas show weed densities up to 30 plants m^{-2}. Possible reasons for this weed infestation (Fig. 4a) are insufficient herbicide efficacy and the late germination of weeds.

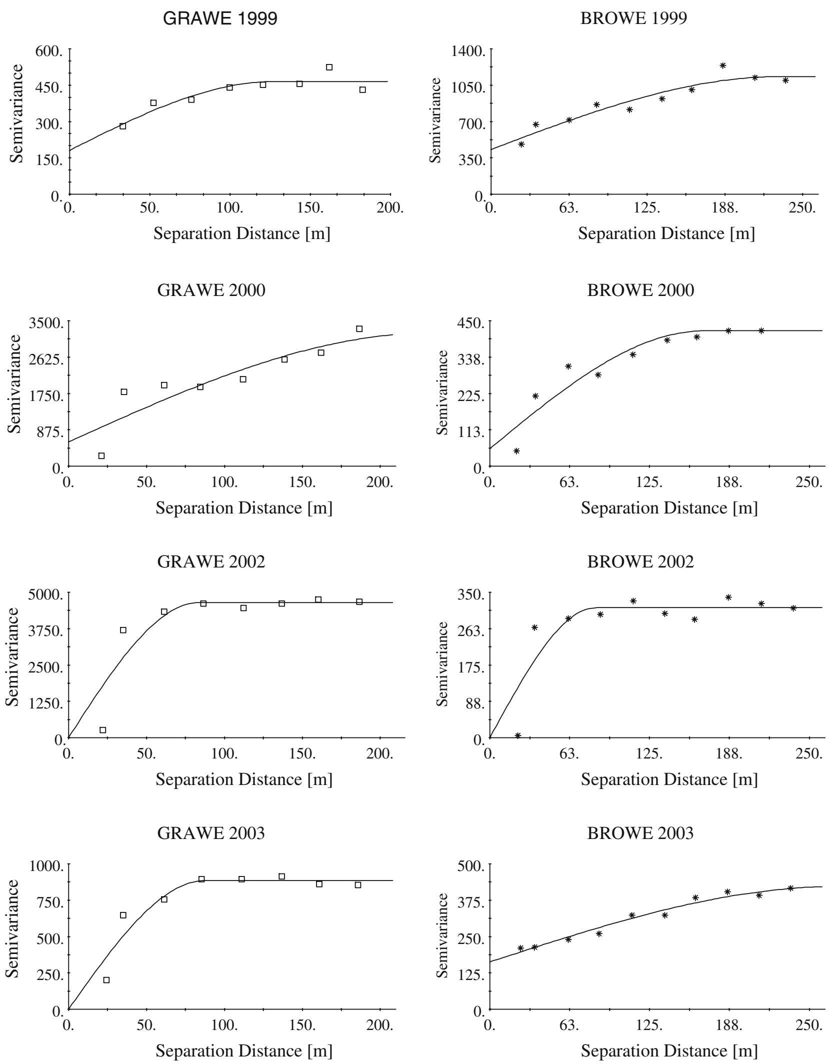

Fig. 1 Variograms for grass weeds (GRAWE) and broad-leaved weeds (BROWE) from 1999 to 2003 (field GRW)

Table 3 Model parameters fitted to experimental variograms and used for kriging

Weed	Year	Model	Nugget variance (c_0)	Sill variance ($c_0 + c$)	Range
GRAWE	1999	Spherical	144.5	460.3	109.8
	2000	Spherical	586.0	3205.0	232.8
	2002	Spherical	10.0	4643.0	83.6
	2003	Spherical	1.0	884.2	87.4
BROWE	1999	Spherical	431.0	1132.0	231.6
	2000	Spherical	54.0	418.9	167.6
	2002	Spherical	0.1	312.7	83.0
	2003	Spherical	162.7	422.1	272.4

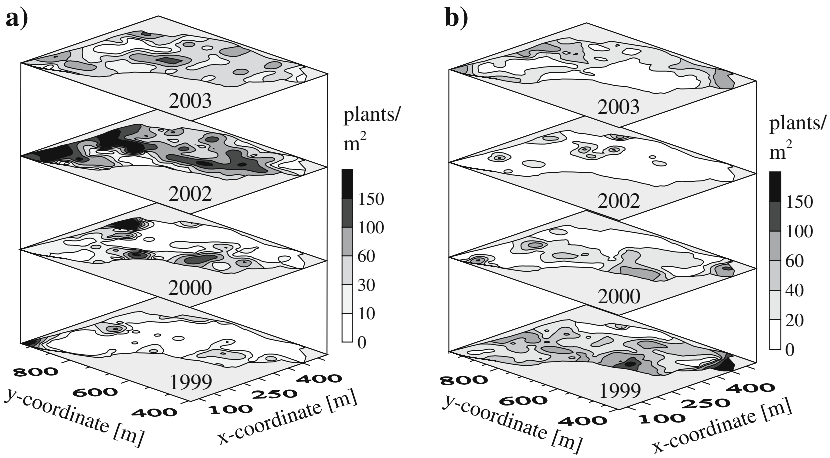

Fig. 2 Kriged maps of weed distribution before herbicide application for grass weeds (**a**) and broad-leaved weeds (**b**) over a 4-year period at GRW

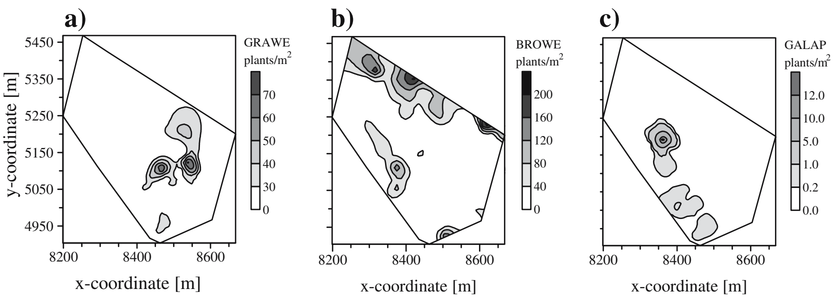

Fig. 3 Weed distribution before herbicide application for (**a**) grass weeds (GRAWE), (**b**) broad-leaved weeds (BROWE, and (**c**) *Galium aparine* (GALAP) at SW

Table 4 summarises the percentage area of each field treated with herbicides each year. In most cases, herbicide treatment of the whole field was unnecessary. The parts of the field that needed to be treated differed considerably between fields and years. Control of grass weeds was unnecessary for fields SW in 2000, B244 in 2001, and GM in 2001 and 2002. On the other hand, herbicide treatment was necessary over the entire field for GALAP in fields B244 and GRW in 1999 as well as GRW and SW in 2000. In general, however, over a period of 5 years herbicide use was reduced significantly, when compared with broadcast application. On average an area of only 38.6% for GRAWE, 44.2% for BROWE and 46.5% for GALAP had to be treated with herbicides.

Figure 5 shows the frequency of treatment at the grid points of field SF over a 3-year period. A frequency of three denotes herbicide application in all 3 years. A frequency of zero (untreated area) indicates that during the period of investigation, no weeds or weed densities below threshold values only were mapped at this grid point for years with winter cereals in the crop rotation, therefore there was no herbicide application.

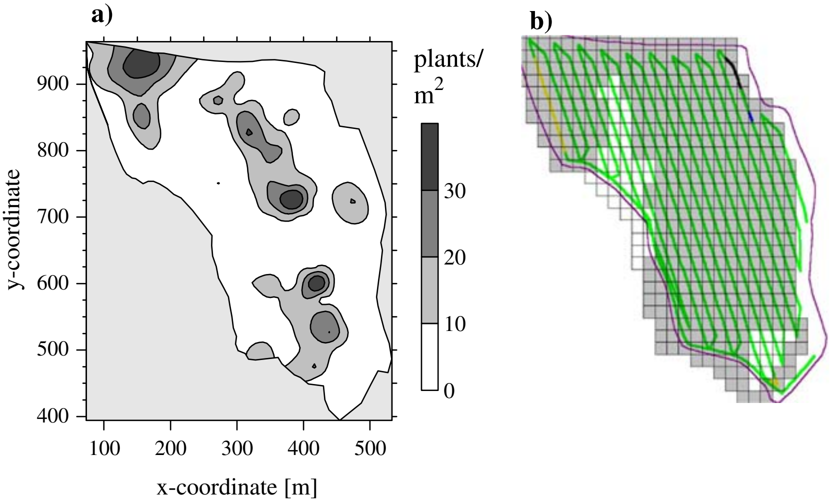

Fig. 4 Weed distribution after herbicide application at GRW in 2002 (**a**) and herbicide application map of the same year (**b**), sprayed subunits (18 × 18 m) are marked in grey

Over a period of 3 years, 139 points (82.6%) were free of GRAWE, 66 (39.5%) were free of BROWE, and 113 (67.7%) were free of GALAP.

To assess temporal variability of grouped and single weed species, the Spearman rank correlation coefficients were calculated (Table 5). For fields SF and GRW, the coefficients were positive and statistically significant, indicating similar patterns of weed distribution during the period investigated.

Correlations of 0.4–0.519 show a moderate relation between the years examined with some similarity in the distribution of weeds. For correlations <0.4 the relations are weak and show limited correspondence in the patterns between years.

Indices of aggregation (Lloyd's (PI) and Green's index (GI)) for grouped and single weed species are given in Table 6 for all fields. Values of PI > 1 and GI > 0 indicate aggregation. In all cases a more or less aggregated spatial weed distribution is evident. In most cases the aggregation of GRAWE is greater than that for BROWE. Single weed species like GALAP showed higher aggregation than that of BROWE (exception B244, 2000 and 2001). The maximum PI value is 66.6 (GALAP, GE 2001) indicating strong aggregation. BROWE shows less change in aggregation for all fields with PI-values from 1.3 to 8.9 compared to GRAWE (1.5 to 60.2).

Field MB shows a range in PI from 1.5 to 24.8 for GRAWE indicating a high variation in weed distribution between the years. Over all years field SF and GE showed a higher aggregation for GRAWE compared to other fields.

Discussion

The results presented above on the spatial variation of weed populations confirm the need for site-specific weed control. In all cases the weeds were aggregated, but the levels of infestation varied considerably for the years studied in the same field. The infestation level of large areas of these fields was often below threshold densities. The presence of areas below the economic threshold value is a prerequisite

Table 4 Percentage of total field area treated for the control of grass weeds (GRAWE), broad-leaved weeds (BROWE) and *Galium aparine* (GALAP) in each year

Field	1999			2000			2001			2002			2003		
	GRAWE	BROWE	GALAP	GRAWE	BROWE	GALAP	GRAWE	BROWE	GALAP	GRAWE	BROWE	GALAP	GRAWE	BROWE	GALAP
B244	11	72	100	□	□	□	0	4	13	+	+	+	0	17	100
GRW	77	77	100	71	71	100	□	□	□	88	39	39	100	70	70
SF	73	73	53	□	□	□	24	65	43	7	49	21	11	40	75
GM	7	79	79	□	□	□	0	30	4	0	0	0	□	□	□
MB	64	0	0	71	0	0	□	□	□	95	45	45	100	0	0
SW	-	-	-	0	77	100	14	24	46	□	□	□	26	52	23
GE	-	-	-	66	66	62	6	16	40	36	55	55	□	□	□
OB	-	-	-	84	0	0	54	4	7	□	□	□	70	50	0

-Fields not included in the research programme

□Sugar beet in the crop rotation – no site-specific weed control

+Potatoes in the crop rotation – no site-specific weed control

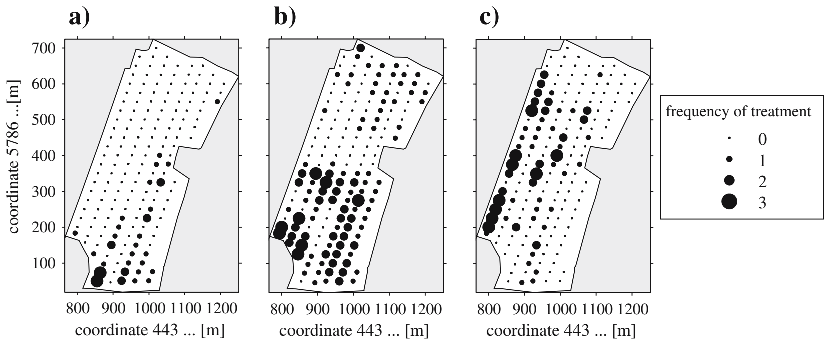

Fig. 5 Frequency of herbicide treated and untreated areas at the grid points of field SF over a 3-year period (1999, 2001, 2002) for GRAWE (**a**); BROWE (**b**); GALAP (**c**)

for site-specific weed control. The size of patches depends on the weather and soil conditions at the time of weed emergence. Patches will be larger in years with a large rate of weed emergence and smaller when there is less emergence.

In general, weed mapping with grid spacings of 25 × 36 m provides, a sufficiently detailed map for the application of herbicides. Estimation of weeds during the growth period after site-specific herbicide application verifies this assessment. The work showed that it is possible to create weed maps with sufficient accuracy by sampling along the tramlines. For site-specific weed control to be successful there must be a concentrated distribution of weed species without changes in weed density at short distances.

Averaging the results for all fields and years, the total field area treated with herbicides was 39.4% for grass weeds, 43.7% for broad-leaved weeds (without *Galium aparine*), and 48.5% for *Galium aparine.* Some areas in the cereal crop remained untreated with herbicides for the period of investigation. Other research data show similar results (e.g. Gerhards and Christensen 2003; Heisel et al. 1997), but not over so many years. Gerhards et al. (1997) and Gerhards and Sökefeld (1999) found that herbicide treatment in two fields of winter wheat was only warranted on 55% and 58% of their areas, respectively, and in another field only 54% required treatment. However, herbicide reduction was considerably less than that reported by Hanson and Wicks (1993) and Hanks and Beck (1998) using weed

Table 5 Spearman' s rank correlation coefficient (r_s) between years for grouped and single weed species

Field	Weed species	1999 and 2001	1999 and 2002	2001 and 2002
SF	GRAWE	0.455*	0.354*	0.358*
	BROWE	0.159*	0.296*	–0.066
	GALAP	0.407*	0.337*	0.377*
		1999 and 2000	1999 and 2002	2000 and 2002
GRW	GRAWE	0.366*	0.217*	0.152
	BROWE	0.519*	0.112	0.002
	GALAP	0.331*	0.503*	0.280*

* $P \leq 0.05$

Table 6 Lloyd's Patchiness (PI) and Green's Index (GI) of grass weeds (GRAWE), broad-leaved weeds (BROWE) and *Galium aparine* (GALAP)

Field	Year	GRAWE		BROWE		GALAP	
		PI	GI	PI	GI	PI	GI
B244	1999	60.2	0.519	1.6	0.005	2.4	0.011
	2000	+	+	4.5	0.028	1.9	0.008
	2001	4.1	0.034	7.9	0.057	1.9	0.007
	2002	-	-	-	-	-	-
	2003	7.4	0.040	3.2	0.014	5.5	0.029
GRW	1999	5.6	0.034	1.6	0.004	2.8	0.013
	2000	5.3	0.032	1.8	0.006	3.0	0.015
	2001	6.9	0.044	1.5	0.004	13.2	0.093
	2002	1.6	0.005	3.2	0.017	10.6	0.075
	2003	1.5	0.004	1.6	0.004	33.2	0.013
SF	1999	8.2	0.043	3.4	0.014	10.6	0.057
	2000	20.3	0.118	3.2	0.014	4.0	0.019
	2001	11.7	0.064	2.3	0.008	11.8	0.067
	2002	4.9	0.024	2.4	0.009	15.5	0.088
	2003	15.8	0.089	2.3	0.008	5.6	0.028
GM	1999	+	+	1.5	0.004	9.8	0.071
	2000	+	+	1.8	0.007	18.2	0.152
	2001	+	+	2.9	0.019	23.7	0.246
	2002						
	2003	+	+	1.8	0.008	+	+
MB	1999	5.2	0.056	2.6	0.022	30.1	0.437
	2000	8.1	0.095	5.4	0.060	+	+
	2001	24.8	0.360	4.7	0.054	+	+
	2002	1.8	0.012	4.6	0.053	+	+
	2003	1.5	0.007	+	+	+	+
SW	1999	-	-	-	-	-	-
	2000	7.0	0.043	6.6	0.040	7.0	0.043
	2001	14.2	0.115	8.9	0.068	11.8	0.096
	2002	6.2	0.048	2.0	0.009	4.4	0.031
	2003	4.0	0.020	4.2	0.021	47.4	0.321
GE	1999	-	-	-	-	-	-
	2000	15.8	0.080	3.4	0.013	21.6	0.112
	2001	41.8	0.219	3.7	0.015	66.6	0.351
	2002	9.2	0.053	3.1	0.014	11.3	0.067
	2003	29.0	0.155	2.5	0.008	3.8	0.015
OB	1999	-	-	-	-	-	-
	2000	2.5	0.019	+	+	53.4	0.757
	2001	2.6	0.021	3.2	0.029	+	+
	2002	8.2	0.116	1.3	0.005	59.8	1.000
	2003	+	+	2.9	0.024	60.0	0.811

-Fields not included in the research programme

+No calculations (low weed density)

sensors. Consequently, weed treatment with herbicides over the whole field is not required and spatially directed applications do have the potential to reduce herbicide use, with economic and environmental benefits.

Other studies have shown that estimates from data on a grid and kriging are not sufficiently accurate for site-specific weed control (e.g. Rew et al. 2001). They often result in under- or over-estimates of weed densities. The distance over which weed densities change can be very short. So weed distribution and sampling strategy are important for creating weed maps (Cousens et al. 2002). Often a grid spacing of 25×36 m is not sufficient and information has been lost through undersampling.

Previous research has documented the stability of weed populations (Wilson and Brain, 1991); however, predicting weed densities before emergence has been difficult to achieve. The results presented demonstrate a temporal stability of weed patches in parts of fields, but the patches are not identical from year to year. In addition, the weed densities varied considerably depending on the method of soil cultivation, weather conditions, and crop and weed emergence.

A key problem in site-specific weed control that still remains is data acquisition, which has not changed since early 1990. Manual weed counting is time consuming and expensive and not acceptable for agricultural practice. Automatic weed detection systems are necessary, and then it will be feasible to integrate site-specific weed control into the concept of precision agriculture.

Site-specific weed control represents a strategy to reduce herbicide use. In recent discussions about consumer protection, management in agriculture, environmental tolerance and transparency in the food production process, this type of weed control will have important implications for the future.

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