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Spatial and temporal dynamics of *Apera spica-venti* seedling populations

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ABSTRACT

Apera spica-venti is an important weed problem in winter cereals in Europe. Spatial and temporal dynamics of *A. spica-venti* were investigated to test the hypothesis that this species has a spatially aggregated distribution. *A. spica-venti* distribution was quantified over several crop rotation sequences in three commercial fields. From 1999 to 2006, the spatial pattern of *A. spica-venti* was sampled yearly at the same grid points. Geostatistical techniques were used to characterise the spatial and temporal variability of *A. spica-venti* density. The spatial pattern was analysed by Lloyd's index of patchiness. From year to year, differing aggregation of *A. spica-venti* resulted in weed patchiness. The Spearman Rank Correlation Coefficient (r_s) was used to discover the strength of *A. spica-venti* occurrence in several years. For two sites there were significant correlations of weed occurrence between years but the relationship was less strong for the third field. Based on rank correlation coefficients, the temporal dynamics were marked by an overall continuity of distribution patterns. Knowing that spatial distributions of weeds vary little in time can reduce sampling efforts, and increases feasibility of site-specific weed control.

1. Introduction

Apera spica-venti (L.) P. Beauv. is a common annual grass weed that occurs in winter cereals and winter oilseed rape in Germany. Furthermore, it is a wide-spread weed species in Europe and it is well known that infestations tend to increase when the proportion of winter cereals in the crop rotation is increased. In Eastern Europe, *A. spica-venti* spreads constantly (Kvartekova, 1990). Soukup et al. (2006) estimated an increasing occurrence in winter cereals in the Czech Republic. *A. spica-venti* is an invading weed to North America from Europe. In the USA and Canada, *A. spica-venti* is an increasing winter wheat weed problem (Northam and Callihan, 1992; Chomas and Kells, 2001; Warwick et al., 1987). Further spreading of *A. spica-venti* in temperate cereal producing areas around the world is expected.

A. spica-venti is primarily found on sandy or light loamy soils. Plants have been found to produce up to 2000 seeds (Warwick et al., 1985). The stability of spatial structure of *A. spica-venti* populations over several years, although essential for patch development through time, has not been studied extensively.

Weed populations have been reported to exhibit varying degrees of spatial aggregation and in most cases were highly aggregated resulting in clearly defined patches (Gerhards et al., 1997; Webster et al., 2000; Perry et al., 2002; Gerhards and Christensen, 2003; Jurado-Exposito et al., 2003). Weed patchiness offers the opportunity to reduce herbicide use if low or non-infested areas can be identified. Depending on the extent of heterogeneity and weed threshold values, herbicide application could be site-specific and lead to considerable savings in the amount of herbicides used (Oebel and Gerhards, 2005). Stable spatial distributions of weeds over years could help to decrease the costs of acquiring data. At limited temporal variation in the spatial pattern of weeds, one year's weed distribution may predict patterns in subsequent years, and thus facilitate weed monitoring for patchy weed control. Some weed species are spatially stable over time with low changes in weed density and patch margins (Johnson et al., 1996; Colbach et al., 2000). For example, *Alopecurus myosuroides* was distributed in clumped patterns in winter cereals (Wilson and Brain, 1991). A patchy distribution of several annual broad-leaved weeds was found in cereals and sugar beet (Nordbo et al., 1994; Walter, 1996); grass weeds were also distributed in patches (Nordmeyer et al., 2003). This patchy weed distribution (including *A. spica-venti*) allowed site-specific weed control in winter cereals (Nordmeyer, 2006). The previous paper assessed data from 1999 to 2003; the present research extends the data base to 2006.

The dispersion of a population and the description of the pattern of distribution in space is important. The analysis of spatial distribution pattern is recognized as an indispensable procedure for weed population studies. The first step is to divide an area into units of equal size and then to describe the pattern using mathematical distribution models. The simplest model is the Poisson distribution with the single mean parameter. This model assumes

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a purely random distribution of weed species so that it serves as a criterion for classifying data in three categories: uniform, random, and patchy distribution. Most weed occurrences show patchy distributions, with the variance larger than the mean. For such a distribution a two-parameter mathematical model has been proposed. Ecologists often use the negative binomial distribution and have interpreted the function as indicating that populations tend to be aggregated. The negative binomial distribution is suitable to fit data over time and space for weed populations (Johnson et al., 1995). Wiles et al. (1992) found that in most cases the data could be represented by a negative binomial distribution. Associated with the negative binomial distribution is the *k* parameter that is a non-spatial aggregation parameter related to the variance at a given mean value. Johnson et al. (1995) estimated that there was no stable or common *k* value across field sites and years. The *k* value has often been misinterpreted to describe spatial weed aggregation. Nevertheless Nicot et al. (1984) demonstrated that the negative binomial could be associated with regular, random or aggregated spatial patterns. For measuring weed patchiness different indices are appropriate (Morisita, 1962; Lloyd, 1967; Iwao, 1970; Kuno, 1991). The use of these indices is sometimes criticized because data are often – significantly correlated with mean densities.

The objectives of this study were to characterise the spatial and temporal variability of *A. spica-venti* in winter cereals. Over seven growing seasons, three commercial fields were investigated while under site-specific weed management.

2. Materials and methods

2.1. Site description

Three commercial fields in an arable area in northern Germany with winter cereals and sugar beet in the crop rotation were chosen for this investigation. The conventionally managed fields varied in size between 9.1 and 17.8 ha. They were ploughed annually and treated with post-emergence herbicides in spring. Herbicides were sprayed site-specifically in winter cereals according to weed distribution maps and weed threshold concepts. Further details are described by Nordmeyer (2006). Sugar beet crops in the rotation were not site-specifically sprayed and not included in the investigations reported here.

2.2. Weed estimation

Weed were monitored from 1999 to 2006 using a grid coordinate system ($25 \text{ m} \times 36 \text{ m}$). *A. spica-venti* was identified and counted at each grid point ($0.32 \text{ m} \times 0.32 \text{ m}$) once a year prior to post-emergence weed control in spring (March/April). No earlier herbicide treatments were done. Weed densities were calculated per square metre. The sampling grid points were recorded by DGPS (Differential Global Positioning System) with an accuracy of <1 m.

2.3. Data analysis

Spatial variability of *A. spica-venti* within a specific field was described using the empirical semi-variogram (equation (1)). The semi-variogram characterises the average degree of similarity between values as a function of separation distance and direction (Rossi et al., 1992). Variability of *A. spica-venti* was characterized by experimental semi-variogram $y(h)$ using the following equation:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i + h) - z(x_i)]^2 \quad (1)$$

where $\gamma(h)$ is the semi-variance for interval distance class h, $z(x)$ and $z(x+h)$ are *A. spica-venti* densities at points x and $x+h$, and $N(h)$ is the total number of pairs within the distance interval h.

The geostatistical analysis software GS+ (Gamma Design Software) was used for calculating semi-variances and fitting semi-variogram models. Spherical and linear models were fitted to the experimental semi-variograms. There are three important parameters in the experimental semi-variogram: the nugget variance, sill and range. The nugget variance is the variance at zero distance and could be the result of variability due to sampling error and represent small-scale variation that cannot be described with the present sampling scheme. The sill is the asymptotic plateau of the semi-variogram function, describes the variance and is used to estimate the range. The range is the distance, at which the sill occurs and data are no longer autocorrelated. Semi-variograms were plotted for each year of sampling. Kriging is an interpolation procedure and was used to provide the best possible estimates of weed seedling densities at locations across the field that were not sampled. The parameters of the semi-variogram model are used in the kriging procedure. Contour maps were calculated using the kriging-interpolation with the software package SURFER 7.0 (Golden Software, Inc.).

A further step in the analysis of the spatial pattern of populations is quantifying the degree of aggregation. Descriptive statistics (mean, standard deviation, skewness) and an index of aggregation were calculated for *A. spica-venti* for each field by year. Lloyd's index of patchiness (Lloyd, 1967) was calculated to characterise the patchiness of distribution:

2.4. Lloyd's index of patchiness

$$\text{Lloyd's index of patchiness (PI)} : \text{PI} = \frac{\bar{x} + \left(\frac{s^2}{\bar{x}} - 1\right)}{\bar{x}} \quad (2)$$

where $\bar{x}$ = mean, s^2 = variance

If PI > 1, the weed population is described as an aggregated or patchy distribution across the field. With increasing patchiness, the index increases.

2.5. Spearman's rank correlation coefficient

Spearman's rank correlation coefficient (r_s was used to determine the strength of relation between data of different years; and to test distribution patterns overlap to a high degree with the field area that was treated with herbicide. Spearman's correlation coefficient is given by

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

where D = the difference between the ranks of corresponding values of X and Y, and n = 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 ($-1 \le r_s \le +1$).

3. Results

Winter cereals and sugar beet were in the crop rotation of the studied fields. Only few *A. spica-venti* plants were present in sugar beet (less than 1 plant/m^2). Consequently, the years when the fields were planted to sugar beet were omitted from analyses. Density and spatial distribution of *A. spica-venti* varied with years within fields. Mean densities ranged from <2 to 235 plants/m^2 (Table 1) with a wide range of min/max values. Mean densities varied considerably across fields and years. Standard deviations of the means were high. Weed density data were positively skewed because of a large proportion of grid points contained no seedlings. The skewness values for *A. spica-venti* indicated non-normal distributions.

To describe the spatial dependence the isotropic semi-variogram was chosen. No differences in spatial dependence were estimated with the directions (anisotropic semi-variograms). According to semi-variogram analyses, *A. spica-venti* density data showed differences in spatial dependence. Different modelled semi-variograms were defined (Table 2). The semi-variograms of *A. spica-venti* are shown in Fig. 1 for field OB and SF for the years 2005 and 2006. For both sites the computed semi-variograms are similar following a spherical curve.

Nugget variance, sill and range varied greatly among years and between years. Field GRW and SF showed the highest nugget variance and sill. Overall the range varied from 20.7 m to 211.8 m (Table 2).

In general, the results support the assumption of an aggregated occurrence of *A. spica-venti*. Fig. 2 shows distribution maps of *A. spica-venti* for field SF in different years. The initial distribution (1999) of *A. spica-venti* was heterogeneous, with an area relatively free of weed plants in the upper part of the field. Over the period of investigation the weed densities varied between 0 and >350 plants per square metre. Changes in spatial pattern could be observed. Patches of *A. spica-venti* varied in size and density. In 2002/2003, a new patch with a plant density up to 150 plants per square metre arose in the middle of the field. From 1999 to 2003, most of the field (50–80%) was nearly free of *A. spica-venti.*

For field OB for each year, low densities of *A. spica-venti* were estimated in year 2003 and 2006 (Fig. 3). In 2006, the field was nearly free of weeds; *A. spica-venti* was aggregated in all years. *A. spica-venti* populations did not have abrupt density changes.

Lloyd's patchiness index was used to assess the aggregation of *A. spica-venti.* The index of aggregation for each field and year is given in Table 1. Lloyd's patchiness index shows a very clear trend to aggregation. Values indicating aggregation are $PI > 1$. A low spatial aggregation was found for GRW (data sets of 2002, 2003, 2006), OB (data sets of 2000, 2001, 2003, 2004, 2005) and SF (data sets of 2005, 2006) indicated by low values of Lloyd's index of patchiness (Table 1). The highest aggregation was estimated for OB (2006) and SF (1999, 2001, 2003). In the mean of all years, SF showed the highest aggregation of *A. spica-venti.*

Apart from the overall tendency of weed seedling populations to form aggregated spatial patterns, the table illustrates that marked patchiness is connected with low densities and vice versa. In these results, *A. spica-venti* populations in cereal fields had an aggregated spatial pattern.

In the Spearman's correlation analysis between seasons, weed distribution patterns within a field were assessed by rank correlation coefficients between pairs of weed counts for *A. spica-venti.* Significant temporal stability occurred in each field (Table 3). The highest correlation was greater than $R = 0.7$. Field SF and OB are

Table 2
Model parameters fitted to experimental variograms and used for kriging.

Weed	Year	Model	Nugget variance (c_0)	Sill variance ($c_0 + c$)	Range (m)
GRW	1999	Spherical	14.0	503.0	22.1
	2000	Spherical	564.0	2947.0	211.8
	2002	Spherical	10.0	4394.0	86.6
	2003	Spherical	1.0	899.9	88.6
	2004	Spherical	10.0	26470	81.6
	2006	Spherical	9200.0	69750.0	181.6
OB	2000	Exponential	390.0	2422.0	84.6
	2001	Spherical	249.0	2564.0	95.9
	2003	Spherical	0.1	134.5	20.7
	2004	Spherical	1.0	596.1	74.9
	2005	Spherical	1.0	1717.0	63.1
	2006	Spherical	0.1	54.6	45.6
SF	1999	Linear	348	529.2	184.7
	2001	Linear	115.2	156.8	184.7
	2002	Spherical	39.8	89.5	127.2
	2003	Spherical	1.0	389.3	98.4
	2005	Spherical	3210.0	12550.0	106.6
	2006	Spherical	1.0	1542.0	62.4

Table 1
Field details, descriptive statistics of *A. spica-venti* density (plants m^{-2}) and Lloyd's index of aggregation.

Field	Year	Crop	Mean	Min	Max	Std deviation	Skewness	Lloyd's patchiness index (PI)
GRW (14.1 ha)	1999	WW	11	0	195	24.1	4.53	5.8
	2000	WW	24	0	435	50.1	5.00	5.3
	2001	SB	#	#	#	#	#	#
	2002	WW	84	3	325	65.2	1.26	1.6
	2003	WW	41	0	100	28.6	1.00	1.5
	2004	WW	69	0	830	150.2	5.39	5.8
	2005	SB	#	#	#	#	#	#
	2006	WW	235	0	1250	278.4	1.61	2.4
OB (9.1 ha)	1999	SB	#	#	#	#	#	#
	2000	WW	33	0	160	40.6	1.66	2.5
	2001	WW	35	0	185	45.3	1.69	2.6
	2002	SB	#	#	#	#	#	#
	2003	WW	13	0	30	10.6	0.33	1.7
	2004	WW	28	5	100	24.2	1.57	1.7
	2005	WW	36	0	175	39.5	1.89	2.2
	2006	WB	4	0	55	8.5	3.78	10.3
SF (17.8 ha)	1999	WB	9	0	150	24.8	3.87	8.4
	2000	SB	#	#	#	#	#	#
	2001	WW	2	0	85	9.2	5.92	18.4
	2002	WW	4	0	50	9.1	2.61	5.2
	2003	WW	5	0	220	18.6	9.75	15.8
	2004	SB	#	#	#	#	#	#
	2005	WW	98	0	490	118.5	1.60	2.5
	2006	WW	30	0	250	40.1	2.32	2.8

WW = winter wheat; WB = winter barley; SB = sugar beet.
# No calculations possible; absence of *A. spica-venti* in sugar beet.

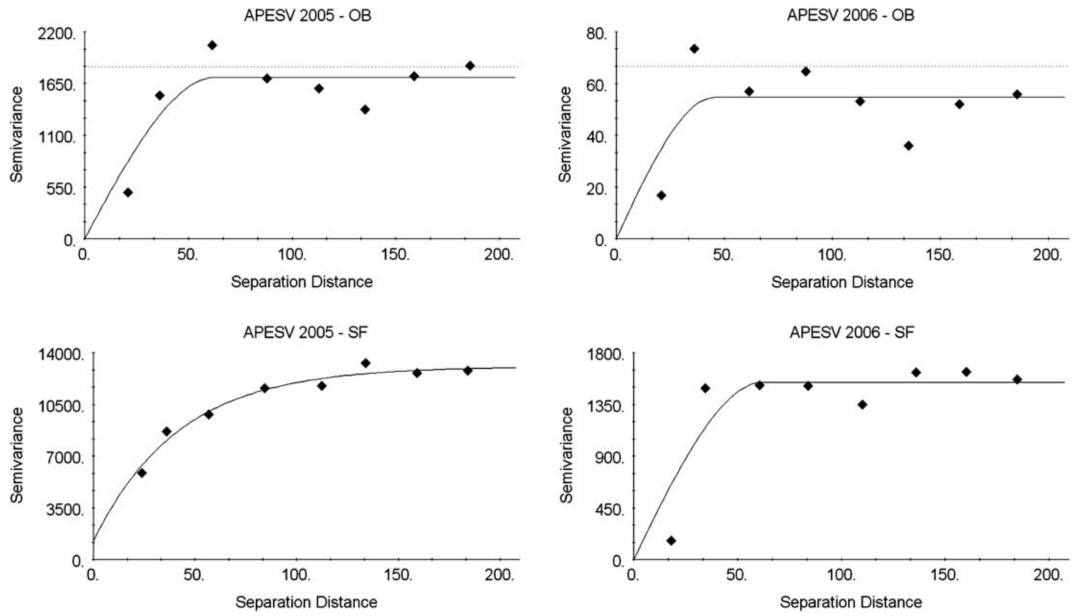

Fig. 1. Weed density semi-variograms for *Apera spica-venti* in 2005 and 2006 (field OB and SF).

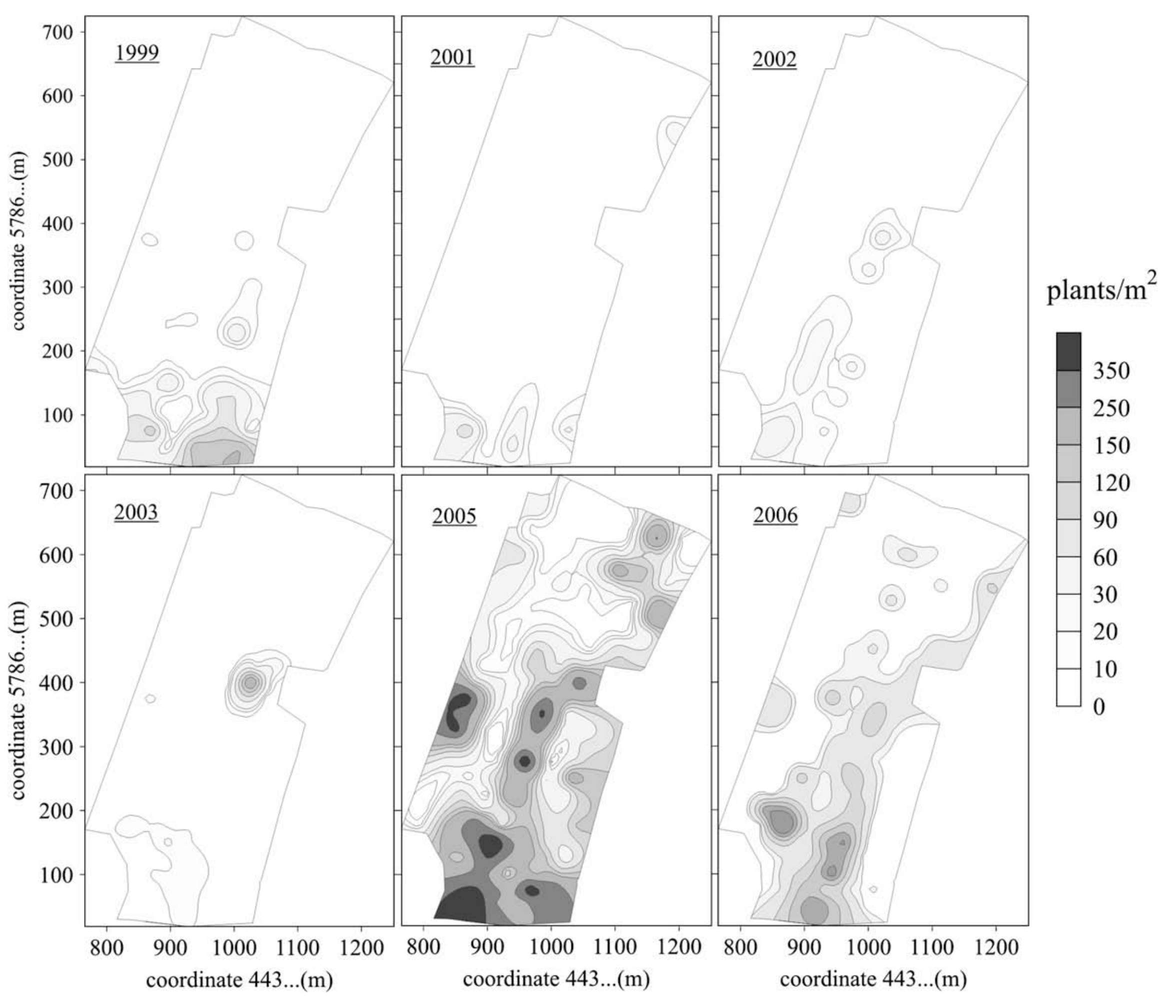

Fig. 2. *Apera spica-venti* distribution maps (field SF).

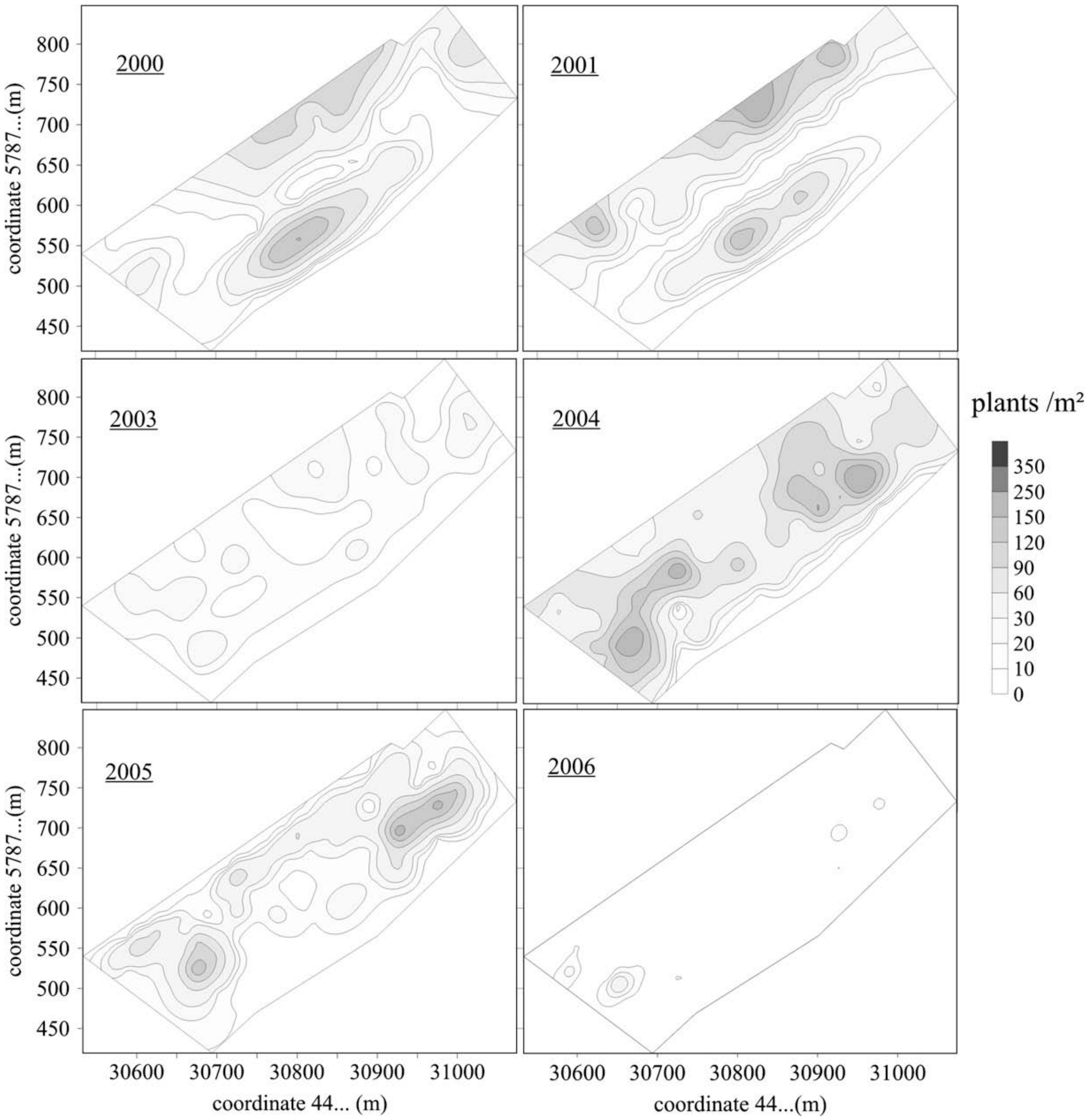

Fig. 3. *Apera spica-venti* distribution maps (field OB).

showing the highest positive coefficients (SF 2002/2003 und 1999/2001; OB 2000/2001 und 2003/2005), indicating a strong association between the weed patch location in the different years. Field GRW showed not such a strong relation between different years; values varied between −0.194 and +0.370. A negative coefficient was calculated for GRW for several years. A significant negative coefficient was calculated for the pair of years 2004 and 2006.

4. Discussion

To estimate and assess the spatial and temporal variability of weeds, grid sampling of *A. spica-venti* was carried out, semi-variograms were estimated, distribution maps were created, aggregation indices and Spearman's rank correlation coefficients were calculated.

The results presented of *A. spica-venti* populations indicate a heterogeneous occurrence and a relatively high continuity of distribution patterns in time. The results suggest an overall tendency of *A. spica-venti* populations to form aggregated spatial patterns within agricultural fields and that weed emergence changed over time within fields. In the literature, other weed species have been reported to be quite stable spatially over time with moderate fluctuations in density and patch location (e.g. Gerhards et al., 1997; Dieleman and Mortensen, 1999). In general, reasons for the spatial and temporal dynamics of weeds within agricultural fields are manifold, and as complex as the agricultural ecosystem itself (Cousens and Mortimer, 1995). Environmental factors such as the spatial distribution of suitable habitats, weed biology, e.g. seed production characteristics, and soil variability play an important role. In addition, agricultural management factors modify the spatial distribution of weeds to a certain extent, e.g. tillage can distribute weed seeds. In the current investigation, it is assumed that environmental factors and soil variability are the main reasons for the different spatial distribution between the fields. No differences in agricultural management were present.

Table 3
Spearman's rank correlation coefficient (r_s) for *A. spica-venti*.

Field GRW						
Year	1999	2000	2002	2003	2004	2006
1999	–	0.370[a]	0.228[a]	−0.074	−0.141	0.240[a]
2000	0.370[a]	–	0.152	−0.123	−0.110	0.205[a]
2002	0.228[a]	0.152	–	0.096	−0.019	0.159
2003	−0.074	−0.123	0.096	–	−0.057	0.053
2004	−0.141	−0.110	−0.019	−0.057	–	−0.194[a]
2006	0.240[a]	0.205[a]	0.159	0.053	−0.194*	–
Field OB						
Year	2000	2001	2003	2004	2005	2006
2000	–	0.726[a]	0.459[a]	0.097	0.209	−0.168
2001	0.726[a]	–	0.458[a]	0.058	0.301[a]	−0.208
2003	0.459[a]	0.458[a]	–	0.416[a]	0.655[a]	0.035
2004	0.097	0.058	0.416[a]	–	0.408[a]	0.161
2005	0.209	0.301[a]	0.655[a]	0.408[a]	–	0.145
2006	−0.168	−0.208	0.035	0.035	0.161	–
Field SF						
Year	1999	2001	2002	2003	2005	2006
1999	–	0.568[a]	0.402[a]	0.398[a]	0.419[a]	0.393[a]
2001	0.568[a]	–	0.431[a]	0.335[a]	0.336[a]	0.364[a]
2002	0.402[a]	0.431[a]	–	0.598[a]	0.435[a]	0.561[a]
2003	0.398[a]	0.335[a]	0.598[a]	–	0.495[a]	0.528[a]
2005	0.419[a]	0.336[a]	0.435[a]	0.495[a]	–	0.548[a]
2006	0.393[a]	0.364[a]	0.561[a]	0.528[a]	0.548[a]	–

[a] Significant (p-value below 0.05).

Rew and Cousens (2001) reviewed the literature concerning the spatial distribution of weeds and found that more detailed information is required to understand the spatial processes in a whole field environment. The results of Wiles et al. (1992) indicated clumping of broad-leaved populations represented by a negative binomial distribution. They found, that the distribution of the entire population is less patchy than the distribution of individual species.

Lloyd's Patchiness Index measures patchiness independently of the mean density (Kuno, 1991). Therefore, a comparison of different samples with different plant densities and sample sizes is possible. The use of this index is sometimes criticized because field data of insect populations often show significant correlations with mean densities (Taylor, 1984). But this confounding effect does not invalidate the usefulness of the index; rather, this correlation indicates that patchiness itself changes according to the density (Kuno, 1991). Often a ratio of variance to the mean significantly greater than 1 has been used to describe aggregation, but this ratio seems improper for logical reasons (Hurlbert, 1990). In the present study, patchiness indices varied between fields and years. Assuming a more or less non-varying weed seedbank between these environments, this may have been affected by variable weather conditions at the time of soil cultivation and weed emergence. The study years differed considerably in terms of both rainfall and temperature.

The temporal variation of *A. spica-venti* distribution is more complex than the spatial variation. The Spearman's coefficient allowed the comparison of the consistency in population location. The results indicated that there was temporal stability of *A. spica-venti*. For fields SF and GRW, the coefficients were positive and statistically significant, indicating similar patterns of distribution during the investigation periods. Correlations of 0.4–0.5 indicate a moderate similarity between the years in the distribution of weeds. Correlations <0.4 are weak and indicate limited correspondence in the patterns between years. The highest positive correlation coefficients were calculated when comparing years with winter wheat in the crop rotation. The stability of weed patches is probably associated with the fact that most seeds are already shed at harvest and that the distribution by wind is low. Perry et al. (2002) found that seeds of *Avena fatua* moved also only 1–3 m away from the parent plant. The data of this study are similar to those in studies of *Avena sterilis* where population levels were substantially reduced by annual spraying, but where patches remained at a stable location (Barroso et al., 2004).

Patchiness of weed distribution was also demonstrated in other investigations based on weed monitoring on fields in conventional agricultural use (e.g. Walter, 1996). Nordbo et al. (1994) found positive correlations between weed species with high densities and sums of all other species on a field of winter barley. Investigations of Walter (1996) over a three year period underline the temporal stability of *Viola arvensis*. Congruence of *A. myosuroides* distribution patterns was found by Wilson and Brain (1991) which is supported by the presented research findings. Rew et al. (2001) used the Pearson correlation coefficient to estimate the stability of weed patches (*Avena* spp.).

The present study verifies the hypothesized patchy distribution of *A. spica-venti* and characterises the degree of patchiness. This information is essential for modelling weed distribution in line with site-specific weed control (Sandt et al., 2008). Spatial aggregation and temporal stability indicate that opportunities exist for site-specific control of *A. spica-venti*. Assured prediction of spatial weed infestation can help to reduce efforts for weed scouting. It should be considered that occurrence and patchiness of *A. spica-venti* may vary with crop rotation, soil cultivation and weed control practices.

More information on population dynamics and on distribution pattern of *A. spica-venti* within agricultural fields is needed to quantify the percentage of a field that is infested with *A. spica-venti*. The stability or lack of stability of *A. spica-venti* populations is important in understanding population dynamics. Subsequent investigations with higher spatial resolution and covering a longer period of time are required to verify the results. In all, the findings could contribute to an improvement of weed monitoring and therefore facilitate the integration of site-specific weed control in the concept of precision agriculture.

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