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Characterizing Population Growth Rate of *Convolvulus arvensis* in Wheat–Sunflower No-Tillage Systems

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ABSTRACT

Convolvulus arvensis **L. is an important perennial weed that infests wheat (*Triticum aestivum* L.) and sunflower (*Helianthus annuus* L.) in Spain. Many fields of this rotation have been converted to no-tillage or reduced tillage, so perennial weeds such as *C. arvensis* have become more troublesome since they cannot be reduced in abundance by repeated tillage or cultivation. The population growth rate (PGR) is important in forecasting future population trends, and it can be used to develop weed control strategies in which applications of herbicides are spatially targeted to minimize possible damage. The objectives of this study were to assess and map PGR of *C. arvensis* in a wheat–sunflower no tillage rotation and to determine the temporal stability of the distribution function of *C. arvensis*. PGR was calculated over the course of four growing seasons (1999–2002) in a wheat–sunflower crop rotation in no-tillage systems. Spatial variability of PGR was analyzed by geostatistics. Temporal stability of the distribution function of *C. arvensis* PGR over time was established by a generalization of the two-sample Cramér-von Mises test for a difference between two univariate probability distributions. Year and crop influenced PGR, being larger in the sunflower phase (PGR = 0.52) than in the wheat phase (PGR = 0.16) of a sunflower–wheat rotation system because the density of *C. arvensis* was greater when growing in competition with wheat than with sunflower. The PGR showed a moderate degree of aggregation in patches in both rotations, although the temporal stability of the PGR distribution function was not observed. Overall, PGR became stable over the four growing seasons. Knowledge of growth rate spatial dynamics could improve *C. arvensis* management if it were complemented with spatially herbicide targeted applications.**

In recent years, several authors have reported the importance of weed spatial distribution in sampling populations, modeling population dynamics, and long-term management (Rew and Cousens, 2001; Jurado-Expósito et al., 2003) and have drawn attention to the need for methods to improve future weed management strategies (González-Andújar and Saavedra, 2003).

Weeds are usually distributed in patches (Donald, 1994; Heisel et al., 1996a; Wiles and Schweizer, 2002). A weed patch is considered stable if it is constant in density and location over time (Gerhards et al., 1997; Rew and Cussans, 1995; Wyse-Pester, 1996, Dieleman and Mortensen, 1999). Stability is important for managing patches, such that a patch map from one year can be used to guide weed control in subsequent years (Mortensen et al., 1993, 1995; Lutman et al., 1998). This is especially true for perennial weeds in reduced tillage systems (Webster et al., 2000). However, most of the studies of spatial variation of weed populations have been based on density data and none had taken into consideration the spatial variability or temporal stability of population growth rate of weeds.

PGR is a central concept in ecology, unifying variables linking the various facets of population ecology. In conservation biology, the aim is to preserve species, i.e., to promote faster growth. Weed control is the opposite, where the aim is to minimize growth (Sibly and Hone, 2002). PGR is important in forecasting future population trends, and it can be used to develop weed control strategies in which applications of herbicides are spatially targeted to minimize possible damage.

Convolvulus arvensis (field bindweed) is an important perennial weed that infests wheat and sunflower in Spain (Saavedra-Saavedra et al., 1989; Hidalgo et al., 1990; Jurado-Expósito et al., 2003). It produces few viable seeds when growing in competition with crops and reproduces primarily vegetatively from underground rootstocks. In addition, adventitious shoots arising from a network of rootstocks reduce crop yields and interfere with harvest (Liebman et al., 2001).

Reduced and no-tillage production has increased in Spain in the last 10 yr, accounting for 2 million hectares of the annual crops (AELC/SV, 1998). Wheat–sunflower is the main crop rotation in Andalusia (southern Spain). Many fields of this rotation have been converted to no-tillage or reduced tillage, so perennial weeds such as *C. arvensis* have become more troublesome since they cannot be reduced in abundance by repeated tillage or cultivation (Liebman et al., 2001).

Jurado-Expósito et al. (2003) characterized the spatial distribution of weeds within sunflower and wheat crops. Although they did not deal with the spatial variability and temporal stability over time of the weed population growth rate over crop rotations, knowledge of these variables is needed to target herbicide application. Furthermore, there are no studies on the spatial variability of *C. arvensis* PGR or temporal stability in no-tillage systems where this weed is most common.

The objectives of this study were: (i) to assess and map the PGR of *C. arvensis* in a wheat–sunflower no tillage rotation, (ii) to characterize the spatial variability of *C. arvensis* PGR, and (iii) to determine the temporal stability of the distribution function of *C. arvensis* PGR.

MATERIALS AND METHODS

Study Area and Sampling Scheme

The study was conducted at La Monclova (La Luisiana, Seville, southern Spain, 38–36° N and 4–6° W) over the course

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Abbreviations: PGR, population growth rate.

of four growing seasons (1999–2002) in a field naturally infested with *C. arvensis* and managed with a rotation of wheat and sunflower under a no-tillage system. Cropping practices representative of the Mediterranean region were as follows: wheat was sown in early December and harvested in mid-June, and sunflower was sown in late February and harvested in late July. Nitrogen fertilizer was applied to wheat only as ammonium nitrate at 130 N kg ha^{-1}. The N was applied in late February as top dressing at the beginning of wheat tillering corresponding to stage 21 of Zadoks scale (Zadoks et al., 1974). A nonresidual herbicide glyphosate [*N*-(phosphomethyl)glycine] was applied pre-emergence at 2 L a.i. ha^{-1} to control annual weeds in wheat and sunflower. This treatment generally does not affect *C. arvensis* grown from perennial shoots.

The density of *C. arvensis* was sampled in late May before harvesting, when wheat was in its last maturation stage (corresponding to wheat ripening, Stage 90 of Zadoks scale), sunflower at 14 to 16 leaf stage and *C. arvensis* shoots 4 to 10 cm in height. An area measuring 65 × 250 m (1.6 ha) was selected for the intensive field survey in 1999, and the same area was resampled in 2000, 2001, and 2002. The study area was situated within a larger field (around 40 ha), and its borders were at least 50 m from the main borders of the field. *Convolvulus arvensis* density assessments were performed in a 7- × 7-m grid pattern, resulting in a total of 261 sampling units. The position of each grid point was georeferenced with a Differential Global Positioning System (DGPS, Trimble Pathfinder Pro-XRS, Trimble Navigation Limited, Sunnyvale, CA). At each node, the number of *C. arvensis* shoots were counted in a 2- × 2-m quadrat.

Population Growth Rate (PGR)

Convolvulus arvensis PGR was calculated at each grid node as follows:

$$PGR_{x,y} = \log\{[N_{(x,y)t+1}/N_{(x,y)t}] + 1\}$$

where $N_{(x,y)t+1}$ is weed density in Year $t + 1$ at Site (x,y), and $N_{(x,y)t}$ is *C. arvensis* density in Year t at Site (x,y). PGR was calculated for three crop rotations: wheat phase (1999–2000), sunflower phase (2000–2001), and wheat phase (2001–2002). To evaluate the PGR value over the four years, an overall PGR was calculated between Years $t = 1$ (1999) and $t + 1 = 4$ (2002).

PGR data from each rotation were treated as a study case and were analyzed statistically. Data distribution was described by classical descriptors (mean, median, and standard deviation).

Dynamics of Population Growth Rate Spatial Variability

Spatial variability of *C. arvensis* PGR over the crop rotations was described by semivariograms. The semivariogram characterizes the average degree of similarity between *C. arvensis* PGR as a function of separation distance and direction. A semivariogram was calculated for each time interval as follows (Journel and Huijbregts, 1978; Isaaks and Srivastava, 1989; Webster and Oliver, 2001):

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

where $\gamma(h)$ is the experimental semivariance value at distance Interval h; $N(h)$ = number of PGR value pairs within the distance Interval h; and $z(x_i)$, $z(x_i + h)$ = PGR values at two points separated by a distance Interval h. All pairs of points separated by distance h were used to calculate the experimental semivariogram.

Several semivariogram functions were evaluated to choose the best fit with the data. Semivariograms were calculated both isotropically and anisotropically by VARIOWIN (Software for Spatial Data Analysis in 2D. Spring Verlag, New York) software. The anisotropic calculations were performed in four directions (0, 45, 90, and 135°) with a tolerance of 22.5° to determine whether the semivariogram functions depended on the sampling orientation and direction (i.e., they were anisotropic) or not (i.e., they were isotropic) (Journel, 1986). The direction 0° corresponded to E–W and 90° to the N–S direction. A lag spacing of 5 m over a distance of 90 m produced the clearest semivariogram with a sufficient number of data points to be confident in the empirical semivariogram estimates. The experimental semivariograms were fitted by the least-squares procedure by VARIOWIN software. Nested semivariogram structures were not used, as we were able to obtain adequate fits with a simple structure.

Spherical and exponential models were fitted to the experimental semivariograms. The parameters of the model: nugget semivariance, range, and sill or total semivariance were calculated. Semivariogram models were cross-validated comparing PGR values estimated from the semivariogram model with actual PGR values. A trial-and-error procedure was used and the estimated parameters of the model were modified until adequate cross-validation statistics were obtained (Isaaks and Srivastava, 1989; Webster and Oliver, 2001), i.e., mean estimation error (MEE) not significantly different than zero; mean squared error (MSE) less than the variance of the sample values (Hevesi et al., 1992), and standardized mean squared error (SMSE) were within the interval $1 \pm 2\sqrt{2/n}$ (Isaaks and Srivastava, 1989; Hevesi et al., 1992).

Once cross-validated, parameters of the semivariogram models were used in the kriging process to provide estimates of *C. arvensis* PGR at unsampled points. Ordinary point kriging was performed on a regular grid of 2.5 m. Cross-validation and kriging were conducted by WinGSLIB (Geostatistical Software Library and User's guide. Oxford University Press). Kriging estimates were used to map the PGR by SURFER (Win 32, Surface Mapping System, Golden Software Inc. 809, 14th Street. Golden, CO) contour mapping software.

PGR mean > 0.3 was estimated as the PGR critical value for the *C. arvensis* population increased. PGR maps achieved by kriging were used to estimate the percentage of surface where PGR > 0.3, which means foci where *C. arvensis* was increasing.

To define distinct classes of *C. arvensis* PGR spatial dependence, the nugget variance was expressed as a percentage of the total semivariance. If the ratio was ≤25%, *C. arvensis* PGR was considered strongly spatially dependent or strongly distributed in patches; if the ratio was between 25 and 75%, PGR was considered to be moderately spatially dependent, and if the ratio was >75%, PGR was considered weakly spatially dependent (Cambardella et al., 1994; Cambardella and Karlen, 1999; González-Andújar et al., 2001; López-Granados et al., 2002, Jurado-Expósito et al., 2003).

Population Growth Rate Temporal Stability

To test the temporal stability of the distribution function of *C. arvensis* PGR over time (Syrjala, 1996), the bivariate generalization of the Cramer-von Mises nonparametric test was applied. The method tests the null hypothesis that there is no difference in the spatial distribution of PGR over time, i.e., that the PGR distribution has not changed from one year to the next. The alternative hypothesis is that there is some unspecified difference between PGR distributions over years.

The statistic (ψ) used to test the null hypothesis is defined

Table 1. *Convolvulus arvensis* density (number of shoots m^{-2}), population growth rate, spatial distribution characteristics and cross validation statistics over four growing seasons.

Years and crops	Density		Population growth rate					Semivariogram parameters						Cross validation		
	Mean	SD	Rotation years	Crop rotation	Mean	Median	SD	Model	Range (m)	Nugget	Sill	Nugget ratio† (%)	Spatial class‡	MEE	MSE	SMSE
1999-W§	30.4	37.45	1999–2000	W-S	0.159	0.153	0.265	Exponential	43.5	0.032	0.070	45.71	M	0.0007	0.0635	1.179
2000-S	20.6	20.2	2000–2001	S-W	0.524	0.477	0.424	Spherical	34.0	0.122	0.172	70.93	M	0.0020	0.1666	1.095
2001-W	53.7	54.87	2001–2002	W-S	0.158	0.138	0.170	Spherical	43.2	0.019	0.027	70.37	M	0.0006	0.0281	1.690
2002-S	24.0	20.8	1999–2002	W-S	0.187	0.158	0.261	Spherical	23.6	0.042	0.064	65.62	M	0.0002	0.0657	1.156

† Nugget ratio = (nugget semivariance/total semivariance)*100.
‡ Spatial class: S = strong spatial dependence; M = moderate spatial dependence; W = weak spatial dependence.
§ Crop: W: wheat, S: sunflower.
¶ Overall PGR.

by the square of the difference between the two cumulative distribution functions, summed over all sampling locations; that is:

$$\psi = \sum_{k=1}^{K} [\Gamma_1(x_k, y_k) - \Gamma_2(x_k, y_k)]^2$$

where Γ represents the cumulative distribution function at the location (x_k, y_k) for the ith population (Syrjala, 1996).

The level of significance of the test statistics ψ can be determined by a randomization test. Thus, to calculate the level of significance of the test statistics ψ, 1000 permutations of the data were examined (the observed permutation and 999 pseudorandom permutations). The P value is the proportion of those 1000 test statistics values that were lower than, equal to, or greater than the observed test statistic ψ, indicating that the observed difference between PGR distribution maps over time was or was not statistically significant (Edgington, 1980; Syrjala, 1996).

RESULTS AND DISCUSSION

Dynamics of Population Growth Rate Spatial Variability

Year and crop rotation influenced the number of *C. arvensis* shoots: the density was greater in wheat (30.4 and 53.7 plants m^{-2} in 1999 and 2001, respectively) than in sunflower years (20.6 and 24.0 plants m^{-2} in 2000 and 2002, respectively) (Table 1). The difference in density affected on the PGR. Thus, PGR mean was higher in sunflower phase (PGR mean = 0.524) than in wheat phase rotation. PGR means were similar in both wheat-sunflower rotation years (Table 1).

Anisotropic semivariograms did not show any differences in spatial dependence with the directions; therefore, isotropic semivariograms were chosen. Spherical semivariograms were defined in 2000–2001, 2001–2002, and for the overall PGR calculated between year 1999 and 2002, and an exponential model was used to depict the data in the first year of rotation (wheat phase, 1999–2000) (Fig. 1) (Table 1). Each model describes continuity differently. The exponential model indicates greater spatial correlation at shorter distances than does the spherical model. However, the spherical model reaches the sill more quickly than the exponential, indicating that data are not as continuous across the study area (Goovaerts, 1997).

The semivariance for each lag was much larger in the sunflower phase (2000–2001) (Fig. 1b) than in the wheat phases (Fig. 1a and 1c), indicating that the difference between observations is lower in the latter rotation. This is a result of a higher relative PGR values and variance in sunflower phase rotation (0.524) compared with the wheat phases (0.159 and 0.158) (Table 1).

Convolvulus arvensis PGR displayed differences in spatial variability as determined by semivariogram analyses (Table 1). Semivariogram parameters greatly varied between crop rotations. For example, the sill parameter was higher in sunflower phase (0.172, in 2000–2001) than in wheat phases (0.070 and 0.027, in 1999–2000 and 2001–2002, respectively). This result indicated that the PGR variance was higher in sunflower phase rotation than in the wheat.

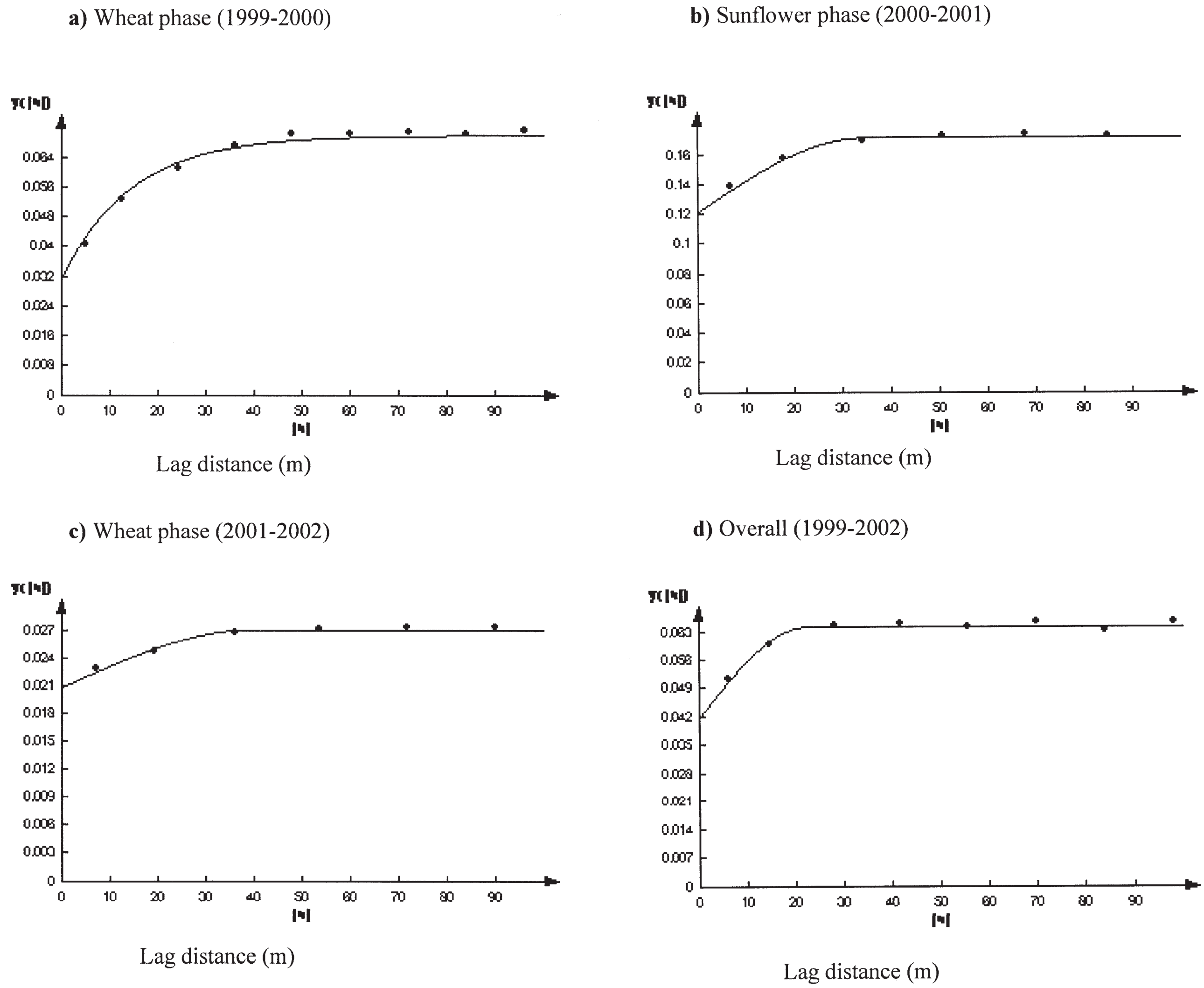

Fig. 1. Experimental (circles) and modeled semivariograms of *C. arvensis* population growth rate (PGR), corresponding to (a) wheat phase (1999–2000), (b) sunflower phase (2000–2001), (c) wheat phase (2001–2002), and (d) overall PGR (1999–2002).

The nugget semivariance was greater than zero in all cases, meaning that PGR observations separated by small distances were dissimilar (Isaaks and Srivastava, 1989). This dissimilarity may result from differences in demography or dispersal, mortality events, edaphic factors and cropping, or control actions among other processes influencing patchiness at scales smaller than 7 m or may simply be the result of sampling error (Cousens and Mortimer, 1995; Heisel et al., 1996a, 1996b; Cousens and Croft, 2000; Jurado-Expósito et al., 2003).

The nugget semivariance expressed as a percentage of the total semivariance (or sill) was used to define distinct classes of PGR spatial dependence (Table 1). Medium nugget ratios (between 45 and 70%) were found which indicates a moderate spatial dependence of PGR, or moderate degree of aggregation in patches in all rotations.

The range of the semivariogram gives the average extent of the PGR patches when PGR distribution is moderately spatially correlated. The range was similar in wheat phase rotation years (1999–2000 and 2001–2002) (Table 1), with a spatial dependence of up to 43.5 m and up to 34 m for the sunflower phase. A larger range indicated that PGR is influenced by other PGR values over greater distances than PGR, which have smaller ranges (Samper-Calvete and Carrera-Ramírez, 1996).

Assuming that an average of PGR $\leq$ 0.3 indicated that the weed population was not increasing, *C. arvensis* population grew in the sunflower phase (PGR = 0.524) (Table 1). A visual assessment of PGR maps for each crop rotation (Fig. 2) reveals a distinct aggregation pattern depending on rotation. PGR highly aggregated with several small foci of increase, where PGR > 0.3, in the first wheat phase (Fig. 2a). These results suggest that a decrease in the *C. arvensis* density was recorded due to the introduction of sunflower crop in the rotation. As a consequence, a population fragmentation in small foci was produced in the field, which caused lower PGR values in wheat phase (Fig. 2a and 2c). The percentage of surface where *C. arvensis* population was not increasing, i.e., where PGR $\leq$ 0.3, was calculated at 86.5% and 99.3% in 1999–2000 and 2001–2002, respectively (Fig. 3a and 3c).

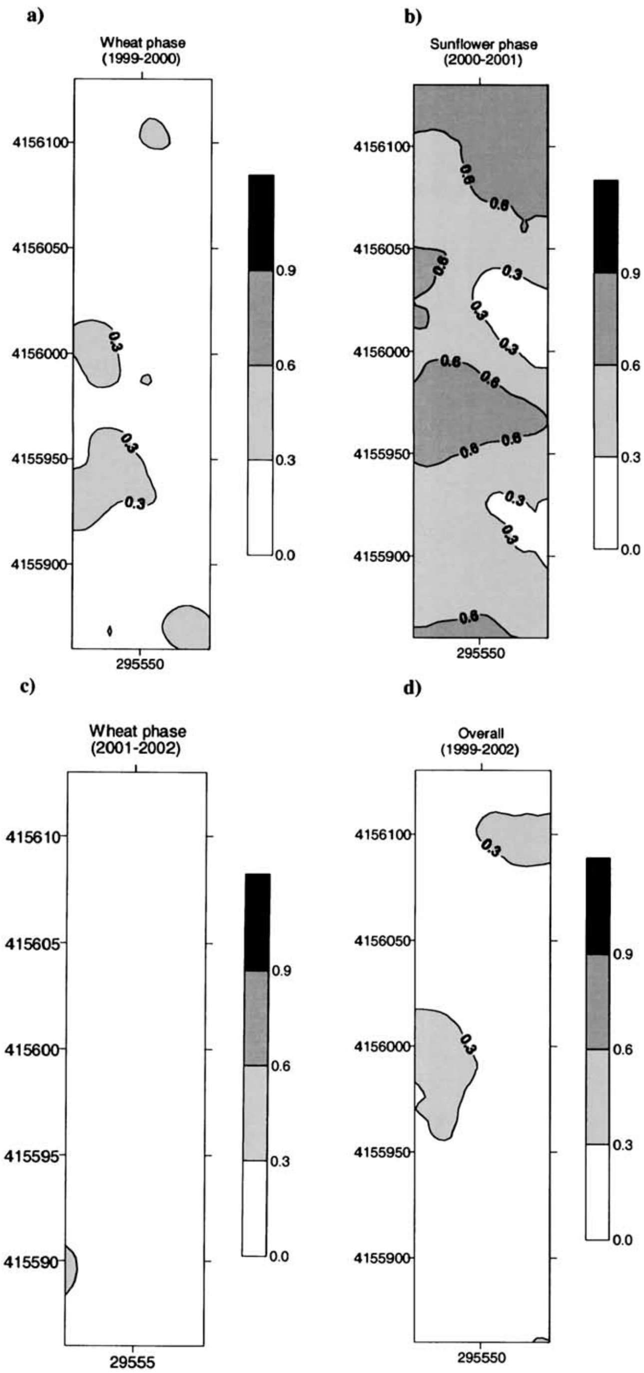

Fig. 2. Isoline maps of *C. arvensis* population growth rate (PGR) corresponding to (a) wheat phase (1999–2000), (b) sunflower phase (2000-2001), (c) wheat phase (2001–2002), and (d) overall wheat-sunflower (1999–2002). Axes are in Universal Transverse Mercator units (m). Vertical axis, northings; horizontal axis, eastings.

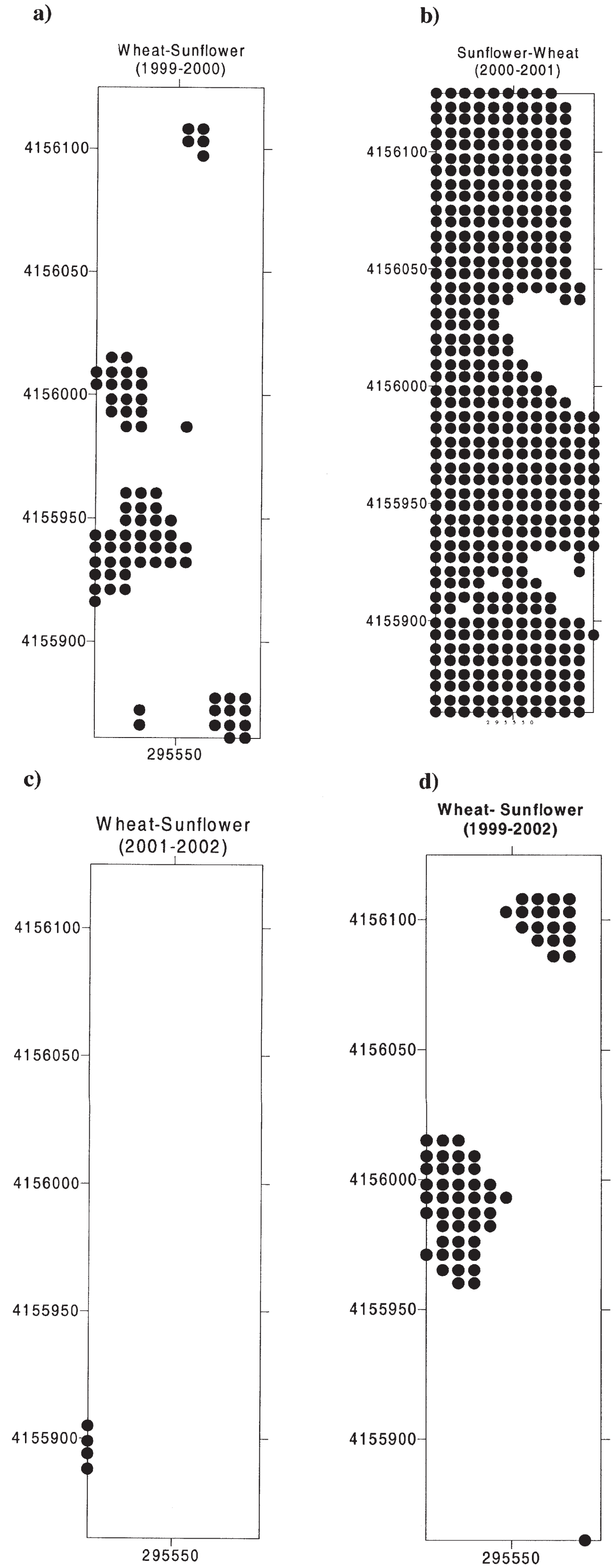

Fig. 3. Percentage of surface where population growth rate (PGR) was >0.3 (●) in (a) wheat phase (1999–2000), (b) sunflower phase (2000–2001), (c) wheat phase (2001–2002), and (d) overall PGR (1999–2002). Axes are in Universal Transverse Mercator units (m). Vertical axis, northings; horizontal axis, eastings.

Regarding sunflower phase, 88.5% of the surface was with a PGR > 0.3 (Fig. 2b and 3b), suggesting that most of the surface exhibited an increase in *C. arvensis* PGR. This illustrates the high potential PGR that *C. arvensis* can achieve under conditions when it is growing with no specific control. However, whether sunflower is included in the rotation, even in the absence of specific control, PGR becomes stable over the four growing seasons, as illustrated in Fig. 2d. Thus, the percentage of surface with an overall PGR >0.3 was 11.3% (Fig. 3d). Results indicate that overall PGR mean had become stabilized because of an appropriate crop rotation (0.187, Table 1).

Population Growth Rate Spatial Stability

Comparison between *C. arvensis* PGR maps for 1999–2000 and 2000–2001 (Fig. 2a and 2b) indicated a nonsignificant spatial stability of PGR distribution function ($\psi = 3.98$; $P = 0.001$). Similar results were found in 2000–2001 and 2001–2002 comparison (Fig. 2b and 2c; $\psi = 2.71$; $P = 0.001$), which indicated that significant spatial changes occurred in *C. arvensis* PGR patches over time and crops. Similarly, comparison between sunflower phases (Fig. 2a and 2c) did not show any spatial stability ($\psi = 0.353$; $P = 0.001$).

According to Syrjala (1996), differences between distributions over time can be characterized by different environmental conditions, which are defined in this study by the different crop sown. The lack of spatial stability of PGR is, therefore, probably due to the different *C. arvensis* population pattern in sunflower and wheat. Similar results have been found by Dieleman and Mortensen (1999) who concluded that weed patch persistence depends on the crop in which the patches occur. Stability in weed density maps over years has been found by several authors (Wilson and Brain, 1991; Cardina et al., 1995). Gerhards et al. (1997) and Webster et al. (2000) found that the patches of perennial weeds like hemp dogbane (*Apocynum cannabinum* L.) occurred at about the same location over 4 yr and that regression analysis indicated that there was strong relation between patch area in consecutive years, although they reported that patch area increased more than 100% when a fallow was included in the rotation.

Convoluvulus arvensis PGR showed aggregation in patches in both crop rotations, although location of patches was different within rotations. Our study provides valuable information about PGR dynamics since it can be used to define the areas with a PGR >0.3, where *C. arvensis* population is increasing. Knowledge of estimated PGR areas at a given point during the crop rotation can be a guide to improve future multiple-season weed management systems by defining potential herbicide targeted applications against this perennial weed. This information could be used to prevent *C. arvensis* from becoming a hard-to-control weed in our no-tillage systems, where perennial weeds cannot be reduced by tillage or cultivation.

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