

Interannual variation in weed biomass on arable land in Sweden

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Summary

Data were analysed on weed biomass from untreated plots in 2672 field experiments conducted in spring- and autumn-sown cereal and oilseed crops in Sweden 1972–1992. The coefficient of variation (CV) among years in the biomass of annual weeds per square metre was 29% in autumn-sown crops. In spring-sown crops, which had less weed biomass, the corresponding value was 49%. The biomass of summer annuals varied most (105%). Low winter temperatures seemed to increase the biomass of weeds in autumn-sown crops. In spring-sown crops, weed biomass production was higher in years with high rainfall during late spring. Partial ordination (pCCA) of weed data indicated that the interannual variations in autumn-sown crops were mainly manifested by the occurrence of summer annuals. Results from similar ordination of data from spring-sown crops were partly explained by the occurrence of winter annuals.

Keywords: community, exploratory analysis, CCA, summer annual, Sweden, weed, winter annual.

Introduction

Populations of short-lived plant species often vary greatly in number between years (Symonides *et al.*, 1986; Firbank, 1993; Hobbs & Mooney, 1995; O'Connor & Roux, 1995; Guo & Brown, 1996; Geisselbrecht-Taferner *et al.*, 1997). Interannual variability in the occurrence of weed species and in the total biomass of weeds makes predictions about the weed community difficult and adversely impacts the ability to make weed management decisions. Although the importance of interannual weed variability is well known to farmers and scientists, we are not aware of any case in which weed community variability has been quantified (although individual species have been studied in detail over longer time periods, e.g. Wilson & Brain, 1991). A better understanding of the magnitude of interannual variation and of the main factors involved in causing it might help to forecast the need for weed control.

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In this exploratory study, we investigated the interannual variation in the biomass of annual weeds. We used data from unsprayed control plots in 2672 field experiments conducted over a 21-year period in spring- and autumn-sown cereal and oilseed crops in Sweden. More specifically, we wanted to compare the interannual variation of weed biomass in autumn- and spring-sown crops. As germination syndromes greatly influence the composition of the weed community (Andersson & Milberg, 1998a; Hald, 1999), we distinguished between summer annuals, winter annuals and germination generalists (weeds that can germinate substantially in both spring and autumn). Furthermore, we wanted to relate biomass of weeds to rainfall and temperature. Finally, we wanted to determine how weed species composition varied between years using a multivariate gradient analysis technique.

Materials and methods

Data on biomass of weed species were collected from unsprayed control plots from field experiments conducted to evaluate new herbicides against dicotyledonous weeds. The experiments were carried out in the southern part of Sweden. Data on weeds in cereals were from the period 1972–1992 and in oilseed crops from 1980 to 1992. Of the 1324 experiments in autumn-sown crops, 73.1% were in cereal crops and 26.9% in oilseed crops. Corresponding values for the 1348 experiments in spring-sown crops were 67.7% and 32.3% respectively.

Each experiment consisted of four blocks with randomly distributed plots within the blocks. In late June–early July, weeds were collected, sorted into species and their fresh weight measured in at least two sample plots (each of 0.25 m²) per treatment plot. According to the sampling protocol for the experiments, the sample area should be sufficiently large to include at least 20 plants or shoots of the most frequent species within untreated plots. Occurrence of a species in an experiment was only noted when there were \geq five plants m⁻². Species with fewer individuals were grouped together in an 'other weeds' category (10.7% of the total weed biomass recorded).

In the present analysis, we used data on the 28 most abundant annual species (84.1% of the identified fraction), while perennial and biennial species and less abundant annual species were excluded.

For some analyses, we merged data from different species into three categories: (i) summer annuals; (ii) winter annuals; and (iii) 'germination generalists' (Table 1). From a germination ecological perspective, the latter two categories would be considered facultative winter annuals (Baskin & Baskin, 1998), and the distinction between them is subjective. The classification is according to Swedish conditions and is based on the literature (Fogelfors, 1977; Håkansson, 1995) and our previous field experience with the species.

Parts of the data set have been presented previously elsewhere: Hallgren (1996) ranked the most important weed species in different crops and soil types; and Hallgren *et al.* (1999) analysed how the weed community was related to various environmental variables.

Coefficient of variation

The interannual variation in the average biomass of annual weeds per year was evaluated by calculating the coefficient of variation (CV), i.e. $100 \times \text{SD} / \text{mean}$. There were between 29 and 97 experiments per year in autumn-sown crops (mean \pm SD, 63 ± 16.9). Corresponding values in spring-sown crops were 28–118 (64 ± 27.9).

Table 1 Weed taxa recorded in the experiments and used in the present analyses (nomenclature follows Tutin *et al.* 1964–80)

Species	Abbreviation used in figure	Frequency (%)	
		Autumn-sown (n = 1256)	Spring-sown (n = 1280)
Summer annuals			
<i>Chenopodium album</i> L./ <i>C. suecicum</i> J. Murr	Chenopodium	6.3	45.3
<i>Galeopsis bifida</i> Boenn./ <i>G. speciosa</i> Miller/ <i>G. tetrahit</i> L.	Galeopsis	9.2	33.6
<i>Bilderdykia convolvulus</i> (L.) Dumort.	Bilderdykia	8.2	14.9
<i>Polygonum lapathifolium</i> L./ <i>P. persica</i> L.	Poly spp.	1.4	14.3
<i>Fumaria officinalis</i> L.	Fumaria	2.0	11.9
<i>Spergula arvensis</i> L.	Spergula	0.5	7.6
<i>Erysimum cherianthoides</i> L.	Erysimum	0.6	6.2
<i>Sinapis arvensis</i> L.	Sinapis	0.5	5.5
<i>Polygonum aviculare</i> L.	Poly avic	8.1	4.6
<i>Sonchus asper</i> (L.) Hill/ <i>S. oleraceus</i> L.	Sonchus	–	1.6
Winter annuals			
<i>Matricaria perforata</i> Mérat	Matricaria	44.2	11.4
<i>Myosotis arvensis</i> (L.) Hill	Myosotis	23.0	11.1
<i>Veronica agrestis</i> L./ <i>V. arvensis</i> L./ <i>V. hederifolia</i> L./ <i>V. persica</i> Poirét	Veronica	16.2	2.3
<i>Galium aparine</i> L./ <i>G. spurium</i> L.	Galium	15.6	8.6
<i>Capsella bursa-pastoris</i> (L.) Medicus	Capsella	12.5	3.9
<i>Papaver argemone</i> L./ <i>P. dubium</i> L./ <i>P. rhoeas</i> L.	Papaver	2.7	–
<i>Centaurea cyanus</i> L.	Centaurea	2.6	–
<i>Apera spica-venti</i> (L.) Beauv.	Apera	2.2	0.1
<i>Chamomilla recutita</i> (L.) Rauschert	Chamomilla	1.8	0.7
<i>Poa annua</i> L.	Poa	1.7	1.0
<i>Consolida regalis</i> S.F. Gray		1.6	–
Germination generalists			
<i>Stellaria media</i> (L.) Vill.	Stellaria	47.7	35.1
<i>Viola arvensis</i> Murray	Viola	34.1	22.4
<i>Lamium amplexicaule</i> L./ <i>L. hybridum</i> Vill./ <i>L. purpureum</i> L.	Lamium	13.9	13.1
<i>Thlaspi arvense</i> L.	Thlaspi	2.9	7.0
<i>Lapsana communis</i> L.	Lapsana	1.4	6.0

Weed biomass and weather data

When evaluating the relationship between weather and weed biomass, we restricted the geographical region under consideration to the southernmost part of Sweden (Götaland; 87,000 km²) to reduce the variation in meteorological variables. This data subset contained 77.5% and 54.7% of the experiments in autumn- and spring-sown crops respectively. We used monthly compilations of rainfall and temperature data from two meteorological stations to construct several different weather variables (Table 3). The two sites (Göteborg and Växjö) were considered to represent the overall weather situation in Götaland (Sigfridsson & Sigfridsson, 1997). Correlation analyses were conducted to evaluate the relationship between weather variables and biomass of weeds (log-transformed average biomass of weeds per year; total as well as summer annuals, winter annuals and germination generalists separately). The probability value reached in a statistical analysis rests on the assumption that the test has been planned a priori. This is rarely the case in exploratory studies, in which numerous unplanned tests are conducted instead. Therefore, we stress that the *P*-values given should only be considered as indicators of potentially important relationships.

Multivariate analyses

Multivariate gradient analysis is a useful tool for arranging samples along gradients of species composition. Such gradients are typically related to important environmental factors (ter Braak & Prentice, 1988). Although gradient analysis typically examines variation in species composition through space, it is also ideally suited for examining fluctuations through time. We performed partial canonical correspondence analysis (pCCA) (ter Braak, 1988) on data from spring- and autumn-sown crops separately, treating the different years as category variables and several other variables as covariables. We used CANOCO 4 (ter Braak & Smilauer, 1998) and employed default options (i.e. biplot scaling focused on interspecies distances), except that we square-root-transformed weed biomass. This transformation had previously appeared to be appropriate for the data (Hallgren *et al.*, 1999). A previous study (Hallgren *et al.*, 1999), partly using the same data, revealed that 'geographical region' (eight regions), 'soil type' (seven types) and 'crop species' (10 different) all had a significant influence on the composition of the weed flora. As we were primarily interested in interannual variability, we factored out these variables by treating them as covariables (categorical variables, entered as dummy variables). Furthermore, the previous study (Hallgren *et al.*, 1999) had identified minor but partly significant long-term changes (1970–1994). As our focus was on shorter term variation, we included 'year' as a continuous covariable in our analyses, hence controlling for long-term temporal trends. We tested the significance of interannual variation using a Monte Carlo test with 200 permutations (reduced model; permutation blocks defined by the categorical covariables) (ter Braak & Smilauer, 1998).

Results

Autumn-sown crops had more weed biomass than spring-sown crops when compared in late June–early July ($t_{(40)} = 3.837$, $P < 0.001$) (Table 2). Most of the weed biomass in autumn-sown crops was of winter annuals. Spring-sown crops were dominated by summer annuals, while the germination generalists were less specific (Table 2).

Coefficient of variation

The temporal CV of weed biomass tended to be smaller in autumn-sown crops than in spring-sown crops, the only exception being summer annuals, whose biomass varied tremendously in autumn-sown crops (Table 2).

Table 2 Average biomass of annual weeds per year and its coefficient of variation (CV) in autumn-sown crops and spring-sown crops over a 21-year period

	Biomass of weeds (g m ⁻²)	SE	CV (%)	SE
Autumn-sown crops				
Total	329	20.6	28.7	4.78
Summer annuals	19	4.4	104.8	28.91
Winter annuals	184	15.4	38.2	6.70
Germination generalists	126	11.9	43.5	7.88
Spring-sown crops				
Total	211	22.8	49.4	9.29
Summer annuals	153	19.2	57.5	11.42
Winter annuals	14	1.5	46.9	8.68
Germination generalists	44	4.6	47.8	8.90

Weed biomass and weather data

In autumn-sown crops, biomass of both summer and winter annuals was negatively correlated with winter temperatures (Table 3). More surprisingly, biomass of germination generalists, which made up a substantial part of the total weed biomass, was not correlated with the weather variables (Table 3). Total weed biomass was correlated with low temperatures in late winter (February–March) and a rainy spring (April–June) (Table 3).

In spring-sown crops, the biomass of winter annuals and germination generalists was correlated with temperature and rainfall in May and June (Table 3). Temperature and rainfall in June as well as May–June were highly correlated ($P < 0.001$ in both cases), with low rainfall

Table 3 Correlation matrix of average biomass of weeds m^{-2} (log-transformed) per year and weather variables for 21 years

	Total	Summer annuals	Winter annuals	Germination generalists
Autumn-sown crops				
Summer annuals	0.238			
Winter annuals	0.793***	0.440*		
Germination generalists	0.614**	-0.365	0.069	
Rainfall				
April	0.173	-0.096	0.0038	0.206
May	0.424	0.044	0.148	0.385
June	0.314	0.444*	0.413	-0.021
April–May	0.430	-0.035	0.111	0.425
May–June	0.534*	0.427	0.460*	0.209
April–June	0.612**	0.360	0.447*	0.316
Daily average temperature				
December	0.018	-0.417	-0.269	0.429
January	-0.471*	-0.552**	-0.646**	0.115
February	-0.526*	-0.639**	-0.612**	0.045
March	-0.670***	-0.481*	-0.769***	-0.092
December–January	-0.311	-0.564**	-0.560**	0.274
December–February	-0.425	-0.641**	-0.627**	0.202
December–March	-0.518*	-0.660***	-0.714***	0.152
February–March	-0.657***	-0.650***	-0.760***	-0.010
April	-0.403	-0.254	-0.408	-0.090
May	-0.242	-0.344	-0.324	0.140
June	-0.325	-0.184	-0.397	-0.053
April–May	-0.526*	-0.481*	-0.594**	0.035
May–June	-0.331	-0.285	-0.418	0.031
April–June	-0.550**	-0.425	-0.642**	-0.015
Spring-sown crops				
Summer annuals	0.969***			
Winter annuals	0.513*	0.366		
Germination generalists	0.756***	0.595**	0.521*	
Rainfall				
May	0.103	0.0064	0.242	0.323
June	0.490*	0.427	0.449*	0.498*
May–June	0.503*	0.389	0.549*	0.640**
Daily average temperature				
May	-0.226	-0.148	-0.267	-0.373
June	-0.300	-0.191	-0.452*	-0.448*
May–June	-0.307	-0.197	-0.427	-0.475

Asterisks indicate significance at * $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$.

occurring when temperatures were high. The biomass of summer annuals did not correlate with any of the weather variables (Table 3).

Multivariate analyses

Eigenvalues, i.e. the importance measure of an ordination axis (Jongman *et al.*, 1995), were low in both pCCAs (Figs 1 and 2). This is not surprising, as the variation explained by several important variables had been covaried out (geographical region, soil type, crop species, temporal trends). Nevertheless, both ordinations explained a significant part of the variation ($P < 0.005$ in both cases in Monte Carlo tests). In autumn-sown crops, the first ordination axis separated the summer annuals (*Chenopodium* spp., *Galeopsis* spp., *Polygonum aviculare*, *Bilderdykia convolvulus*) from the other species (Fig. 1). The centroids for years correlated well with the Götaland average temperature February–March ($P < 0.001$; note that the pCCA was

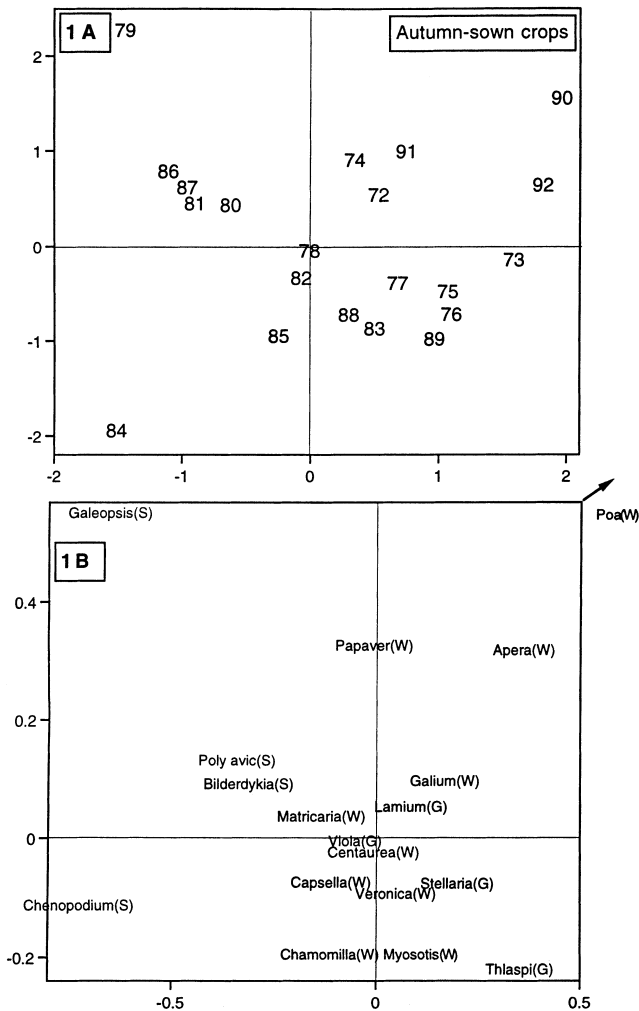


Fig. 1 pCCA of weed data from autumn-sown crops, using the sampling years as dummy variables. Eigenvalues for axes 1 and 2 are 0.0632 and 0.0365 respectively. (A) Centroids of years. (B) Species scores (although all 28 species were included in the analysis, only those with a weighted total abundance of >100 are displayed); see Table 1 for abbreviations of species names; S, W and G refer to summer annual, winter annual and germination generalist respectively.

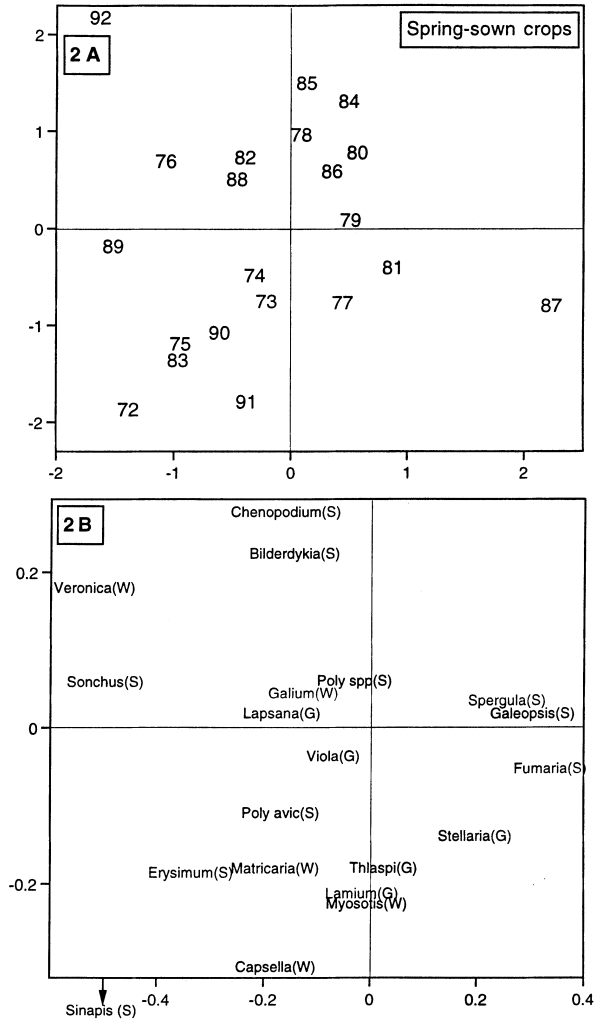


Fig. 2 pCCA of weed data from spring-sown crops, using the sampling years as dummy variables. Eigenvalues for axes 1 and 2 are 0.0638 and 0.0387 respectively. (A) Centroids of years. (B) Species scores (although all 28 species were included in the analysis, only those with a weighted total abundance of >100 are displayed); see Table 1 for abbreviations; S, W and G refer to summer annual, winter annual and germination generalist respectively.

conducted on the full data set). The ordination of species in spring-sown crops was less easily interpreted (Fig. 2), but winter annuals (*Veronica* spp., *Matricaria perforata*, *Capsella bursa-pastoris*, *Galium* spp., *Myosotis arvensis*) all had negative ordination scores along the first axes. The year centroids on the first ordination axis correlated better with Götaland rainfall ($P < 0.01$) than with temperature ($P = 0.067$) in May–June.

Discussion

Exploratory approach

An exploratory analysis of this type includes making a number of decisions based on intuition, a general ‘feel’ for the data, and on results emerging from the process of analysing. In contrast, in an hypothesis-driven analysis with a specific hypothesis under evaluation, such decisions are

fewer and ideally made beforehand. This also means that *P*-values reached in an exploratory study should not be taken at face value but as indicators of potentially important relationships (because of multiple and unplanned comparisons). As weed scientists and ecologists rarely distinguish between exploratory studies and hypothesis-driven ones (Andersson & Milberg, 1998b; Hallgren *et al.*, 1999), we start by explaining in some detail the rationale for some of the decisions involved during data exploration.

First of all, we decided to use the current data set to explore three issues: (i) the magnitude of interannual variation in biomass of weeds; (ii) the relationship between biomass of weeds and rainfall and temperature; and (iii) the relationship between a year's weed species composition and its weather. We did this fully aware of some limitations of the data. One problem is that species that were rare in experiments had, in the field, been lumped into an 'other weeds' category, i.e. small occurrences of otherwise common species were unaccounted for. Additional variation results from the fact that numerous people had been involved in weed assessments over the years, and experiments had been dispersed over a large geographical area, over many soil types and in different crops (note that some of this type of variation could be covaried out during analysis). We still considered the data to be useful because a better data set on annual weeds, spanning a long time period, is unlikely to exist or to be compiled in the future. The large amount of variation in the data is likely to obscure patterns but, on the other hand, detectable patterns must be relatively strong and consistent over a large geographical area.

Furthermore, we decided not to analyse individual species but, instead, to analyse groups of species and to analyse from a community perspective. One reason was that most species were present in relatively few experiments per year; another was that small occurrences of the common species were hidden in the 'other weeds' category. We also believed that several species would respond in concert to a particular meteorological situation, rather than completely independently of each other. Finally, as germination syndromes are known to be very important for structuring weed communities (Håkansson, 1983; Andersson & Milberg, 1998a), we expected that summer annuals, winter annuals and germination generalists would respond differently.

We decided to use pCCA, hence looking at the residual variation after covarying out a number of factors known or suspected to influence the weed community (geographical location, soil type, etc.). Therefore, there is a risk that 'interesting' variation can also be lost (e.g. if there are correlations or interactions between covariables and the 'year' variables). In particular, as we factored out long-term temporal trends, we lost some ability to examine differences between years. However, as there were no strong climatic trends through time, we do not think that this is a serious problem. Also worth noting is the fact that some important variables that were not included in the analyses, such as soil cultivation and the timing of sowing of the crop, could directly or indirectly cause some of the interannual variation.

Magnitude of interannual variation in weed biomass

There tended to be more weed biomass in autumn-sown than in spring-sown crops. This is not unexpected as, at the time of weed survey, autumn-germinated weeds had had a longer growth period than spring-germinated ones. Furthermore, seedlings had been recruited over a much longer time period in autumn-sown crops than in spring-sown ones, in which all had probably emerged after sowing in the spring. On the other hand, autumn-sown crops, that gave greater yield than corresponding spring-sown ones (data not shown), would have been larger and more competitive at the time of weed survey.

In autumn-sown crops, the biomass of summer and winter annuals was positively correlated (Table 3); hence, years with a lot of summer annuals would also have a lot of winter annuals. In spring-sown crops, the correlation matrix was different with the biomass of germination generalists covarying with that of both summer and winter annuals (Table 3). Therefore, the overall impression is that weedy years tend to be characterized by large amounts of all three groups of weeds.

The interannual variation was generally large, with 30–50% variation in the total biomass of weeds in autumn- and spring-sown crops (Table 2). Although the average biomass of summer annuals in autumn-sown crops was small, some years had a lot of summer annuals, reflected by $CV > 100\%$ (Table 2). The magnitude of the interannual variation is so large that some years are exceptionally weedy, whereas weed abundance in other years might, in some cases, not justify weed management economically. With a better understanding of the factors causing this variation, it might be possible to identify weedy/non-weedy years before weed management decisions need to be taken.

Relationship between weather and weed biomass

The correlation matrix of weed biomass and weather (Table 3) showed that summer and winter annual weeds in autumn-sown crops seemed to be most influenced by winter temperatures, especially during the later part of the winter (February–March). No weather variable correlated with the biomass of germination generalists. They made up a substantial part of the total biomass (38%), and their interannual variation was large ($CV = 43.5\%$) (Table 2). Nevertheless, weather variables could not explain this variation. It is possible that their ability to germinate over an extended time period in both autumn and spring smoothes out the weather-related component of the interannual variation.

Two scenarios seemed to be worst from the point of view of total weed problems in autumn-sown crops: a cold late winter (February–March) and a rainy spring (April–June).

In spring-sown crops, both temperature and rainfall in May and June seemed to affect the biomass of winter annuals and germination generalists. As warm weather during this period tended to be dry, it is difficult to know which is the proximate cause for the interannual variation. Furthermore, it is not clear whether low temperatures exert their influence by promoting germination, growth or both. Still, it is noteworthy that the summer annuals seemed to be least affected by rainfall (Table 3). In contrast to summer annuals, whose seed have normally been induced into secondary dormancy by the end of May (Milberg, 1994a,b; Milberg & Andersson, 1997), the winter annuals and germination generalists should be non-dormant or conditionally dormant during this time period. This suggests that water availability in May–June could promote seedling emergence during this period.

Ordination of 'years'

The summer annuals were most abundant in spring-sown crops, while those classified as winter annuals dominated in autumn-sown crops (Table 2). This is hardly surprising as the germination syndromes are among the most important determinants of the weed flora in temperate regions (Andersson & Milberg, 1998a; Hallgren *et al.*, 1999). Still, the most important factor distinguishing years in autumn-sown crops was related to the quantity of summer annuals (Fig. 1B), also indicated by their high temporal CV (Table 2). What enables strict summer

annuals to appear in substantial amounts in some years? Summer annual species, such as *Galeopsis* spp., *Bilderdykia convolvulus* and *Polygonum* spp., can germinate very early in the spring (Håkansson, 1983; Baskin & Baskin, 1990). It is possible that their relatively large seed mass (Milberg *et al.*, 1996), providing the seedlings with extra support (Westoby *et al.*, 1996), contributes to their ability to establish in autumn-sown crops. Furthermore, as large amounts of summer annuals mainly appear in autumn-sown crops after cold winters (Table 3), the winter survival and vigour of the crop is probably important. A more speculative explanation could be that the temperature during the winter affects the dormancy-breaking treatment that seeds experience (Noronha *et al.*, 1997) and this, in turn, might affect the timing and amount of germination.

The determinant(s) of weed biomass variation in spring-sown crops was less clear (Fig. 2), but winter annuals were only on the negative side of the first axis in this ordination (Fig. 2B). Winter annuals were relatively scarce in spring-sown crops (7% of the biomass), and their interannual variation was relatively modest (47%) (Table 3). Still, the ordination correlated with rainfall in May–June, suggesting that this variable could be used to forecast the need for weed management by mid-June.

The two most extreme outliers in the ordinations were *Poa annua* (Fig. 1B) and *Sinapis arvensis* (Fig. 2B). Our previous analysis had shown that these species to be associated with winter and spring oilseed rape respectively (Hallgren *et al.*, 1999). There were no experiments in oilseed crops from 1972 to 1980, but treating ‘crop species’ as a covariable should have accounted for this skewness in the data. Instead, the extreme ordination of these species suggests a strong interaction between the oilseed rape and some unknown variable(s) not considered in the present analysis.

Conclusions

The results from the present study that surprised us most were that: (i) clear and interpretable interannual patterns could be detected in a data set spanning such a large geographical area, many soil types and crop species; (ii) winter temperatures could predict weed biomass in autumn-sown crops; (iii) there were often positive correlations between biomass of the three types of annual weeds.

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