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Factors influencing the weed vegetation of Hungarian sunflower fields with special attention to the incidence of *Ambrosia artemisiifolia*

Gyula Pinke [1], Péter Karácsony [1], Zoltán Botta-Dukát [2], Bálint Czúcz [2]

[1]*Faculty of Agricultural and Food Sciences, University of West Hungary, H-9200 Mosonmagyaróvár, Vár 2, Hungary*

[2]*Institute of Ecology and Botany, Hungarian Academy of Sciences, H-2163 Vácrátót, Hungary*

Correspondence

Gyula Pinke*, University of West Hungary, Faculty of Agricultural and Food Sciences, H-9200 Mosonmagyaróvár, Vár 2, Hungary.*

Tel: (+36) 70 5735590;

Fax: (+36) 96 566610;

E-mail: pinkegy@mtk.nyme.hu

Abstract

The weed control of sunflower is a 'great challenge' for farmers throughout the World. The main goal of this study is to identify management and environmental factors which determine the weed species composition of sunflower fields. Altogether 49 sunflower fields across Hungary were surveyed for their weed flora, and 11 environmental and 19 management factors (including the use of mechanical weed control and 6 herbicide treatments) were also recorded for the same fields. Using stepwise backward selection this set of predictors was reduced to a minimal adequate model containing 14 terms explaining 37.8% of the total variation in species data. The net effects of 5 variables on species composition were significant, these were soil Mg and Ca content, preceding crop, temperature, and field size. We also performed exploratory forward/backward model selection to reveal influential predictors for several predetermined species groups and individual species. Most of the herbicides appeared to be effective against annual grass species, but no herbicide was universally effective against broad-leaved weeds. Almost all types of weeds were efficiently reduced with mechanical weed control. We obtained a relatively high share of environmental factors in the variation of species composition, which suggests that the success of agro-technical treatments in sunflower fields strongly depends on a complex of edaphic and climatic constraints. The abundance of the most troublesome weed, *Ambrosia artemisiifolia* was positively correlated with high soil Ca content, lower temperature, preceding crop cereal, and lower field sizes, while it seemed to be most sensitive to fluorchloridon and propisochlor application.

Keywords: agroecology, Helianthus annuus, common ragweed, redundancy analysis, survey, weed flora, weed management, weed control.

Introduction

Sunflower (*Helianthus annuus* L.) is a versatile plant that produces oil for both edible and industrial uses and it is one of the most important crop species in many American, Asian and European countries (Cantamutto and Poverene 2007; Meakin 2007; Pannacci et al. 2007; Fried at al. 2009; Adegas et al. 2010). The Hungarian sunflower production has increased threefold since the year of 2000, and it has been cropped over 500.000 hectares in each of the recent years. However, this dramatic boom is associated with many unexpected challenges for Hungarian farmers with regard to crop protection. The massive build-up of several noxious species in sunflower fields makes weed control highly challenging not only in that specific year, but also in the subsequent years in other crops, which is generally exacerbated by the mass appearance of sunflower volunteers.

Recent weed surveys have shown that common ragweed (*Ambrosia artemisiifolia* L.), which produces large quantities of allergenic pollen, is the far most abundant weed species in Hungarian sunflower fields with nearly 10% mean cover value (Pinke and Karácsony 2010) (Fig. 1). A remarkable ragweed preference to this crop was also revealed with the help of decision tree models (Pinke et al. 2011a). A parallel study investigating the species composition of summer arable weed vegetation (including sunflower fields), also showed that crop type was one of the most important variables (Pinke et al. 2012). Nevertheless, both of these latter studies focused on the effects of management and environmental factors on summer annual weed vegetation as a whole, involving several different crop types. Furthermore, the effect of herbicides could not be explicitly addressed in these studies owing to the great variety of herbicide treatments applied (53 active ingredients). Thus, neither the influence of specific management factors relating to sunflower cultivation could be assessed, nor it was possible to recommend any management policy for reducing the incidence of ragweed.

In the present study, focusing exclusively on sunflower fields, we seek answer to the following questions: (1) Which management and environmental factors determine weed species composition and ragweed incidence in sunflower fields? (2) Are there any management variables that might be used to optimise weed control strategies against *A. artemisiifolia* and other 'difficult to control' weeds?

Materials and methods

Data collection

71 sunflower fields were surveyed across Hungary at the seasonal peak of summer annual weed vegetation, between Jul 27 and Aug 25 2009 (Pinke et al. 2011a; 2012). Weed vegetation of the fields was sampled in three randomly located 50m^2 plots inside the fields (at least 10m from the field margin). Percentage ground cover of weed and crop species in each plot was estimated visually.

Crop management information was obtained directly from the farmers. Altogether 22 active herbicide ingredients were used in the 71 sunflower fields. In order to avoid rare levels of categorical variables, fields that were treated with less common herbicides (less than five cases) were omitted (as well as one field with a singular preceding crop type, see later). In the remaining 49 fields seven herbicide ingredients were applied (the product name, its concentration and the supplier is indicated in brackets): dimethenamid-P (Wing-P, 212.5 g a.i. L^{-1}; BASF), pendimethalin (Wing-P, 250 g a.i. L^{-1}; BASF), propisochlor (Proponit 720 EC, 720 g a.i. L^{-1}; Arysta LifeScience), oxyflourfen (Oxy, 480 g a.i. L^{-1}; Goal Duplo, 480 g a.i. L^{-1}; Dow AgroSciences; Galigan, 240 g a.i. L^{-1}; Agan), S-metolachlor (Dual Gold 960 EC, 960 g a.i. L^{-1}; Syngenta), imazamox (Pulsar, 40 g a.i. L^{-1}; BASF Agro), fluorchloridon (Racer, 25% a.i.; Agan). Of the 49 fields involved in this study 2 fields did not receive any herbicide, one treatment was applied to 18 fields and 30 fields received two different herbicides. The main crop of 29 fields consisted of conventional sunflower, and 20 fields were cropped with imazamox resistant cultivars. To represent herbicide treatments among the management variables the dosage of each active ingredient was used as a standalone variable, except for dimethamid-P and pendimethalin, which occurred only in a fixed combination (Wing-P, BASF) and thus could only be evaluated jointly. We also included into the analysis the number of mechanical weed control treatments, which together with the herbicide treatment were considered as a distinguished group of management variables (weed control treatments) being the primary focus of our study.

Data on the crop history of the fields was also collected from the farmers. Previous crops used included wheat (*Triticum aestivum* L.), triticale (*Triticosecale rimpaui* Wittm.), barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), alfalfa (*Medicago sativa* L.), and maize (*Zea mays* L.). In order to meaningfully avoid the factor levels with few cases in our analysis cereal species were assembled into one category as 'cereal', and the singular field with preceding alfalfa was dropped from the analysis. The amount of organic manure and fertilizers applied were also involved into the analysis, as well as crop cover, crop row spacing, field size and maximum tillage depth.

For each investigated field, we also compiled a set of environmental variables including soil properties, climatic conditions, and altitude. A soil sample of $1000cm^3$ and 10cm depth (excluding litter) was collected from each field and analysed by UIS Ungarn GmbH (Mosonmagyaróvár, Hungary). Climatic conditions were represented by mean annual temperature values obtained from the WorldClim database (Hijmans et al. 2005), and mean annual precipitation values obtained from the Hungarian Meteorological Service (HMS, 2001). Altitude above sea level was measured by a GPS receiver. Altogether 19 management and 11 environmental variables were included in the analysis (Table 1).

Data analysis

To determine an average community composition, we averaged the cover values of the weed species across all three plots in the field cores for each individual field. Mean cover values were then subjected to a Hellinger transformation (Legendre and Gallagher 2001), and were examined in a redundancy analysis (RDA) together with the environmental and management data. According to Legendre and Gallagher (2001) this combination of Hellinger transformation and RDA is able to relate species data to explanatory variables more accurately than several commonly applied multivariate techniques including canonical correspondence analysis (CCA), even if the species response curves are unimodal.

We first fitted a full RDA model to the Hellinger transformed weed cover data using all of the environmental variables as constraining variables. Nevertheless, as variance inflation factors (Fox and Monette 1992) indicated significant intercorrelations among the environmental variables, we intended to establish a reduced model with a limited set of environmental variables, optimised for their useful information content. To this end an RDA model containing all explanatory variables except for the weed control treatments (herbicides and mechanical control) was subjected to a stepwise backward selection using a $p<0.05$

threshold for type I error. This led to a reduced set of variables containing organic manure, field size, preceding crop, annual precipitation, annual mean temperature, soil Ca and Mg content. As weed control measures (herbicides and mechanical control) form the primary focus of this study, these variables were added to this set, constituting together a set of 14 environmental and management predictors which was used to build the reduced RDA model. Variance inflation factors for this reduced model were all below 3.2, thus showing no signs of problematic collinearity (Chatterjee et al 2000).

As a next step of the multivariate analysis, we assessed gross and net effects of each explanatory variable of the reduced model according to the methodology of Lososová et al. (2004). The gross effect of a variable was defined as the variation explained by a 'univariate' RDA containing the studied predictor as the only explanatory variable. The net effect, on the other hand, was assessed as the significance of a partial-RDA (pRDA) with the studied predictor still being the only constraining variable, but with all the other variables of the reduced model used as conditioning variables ('covariables'), the effect of which was 'partialled out' (i.e. removed before the actual RDA). In case of the net effects, model significances were assessed as type I error rates obtained by permutation tests.

To identify the unique and shared contributions of the most important groups of variables (weed control variables, other management factors and environmental factors), we applied variation partitioning to the reduced RDA model based on partial RDA (Borcard et al 1992). Furthermore, to explore the effect of the significant management and environmental factors, we identified those 10 species (with >5 occurrences) which expressed the highest explained variation by the constrained axis in each partial RDA. In addition we generated an overview ordination diagram for the reduced RDA model, where the coordinates of continuous variables were calculated from their linear constraints, while the categorical variable preceding crop, was transformed to a 'dummy' indicator variable which was placed in the ordination space by weighted averaging.

As closely related species and species sharing common ecological characteristics can express a similar response to environmental and management factors (Storkey et al. 2010; Silc 2010; Gunton et al 2011), we also performed an exploratory analysis for preselected species groups (4 major functional groups and the 3 most important plant families) and individual species (the 10 most abundant weed species according to the latest weed survey in sunflower fields – Pinke and Karácsony 2010). Cover values for groups were summed first and, along with cover values for individual species, they were subjected to a variance stabilizing arcus sinus – square root transformation (Zar 1998). Two linear models were fitted to each transformed cover value thereafter: a constant model (containing just an intercept), and a full model (containing all terms from the reduced model without interactions). These models were used as starting points for a stepwise forward / backward search (respectively) based on AIC values. The coefficients of variables identified as relevant for a specific species group during the stepwise selection were recorded, but no statistical testing was made. Nevertheless, variables, which were identified as relevant by both of the stepwise searches and share the same sign of coefficient in both cases seem to be particularly influential in this exploratory analysis.

The entire statistical analysis was performed in the R Environment (R Development Core Team 2011) using the vegan add-on package (Oksanen et al. 2011).

Results

A total of 89 weed species were recorded in the 49 sunflower fields examined. The full RDA model explained 69% of the variance, while the reduced model (comprising 14 explanatory variables) still explained 37.8% of the total variation in community composition. According to the individual RDA and pRDA models, the most important predictors were soil Mg and Ca content, preceding crop, temperature, and field size (Table 2). Although precipitation and organic manure remained in the model during the backward selection procedure, they did not explain any significant amounts of variation in species composition, just like herbicides and mechanical weed control. The responses of the weed species with the highest fit are listed in Tables 3, 4; and the results of the exploratory analysis for pre-selected species and species groups are shown in Table 5.

In the reduced RDA ordination, the first axis can be most related to the explanatory variable soil Ca content and the quantity of imazamox herbicide applied, while the second axis is strongly correlated with temperature, field size and soil Mg content (Fig. 2). Negative values along the first axis indicate fields treated with imazamox herbicide with the presence of *Chenopodium album* L., while high axis 1 values tend to be sites without imazamox on Ca poor soils with frequent incidences of *Echinochloa crus-galli* (L.) P. Beauv and *Xanthium italicum* Moretti. Samples from larger fields in the warmer parts of Hungary with preceding crop maize, which are also typically characterised with the presence of the *C. album* and *Amaranthus retroflexus* L. generally exhibit high values on the second RDA axis (Fig. 2). On the other hand, sites with smaller fields in the cooler areas planted after cereals and no propisochlor application can be characterised with low axis 1 values and the frequent presence of *A. artemisiifolia* and *Setaria pumila* (Poir.) Schult.

The variation partitioning of the RDA model revealed that the environmental, management and weed control variables explain virtually disjunct different fractions of the total variation, with only management and weed control sharing some variance. Environmental variables altogether stand for 2 times more variance than management variables excluding weed control, and 2.4 times more than the weed control alone, and still 1.2 times more variance than all management variables together (Fig. 3).

Discussion

Soil properties and climatic conditions

Among soil properties, the effect of soil Mg and Ca ($CaCO_3$) content were the most important predictor variables. *X. italicum* and *X. strumarium* L. responded more strongly to high Mg, while *C. album* and *Digitaria sanguinalis* (L.) Scop. were associated with low concentrations. The weed species that most strongly responded to Ca content were *A. artemisiifolia* and *Convolvulus arvensis* L. preferring high, while *E. crus-galli* and *X. italicum* preferring low concentrations (Table 3). A similar investigation in Hungarian poppy fields found these two soil elements to be some of the most important factors as well (Pinke et al. 2011b), and Mg also seemed to influence the occurrence of some species in Italian (Otto et al. 2007) and Danish (Andreasen and Skovgaard 2009) arable fields. The association of weed flora with soil Mg is likely to be driven by complex soil chemical interactions with plant functions. Sandy and highly calcareous soils tend to contain less Mg, and large doses of fertilizers can enhance Mg deficiency as well (Bohn et al. 1979; Kalocsai 2006). Calcium is beneficial to the soil structure and fertility and soil pH is also influenced by its content. The known acidic soil preference of *A. artemisiifolia* (Pinke et al. 2011a) seems to be inconsistent with the positive correlation between Ca content and ragweed abundance, because acidic soils have potential nutrient deficiencies of calcium. This might be attributed to the fact, that although our results suggest a clear preference of ragweed for Ca, the concentration of this element in soils along the studied gradient is not a limiting factor for ragweed occurrences. *Ambrosia artemisiifolia* is likely to behave highly competitive along almost the whole gradients of many soil nutrients, a similar behaviour at various N rates has been documented by Leskovsek et al. (2012).

Of the studied climatic factors, it was only mean annual temperature that exerted significant influence on weed composition in our study. The species most associated with higher temperature values were *Datura stramonium* L. and *X. italicum*, whereas *A. artemisiifolia* and *D. sanguinalis* favoured lower temperatures (Table 3). One of our previous studies (Pinke et al. 2011a) also suggested that ragweed grows best in the cooler regions of Hungary, and according to Chauvel et al. (2006) areas with hot summers are not optimal for this species. In our earlier study on the late summer weed flora of Hungary, precipitation was also a significant explanatory variable on species composition in addition to temperature (Pinke et al. 2012). However, as sunflower is susceptible to several noxious diseases under wet circumstances, most of the intensive sunflower cultivation is concentrated in the drier regions of Hungary, and this may give an explanation for the relatively low importance of precipitation in this study. Hence, regions with high precipitation were scarcely involved in this study and shorter climatic gradients generally result in reduced influence of the respective climatic variables (Cimalová and Lososová 2009).

Management variables

Preceding crop and field size

Our results that weed flora is significantly affected by the preceding crop are in complete accordance with the results of e.g. Pinke et al. (2011b) in Hungarian poppy fields, Hanzlik and Gerowitt (2011) in German oilseed rape, Fried et al. (2008) in French arable fields, and a centuries-old experience of most farmers worldwide. Table 3 shows that *Solanum nigrum* L. and *Amaranthus powellii* S. Wats. were most strongly associated with preceding crop maize, while *A. artemisiifolia* and *Fallopia convolvulus* (L.) A. Löve. preferred cereals as preceding crops. *Ambrosia artemisiifolia* can thrive with a dense cover in stubble fields after harvesting the cereals and *F. convolvulus* is also a typical stubble weed species (Novák et al. 2009). These two species can certainly replenish the soil seed banks before stubble ploughing, triggering greater infestations in the subsequent crops. Maize as a previous crop led to an increased proportion of spring germinating weeds in oilseed rape (Hanzlik and Gerowitt 2011), and according to Mas et al. (2010), a preceding maize crop also affected weed community structure in soybean. Subbulakshmi et al. (2009) also reported significant changes in weed species composition in a maize and sunflower cropping system as a consequence of crop rotation.

Interestingly, field size was also found to exert a significant effect on weed species composition and *A. artemisiifolia* associated most strongly with smaller field sizes (Table 3). A study of maize, sunflower and cereal crops in eastern Hungary showed that ragweed infestation in field edges was generally lower in larger fields (Pinke et al. 2011a). Focusing only on the cores of sunflower fields this phenomenon seems to be valid for the whole country. Nevertheless, the existence of a hidden management factor correlated with field size can also give a plausible explanation for this phenomenon. Some agro-technical operations could be less efficient in smaller fields, and farmers cultivating small fields might tend to have limited access to technology or expertise, which can make a difference as the weed control of sunflower culture is rather complicated. A similar investigation of Gaba et al. (2010) in France also revealed that weed diversity increased significantly as field size decreased. Accordingly, the availability of more intensive management and more efficient weed control seem to reduce weed diversity in larger fields.

Weed control methods

Even though none of the herbicides proved significant in the pRDA permutation tests, it is a herbicide, imazamox, which is most correlated with the first axis in the reduced RDA ordination (Fig 2). Our investigation also shows that *D. stramonium*, *X. italicum*, *Persicaria amphibia* L.*, E. crus-galli, Hibiscus trionum* L. and *Abutilon theophrasti* Medic. were the species most sensitive to imazamox, while *C. album* and *A. powellii* seem to have tolerated its application (Table 4). Imazamox is only used in imidazolinone-resistant sunflowers, which are increasingly cultivated in many European countries (Bozic et al. 2012; Elezovic et al. 2012), and our results suggest that this technology has resulted in slightly distinct weed communities. The lack of a significant multivariate relationship in the pRDA model for imazamox might be attributed to the masking effect of the frequent application of other conventional herbicides in this type of sunflower.

Keeping *A. artemisiifolia* at bay in sunflower is a 'great challenge' for farmers. There are several potential factors behind the low efficiency of chemical control with conventional herbicides, including the high level of botanical similarity between crop and weed, and the failure of pre-emergent herbicides during dry springs (Kazinczi et al. 2008). Notwithstanding the results of Kukorelli et al. (2011) and the expectation of most growers (Nagy et al. 2006; Schröder and Meinlschmidt 2009), herbicide-tolerant sunflower varieties might not seem to offer a solution for the ragweed problem. *Ambrosia artemisiifolia* is notably absent from the list of the most imazamox-sensitive species (Table 4), and the exploratory analysis (Table 5) did not suggest any remarkable efficiency of imazamox against this weed species, either. Considering the position of ragweed in the RDA ordination (Fig. 2) ragweed even might be tolerant to imazamox. This might be explained with the observation of Kukorelli et al. (2011) that imazamox could only control ragweed at a 2-4 leaf stage, but the larger individuals survived. Bohren et al. (2008) also emphasised that the efficacy of some active substances against ragweed was clearly influenced by the plant stage during the application. Among the conventional herbicides fluorchloridon and propisochlor appear to have the highest efficiency against ragweed, while seemingly it was most tolerant to oxyflourfen (Table 4 and 5). Kukorelli et al. (2011) also experienced the low efficiency of oxyflourfen with different combinations, while according to Kazinczi et al. (2008) as well ragweed is sensitive to fluorchloridon. However, Simic et al. (2011) found the effect of fluorchloridon and S-metolachlor on ragweed unsatisfactory, manly due to inappropriate weather conditions. The good effectiveness of propisochlor against ragweed is an unexpected result, as this ingredient primarily targets annual grass species, which were also effectively controlled by this chemical according to our results (Table 5). Nevertheless, as a documented "side-effect" propisochlor can also impact some broad-leaved weed species, and the susceptibility of ragweed to propisochlor in combination with other ingredients has been reported in sugar beet by Konstantinovic and Meseldzija (2006).

With respect to species groups Table 5 shows that all the applied ingredients, except S-metolachlor are effective against annual grass species, but not a single herbicide can be used efficiently against the whole spectra of broad-leaved weeds. This phenomenon highlights the week point of chemical weed control in sunflower, namely each 'difficult to control' broad-leaved weed species might require specific treatments. At the same time Table 5 also shows that almost all species groups and noxious weed species can be reduced with mechanical weed control. Meakin (2007) even recommends inter-row cultivation in sunflower under weedy situations, and according to Kukorelli et al. (2011) the efficiency of weed management methods could be highly enhanced by using cultivator.

Conclusions

Although none of the herbicides proved to be significant in our present study, it should be emphasised that this was a survey, not a field trial for testing the effect of herbicides. Due to the length of environmental gradients and the uncontrolled multitude of other management factors the specific influences of single herbicides can remain hidden in a country-wide survey-type study. Variation partitioning of the RDA model (Fig 3.) shows that weed control alone stand for 2.4% variance on species composition, which is very similar to the net share of all other management factors (2.9%). Our earlier investigations showed that without herbicides, management variables accounted for twice less variance than environmental variables (Pinke et al. 2012), now the participation of all management (including herbicides) and environmental factors are closer to each other (5.9 and 7% respectively). However, taking into account that sunflower is a highly intensively cultivated crop species and we focused only on the field cores, which are more affected with management regimes than field edges (José-María et al. 2010; Pinke et al. 2012), it is the high variance share of environmental factors which might seem to be unexpected. This also suggests that the success of agro-technical treatments in sunflower fields depends on a complex of edaphic and climatic constraints. The reduction of noxious broad-leaved weed species could demand specific herbicide mixtures, and mechanical weed control should be integrated in weed management as well. The goal of eliminating of *A. artemisiifolia* and a respect for environmental conditions and weed development stages should remain key points in weed control strategies. Consequently, the applicability of the recent Western-European initiative to reduce pesticide use to avoid unwanted side effect of the increasing cropping intensification (Andreasen and Stryhn 2012) regrettably must be carefully tested for sunflower production in ragweed infested areas.

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Table 1 Units and ranges of continuous variables and values of categorical variables used in the analysed data set

Variable (unit)	Range / Values
Date of sowing	28 March 2009 – 15 May 2009
Preceding crop	cereal, maize
Herbicides (g ha^{-1})	
Imazamox	0-52
Oxyflourfen	0-336
Pendimethalin + Dimethenamid-P (1:0.85)	0-1250 0-1062.5
Propisochlor	0-2016
S-metolachlor	0-1536
Herbicides (L ha^{-1})	
Fluorchloridon	0-0.75
Mechanical weed control (times)	0-2
Organic manure (t ha^{-1})	0-50
Amount of fertilizer (kg ha^{-1})	
N	0-102
P_2O_5	0-52
K_2O	0-96
MgO	0-14
CaO	0-21
Crop cover (%)	15-95
Field size (ha)	0.8-113
Tillage depth (cm)	20-55
Altitude (m)	87-195
Mean annual precipitation (mm)	492-695
Mean annual temperature (ºC)	9.91-11.25
Soil pH (KCl)	3.48-7.85
Soil texture (KA)	20-49.4
Soil properties (m $m\%^{-1}$)	
Humus	0.68-4.72
$CaCO_3$	0.03-21.9
Soil properties (mg kg^{-1})	
P_2O_5	56.3-2770
K_2O	102-1310
Na	19-482
Mg	30.8-990

Table 2 Gross and net effects of the reduced set of explanatory variables on weed species composition identified using single predictor RDA / pRDA analyses respectively, and permutation test-based p-values for the pRDA models. NS = not significant

Factors	Gross effect	Net effect	P-value
Soil Mg content	3.69	3.51	0.01
Soil Ca content	4.12	2.97	0.005
Preceding crop	3.12	1.93	0.024
Temperature	3.17	1.87	0.03
Field size	3.21	1.58	0.044
Propisochlor	2.68	1.37	NS
Precipitation	3.08	1.08	NS
Organic manure	2.59	0.97	NS
Oxyflourfen	2.53	0.46	NS
Fluorchloridon	2.57	0.43	NS
Imazamox	3.32	0.39	NS
Pendimethalin + Dimethenamid-P	2.59	0.05	NS
S-metolachlor	1.85	0	NS
Mechanical weed control	2.25	0	NS

Table 3 Names, fit and score values of the ten species giving the highest fit along the first constrained axis in the single predictor partial- RDA models for the significant environmental and management variables specified in Table 2, and for the variable "mechanical weed control".

Soil Mg content (+ high; – low)	Ax 1 score	Fit	Soil Ca content (+ low; – high)	Ax 1 score	Fit
Xanthium italicum	0.121	0.072	*Echinochloa crus-galli*	0.180	0.159
Xanthium strumarium	0.118	0.247	*Xanthium italicum*	0.134	0.087
Rubus caesius	0.095	0.171	*Setaria pumila*	0.129	0.087
Lathyrus tuberosus	0.058	0.181	*Solanum nigrum*	0.084	0.060
Medicago lupulina	-0.031	0.051	*Persicaria amphibia*	0.070	0.056
Setaria viridis	-0.072	0.073	*Polygonum aviculare*	0.055	0.071
Fallopia convolvulus	-0.083	0.06	*Euphorbia helioscopia*	-0.047	0.162
Portulaca oleracea	-0.095	0.098	*Reseda lutea*	-0.092	0.206
Digitaria sanguinalis	-0.127	0.127	*Convolvulus arvensis*	-0.119	0.082
Chenopodium album	-0.237	0.188	*Ambrosia artemisiifolia*	-0.198	0.078
Temperature (+ high; – low)	Ax 1 score	Fit	Preceding crop (+ maize; – cereal)	Ax 1 score	Fit
Datura stramonium	0.125	0.065	*Solanum nigrum*	0.141	0.170
Xanthium italicum	0.121	0.071	*Amaranthus powellii*	0.127	0.180
Sorghum halepense	0.068	0.056	*Chenopodium hybridum*	0.114	0.110
Polygonum aviculare	0.043	0.045	*Euphorbia helioscopia*	0.028	0.059
Euphorbia helioscopia	-0.026	0.050	*Brassica napus*	0.028	0.052
Brassica napus	-0.033	0.069	*Medicago lupulina*	-0.028	0.042
Fallopia convolvulus	-0.078	0.053	*Portulaca oleracea*	-0.069	0.052
Solanum nigrum	-0.111	0.104	*Elymus repens*	-0.076	0.043
Digitaria sanguinalis	-0.118	0.108	*Fallopia convolvulus*	-0.077	0.052
Ambrosia artemisiifolia	-0.203	0.083	*Ambrosia artemisiifolia*	-0.155	0.048
Field size (+ high; – low)	Ax 1 score	Fit	Mechanical weed control (+ high; – low)	Ax 1 score	Fit
Echinochloa crus-galli	0.111	0.06	*Solanum nigrum*	0.081	0.056
Solanum nigrum	0.096	0.079	*Equisetum arvense*	0.080	0.043
Datura stramonium	0.080	0.027	*Polygonum aviculare*	0.056	0.074
Xanthium strumarium	0.038	0.026	*Lathyrus tuberosus*	0.034	0.062
Medicago lupulina	-0.029	0.046	*Euphorbia helioscopia*	-0.021	0.033
Portulaca oleracea	-0.062	0.038	*Medicago lupulina*	-0.037	0.071
Digitaria sanguinalis	-0.063	0.031	*Reseda lutea*	-0.037	0.034
Setaria viridis	-0.068	0.066	*Rubus caesius*	-0.053	0.053
Convolvulus arvensis	-0.076	0.033	*Persicaria amphibia*	-0.061	0.043
Ambrosia artemisiifolia	-0.246	0.127	*Panicum miliaceum*	-0.110	0.083

Table 4 Names, fit and score values of the ten species giving the highest fit along the first constrained axis in the single predictor partial- RDA models for the herbicide variables

Fluorchloridon (+ high; – low)	Ax 1 score	Fit	Imazamox (+ low; – high)	Ax 1 score	Fit
Chenopodium album	0.160	0.086	*Datura stramonium*	0.113	0.053
Amaranthus powellii	0.086	0.083	*Xanthium italicum*	0.106	0.055
Digitaria sanguinalis	0.060	0.028	*Persicaria amphibia*	0.090	0.093
Brassica napus	-0.023	0.035	*Echinochloa crus-galli*	0.087	0.037
Lathyrus tuberosus	-0.024	0.032	*Hibiscus trionum*	0.078	0.032
Xanthium strumarium	-0.057	0.059	*Abutilon theophrasti*	0.045	0.018
Setaria viridis	-0.057	0.046	*Medicago lupulina*	0.021	0.023
Panicum miliaceum	-0.074	0.038	*Amaranthus blitoides*	-0.043	0.038
Echinochloa crus-galli	-0.076	0.028	*Amaranthus powellii*	-0.061	0.042
Ambrosia artemisiifolia	-0.144	0.041	*Chenopodium album*	-0.132	0.058
Oxyflourfen (+ low; – high)	Ax 1 score	Fit	Propisochlor (+ low; – high)	Ax 1 score	Fit
Echinochloa crus-galli	0.115	0.065	*Ambrosia artemisiifolia*	0.196	0.077
Hibiscus trionum	0.089	0.041	*Panicum miliaceum*	0.098	0.066
Abutilon theophrasti	0.081	0.060	*Digitaria sanguinalis*	0.073	0.041
Persicaria amphibia	0.074	0.063	*Brassica napus*	0.022	0.032
Polygonum aviculare	0.047	0.053	*Polygonum aviculare*	-0.032	0.025
Amaranthus retroflexus	0.045	0.029	*Sorghum halepense*	-0.052	0.033
Rubus caesius	-0.039	0.029	*Fallopia convolvulus*	-0.071	0.044
Amaranthus powellii	-0.052	0.030	*Elymus repens*	-0.083	0.052
Cannabis sativa	-0.081	0.032	*Amaranthus retroflexus*	-0.099	0.140
Ambrosia artemisiifolia	-0.122	0.030	*Chenopodium album*	-0.176	0.104
S-metolachlor (+ low; – high)	Ax 1 score	Fit	Pendimethalin & Dimethenamid-P (+ high; – low)	Ax 1 score	Fit
Hibiscus trionum	0.085	0.038	*Cannabis sativa*	0.12	0.070
Echinochloa crus-galli	0.065	0.021	*Datura stramonium*	0.075	0.023
Portulaca oleracea	0.048	0.025	*Sorghum halepense*	0.055	0.037
Medicago lupulina	0.035	0.063	*Fallopia convolvulus*	0.050	0.022
Lathyrus tuberosus	-0.025	0.035	*Persicaria amphibia*	0.047	0.025
Stachys annua	-0.035	0.023	*Xanthium strumarium*	0.035	0.022
Sorghum halepense	-0.067	0.055	*Amaranthus retroflexus*	-0.039	0.022
Cirsium arvense	-0.079	0.034	*Convolvulus arvensis*	-0.056	0.018
Setaria viridis	-0.092	0.119	*Equisetum arvense*	-0.075	0.037
Cannabis sativa	-0.112	0.062	*Panicum miliaceum*	-0.090	0.056

Table 5 The impact of weed control methods on major species groups and troublesome weed species estimated with linear models. Each cell contains two signs separated by a space, which represent the sign of the coefficients after a stepwise forward / backward model selection on the reduced set of predictor variables. Zero values mean terms missing from the optimized models, whereas double + or – signs indicate consistently strong relationships. (– – = sensitivity; + + = tolerance)

Species groups and species	Fluorchloridon	Imazamox	Oxyflourfen	Propisochlor	S-metolachlor	Pendimethalin & Dimethenamid-P	Mechanical weed control
Broad-leaved annuals	0 +	– 0	– 0	0 0	0 0	0 0	– –
Broad-leaved perennials	+ +	0 0	0 0	0 0	0 0	0 0	– –
Annual grasses	– –	– –	– –	– –	0 0	– –	– –
Perennial grasses	0 0	– 0	– –	0 0	– 0	0 0	0 0
Asteraceae	0 +	– 0	0 0	– 0	0 0	0 0	– –
Poaceae	0 0	– –	– –	0 0	0 0	0 0	– –
Chenopodiaceae	+ +	0 0	0 0	+ +	0 0	0 0	+ –
Ambrosia artemisiifolia	– 0	0 0	+ +	– –	+ 0	0 0	– 0
Chenopodium album	+ +	0 0	0 –	+ +	0 –	0 0	– –
Convolvulus arvensis	0 0	0 0	0 0	– –	0 0	0 0	– –
Xanthium italicum	+ +	– 0	– 0	0 0	– 0	0 0	0 0
Echinochloa crus-galli	– 0	– 0	– 0	0 0	0 0	0 0	– –
Cirsium arvense	0 0	0 0	0 0	0 0	0 0	0 0	– –
Panicum miliaceum	– –	0 0	0 –	– 0	0 0	– 0	– –
Setaria pumila	0 0	0 0	0 0	0 0	+ +	0 0	– –
Elymus repens	0 0	+ +	0 0	0 0	0 0	0 0	0 0
Hibiscus trionum	0 0	– –	– 0	0 0	– 0	0 0	0 0
Datura stramonium	0 0	– 0	– 0	0 0	0 0	+ +	– –

Fig. 1 Sunflower fields, heavily infested with *Ambrosia artemisiifolia*

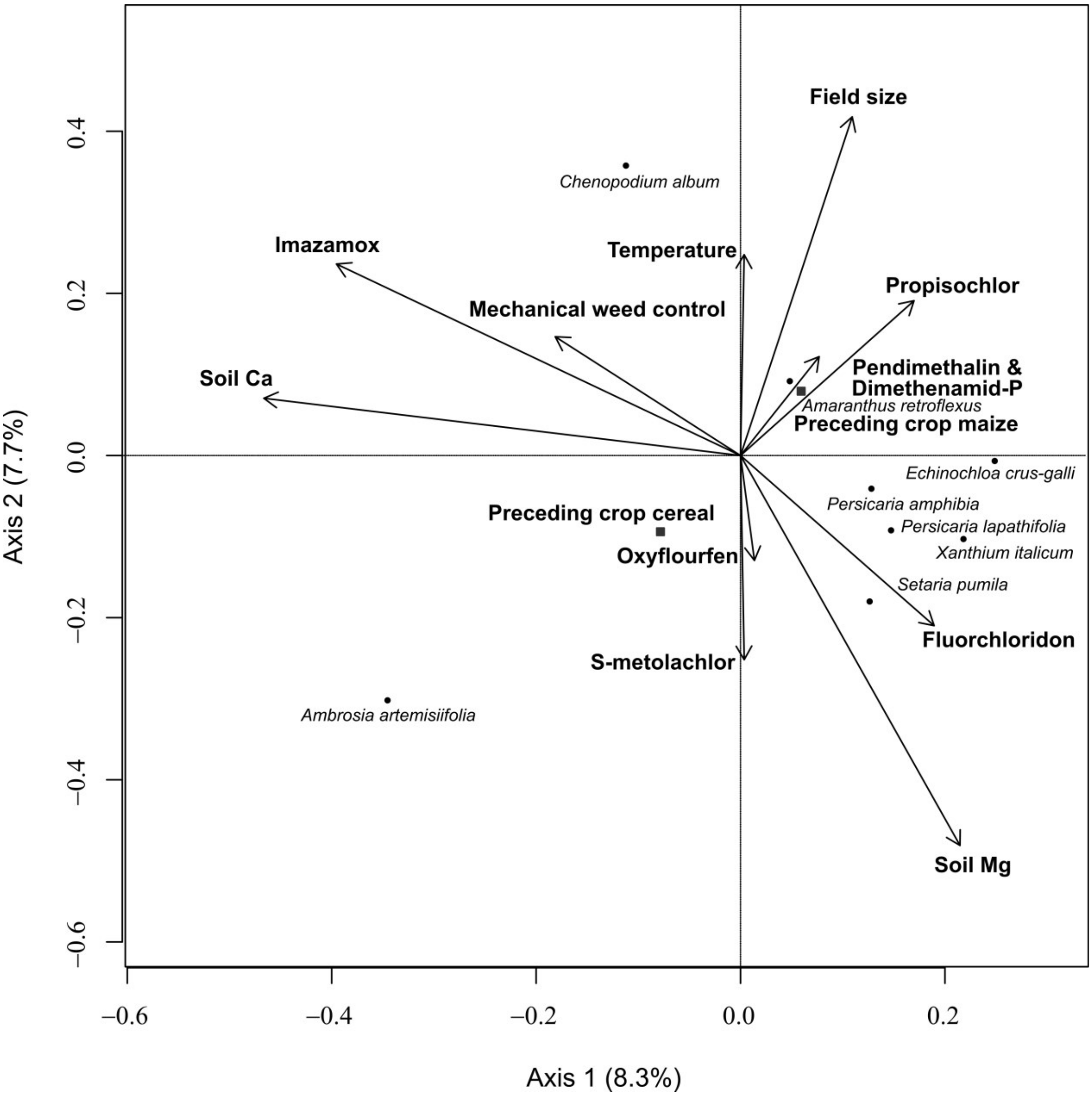

Fig. 2 Ordination diagrams of the reduced RDA model containing the 5 significant explanatory variables, all weed control variables and the 10 species with the highest goodness of fit. (Arrows = continuous variables; squares = categorical variables (preceding crop); dots = species)

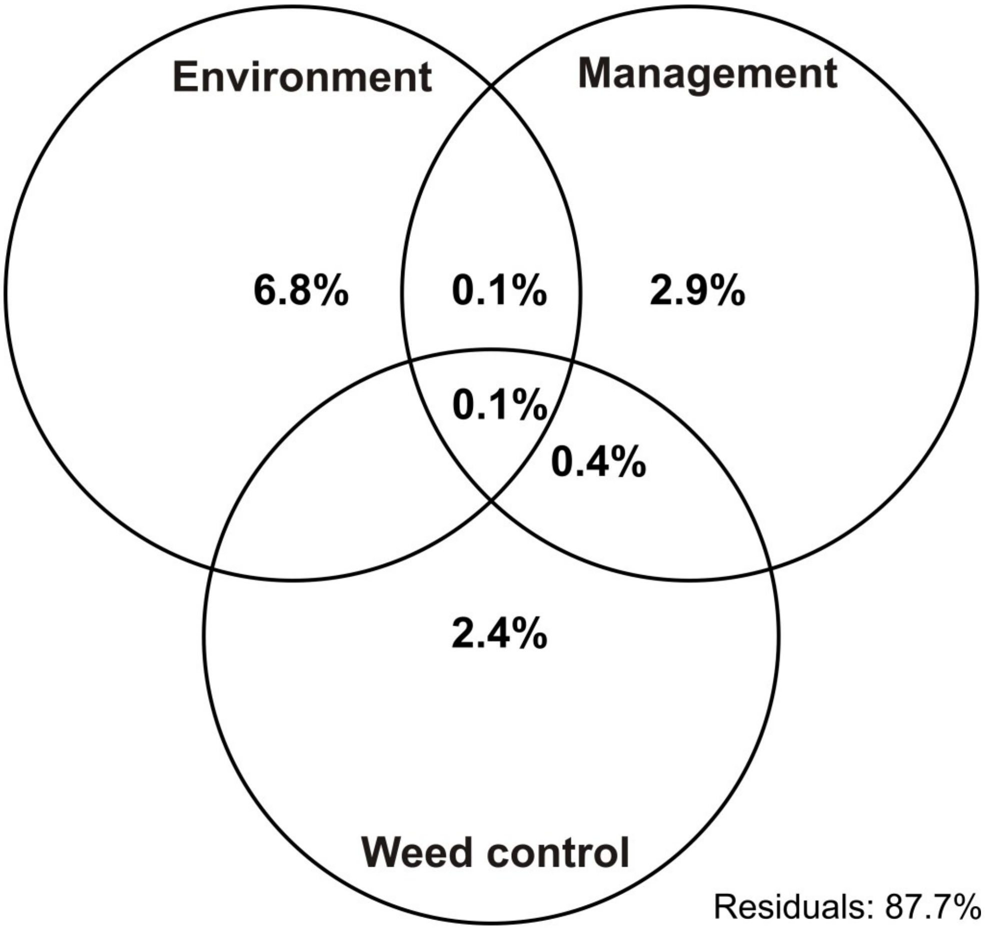

Fig. 3 Percentage contributions of three groups of explanatory variables to the variation in weed species composition, identified by variation partitioning.