Weed species composition of small-scale farmlands bears a strong crop-related and environmental signature

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Summary

Weed species loss due to intensive agricultural land use has raised the need to understand how traditional cropland management has sustained a diverse weed flora. We evaluated to what extent cultivation practices and environmental conditions affect the weed species composition of a small-scale farmland mosaic in Central Transylvania (Romania). We recorded the abundance of weed species and 28 environmental, management and site context variables in 299 fields of maize, cereal and stubble. Using redundancy analysis we revealed 22 variables with significant net effects, which explained 19.15% of the total variation in species composition. Cropland type had the most pronounced effect on weed composition with a clear distinction between cereal crops, cereal stubble and hoed crops. Beyond these differences, the environmental context of croplands was a major driver of weed composition, with significant effects of geographic position, altitude, soil parameters (soil pH, texture, salt and humus content, $CaCO_3$, P_2O_5, K_2O, Na and Mg) as well as plot location (edge vs core position) and surrounding habitat types (arable field, road margin, meadow, fallow, ditch). Performing a variation partitioning for the cropland types one by one, the environmental variables explained most of the variance compared with crop management. In contrast, when all sites were combined across different cropland types, the crop specific factors were more important in explaining variance in weed community composition.

Keywords: Transylvania, weed flora, arable fields, agroecology, agro-ecosystem, altitude, field edges, redundancy analysis

Introduction

Changes in farming systems, mechanization, increases in field size as well as the use of chemical fertilisers and herbicides have had a marked negative impact on weed species diversity and abundance (Marshall *et al.*, 2003, Albrecht *et al*., 2016). Many European countries have reported significant decrease in abundance or even extinction of typical arable weed species (Storkey *et al*., 2011).

Despite their potential importance for the health of agricultural ecosystems, weed species may also cause significant economical losses for farmers and weed control can be the most expensive agricultural practice aimed at improving crop production (Marshall *et al.*, 2003). In order to develop efficient, sustainable and environmentally friendly weed control practices, it is urgent to understand the drivers of weed presence and abundance on cultivated lands (Swanton *et al.*, 1999). We need to investigate how the interaction between farming and weed management systems and the environment affects the composition of weed vegetation in different croplands (Pyšek *et al.*, 2005, Pinke *et al.*, 2011, 2012, 2013).

Existing evidence is mixed, suggesting that the weed composition of arable lands may primarily be determined by ecological factors (Lososová *et al*., 2004) or by human activity (Fried *et al*., 2008, Andreasen & Skovgaard, 2009, Cimalová & Lososová, 2009, Pinke *et al.*, 2012). It is however sensible to expect that the two types of factors interact, and the prevalence of one or the other is context-dependent. For instance, where environmental conditions are less favourable to cropping, the degree of agricultural intensification is also lower and the environmental imprint on weed composition is strong (Lososová *et al*., 2004, Nowak *et al*., 2015). In upland areas the frequency of herbicide treatments is usually lower than elsewhere (Pál *et al*., 2013), the proportion of alien weed species is lower and weed species richness is higher (Lososová *et al*., 2004). Nevertheless, the composition of the weed flora also depends on the crop type, including the division between winter- and summer-sown crops and crop-specific management (Fried *et al*., 2008). Superimposed on this pattern may be the often-reported increase of weed species richness towards field margins, due to a lower competition pressure from crops and release from chemical stressors in border areas (Seifert *et al*., 2015). The role of these marginal cropland habitats in conservation is very important and increasingly recognised (Wrzesień & Denisow, 2016). Rare weed species are usually restricted to the outermost few metres of the croplands, where weed species richness and cover are higher compared to the field centre (Wilson & Aebischer, 1995, Fried *et al.*, 2009). The study fields in our area were characteristically small, potentially magnifying this affect as the boundary/area ratio would be increased.

In many parts of Eastern Europe, the traditional management practices have been preserved for longer compared to Western Europe, conserving important arable biodiversity in small-scale mosaic landscapes (Loos *et al.,* 2015). Although significant land use changes are currently underway (Nyárádi & Bálint, 2013, Loos *et al*., 2015), due to the high number of small farmlands and a high variety of cropping practices, these landscapes still provide ideal ground for gauging the imprints of environment on weed composition in agricultural lands.

In this study we investigated the relative effect of agricultural management and environmental factors on weed species composition of arable fields in small-scale farmlands. Our study system was a mosaic of small farmlands in Central Transylvania (Romania) characterised by a high diversity of cropping practices. Detailed surveys of weed vegetation of arable lands in the area have been scarce and the existing studies provided little mechanistic understanding of the persistence of weed species in traditional landscapes (Chirilă, 2001, Ciocârlan *et al*., 2004, Loos *et al*., 2015).

We performed a comprehensive survey of weed vegetation in this area and examined the effects of 14 management-, 12 environment- and two site context variables on species composition of weed communities. We hypothesized that, due to the persistence of traditional management practices and the small-scale farms, the weed composition of arable lands would carry a strong imprint of environmental factors in addition to the effect of management techniques.

Materials and Methods

Site description

We carried out our survey in 2013 in Central Transylvania, Romania (23°59’260” – 26°11’992” North, 46°08’520” – 46°54’597” East), covering nearly the total area of 6714 km^2 of Mureş county in this region (Fig. 1). The proportion of agricultural land in this county is 61%, of which 54% is classified as arable land. The most widely cultivated crops are cereals and maize (INS, 2016). Our study covered an elevational gradient ranging between 260–543 m (Table 1). The lower elevations included the Transylvanian Plateau, more suitable for agriculture due to wide valleys and a milder climate. The higher elevation North-Eastern corner of the county consisted of the Călimani and Gurghiu Mountain foothills, where arable fields were rarer. Here, the temperature and precipitation regimes have been less suitable for crop production and therefore agricultural intensification has been lower, e.g. 4-6 times lower doses of chemical fertilisers and herbicides in average compared to France or Germany (Storkey *et al*., 2012).

Fig. 1 near here

Data collection

We selected a total of 299 arable fields for the survey in a broadly random pattern, but also depending on farmer's cooperation (Fig. 1). Within each field we sampled weed vegetation in six randomly selected, 4 m^2 plots (2×2 m), totaling 1794 plots. Three plots were located on the field edge (within 2 m from the outermost seed drill line), and three were in the field centre. 101 fields were cereal crops (74 *Triticum aestivum* L., 11 *Triticosecale* x *rimpaui* Wittm., 8 *Hordeum vulgare* L., 5 *Hordeum distichon* L., 3 *Avena sativa* L.) and 97 maize (*Zea mays* L.). The remaining 101 sites were stubbles of cereal fields. While cereal stubbles are not crops, we analysed them as a separate cropland type due to their unique weed vegetation (Pinke *et al*., 2010). We surveyed the cereal fields between May 10 and June 6, and the maize and the cereal stubble fields between July 31 and August 20 to ensure that we captured the most comprehensive set of weed species within each cropland type.

Within each 4 m^2 plot, we estimated visually the percentage ground cover of all species, including crop species, and the vegetation data recorded was subsequently digitized and stored in TURBOVEG format (Hennekens & Schaminée, 2001). In addition, we interviewed landowners for information on crop management of each investigated field. We recorded the cropping history (indicating the preceding crop as either cereal or hoed crop), the amount of organic manure applied, whether farmers used chemical fertilisers (N, P_2O_5, K_2O), as well as crop sowing season (previous fall or spring) and field size. Information on weed management (type of herbicides used and number of times mechanical weed control treatments were applied) were also recorded. Herbicides applied on less than 10 fields out of the total of 299 were subsequently dropped from the analyses. To reduce the number of management categories, the ’cropland type’ variable was coded as cereal crop, maize crop or cereal stubble.

We used soil chemical and physical properties as local environmental variables. From each field we collected one soil sample of 1,000 cm^3 from the top 10 cm layer. Soil samples were air dried and stored at room temperature until further analyses were performed at UIS Ungarn GmbH (Mosonmagyaróvár, Hungary). Soil variables included: soil pH, texture, salt and humus content, $CaCO_3$, P_2O_5, K_2O, Na and Mg. In addition, we used three proxies of regional environmental conditions quantified as the geographic latitude, longitude and elevation above sea level of each field, as recorded by a GPS device.

Finally, we considered two site variables: plot location (edge or field core) and neighbouring habitat (arable field, road margin, meadow, fallow or ditch) to represent composite management and environmental effects.

Overall we recorded 28 parameters: two site variables, 12 environmental variables and 14 management variables (Table 1).

Table 1 near here

Statistical analyses

Prior to analyses we averaged the abundance of species across field edge and field core plots respectively, which we subsequently transformed following the Hellinger approach (Legendre & Gallagher, 2001). We also transformed the categorical variables (the amount of chemical fertilisers and herbicides) into ‘dummy’ indicator variables.

To analyse the relationship between the composition of weed vegetation and site, environmental and management variables, we performed a Redundancy Analysis (RDA). RDA links species abundance data to explanatory variables more accurately than the commonly used Canonical Correspondence Analysis (CCA), even when species responses to environmental gradients are unimodal (Legendre & Gallagher, 2001). Only species with >10 occurrences were involved in the analyses. We reduced the number of explanatory variables using stepwise backward selection with a $P<0.05$ threshold. With this procedure six variables were eliminated: soil pH, Na and salt content, mechanical weeding and herbicides 2,4 D and bromoxinil, resulting in a reduced RDA model with 22 terms with significant effects. The generalised variance inflation factor GVIF (Fox & Monette, 1992) ranged between 1.0 and 5.51, indicating no serious collinearity between explanatory variables.

We then compared the gross and net effects of each explanatory variable, following the methodology described in Lososová *et al*. (2004). The gross effects represented the variation explained by a 'univariate' RDA containing the predictor of interest as the only explanatory variable. The net effect was calculated using a partial RDA (pRDA), which included the variable of interest as explanatory variable and the other 21 variables as conditional variables ('co-variables'). We extracted the explained variance and the adjusted R-squared (R^2_{adj}) for models of both gross and net effects of each variable. In models of net effects, model fit was also assessed by the *F*-value for which a type I error rate was estimated using 999 permutation tests of the constrained axis. The importance of each explanatory variable was 'ranked' using the R^2_{adj} values of the pRDA (i.e. net effect) models. Subsequently, we identified the 10 species with the highest fit for each explanatory variable.

We report only the RDA ordination diagrams of the reduced model with the finally selected 22 variables. In these diagrams, continuous variables were represented by their linear constraints, while positions of categorical variables were calculated by weighted averaging of coordinates of plots representing each level.

In addition, we performed a variation partitioning analysis to assess the relative effects of site, environmental and management variables on weed species composition either within each cropland type separately or across all the fields, and separated by edge vs. centre position (Borcard *et al.*, 2011). This procedure identifies unique and shared contributions of groups of variables using adjusted R-squared values.

Statistical analyses were performed using the *vegan* (version 2.3-3) and *car* (version 2.0-25) packages in R 3.1.2 (R Development Core Team). Species fit on the constrained ordination axes was calculated using the 'inertcomp' function of *vegan* package.

Results

Across the 1794 plots sampled from 299 arable fields we found a total of 141 weed species, 110 in cereals, 88 in stubble fields and 76 in maize crops. From the top most threatened 48 arable weeds in Europe (Storkey *et al*., 2012) only four occurred in our dataset, all in cereal fields. Their frequency of occurrence ranged between 1.0 and 9.7% (*Adonis aestivalis* L. 9.7%, *Centaurea cyanus* L. 6.1%, *Ranunculus arvensis* L. 5.9%, *Lathyrus aphaca* L. 1.0%).

The full RDA model comprising all 28 explanatory variables explained 20.25% of the variance, while the reduced model with 22 explanatory variables still explained 19.15% of the total variation in species composition. All 22 variables (cropland type, geographic position, altitude, soil parameters, plot location and neighbouring habitat) had significant net effects at a $P<0.05$ level (Table 2). Weed species with the strongest responses to these factors are listed in Tables S1, S2, and S3 in Supporting Information.

Table 2 near here

In the reduced RDA ordination (Fig. 2) the first two axes explained 7.65% and 2.51% of the total variation, respectively. Cropland type (cereal crop, maize crop and cereal stubble) resulted in the largest distinction in weed species composition, followed by the sowing season (autumn and spring) (9.46 and 3.84 % of explained variation respectively; Table 2). Species positively associated with the first axis were typical of maize crops (e.g. *Amaranthus retroflexus* L., *Chenopodium album* L., *Hibiscus trionum* L.), while species characteristic of cereal crops were negatively associated with the first axis (e.g. *Galium aparine* L., *Papaver rhoeas* L., *A. aestivalis*). Species found in cereal stubbles had a positive weight on the second axis (e.g. *Stachys annua* L., *Anagallis arvensis* L. and *Setaria viridis* (L.) P. Beauv) (Fig. 2). Neighbouring habitat (a site variable) was the next best important predictor of variation in weed composition (net effect: 0.76% and gross effect: 1.42% explained variation; Table 2). Arable fields were positively, and road margins and meadows were negatively associated with the first axis, while ditches weighted positively on the second axis.

Further variables with a strong weight on the first axis were organic manure and soil properties (calcium, potassium and humus content), while variables with strong weight on the second axis were soil texture, chemical fertilisers and latitude (Table 2, Fig. 2).

Fig. 2 near here

The variation partitioning within each cropland type revealed that environmental variables outperformed the management and site variables, with nearly equal values in stubbles and maize, and slightly lower in cereals (6.6%, 6.5% and 4.8% respectively Fig. 3). The management variables had the highest relative effect in maize and equally lower in cereals and stubbles. The relative effects of site and management variables were similar in cereals (2.5% vs. 2.6% respectively), but in maize and stubbles site explained only a tiny fraction of the variance (0.9–0.2%) (Fig. 3). Variation partitioning over all the 299 fields resulted the highest influence of management variables, being largely driven by crop type, explaining three times more of the total variance compared to the environmental variables (10.9% vs. 3.4%) (Fig. 4). The variation partitioning of the RDA according to the plot location revealed that the effect of environmental variables is only slightly higher in field edges than in the cores (3.2% vs. 2.6% respectively), while the influence of management was nearly equal (10.4% vs. 10.5) (Fig. 5).

Fig. 3, 4, 5 near here

Discussion

Farmland management practices such as cropland type, fertilisation and sowing season were the major drivers of weed composition in the studied system. However, environment and site effects were also important contributors to the revealed patterns. Our report represents the most exhaustive assessment to date of the weed vegetation of arable lands in Central Transylvania, showcasing factors that structure weed composition under agronomical practices currently typical of Eastern Europe.

Management effect

We found that 11 of the 22 significant predictors of weed composition were elements of the management system. From all management variables involved in the study only three (two herbicides and frequency of mechanical weeding) were dropped during the backward selection process, and the effect of all of the remaining management variables were significant. Of these, cropland type had the most pronounced effect, reinforcing the view that crop type is a primary driver of weed vegetation (Cimalová & Lososová, 2009). This can be explained by major differences in cultivation practices between cereals and hoed crops (Andreasen & Skovgaard, 2009, Nowak *et al*., 2015). Cereal fields are exposed to mechanical disturbance (and stresses caused by herbicides) only at the beginning of the season and after harvesting, ensuring a longer undisturbed growing period for weeds in comparison to hoed crops. Most rare and endangered species (such as *A. aestivalis*, *C. cyanus*, *L. aphaca*, *R. arvensis* in our dataset) have been associated with cereals, because they germinate mainly in autumn and have their life cycle adapted to that of cereals rather than to that of hoed spring sown crops (Kolářová *et al*., 2013). Following cereal harvest, stubbles are left undisturbed until late autumn, leaving open sunny habitats suitable for the establishment of species that are able to germinate at high temperatures and tolerate summer drought, e.g. summer therophytes (*S. annua*, *A. arvensis*, *Kickxia elatine* (L.) Dumort.). In contrast, species identified as typical of maize crops have their germination associated with later crop sowing date (Gunton *et al*., 2011) and able to tolerate continuous disturbance regimes (*Echinochloa crus-galli* (L.) P. Beauv, *Setaria pumila* (Poir.) Schult., *H. trionum*, *C. album*) (Fig. 2). A typical disturbance-tolerance strategy is the steady germination ability of seeds throughout the cultivation period (Fried *et al*., 2012).

It would have been interesting to distinguish between the effect of the season (using the date of observation) and the effect of the management. However, these two factors are confounded in the one variable, cropland type, making impossible their separate analysis. It is likely that season and management interacted to shape the characteristics we associated with stubble in our analysis. Despite similar sowing dates of cereals, subsequent germination later in the season would have contributed to the different floras recorded in their stubble. Preceding management regimes, i.e. cropping technologies applied in cereals and maize, also have their impact on weed floras. Furthermore, environmental conditions in the stubble are different, e.g. free from the shading. Accordingly, not only the flora of cereals and that of their stubbles differs remarkably, but stubble and maize also have different weed flora, even though the fact that they were surveyed in the same season. Consequently, stubble is not a homogenous category among cropland types; its subdivision and introduction of season as a new variable would have made possible to further dissect the causalities behind the patterns of weed composition.

Fertilisation was an important filter of weed species and a selective driver of weed abundance (for similar results see Lososová *et al*., 2006, Pinke *et al*., 2012, Seifert *et al*., 2015). Several species responded to organic manure with increased abundances (e.g. *Convolvulus arvensis* L., *S. pumila*, *E. crus-galli*), while chemical fertilisers could be linked to higher abundances of only three species (*Rubus caesius* L., *H. trionum*, *Elymus repens* (L.) Gould). Almost all weed species that responded positively to higher organic manure were associated with maize fields (e.g. *E. crus-galli, C. album, A. retroflexus*), due to higher doses applied in hoed crops (Lososová *et al*., 2006).

A strong negative relationship between field size and weed diversity at the landscape level has often been reported due to a higher associated heterogeneity of cultivated areas and a larger edge / area ratio in smaller field sizes (Marshall *et al*., 2003, Gaba *et al*., 2010, Fahrig *et al*., 2015). Some mechanical operations are less efficient in smaller fields and farmers cultivating small fields tend to have limited access to weed management technology or expertise (Pinke *et al*., 2013). In our study this effect, albeit significant, was less pronounced (field size ranked only 12th among the explanatory variables), as our data covers only a narrow range of field sizes (most fields in our survey were small, 59% had ≤1 ha).

The sowing season was an important driver of weed composition in our survey, where we investigated winter- and spring-sown cereals and spring sown maize. Winter annual weed species (*Veronica persica* Poir., *Consolida orientalis* (J. Gay) Schrödinger, *G. aparine*, *P. rhoeas*) were strongly associated with autumn-sown cereals, while summer annual weed species (*A. retroflexus*, *C. album*, *H. trionum*, *S. pumila*, *E. crus-galli*) preferred spring-sown cultures, many of the latter being typical weeds of hoed crops (Fig. 2). These results concur with earlier evidence, confirming that the presence of multiple crops and cropping times may considerably increase the regional weed species pool (Marshall *et al*., 2003, Pinke *et al*., 2011, Fried *et al*., 2012, Vidotto *et al*., 2016).

Among preceding crops, winter cereals usually favour winter annuals, while hoed crops summer annuals. In our analysis preceding crop ranked only the 15th among the predictors, not independently from the common practice in the surveyed area to alternate winter cereals with hoed crops. The rotation of cereals and hoed crops aims to interrupt the build-up of weed populations associated with particular crop types (de Mol *et al*., 2015).

We found that the use of herbicides significantly affects the occurrence and abundance of weed species. The active ingredients of the herbicides with significant effect were fluoroxypyr, florasulam, isoxaflutol with ciprosulfamid, thiencarbazone-methyl and dicamba (Table 2). All of these were used for post-emergence control. Florasulam, fluoroxypyr and dicamba can be used against dicotyledonous weeds, and isoxaflutol + ciprosulfamid and thiencarbazone-methyl are broad-spectrum herbicides for the control of both monocotyledons and dicotyledonous weeds. Although we identified several weed species that were correlated with herbicides according to their explained variation in the constrained axes, without a survey before and after herbicide treatment we cannot draw firm conclusions on the effect of herbicides. Accordingly, these correlations are not shown in the supporting information.

Environmental effect

We found nine environmental variables with significant net effects on weed composition, including both regional and local factors (Table 2).

Longitude ranked the 2nd, altitude the 3rd and latitude the 13th among all predictors. These variables have been used as proxies of regional climate conditions such as precipitation and mean temperature (Lososová *et al*., 2004, 2006, Hanzlik & Gerowitt, 2011, de Mol *et al*., 2015). Species strongly associated with lower altitudes were troublesome weeds such as *Solanum nigrum* L., *Xanthium italicum* Moretti, *Polygonum aviculare* L. and *R. caesius,* while species correlated with higher altitudes were cereal weeds typical of traditional farming, e.g. *C. orientalis, C. cyanus*. This pattern has often been reported from agricultural landscapes situated in heterogeneous geographic conditions (Lososová *et al*., 2004, Pál *et al*., 2013, Nowak *et al*., 2015). The north-eastern higher altitude part of our study area is less favourable especially for maize but also for other crops, as a consequence the cultivation is less intense (Fig. 1). We interpret the change in weed composition along this geographical gradient as a result of both environmental effects and differences in farming methods between lowland and upland areas due to environmental constraints.

As expected, soil physical and chemical properties such as texture, Ca, K, Mg, P and humus content exerted significant effects on the occurrence of certain weed species (Pinke *et al*., 2012, 2016). For example we found that *Cirsium arvense* (L.) Scop., a species common in all crop types, preferred soils with high humus and Mg content, but avoided alkaline soils. Although in many studies pH was a crucial determinant of weed species presence (e.g. Pyšek *et al*., 2005, Fried *et al*., 2008, Vidotto *et al*., 2016), other investigations, including ours, found this factor to be non-significant (see also Nowak *et al*., 2015), likely because neutral soils were dominantly prevalent in our study area.

Site effect

The plot location (edge vs core position) and the neighbouring habitat type had moderate effects on weed composition (the 6th and the 14th most important predictors, respectively). Most weeds preferred field edges and only one species, *C. arvensis* had higher abundance towards field interiors. It is well known from other agricultural ecosystems that crop margins support higher species richness and the principle is applied in weed conservation (e.g. Pinke *et al*., 2012, Kolářová *et al*., 2013, Seifert *et al*., 2015, Wrzesień & Denisow, 2016). Mechanisms behind these patterns include the crop's lower competition ability, dilution or lack of chemical stressors in the border areas (Seifert *et al*., 2015), release from competition for light exerted by crop species (Pinke *et al*., 2012) and a higher external propagule supply from adjacent habitats (Gaba *et al*., 2010, Conceptión *et al*., 2012, Pinke *et al*., 2012, Wrzesień & Denisow, 2016).

In our mosaic of small farmlands, neighbouring habitats were diverse (arable field, ditch, fallow, meadow, road margin) and were linked to the presence/abundance of specific weeds in the crop fields. Maintaining a diversity of non-farmed habitats adjacent to farmlands may therefore result in an enriched weed flora in crop fields. Here we have shown that this externally driven enrichment diminishes substantially towards field interiors (see also Gaba *et al*., 2010, Pinke *et al*., 2012).

Environment vs management factors

In the variation partitioning within each cropland type the environmental variables explained the largest fractions of the variance, which is in accordance with the results of previous studies (Lososová *et al*., 2004, Pinke *et al*., 2012, 2016, de Mol *et al*., 2015). The effect of environmental variables reached the highest proportion in cereal stubbles, explaining two and a half time more variance than the effect of management variables. This may be due to the lack of particular cropping practices on stubbles. In maize crops the relative influence of environmental variables was similarly high. Both maize and stubble represented the late summer weed flora, and the higher contributions of environment could be due to the longer period following weed management practices, which allows the weed vegetation to recover from the seed banks primarily under the influence of soil and climatic conditions. Furthermore, in maize the management variables explained a higher proportion of variance in weed communities when compared to cereals and stubbles possibly due to the frequently repeated cultivation tasks typical of maize crops.

In contrast to the crop specific analyses the variation partitioning carried out over all sites highlighted the importance of the management variables. This shows that the involvement of crop type can increase the contribution of management remarkably, highlighting the generally powerful impact of crop-related factors on the weed flora (Fried *et al*., 2008, Gunton *et al*., 2011).

Splitting up the variance allocated to the plot location, the management factors account for approximately three times more variance compared to the environmental variables both in field cores and edges. We found no difference between field edges and cores in the importance of management variables, contrary to the findings of Pinke *et al*. (2012). This could be explained by the generally small field sizes in this study, where the cultural and ecological conditions between edge and core are likely to be more similar than in the large fields (Wilson & Aebischer, 1995).

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Table 1 Units and ranges of continuous variables and values of categorical variables recorded on each cropland for this study.

Variable (unit)	Range / Values
Site	
Plot location	edge, core
Neighbouring habitat	arable field, ditch, fallow, meadow, road margin
Environmental	
Longitude (E)	46°08’520”–46°54’597”
Latitude (N)	23°59’260”–26°11’992”
Altitude (m)	260–543
Soil pH (KCl)*	5.02–7.60
Soil texture (KA)	29–57
Soil properties (m m%$^{-1}$)	
Humus	1.58–7.57
$CaCO_3$	0.1–18.5
Soil salt*	0.02–0.17
Soil properties (mg kg^{-1})	
P_2O_5	20–4460
K_2O	83.3–1030
Na*	14.2–148
Mg	72.1–803
Management	
Field size (ha)	0.06–32
Cropland type	cereal crop, maize crop, cereal stubble
Sowing season	autumn, spring
Preceding crop	cereal, hoed crop
Organic manure (t ha^{-1})	0–45
Chemical fertiliser	yes, no
Mechanical weeding (times)*	0–6
Herbicides	
2,4 D*	yes, no
Bromoxinil*	yes, no
Dicamba	yes, no
Isoxaflutol+ciprosulfamid	yes, no
Florasulam	yes, no
Fluoroxypyr	yes, no
Thiencarbazone-methyl	yes, no

*variables dropped during the backward selection process

Table 2 Gross and net effects of the explanatory variables on the weed species composition identified using (p)RDA analyses with single explanatory variables

		Gross effect		Net effect			
Factors	d.f.	Explained variation (%)	R^2_{adj}	Explained variation (%)	R^2_{adj}	F	p-value
Cropland type	2	9.459	0.0915	5.619	0.0556	19.8414	0.001
Longitude	1	1.469	0.0130	0.696	0.0058	4.9130	0.001
Altitude	1	0.819	0.0065	0.619	0.0050	4.3698	0.001
Organic manure	1	0.818	0.0065	0.507	0.0038	3.5807	0.001
Soil Ca content	1	0.612	0.0045	0.477	0.0035	3.3716	0.001
Plot location	1	0.459	0.0029	0.459	0.0033	3.2407	0.001
Soil texture	1	0.568	0.0040	0.455	0.0033	3.2122	0.001
Soil K content	1	0.787	0.0062	0.442	0.0031	3.1188	0.001
Chemical fertiliser	1	0.568	0.0040	0.383	0.0025	2.7073	0.002
Soil Mg content	1	0.443	0.0028	0.367	0.0024	2.5945	0.001
Fluoroxypyr	1	0.735	0.0057	0.359	0.0023	2.5351	0.001
Field size	1	0.511	0.0034	0.346	0.0021	2.4463	0.003
Latitude	1	0.414	0.0025	0.341	0.0021	2.4085	0.001
Neighbouring habitat	4	1.416	0.0075	0.763	0.0020	1.3480	0.017
Preceding crop	1	0.480	0.0031	0.329	0.0020	2.3231	0.002
Florasulam	1	0.576	0.0041	0.317	0.0018	2.2359	0.003
Soil P content	1	0.328	0.0016	0.290	0.0015	2.0469	0.006
Isoxaflutol+ciprosulfamid	1	0.917	0.0075	0.269	0.0013	1.8981	0.014
Sowing season	1	3.843	0.0368	0.262	0.0013	1.8535	0.018
Soil humus content	1	0.598	0.0043	0.260	0.0012	1.8360	0.012
Thiencarbazone-methyl	1	0.852	0.0069	0.260	0.0012	1.8340	0.013
Dicamba	1	0.222	0.0005	0.235	0.0010	1.6610	0.030

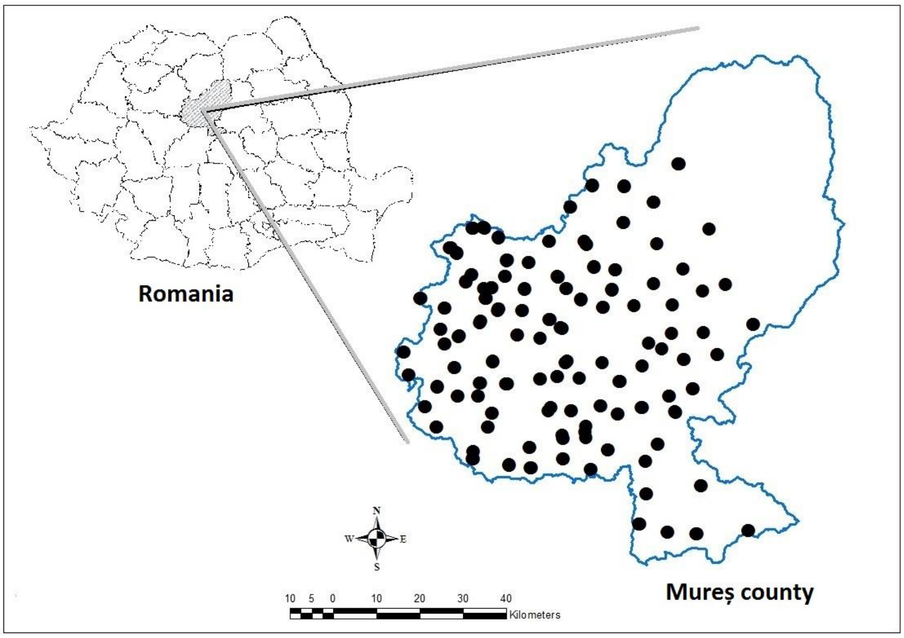

Fig. 1 The distribution of the surveyed arable fields across the study area (Mureș county, Central Transylvania, Romania). At this scale individual points may represent a number of fields with different cropland types.

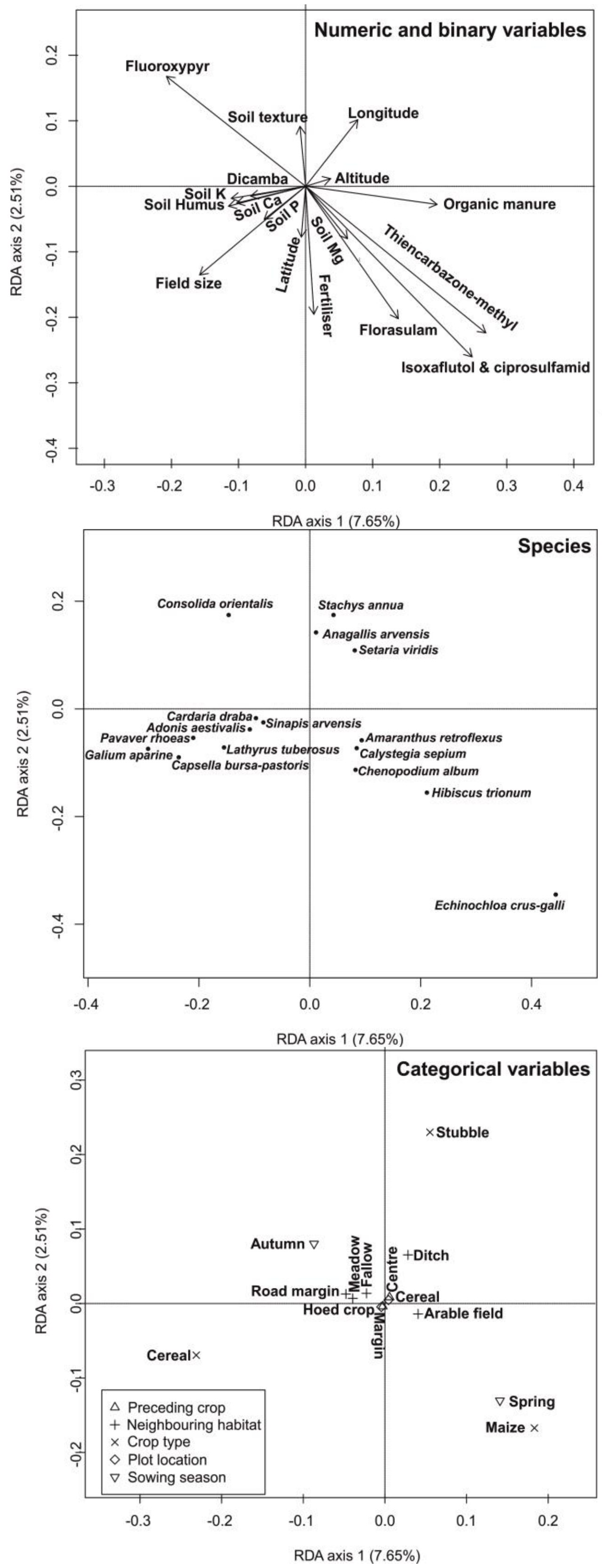

Fig. 2 Ordination diagrams of the reduced RDA model containing the 22 significant explanatory variables and the species. Only the species with the highest weight on the first two RDA axes are presented.

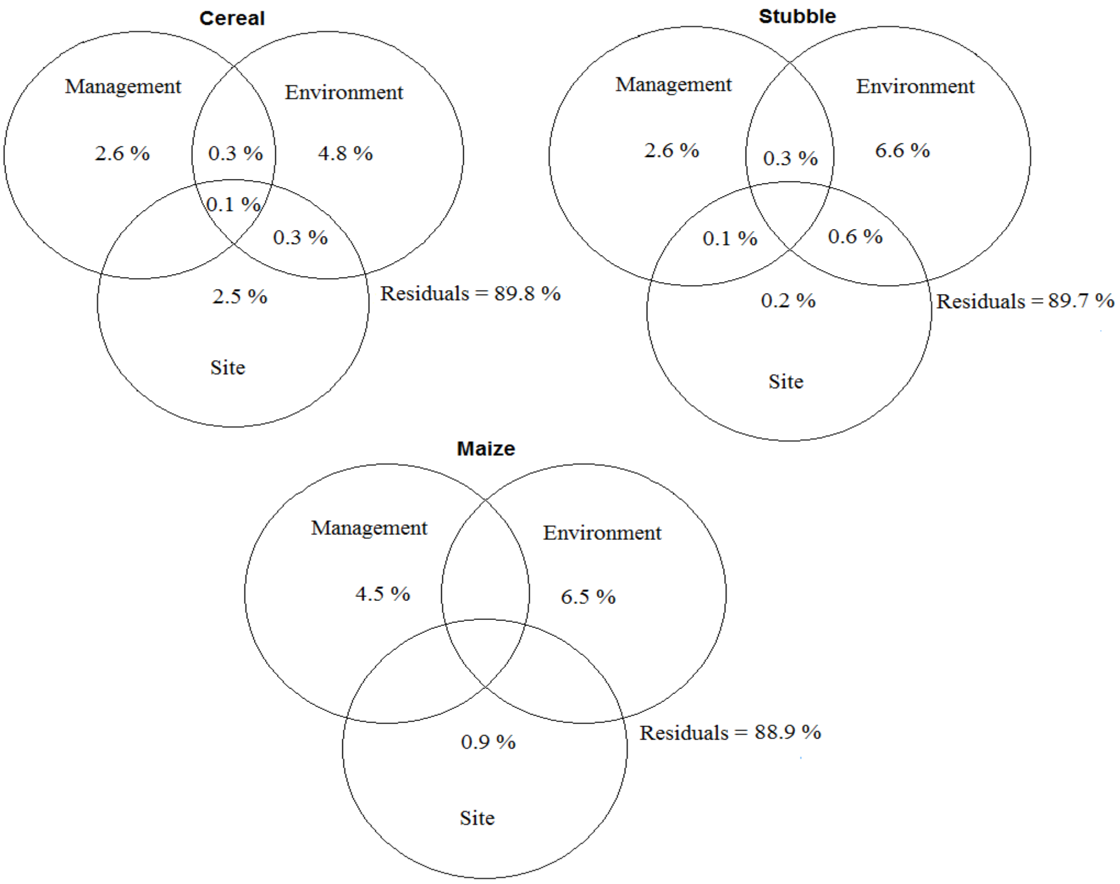

Fig. 3 Percentage contributions of groups of explanatory variables to the variation in weed species composition in the three investigated cropland types, identified by variation partitioning (only non-negative adjusted R-squared values are shown).

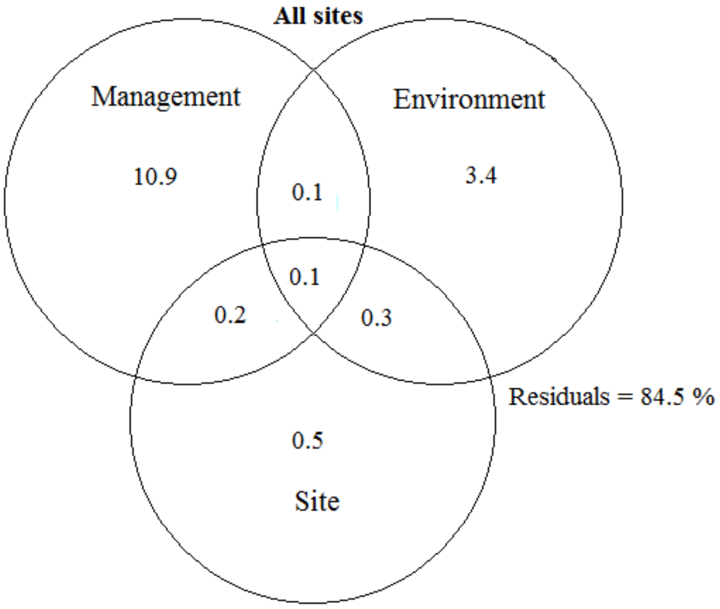

Fig.4 Percentage contributions of groups of explanatory variables to the variation in weed species composition using all the 299 fields, identified by variation partitioning (only non-negative adjusted R-squared values are shown).

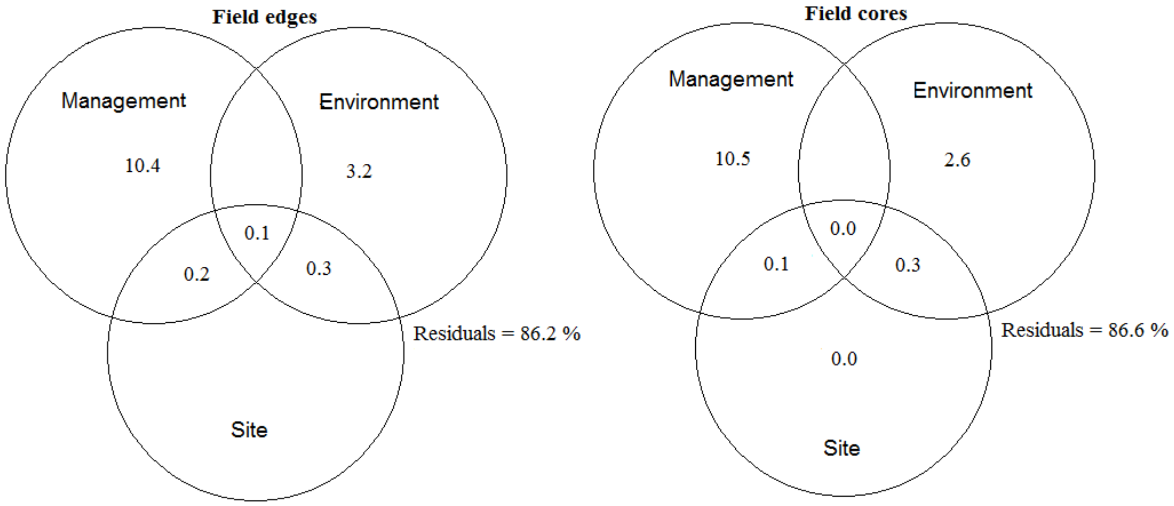

Fig. 5 Percentage contributions of groups of explanatory variables to the variation in weed species composition in field edges and field cores, identified by variation partitioning (only non-negative adjusted R-squared values are shown).

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1 Names, fit and score values of species giving the highest fit along the first constrained axis in the partial-RDA models of the significant environmental variables specified in Table 2. (Only the most abundant ten weed species are shown).

Table S2 Names, fit and score values of species giving the highest fit along the first constrained axis in the partial-RDA models of the significant management variables specified in Table 2. (Only the most abundant ten weed species are shown).

Table S3 Names, fit and score values of species giving the highest fit along the first constrained axis in the partial-RDA models of the significant site variables specified in Table 2. (Only the most abundant ten weed species are shown).