

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

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18 **Running head:** Environmental signatures of small-scale farming

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28 **Summary**

29

30 Weed species loss due to intensive agricultural land use has raised the need to understand
31 how traditional cropland management has sustained a diverse weed flora. We evaluated to
32 what extent cultivation practices and environmental conditions affect the weed species
33 composition of a small-scale farmland mosaic in Central Transylvania (Romania). We
34 recorded the abundance of weed species and 28 environmental, management and site context
35 variables in 299 fields of maize, cereal and stubble. Using redundancy analysis we revealed
36 22 variables with significant net effects, which explained 19.15% of the total variation in
37 species composition. Cropland type had the most pronounced effect on weed composition
38 with a clear distinction between cereal crops, cereal stubble and hoed crops. Beyond these
39 differences, the environmental context of croplands was a major driver of weed composition,
40 with significant effects of geographic position, altitude, soil parameters (soil pH, texture, salt
41 and humus content, CaCO₃, P₂O₅, K₂O, Na and Mg) as well as plot location (edge vs core
42 position) and surrounding habitat types (arable field, road margin, meadow, fallow, ditch).
43 Performing a variation partitioning for the cropland types one by one, the environmental
44 variables explained most of the variance compared with crop management. In contrast, when
45 all sites were combined across different cropland types, the crop specific factors were more
46 important in explaining variance in weed community composition.

47

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

50

51 **Introduction**

52

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

58

59 Despite their potential importance for the health of agricultural ecosystems, weed
60 species may also cause significant economical losses for farmers and weed control can be the
61 most expensive agricultural practice aimed at improving crop production (Marshall *et al.*,
62 2003). In order to develop efficient, sustainable and environmentally friendly weed control
63 practices, it is urgent to understand the drivers of weed presence and abundance on cultivated
64 lands (Swanton *et al.*, 1999). We need to investigate how the interaction between farming and
65 weed management systems and the environment affects the composition of weed vegetation
66 in different croplands (Pyšek *et al.*, 2005, Pinke *et al.*, 2011, 2012, 2013).

67

68 Existing evidence is mixed, suggesting that the weed composition of arable lands may
69 primarily be determined by ecological factors (Lososová *et al.*, 2004) or by human activity
70 (Fried *et al.*, 2008, Andreasen & Skovgaard, 2009, Cimalová & Lososová, 2009, Pinke *et al.*,
71 2012). It is however sensible to expect that the two types of factors interact, and the
72 prevalence of one or the other is context-dependent. For instance, where environmental
73 conditions are less favourable to cropping, the degree of agricultural intensification is also
74 lower and the environmental imprint on weed composition is strong (Lososová *et al.*, 2004,
75 Nowak *et al.*, 2015). In upland areas the frequency of herbicide treatments is usually lower
76 than elsewhere (Pál *et al.*, 2013), the proportion of alien weed species is lower and weed
77 species richness is higher (Lososová *et al.*, 2004). Nevertheless, the composition of the weed
78 flora also depends on the crop type, including the division between winter- and summer-sown
79 crops and crop-specific management (Fried *et al.*, 2008). Superimposed on this pattern may
80 be the often-reported increase of weed species richness towards field margins, due to a lower
81 competition pressure from crops and release from chemical stressors in border areas (Seifert
82 *et al.*, 2015). The role of these marginal cropland habitats in conservation is very important
83 and increasingly recognised (Wrzesień & Denisow, 2016). Rare weed species are usually
84 restricted to the outermost few metres of the croplands, where weed species richness and

85 cover are higher compared to the field centre (Wilson & Aebischer, 1995, Fried *et al.*, 2009).
86 The study fields in our area were characteristically small, potentially magnifying this affect as
87 the boundary/area ratio would be increased.

88

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

96

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

104

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

111

112

113 **Materials and Methods**

114

115 *Site description*

116 We carried out our survey in 2013 in Central Transylvania, Romania (23°59'260" –
117 26°11'992" North, 46°08'520" – 46°54'597" East), covering nearly the total area of 6714
118 km² of Mureş county in this region (Fig. 1). The proportion of agricultural land in this county

119 is 61%, of which 54% is classified as arable land. The most widely cultivated crops are
120 cereals and maize (INS, 2016). Our study covered an elevational gradient ranging between
121 260–543 m (Table 1). The lower elevations included the Transylvanian Plateau, more suitable
122 for agriculture due to wide valleys and a milder climate. The higher elevation North-Eastern
123 corner of the county consisted of the Călimani and Gurghiu Mountain foothills, where arable
124 fields were rarer. Here, the temperature and precipitation regimes have been less suitable for
125 crop production and therefore agricultural intensification has been lower, e.g. 4-6 times lower
126 doses of chemical fertilisers and herbicides in average compared to France or Germany
127 (Storkey *et al.*, 2012).

128

129

130

Fig. 1 near here

131

132 *Data collection*

133 We selected a total of 299 arable fields for the survey in a broadly random pattern, but also
134 depending on farmer's cooperation (Fig. 1). Within each field we sampled weed vegetation in
135 six randomly selected, 4 m² plots (2×2 m), totaling 1794 plots. Three plots were located on
136 the field edge (within 2 m from the outermost seed drill line), and three were in the field
137 centre. 101 fields were cereal crops (74 *Triticum aestivum* L., 11 *Triticosecale x rimpaii*
138 Wittm., 8 *Hordeum vulgare* L., 5 *Hordeum distichon* L., 3 *Avena sativa* L.) and 97 maize
139 (*Zea mays* L.). The remaining 101 sites were stubbles of cereal fields. While cereal stubbles
140 are not crops, we analysed them as a separate cropland type due to their unique weed
141 vegetation (Pinke *et al.*, 2010). We surveyed the cereal fields between May 10 and June 6,
142 and the maize and the cereal stubble fields between July 31 and August 20 to ensure that we
143 captured the most comprehensive set of weed species within each cropland type.

144

145 Within each 4 m² plot, we estimated visually the percentage ground cover of all
146 species, including crop species, and the vegetation data recorded was subsequently digitized
147 and stored in TURBOVEG format (Hennekens & Schaminée, 2001). In addition, we
148 interviewed landowners for information on crop management of each investigated field. We
149 recorded the cropping history (indicating the preceding crop as either cereal or hoed crop),
150 the amount of organic manure applied, whether farmers used chemical fertilisers (N, P₂O₅,
151 K₂O), as well as crop sowing season (previous fall or spring) and field size. Information on
152 weed management (type of herbicides used and number of times mechanical weed control

153 treatments were applied) were also recorded. Herbicides applied on less than 10 fields out of
154 the total of 299 were subsequently dropped from the analyses. To reduce the number of
155 management categories, the 'cropland type' variable was coded as cereal crop, maize crop or
156 cereal stubble.

157

158 We used soil chemical and physical properties as local environmental variables. From
159 each field we collected one soil sample of 1,000 cm³ from the top 10 cm layer. Soil samples
160 were air dried and stored at room temperature until further analyses were performed at UIS
161 Ungarn GmbH (Mosonmagyaróvár, Hungary). Soil variables included: soil pH, texture, salt
162 and humus content, CaCO₃, P₂O₅, K₂O, Na and Mg. In addition, we used three proxies of
163 regional environmental conditions quantified as the geographic latitude, longitude and
164 elevation above sea level of each field, as recorded by a GPS device.

165

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

169

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

172

173 *Table 1 near here*

174

175 *Statistical analyses*

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

180

181 To analyse the relationship between the composition of weed vegetation and site,
182 environmental and management variables, we performed a Redundancy Analysis (RDA).
183 RDA links species abundance data to explanatory variables more accurately than the
184 commonly used Canonical Correspondence Analysis (CCA), even when species responses to
185 environmental gradients are unimodal (Legendre & Gallagher, 2001). Only species with >10
186 occurrences were involved in the analyses. We reduced the number of explanatory variables

187 using stepwise backward selection with a $P < 0.05$ threshold. With this procedure six variables
188 were eliminated: soil pH, Na and salt content, mechanical weeding and herbicides 2,4 D and
189 bromoxinil, resulting in a reduced RDA model with 22 terms with significant effects. The
190 generalised variance inflation factor GVIF (Fox & Monette, 1992) ranged between 1.0 and
191 5.51, indicating no serious collinearity between explanatory variables.

192

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

204

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

209

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

215

216 Statistical analyses were performed using the *vegan* (version 2.3-3) and *car* (version
217 2.0-25) packages in R 3.1.2 (R Development Core Team). Species fit on the constrained
218 ordination axes was calculated using the 'inertcomp' function of *vegan* package.

219

220

221 **Results**

222

223 Across the 1794 plots sampled from 299 arable fields we found a total of 141 weed species,
224 110 in cereals, 88 in stubble fields and 76 in maize crops. From the top most threatened 48
225 arable weeds in Europe (Storkey *et al.*, 2012) only four occurred in our dataset, all in cereal
226 fields. Their frequency of occurrence ranged between 1.0 and 9.7% (*Adonis aestivalis* L.
227 9.7%, *Centaurea cyanus* L. 6.1%, *Ranunculus arvensis* L. 5.9%, *Lathyrus aphaca* L. 1.0%).

228

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

235

236

Table 2 near here

237

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

251

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

255

256 *Fig. 2 near here*

257

258 The variation partitioning within each cropland type revealed that environmental
259 variables outperformed the management and site variables, with nearly equal values in
260 stubbles and maize, and slightly lower in cereals (6.6%, 6.5% and 4.8% respectively Fig. 3).
261 The management variables had the highest relative effect in maize and equally lower in
262 cereals and stubbles. The relative effects of site and management variables were similar in
263 cereals (2.5% vs. 2.6% respectively), but in maize and stubbles site explained only a tiny
264 fraction of the variance (0.9–0.2%) (Fig. 3). Variation partitioning over all the 299 fields
265 resulted the highest influence of management variables, being largely driven by crop type,
266 explaining three times more of the total variance compared to the environmental variables
267 (10.9% vs. 3.4%) (Fig. 4). The variation partitioning of the RDA according to the plot
268 location revealed that the effect of environmental variables is only slightly higher in field
269 edges than in the cores (3.2% vs. 2.6% respectively), while the influence of management was
270 nearly equal (10.4% vs. 10.5) (Fig. 5).

271

272 *Fig. 3, 4, 5 near here*

273

274

275 **Discussion**

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

282

283 *Management effect*

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

306

307 It would have been interesting to distinguish between the effect of the season (using
308 the date of observation) and the effect of the management. However, these two factors are
309 confounded in the one variable, cropland type, making impossible their separate analysis. It is
310 likely that season and management interacted to shape the characteristics we associated with
311 stubble in our analysis. Despite similar sowing dates of cereals, subsequent germination later
312 in the season would have contributed to the different floras recorded in their stubble.
313 Preceding management regimes, i.e. cropping technologies applied in cereals and maize, also
314 have their impact on weed floras. Furthermore, environmental conditions in the stubble are
315 different, e.g. free from the shading. Accordingly, not only the flora of cereals and that of
316 their stubbles differs remarkably, but stubble and maize also have different weed flora, even
317 though the fact that they were surveyed in the same season. Consequently, stubble is not a

318 homogenous category among cropland types; its subdivision and introduction of season as a
319 new variable would have made possible to further dissect the causalities behind the patterns
320 of weed composition.

321

322 Fertilisation was an important filter of weed species and a selective driver of weed
323 abundance (for similar results see Lososová *et al.*, 2006, Pinke *et al.*, 2012, Seifert *et al.*,
324 2015). Several species responded to organic manure with increased abundances (e.g.
325 *Convolvulus arvensis* L., *S. pumila*, *E. crus-galli*), while chemical fertilisers could be linked
326 to higher abundances of only three species (*Rubus caesius* L., *H. trionum*, *Elymus repens* (L.)
327 Gould). Almost all weed species that responded positively to higher organic manure were
328 associated with maize fields (e.g. *E. crus-galli*, *C. album*, *A. retroflexus*), due to higher doses
329 applied in hoed crops (Lososová *et al.*, 2006).

330

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

339

340 The sowing season was an important driver of weed composition in our survey, where
341 we investigated winter- and spring-sown cereals and spring sown maize. Winter annual weed
342 species (*Veronica persica* Poir., *Consolida orientalis* (J. Gay) Schrödinger, *G. aparine*, *P.*
343 *rhoeas*) were strongly associated with autumn-sown cereals, while summer annual weed
344 species (*A. retroflexus*, *C. album*, *H. trionum*, *S. pumila*, *E. crus-galli*) preferred spring-sown
345 cultures, many of the latter being typical weeds of hoed crops (Fig. 2). These results concur
346 with earlier evidence, confirming that the presence of multiple crops and cropping times may
347 considerably increase the regional weed species pool (Marshall *et al.*, 2003, Pinke *et al.*,
348 2011, Fried *et al.*, 2012, Vidotto *et al.*, 2016).

349

350 Among preceding crops, winter cereals usually favour winter annuals, while hoed
351 crops summer annuals. In our analysis preceding crop ranked only the 15th among the

352 predictors, not independently from the common practice in the surveyed area to alternate
353 winter cereals with hoed crops. The rotation of cereals and hoed crops aims to interrupt the
354 build-up of weed populations associated with particular crop types (de Mol *et al.*, 2015).

355

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

367

368 *Environmental effect*

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

371

372 Longitude ranked the 2nd, altitude the 3rd and latitude the 13th among all predictors.
373 These variables have been used as proxies of regional climate conditions such as precipitation
374 and mean temperature (Lososová *et al.*, 2004, 2006, Hanzlik & Gerowitt, 2011, de Mol *et al.*,
375 2015). Species strongly associated with lower altitudes were troublesome weeds such as
376 *Solanum nigrum* L., *Xanthium italicum* Moretti, *Polygonum aviculare* L. and *R. caesius*,
377 while species correlated with higher altitudes were cereal weeds typical of traditional
378 farming, e.g. *C. orientalis*, *C. cyanus*. This pattern has often been reported from agricultural
379 landscapes situated in heterogeneous geographic conditions (Lososová *et al.*, 2004, Pál *et al.*,
380 2013, Nowak *et al.*, 2015). The north-eastern higher altitude part of our study area is less
381 favourable especially for maize but also for other crops, as a consequence the cultivation is
382 less intense (Fig. 1). We interpret the change in weed composition along this geographical
383 gradient as a result of both environmental effects and differences in farming methods
384 between lowland and upland areas due to environmental constraints.

385

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

394

395 *Site effect*

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

407

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

414

415

416 *Environment vs management factors*

417 In the variation partitioning within each cropland type the environmental variables explained
418 the largest fractions of the variance, which is in accordance with the results of previous
419 studies (Lososová *et al.*, 2004, Pinke *et al.*, 2012, 2016, de Mol *et al.*, 2015). The effect of

420 environmental variables reached the highest proportion in cereal stubbles, explaining two and
421 a half time more variance than the effect of management variables. This may be due to the
422 lack of particular cropping practices on stubbles. In maize crops the relative influence of
423 environmental variables was similarly high. Both maize and stubble represented the late
424 summer weed flora, and the higher contributions of environment could be due to the longer
425 period following weed management practices, which allows the weed vegetation to recover
426 from the seed banks primarily under the influence of soil and climatic conditions.
427 Furthermore, in maize the management variables explained a higher proportion of variance in
428 weed communities when compared to cereals and stubbles possibly due to the frequently
429 repeated cultivation tasks typical of maize crops.

430

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

436

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

444

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448

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

556

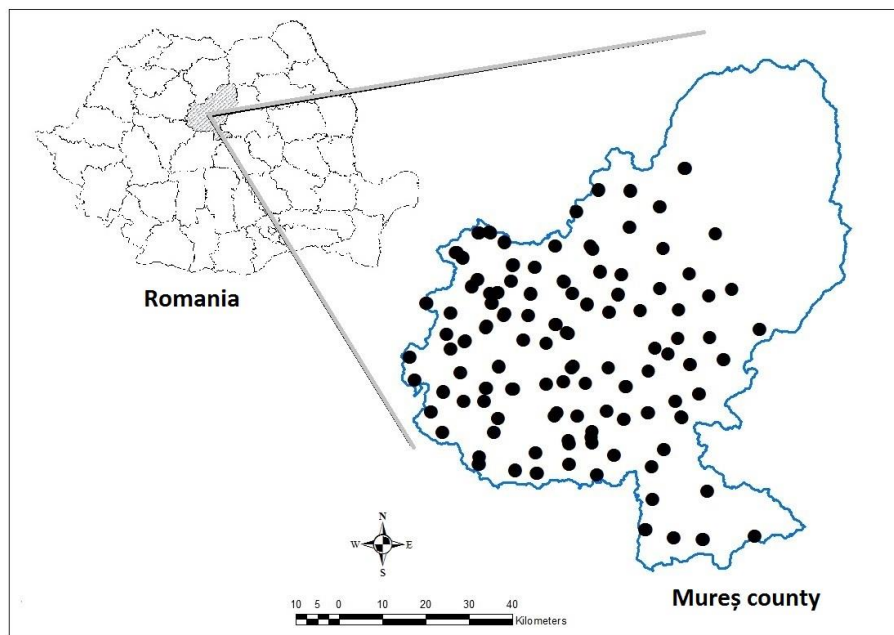
Variable (unit)	Range / Values
<i>Site</i>	
Plot location	edge, core
Neighbouring habitat	arable field, ditch, fallow, meadow, road margin
<i>Environmental</i>	
Longitude (E)	46°08'520''–46°54'597''
Latitude (N)	23°59'260''–26°11'992''
Altitude (m)	260–543
Soil pH (KCl)*	5.02–7.60
Soil texture (KA)	29–57
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 ₂ O ₅	20–4460
K ₂ O	83.3–1030
Na*	14.2–148
Mg	72.1–803
<i>Management</i>	
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
Fluroxypyr	yes, no
Thiencarbazone-methyl	yes, no

557 *variables dropped during the backward selection process

558 **Table 2** Gross and net effects of the explanatory variables on the weed species composition
559 identified using (p)RDA analyses with single explanatory variables
560

Factors	d.f.	Gross effect		Net effect		F	p-value
		Explained variation (%)	R^2_{adj}	Explained variation (%)	R^2_{adj}		
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

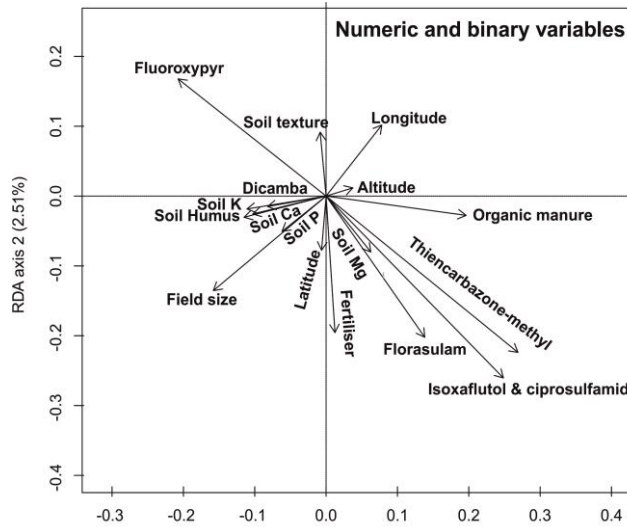
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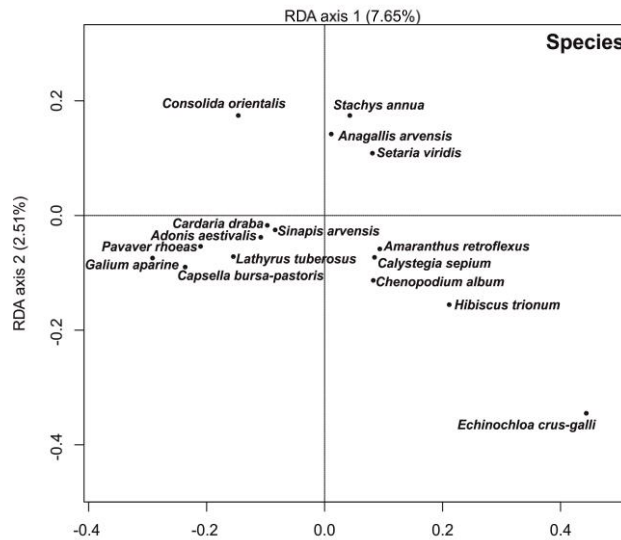
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563 **Fig. 1** The distribution of the surveyed arable fields across the study area (Mureș county,
564 Central Transylvania, Romania). At this scale individual points may represent a number of
565 fields with different cropland types.
566

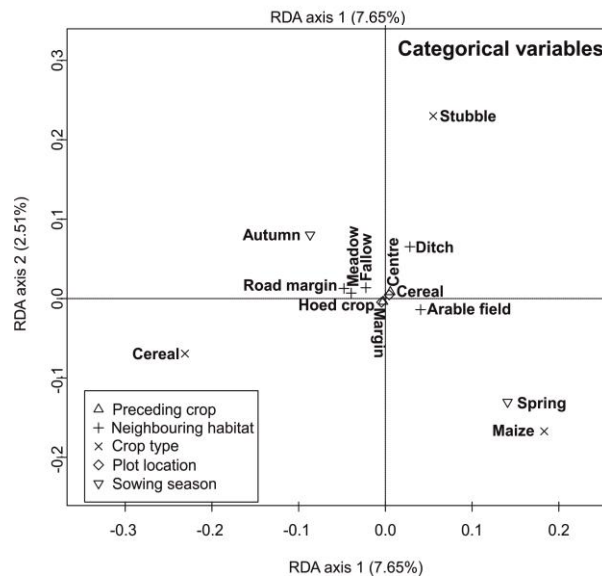
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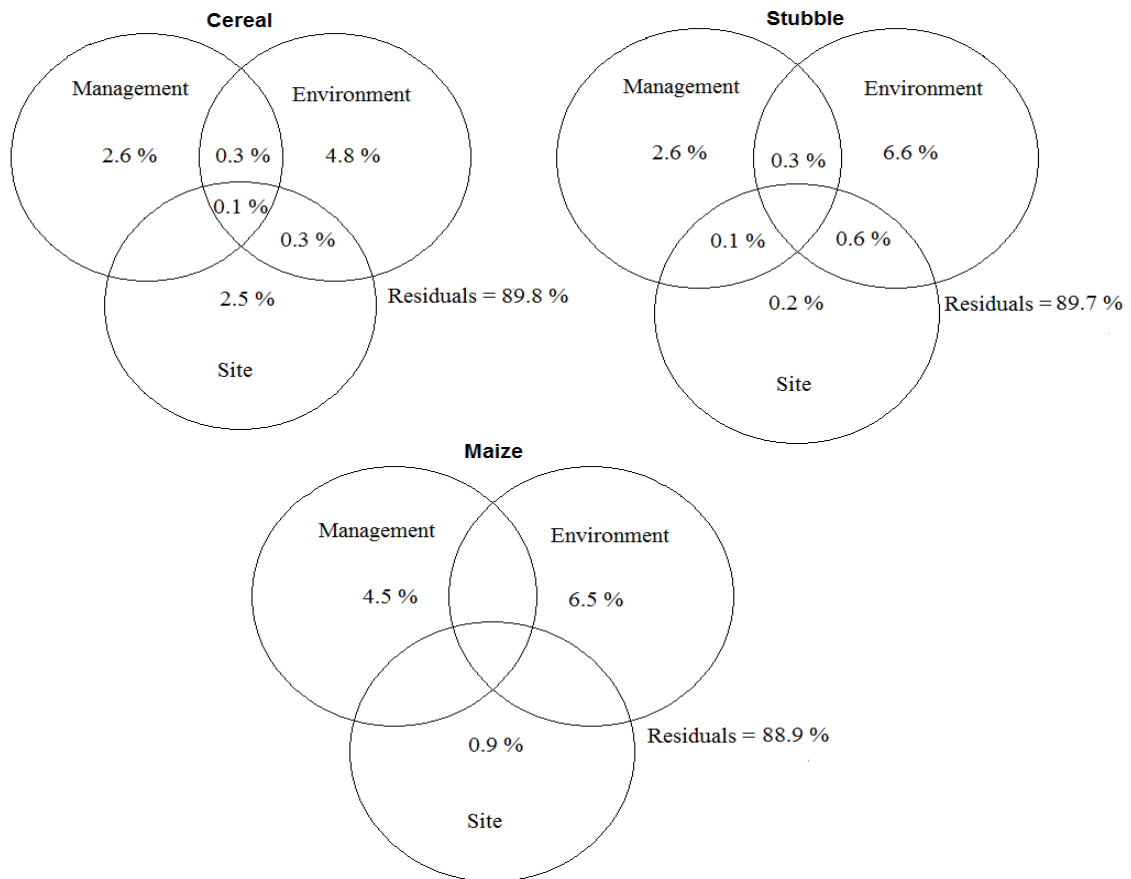
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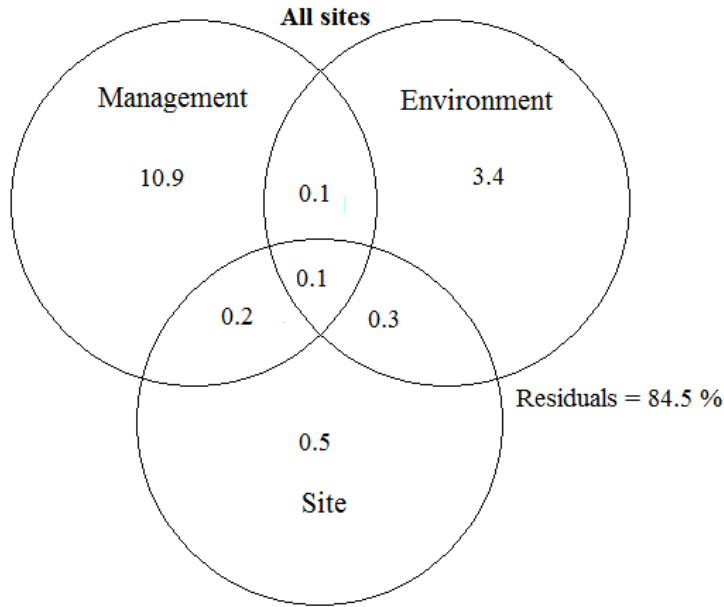
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Fig. 2 Ordination diagrams of the reduced RDA model containing the 22 significant explanatory variables and the species. Only the species with the highest weight on the first two RDA axes are presented.



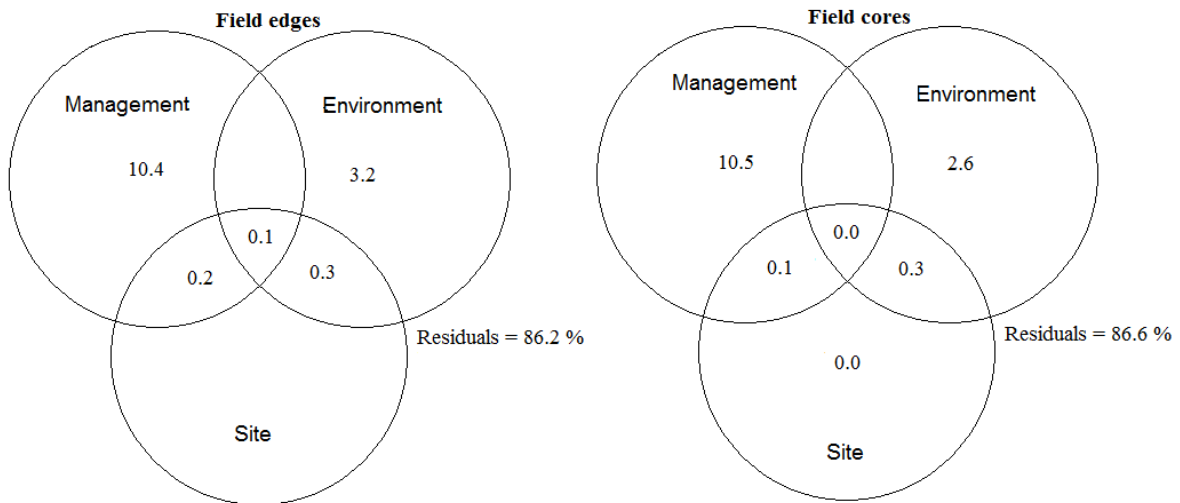
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Fig. 3 Percentage contributions of groups of explanatory variables to the variation in weed species composition in the three investigated cropland types, identified by variation partitioning (only non-negative adjusted R-squared values are shown).



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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).



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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).

590 **Supporting Information**

591

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

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

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

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