



Drivers of weed species composition in Hungarian organic rice paddies

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Abstract

Which factors are the most important determinants of weed species composition in organic rice fields? Which species can be associated with the extreme values of the most important background variables? To answer these questions, we surveyed the weed flora along with 15 management and 3 environmental variables in 42 organically managed rice fields in eastern Hungary. Filamentous algae, *Chara vulgaris*, *Chara braunii*, *Schoenoplectus mucronatus*, *Elatine triandra*, and *Echinochloa crus-galli* were the most dominant weeds. Using a minimal adequate model containing 4 terms with significant net effects, 48.3% of the total variation in weed species data could be explained. Farm holding size (correlated with sowing type, shift crop, organic manure and water depth) was found to be the most important explanatory variable, which was followed by hand weeding, tillage type (correlated with tillage depth, shift crop and supplementary nutrients) and rice cover. Farm holding size was negatively associated with most of the aquatic plants suggesting its adverse impact on farmland biodiversity. Hand weeding appeared to be efficient against *Rumex stenophyllus* and *Echinochloa crus-galli*, but it was tolerated by *Cyperus difformis*. Perennial weeds like *Persicaria amphibia* and *Bolboschoenus planiculmis* were more abundant in sites without soil inversion and *Lemna aequinoctialis* seemed to be most tolerant for the shading effect of crop canopy. The responses of weed species to the studied variables provide new information about the assembly rules of aquatic plant communities, and our findings also can be used to optimise non-chemical weed control strategies in organic rice production.

Keywords Agroecology · Central and Eastern Europe · Charophytes · Macrophytes · *Oryza sativa* · Weed vegetation

Introduction

Organic rice farming is becoming popular throughout the World as a part of sustainable agriculture systems. Compared to other crops, rice can achieve more adequate yields

under organic farming conditions, however, the strong crop-weed competition is one of the major constraints to its profitable ecological production (Hazra et al. 2018). Even though some efficient weed management strategies already existed (Orlando et al. 2020; Vaglia et al. 2022; Palma-Guillén et al. 2024), the omission of herbicides makes these fields particularly vulnerable to the invasion of noxious global rice weeds (Kraehmer et al. 2016). Several years after the conversion from conventional to organic farming, the build-up of troublesome weeds usually means a great challenge for rice cultivation (Uno et al. 2021). Nevertheless, even in no-input rice production systems, some of the weeds have no negative effects on rice yield (Hosoya and Sugiyama 2017; Corli et al. 2025). Accordingly, organic rice farming can also support native and endangered taxonomic groups, which makes them potentially relevant for biodiversity conservation (Martínez-Eixarch et al. 2017; Katayama et al. 2019).

Hungary is situated at the northern limit of rice production in Europe, with a history of about 450 years of rice cultivation (Károlyi 1957; Büchl 1976). In Hungary, the

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total annual growing area of rice has fluctuated between 2330 and 2990 ha in the last decade, with average yields ranging between 3.3 and 4.6 tons ha⁻¹ (Faostat 2022). From this area, organic rice farming has shared about yearly 195–285 ha, with mean yields of about 15% less than those of conventional farming (Society of the Hungarian Rice Producers, unpublished data). In our previous study, we identified the most important variables shaping the weed communities in conventional Hungarian paddies, indicating the crucial roles of the applied herbicides and fertilizers (Pinke et al. 2014). In this study, working with similar methods, we seek answers to the following questions: (1) Which factors are the most important determinants of weed species composition in organic rice fields? (2) Which species can be associated with the extreme values of the most important background variables? Assessing the role of different variables could be used to optimise non-chemical weed control and conservation strategies and might provide new information about the assembly rules of aquatic plant communities.

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

Variable (unit)	Range/Values
<i>Management variables</i>	
Hand weeding (times)	0; 1
Farm holding size (ha)	350–4500
Years after conversion to organic farming ^a	1–15
Shift crop ^a	Cereal, fallow, lucerne, white mustard
<i>Plant nutrition</i>	
Fluid manure (l ha ⁻¹) ^a	0–16
Organic manure (kg ha ⁻¹) ^a	0–4500
P & K supplementary nutrients (kg ha ⁻¹) ^b	0–300
Sowing type ^a	Surface, soil
Time between sowing and flooding of the fields (days) ^a	4–15
Tillage type	Soil inversion; loosen
Tillage depth (cm) ^a	15–25
Crop cover (%)	5–90
Water depth (cm)	
May ^b	4–6
June ^a	14–20
July ^a	3–24
<i>Environmental variables</i>	
Water conductivity (μS cm ⁻¹) ^b	180–845
Water pH ^a	7.41–9.7
Water temperature (°C) ^a	21.5–29.9

^aVariables not included in the analysis due to multicollinearity

^bVariables excluded from the *reduced model* during the backward selection process

Materials and methods

Data collection

We surveyed 42 organically managed rice (*Oryza sativa* L.) fields belonging to four different farm holdings in the Hungarian rice-growing district (Szarvas, Csárdaszállás, and Kisújszállás municipalities) in late July 2012 and 2014. The individual paddies (fields) were of approximately the same size (4–6 ha), and they were separated from each other by levees. The investigated farms were located in relatively close proximity to one another, within a total range of 36 km (between 46°87'N–47°20'N and 20°69'E–20°96'E), and their irrigation systems shared the same watershed. All fields were on heavy clay soils with pH ranging between 6.9 and 7.9. Mean annual temperature and precipitation in the study area were 10.3 °C and 525 mm, respectively (Dövényi 2010). The altitudinal ranges of the sampling points were between 87 and 98 m.

The weed vegetation of the fields was sampled in two randomly located 100 m² plots inside the paddies (at least 10 m from the field margin). The abundance of the crop and the weed species was estimated visually as a percentage of ground cover in each plot (84 plots in total). Macrophyte plant species were identified at species level following the nomenclature of Király (2009), while filamentous algae were recorded as a single (taxonomically heterogeneous) category. We also measured water depth (referring to 'water depth in July') and several water parameters (using Hanna Combo HI98129) at the centre of each plot. Furthermore, we also collected detailed information from the farmers on the management of the individual fields (paddies). Altogether, 15 management, and three environmental variables were recorded during the survey (Table 1). As the investigated fields shared very similar environmental conditions, we focused on the effects of the management variables in the analysis.

Data analyses

The statistical analysis followed the same lines as the analysis described in (Pinke et al. 2014, 2024). Cover values of the weed species as well as the measured water parameters were averaged across the two plots from each field to ascertain the average community composition of the individual fields. First, we assessed the multicollinearity of the variables (potential model terms) by calculating generalised variance inflation factors (GVIF) with the 'vif' function of the car package (Fox and Weisberg 2019). We iteratively discarded the variables with the highest GVIF values until it fell below a threshold of 5. First, we omitted water pH and temperature as they strongly correlated with conductivity.

Eventually, we had to discard seven further variables: sowing type, shift crop, tillage depth, organic manure, P & K supplementary nutrients, June water depths, and years after conversion to organic farming. Correlations among the rest of the variables should not bias the analysis. The highest VIF score was 4.23 for farm holding size due to its correlation with conductivity ($r=0.825$, $p<0.001$). Cover values were subjected to Hellinger transformation (Borcard et al. 2011), and were examined in a redundancy analysis (RDA) together with the management and environmental data. We then applied a two-step procedure to identify a minimal adequate reduced model with a parsimonious set of independent predictors. We created a full RDA model with all of the predictors identified above. Then proceeded with a stepwise backward selection using a $p<0.01$ threshold for type-I error, which led to our reduced RDA model with 4 terms.

As the next step of the multivariate analysis, we estimated the gross and net effects of each explanatory variable in the reduced model. Following Lososová et al. (2004), gross effects were defined as the variation explained in a univariate RDA model having just the focal variable as the only predictor, whereas net effects were quantified as the variance explained by the focal variable in a partial RDA model (pRDA), having all other variables as co-variables.

Based on the R^2 (R^2_{adj}) values of the net effects, we also established a common rank of ‘importance’ among the explanatory variables. To explore the responses of the different weed species, for each variable we identified those 20 species that represented the highest explained variation in the constrained axis/axes (‘strongly associated’ species).

Farm identity was not included in the analysis as a random factor because only 4 farms were investigated and a

random factor should have minimum 5–7 levels. Instead, we explored the relationship between variables excluded because of too high VIF and the four variables in the final model. Following the logic of VIF calculation, each excluded variables were regressed on the four variables in the final model.

The entire statistical analysis was conducted in the R environment (R Development Core Team, version 3.2.2) using the vegan package (vegan 2.3e1) (Oksanen et al. 2022).

Results

Altogether, 45 weed species were recorded. Filamentous algae, *Chara vulgaris* L., *Chara braunii* S.G.Gmel., *Schoenoplectus mucronatus* L., *Elatine triandra* Schkuhr., *Echinochloa crus-galli* (L.) P.Beauv., *Najas minor* All., *Najas gracillima* (A.Braun ex Engelm.) Magnus, *Chara fibrosa* C.Agardh ex Bruzelius and *Lindernia procumbens* (Krock.) Borbás were the most abundant weeds (Fig. 1). The full RDA model (comprising 7 explanatory variables) explained 54.56% of the variance. Three predictors (P & K supplementary nutrients, water depth in May, and conductivity) were dropped during the backward selection process. Accordingly, the reduced RDA model contained four predictors still explained 48.27% of the total variation in species data. All four variables were found to be significant in the pRDA models, and a common order of importance was established. Farm holding size ranked first, hand weeding occupied the second position, and tillage type the third, while rice cover occupied the fourth position (Table 2). The responses of the 20 most associated weed species (the ones

Fig. 1 The mean cover values (% of the surface covered) of the twenty most dominant weed species

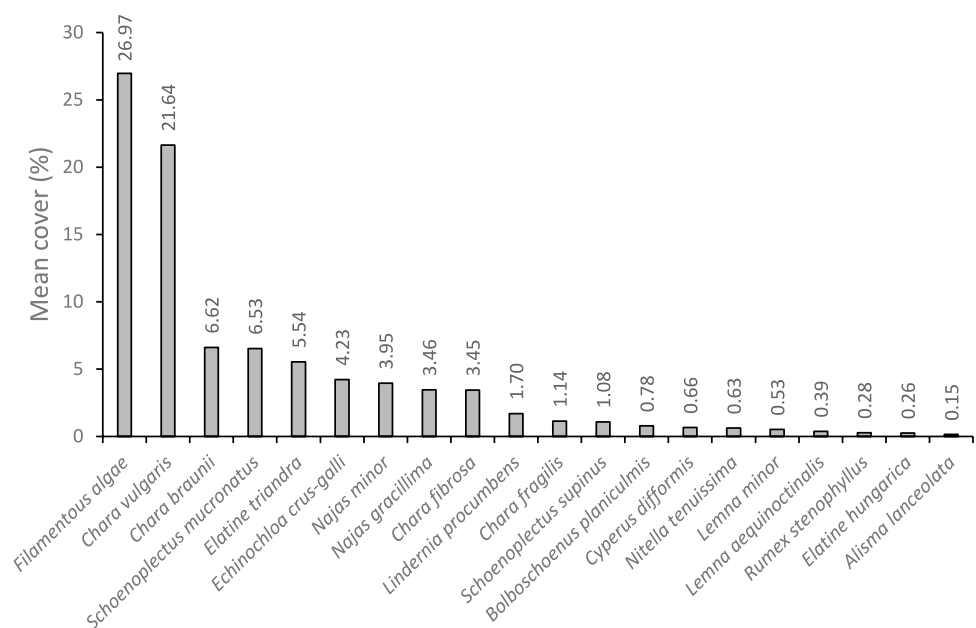


Table 2 Gross and net effects of the explanatory variables on the weed species composition identified using (partial) RDA analyses

Variable (unit)	Range/values	d.f	Gross effect		Net effect			
			Explained variation (%)	R^2_{adj}	Explained variation (%)	R^2_{adj}	F	P-value
Farm holding size (ha)	350–4500	1	24.284	0.2239	27.756	0.2843	19.737	0.001
Hand weeding	Yes, no	1	4.165	0.0177	9.876	0.0914	7.0227	0.001
Tillage type	Loosen, inversion	1	12.559	0.1037	8.029	0.0715	5.7093	0.001
Rice cover (%)	5–90	1	5.663	0.0330	3.567	0.0233	2.5365	0.017

with the highest pRDA fit) for each predictor variable are shown in Table 3.

In the reduced RDA ordination (Fig. 2), the first axis can be most related to the explanatory variable farm holding size. Samples from larger farms with a higher abundance of filamentous algae generally exhibit positive values on the first RDA axis, whereas smaller farms with the dominance of *Echinochloa crus-galli* are characterised by low axis-1 values. The second axis is mostly correlated with tillage type and hand weeding. Negative values along the second axis are mainly characteristic of fields with soil inversion and without hand weeding, generally with a higher abundance of *Rumex stenophyllus* Ledeb. and *Schoenoplectus mucronatus*. High axis-2 values, on the other hand, mainly refer to fields with hand weeding and soil loosening with a higher abundance of *Elatine triandra* and *Chara vulgaris* (Fig. 2a). Two of the farm holdings were also separated clearly along the first axis, while there were no clear distinctions among the farms along the second axis (Fig. 2b).

The correlation between variables excluded from the analysis to avoid multicollinearity and the four variables retained in the final model indicated that farm holding size strongly correlated with sowing type, shift crop (cereal & fallow), organic manure, and June water depth; while tillage type correlated with tillage depth, shift crop (mustard), and P & K supplementary nutrients (Table 4).

Discussion

Farm holding size

In our analysis, farm holding size (correlating with sowing type, shift crop, organic manure and water depth) was found to be the most important factor affecting the weed flora. Among the 20 species strongly accompanied with this variable, only four species associated positively with the farm holding size. Filamentous algae, *Lemna minor* L., *Ranunculus sardous* Crantz and *Bolboschoenus planiculmis* T.V.Egorova appeared to be more abundant in larger fields (Table 3). The high number of negatively associating species (Table 3) suggests that larger farms (or another predictor that was correlated with farm size) created harsh conditions for the majority of weeds and aquatic plants. Submerged

stonewort communities (the species of *Chara*, *Nitella* and *Najas* genera) exhibit a particularly strong response to this group of variables (Table 3) with a strong negative association to large farms, which is remarkable due to the importance of these communities for freshwater biodiversity in agricultural landscapes (Clarke 2015).

Generally, field size is considered as a meaningful indicator for farmland biodiversity (Petit et al. 2013; Tscharncke et al. 2021). Nevertheless, in our study the size of the individual fields (paddies) had only a very narrow range (4–6 ha). On the other hand, the size of the farm holdings varied significantly, as there were smaller family farms with 350–550 hectares and larger farms owned by big companies with 1400–4500 hectares. Interestingly, the large farms in our study converted to organic farming with 8–15 years before our survey was conducted, while for the small farms this timespan was only 1–5 years. These differences would assume higher weed abundances in the larger farms, due to the general tendency highlighted by Uno et al. (2021): the longer the zero herbicide use the higher the weed density could be. Furthermore, farm holding size is strongly correlated with several further variables in our sample, including sowing type, shift crop, organic manure, and water depth (Table 4). Among these correlating factors, organic manure (and the resulting nutrient surplus) can also be responsible for the impacts on stonewort communities and filamentous algae, in line with earlier studies (Lambert and Davy 2011; Pinke et al. 2014). Tscharncke et al. (2021) also highlighted that harmful overfertilisation could occur not only with mineral fertilisers, but also with manure in organic agricultural systems leading to an impoverished accompanying biodiversity.

Other correlating management variables can also have latently contributed to the strong impact of farm holding size. For example, the variable ‘sowing type’ that describes whether rice was sown directly on the surface or 3–5 cm deep in the soil also had a significant effect in the Hungarian conventional rice fields (Pinke et al. 2014). The different reaction of weed seeds to the disturbance caused by the soil sowing operation might be a potential explanation to this relationship, and water depth usually strongly affects weed species composition as well, and inserting a shift crop into the rotation directly targets to hinder the build-up of certain noxious weeds (Pinke et al. 2014).

Table 3 Names, position and explained variation of the twenty species giving the highest fit along the first constrained axis in the partial RDA models of the significant variables specified in Table 2

	Position	Explained variation (%)		Position	Explained variation (%)
Farm holding size (+ high – low)			Hand weeding (+ = yes, – = no)		
Filamentous algae	0.7808	54.92	Filamentous algae	0.4314	16.76
<i>Schoenoplectus mucronatus</i>	–0.3599	41.11	<i>Echinochloa crus-galli</i>	–0.1574	15.74
<i>Najas gracillima</i>	–0.2620	35.10	<i>Schoenoplectus mucronatus</i>	–0.1960	12.20
<i>Najas minor</i>	–0.2559	29.62	<i>Persicaria amphibia</i>	–0.0241	11.81
<i>Lemna minor</i>	0.1507	26.84	<i>Nitella tenuissima</i>	0.0688	9.06
<i>Chara vulgaris</i>	–0.4090	19.58	<i>Chara fibrosa</i>	–0.1467	8.56
<i>Alisma lanceolata</i>	–0.0400	18.53	<i>Cyperus difformis</i>	0.0583	7.92
<i>Chara fibrosa</i>	–0.1975	15.50	<i>Lindernia procumbens</i>	–0.0818	7.18
<i>Rumex stenophyllus</i>	–0.0586	15.10	<i>Typha latifolia</i>	–0.0095	6.50
<i>Ranunculus sardous</i>	0.0328	14.98	<i>Typha angustifolia</i>	–0.0103	5.75
<i>Lindernia procumbens</i>	–0.1123	13.55	<i>Bolboschoenus planiculmis</i>	–0.0568	5.65
<i>Bolboschoenus planiculmis</i>	0.0790	10.94	<i>Alopecurus aequalis</i>	–0.0080	5.64
<i>Potamogeton nodosus</i>	–0.0139	10.89	<i>Najas minor</i>	–0.1071	5.19
<i>Elatine alsinastrum</i>	–0.0126	10.82	<i>Chara fragilis</i>	–0.0576	4.82
<i>Chara braunii</i>	–0.1919	10.31	<i>Najas gracillima</i>	–0.0954	4.65
<i>Chara fragilis</i>	–0.0790	9.06	<i>Polygonum aviculare</i>	–0.0068	3.97
<i>Polygonum aviculare</i>	–0.0101	8.65	<i>Elatine alsinastrum</i>	–0.0075	3.85
<i>Echinochloa crus-galli</i>	–0.1125	8.04	<i>Chara braunii</i>	–0.1109	3.44
<i>Schoenoplectus supinus</i>	–0.0864	7.59	<i>Alisma lanceolata</i>	0.0165	3.17
<i>Nitella tenuissima</i>	–0.0578	6.40	<i>Cirsium arvense</i>	–0.0183	3.08
Tillage type (+ = loosen, – = inversion)			Rice cover (+ high – low)		
<i>Chara vulgaris</i>	0.4547	24.21	<i>Lemna aequinoctialis</i>	0.0722	20.30
<i>Lindernia procumbens</i>	0.1373	20.25	<i>Rumex stenophyllus</i>	0.0608	16.23
<i>Elatine triandra</i>	0.2324	19.96	<i>Echinochloa crus-galli</i>	0.1331	11.26
<i>Persicaria amphibia</i>	0.0291	17.15	<i>Chara fibrosa</i>	–0.1668	11.06
<i>Rumex stenophyllus</i>	–0.0615	16.60	<i>Nitella tenuissima</i>	0.0745	10.63
<i>Chara braunii</i>	–0.2032	11.57	<i>Typha angustifolia</i>	–0.0127	8.79
<i>Bolboschoenus planiculmis</i>	0.0793	11.01	<i>Elatine triandra</i>	0.1511	8.43
<i>Najas gracillima</i>	–0.1373	9.64	<i>Persicaria amphibia</i>	–0.0203	8.37
<i>Schoenoplectus mucronatus</i>	–0.1672	8.88	<i>Schoenoplectus supinus</i>	0.0700	4.98
<i>Lemna aequinoctialis</i>	–0.0440	7.53	<i>Chara braunii</i>	0.1276	4.56
<i>Persicaria lapathifolia</i>	–0.0100	5.18	<i>Chara vulgaris</i>	–0.1659	3.22
<i>Alisma lanceolata</i>	–0.0186	3.99	<i>Potamogeton nodosus</i>	–0.0067	2.54
<i>Najas minor</i>	–0.0828	3.10	<i>Polygonum aviculare</i>	0.0054	2.51
Filamentous algae	–0.1822	2.99	<i>Alisma lanceolata</i>	–0.0132	2.03
<i>Elatine alsinastrum</i>	–0.0065	2.87	<i>Cyperus difformis</i>	0.0274	1.75
<i>Typha angustifolia</i>	0.0072	2.86	Filamentous algae	–0.1327	1.59
<i>Cirsium arvense</i>	0.0175	2.82	<i>Cirsium arvense</i>	0.0129	1.52
<i>Nitella tenuissima</i>	–0.0323	1.99	<i>Lemna minor</i>	0.0359	1.52
<i>Echinochloa crus-galli</i>	0.0549	1.91	<i>Chara fragilis</i>	–0.0274	1.09
<i>Typha latifolia</i>	0.0048	1.66	<i>Alopecurus aequalis</i>	0.0035	1.08

Regarding terrestrial agricultural habitats, studies in Sweden (Belfrage et al. 2005) and in Poland (Kieloch et al. 2018) also demonstrated larger weed biodiversity (more species) and density on small farms than on larger ones, and in the Polish case, this pattern was also explainable by other correlating factors. The size of farm holdings cannot, of course, exert a direct influence on the weeds, but it still seems to have a strong indirect impact through management

practices, such as crop rotation, tillage systems, and weed control methods. Large-sized farms usually apply high-input practices, including high levels of herbicide use, while small-sized farms practice low-input agricultural techniques, including low levels of herbicide use (Kieloch et al. 2018).

Overall, our results with the Hungarian organic rice fields concur with the general trends reported by Tschardt et al.

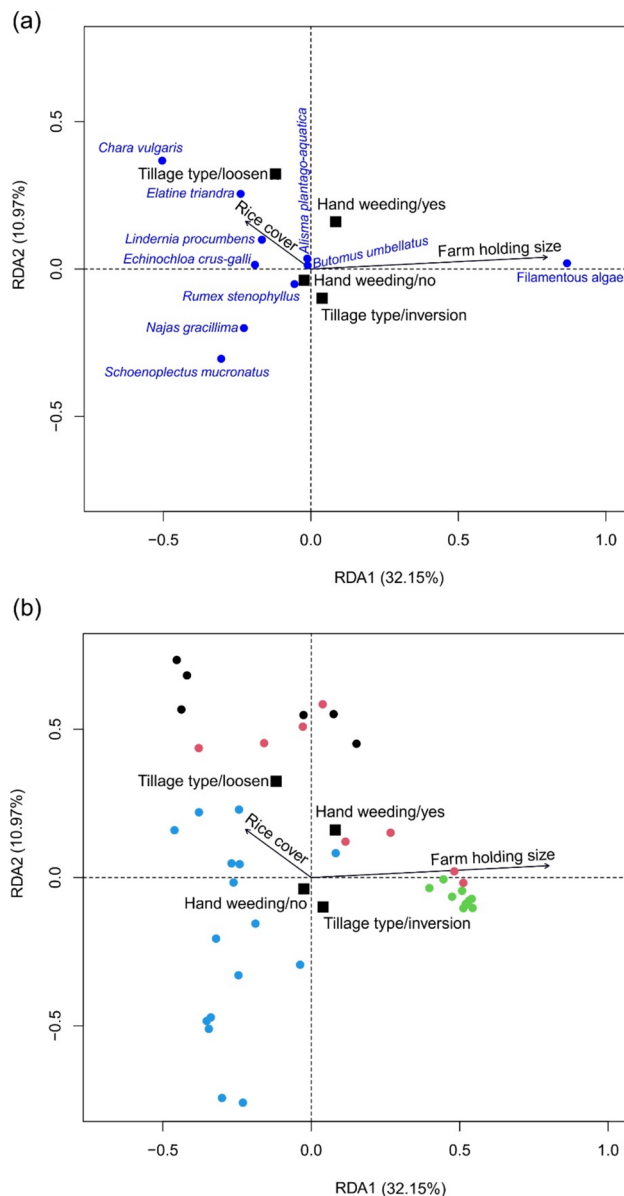


Fig. 2 Ordination diagrams of the reduced redundancy analysis (RDA) model containing the significant variables and **a** species or **b** plots. Only the ten species with the highest weights on the first two RDA axes are presented. Different colours in part b mean different farms

(2021): that “current organic production is increasingly intensified, specialised, and often far away from the idealism and enthusiasm of the original organic movement. In contrast to the small and diversified family farms that characterised the beginning of the organic movement, modern organic arable fields can be huge monocultures, resembling conventional fields. This intensification suggest that certified organic production is not the silver bullet for current biodiversity conservation and agricultural production.”

Table 4 Regression variables excluded from the analysis to avoid multicollinearity (rows) on the four variables in the final model (columns)

	Rice cover	Tillage type: loosen	Farm size	Hand weeding	R^2
Sowing	−0.0088 ^{NS}	0.2320 ^{***}	0.4064 ^{***}	0.2534 ^{***}	0.923
type: soil					
Shift	0.0088 ^{NS}	−0.2320 ^{***}	−0.4064 ^{***}	−0.2534 ^{***}	0.923
crop:					
cereal					
Shift	−0.0088 ^{NS}	−0.1991 ^{***}	0.4064 ^{***}	0.2534 ^{***}	0.915
crop:					
fallow					
Shift	0.0118 ^{NS}	0.1205 ^{**}	0.0101 ^{NS}	0.1666 ^{***}	0.609
crop:					
alfalfa					
Shift	−0.0118 ^{NS}	0.3106 ^{***}	0.0101 ^{NS}	0.1666 ^{***}	0.725
crop:					
mustard					
Tillage	−0.0264 ^{NS}	−1.4594 ^{***}	1.2192 ^{***}	−1.2270 ^{***}	0.978
depth					
Organic	−0.0088 ^{NS}	0.2320 ^{***}	0.4064 ^{***}	−0.1441 ^{***}	0.920
manure					
P & K	−0.0118 ^{NS}	0.3106 ^{***}	0.0101 ^{NS}	0.1666 ^{***}	0.725
supple-					
mentary					
nutrients					
June	−0.2488 ^{NS}	−0.1545 ^{NS}	1.5064 ^{***}	−0.2110 ^{NS}	0.699
water					
depth					

Categorical variables were replaced by binary dummy variables for each category. The table shows the regression coefficients of standardized predictor variables, thus their values are comparable within rows. The last column is the R^2 of the linear model including all of the four variables. NS=non-significant, *= $p < 0.05$; **= $p < 0.01$; ***= $p < 0.001$

Hand weeding

Even though hand weeding was applied only once a year, it was the second most important variable in our study. Our results, including the RDA ordination diagram (Fig. 2a) and the table of the strongly associating species (Table 3) suggest that some species are efficiently regulated by this treatment, providing intuitive proof for the importance of these laborious treatments. This includes in particular easily observable “eye-catching” weeds, like *Rumex stenophyllus*, *Echinochloa crus-galli*, *Schoenoplectus mucronatus*, and *Persicaria amphibia* (L.) Gray, which are already well developed at the time of weeding. All of these species have been considered long ago as the most noxious weeds in Hungarian rice and other moist fields, where they can thrive in massive stands, and their eradication was highly advisable (Ujvárosi 1973). Although hand weeding is one of the recommended options to prevent the subsequent growth of *Cyperus difformis* L. (Chauhan and Johnson 2009), our results indicated that it could withstand this operation in the surveyed fields (Table 3). According to the former observation of Csapody

(1953), this could be explained by the fact that this species blooms relatively late, and it was difficult to distinguish it efficiently from the crop plants at the time of the weeding. Accordingly, the efficient reduction of this species might require a subsequent repetition of manual weeding.

Although hand weeding has long been regarded as an expensive and time consuming operation, it has always been seen as the most important weed control operation in the paddies of the Carpathian Basin (Zlinszky 1905; Obermayer and Somorjai 1937; Büchl 1976). Historically, hand weeding could have been repeated up to three times during the vegetation period, in case of high weed pressures (Krasznay and Reichenbach 1935), and it has retained a status as a complementary operation even after the advent of herbicides (Szöke 1961). Nowadays, hand weeding is getting more and more expensive; consequently, it is usually applied only in special cases by Hungarian rice farmers, for instance in case of heavy infestations of weedy rice.

In some regions of the World, due to the low availability of mechanisation and herbicides, weeding by hand or hand-held hoe is still the main weeding intervention by rice farmers (Fried et al. 2018; Alagbo et al. 2022; Rodenburg et al. 2022). Hand weeding is highly time-consuming and therefore often done too late or inadequately (Rodenburg et al. 2019). In those regions, the low intensity farming system is usually a constraint of poverty, rather than an option among smallholder rice farmers. In organic rice systems, where the type of management is an option to produce for the organic food market, in many regions, weed control is still mainly depending on hand weeding as well, which is becoming problematic due to the shortage of labour and increasing labour costs (Mendoza 2004; Bhatia et al. 2016; Chhun et al. 2020). The study of Gao et al. (2022) also revealed that hand weeding frequency was one of the primary factors associated with the differences in the composition of weed communities in organic fields in China.

Tillage type

Tillage type was the third most relevant variable in our study, which was also correlated with tillage depth, shift crop, and supplementary nutrients (Tables 2 and 4). There were two main types of tillage in the farms surveyed: *ploughing*, which involved soil inversion (deeper tillage), and *disc-harrow*, where usually just the top layer of the soil was loosened. From the weed species *Chara vulgaris*, *Lindernia procumbens* and *Elatine triandra* responded more strongly to the soil loosening, while *Rumex stenophyllus*, *Chara braunii* and *Najas gracillima* were associated with the soil inversion (Table 3). Interestingly, in conventional rice fields, the members of submerged stonewort communities (the species of *Chara*, *Nitella* and *Najas* genera) were uniformly

positively associated with the soil loosening (Pinke et al. 2014), most likely due to the fact that their small oospores tend to be unable to emerge from great depths caused by the soil inversion (Bonis and Grillas 2002). In organic fields, some members of this group seemed to prefer the soil inversion (Table 3), even though it was accompanied with higher tillage depth (22–25 cm), than it was (20 cm) in conventional fields. One possible explanation could be related to the fact that in organic rice systems, a terrestrial shift crop must be inserted directly after each rice in the rotation, to hinder the propagation of troublesome aquatic weeds (Roszík 2013). In the case of conventional cultivation, a shift crop should follow the rice only after 3–5 years (Ruzsányi 1992). The terrestrial conditions in every second year can cause periodic desiccations, through which many aquatic organisms can survive only as dormant propagules (Lukács et al. 2013; Alderton et al. 2017). These desiccations can even increase the germination rate of certain charophytes (Holzhausen et al. 2018). Moreover, the circumstances following the one-year-long dry period can provide a pioneer surface free of the stronger competitors, which are favoured by most of the charophyte communities (Schubert et al. 2018). Furthermore, various abiotic factors (e.g. salinity, light, temperature) could be different between the two management systems or between the two years when they were surveyed, which could also affect the charophyte biomass and oospore bank density (Bonis and Grillas 2002).

In our study, two noxious, perennial weed species, *Persicaria amphibia* and *Bolboschoenus planiculmis* were also more abundant in sites without soil inversion (Table 3). This is in accordance with the observations of other studies showing a higher abundance of perennial weeds in rice fields with reduced or zero tillage (Filizadeh et al. 2007; Singh et al. 2015). In our study, tillage type also correlated with P & K supplementary nutrients (Table 4), which could also greatly impact weed abundances (Ghosh et al. 2022; He et al. 2023).

Rice cover

In our study, rice cover was the fourth most influential variable for the weed species composition in organic rice fields (Table 2), and this variable was not correlated with any of the excluded variables, either. It should be noted that crop cover also exerts a strong influence on weeds in conventional rice paddies in Hungary, where it was the most relevant factor (Pinke et al. 2014). Just like in conventional fields, *Lemna aequinoctialis* Welw. seems to be most tolerant for the shading effect of the crop canopy in organic rice fields, too (Table 3). This is partly due to the free-floating nature of this species, it cannot tolerate strong waves and currents, so it prefers the protective stands of other plant species (Borhidi

et al. 2012). On the other hand, new studies revealed that *Lemna* species can tolerate deep shade on the basis of large light-harvesting complexes and high photochemical efficiency (Stewart et al. 2021; Ziegler et al. 2023). The rapid formation of a dense mat of other duckweed species could even compete with other weeds for nutrients and could create shade to repress their photosynthesis, effectively reducing their density and biomass (Wang et al. 2022). Although most of the macrophytes have high light demand (Bornette and Puijalon 2011), another exception is *Marsilea quadrifolia* L., which in Italy, exhibited unexpectedly higher growth potential in shady conditions provided by rice canopy creating micro-habitats than in open areas (Corli et al. 2021).

Regarding the crop canopy tolerance, the members of submerged stonewort communities showed inconsistent behaviour: *Nitella tenuissima* (Desvaux) Kützing and *Chara braunii* appeared to be tolerant for high rice cover, while *Chara fibrosa* and *C. vulgaris* correlated negatively with this variable (Table 3). Remarkably, these species exhibit a strong negative response to high crop cover in conventional fields (Pinke et al. 2014), which suggests that their ecological behaviour could be greatly influenced by the management system of the rice fields. A possible reason for this could be that light is a more limiting factor for charophytes under higher nutrient concentrations, which often happens in conventional fields (Schubert et al. 2018). Previous research of Schwarz et al. (2002) also revealed that some charophytes possessed an efficient adaptation to shade if the ecological conditions of the habitat were changing. In addition, the shade tolerance of certain aquatic plants in the rice fields could be also indirectly influenced by the site-specific water depth values as well (Chauhan 2012).

Among the pernicious rice weeds, *Rumex stenophyllus*, *Echinochloa crus-galli* and *Schoenoplectus supinus* (L.) Palla also tolerated high rice cover (Table 3), suggesting their strong competitive ability even in denser crop stands. One of the main targets of cultural weed management in organic rice is to increase the competitive strength of the rice crop to suppress weeds, among others by developing cultivars with early canopy closure (Dass et al. 2017) and setting up narrow plant spacing (Erythrina et al. 2023). In their recent study, Ashouri et al. (2022) also documented, that one of the significant factors affecting weed community composition in the irrigated rice paddies of northern Iran was rice cover.

Conclusions

It can be concluded that farm holding size, hand weeding, tillage type, and rice cover appeared to be key drivers shaping weed vegetation in organic rice paddies in Hungary.

However, the relatively small growing area of organic rice in Hungary resulted in only a small sample of farm holdings, which together with relatively uniform management practices, resulted in a reduced ability in distinguishing the effects of the diverse factors. To take this into consideration, for each pattern we found, we also discuss potential alternative explanations relying on other factors correlated with the variables involved in the final analysis, i.e. sowing type, shift crop, tillage depth, organic manure, supplementary nutrients and water depth. Furthermore, it should also be emphasised that other, non-studied factors could also have influenced our results, as each farm had its own particular management operations and the fields of each farm were located in separated spatial blocks. Even though rice is a relatively minor crop in Hungary, these results from the peripheries of the ecological niche and growing area of this major global staple can provide new information about the assembly rules of weed communities, which could be used to optimise weed control and conservation strategies in organic paddy systems. Our findings suggest that a dense rice canopy on its own could not guarantee the suppression of competitive weeds, which can thus only be controlled with multiple manual weedings. Similarly, in sites strongly infested with perennial weeds, ploughing with soil inversion can be advisable. Finally, as farm holding size was negatively correlated with most aquatic plants, any potential measures for biodiversity conservation should preferably target the smaller (family-scale) farms rather than those owned by big companies.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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