



Organic rice farming enhances conservation value, while water conductivity, a proxy for nutrient inputs, best predicts aquatic plant biodiversity in East-Central Europe

Gyula Pinke[✉] · János Csiky[✉] · Attila Mesterházy[✉] · László Tari · Robert W. Pal[✉] · Bálint Czúcz[✉] · Ákos Bede-Fazekas[✉] · Péter Batáry[✉] · Zoltán Botta-Dukát[✉]

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Abstract Organic rice farming has increasingly gained attention for its potential to enhance biodiversity compared to conventional agricultural methods. In this study, we examined the abundance of plant species groups of conservation interest in rice fields in Hungary, located at the northern periphery of rice cultivation. We compared organically and conventionally managed rice fields to determine their

impact on plant biodiversity. Our results indicated that organic fields generally support a greater abundance of non-harmful macrophytes, charophytes, and red-listed species. However, these differences were less pronounced in fields considered less ecologically valuable, irrespective of management types. Our analysis revealed that water conductivity had a more significant impact than farming type. Lower conductivity correlated with weed communities of higher conservation values, particularly in organically managed fields. This effect was significant compared with conventional fields but was only evident in areas with relatively low conductivity, likely reflecting low

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G. Pinke (✉)
Albert Kázmér Faculty of Mosonmagyaróvár, Széchenyi István University, Vár 2., Mosonmagyaróvár 9200, Hungary
e-mail: pinke.gyula@sze.hu

J. Csiky
Faculty of Sciences, University of Pécs, Ifjúság U. 6., Pécs 7624, Hungary

A. Mesterházy
Celldömölk, Hungary

L. Tari
Külkerület II., Tanya 54, Szarvas 5540, Hungary

R. W. Pal
Department of Biological Sciences, Montana Technological University, 1300 Park Street, Butte 59701, USA

B. Czúcz
Norwegian Institute for Nature Research, Torgarden, P.O. 5685, 7485 Trondheim, Norway

Á. Bede-Fazekas
Department of Environmental and Landscape Geography, Institute of Geography and Earth Sciences, ELTE Eötvös Loránd University, Pázmány Péter Sétány 1/C., Budapest 1117, Hungary

Á. Bede-Fazekas · Z. Botta-Dukát
Large-Scale Vegetation Ecology Research Group, Institute of Ecology and Botany, HUN-REN Centre for Ecological Research, Alkotmány U. 2-4, Vácrátót 2163, Hungary

P. Batáry
“Lendület” Landscape and Conservation Ecology, Institute of Ecology and Botany, MTA–HUN-REN Centre for Ecological Research, Alkotmány U. 2-4, Vácrátót 2163, Hungary

nutrient levels in the water. These findings suggest that to maximize biodiversity benefits, organic agriculture should be practiced alongside the judicious use of low amounts of organic manure or nutrients. Such practices could enhance species-rich macrophyte communities, contributing to the preservation of the unique biodiversity found in this historic rice cultivation region.

Keywords Aquatic vegetation · Charophytes · *Oryza sativa* · Macrophytes · Paddy fields · Quantile regression

Introduction

It is prevalingly agreed that the reduced use of agrochemicals in organic agriculture positively impacts the biodiversity of many organisms (Marja et al., 2014; Tuck et al., 2014; Emmerson et al., 2016). It is usually associated with a higher abundance and richness of arable weeds (Armengot et al., 2012; Henckel et al., 2015; Chamorro et al., 2016). While weeds are generally undesirable in arable habitats, there are rare and threatened weeds (Storkey et al., 2012), and weeds that can provide important ecosystem services by supporting whole food chains, including natural enemies of pests and pollinators (Esposito et al., 2023; Marshall et al., 2003). Although organic farming is usually positively associated with such weed species important for biodiversity, certain studies indicated that highly efficient mechanical weed management in organic fields could be as harmful to weed flora as herbicide application is in conventional agriculture (Albrecht et al., 2016).

In the last two decades, several studies have focused on biodiversity comparisons between management systems in paddy ecosystems worldwide. Investigations in Brazil revealed that flooded organic rice fields had a different anuran species composition than conventional fields (Moreira and Maltchik, 2014), however, the richness and abundance of macroinvertebrates and macrophytes were similar in the two rice production schemes (Dalzochio et al., 2016). These studies also suggested that both systems negatively influenced

species diversity compared to natural habitats (Linke et al., 2014; Maltchik et al., 2017). In Costa Rica and Australia, macroinvertebrate communities under organic management regimes exhibited higher levels of diversity (Wilson et al., 2008; Rizo-Patrón et al., 2013). In Japan, organic paddy fields supported the highest richness and abundance of several taxonomic groups (red-listed plants, spiders, dragonflies, and frogs), followed by low-input and conventional fields (Katayama et al., 2019). However, as the percentage area of surrounding semi-natural habitats increased, the difference in the plant richness between organic and other fields decreased (Katayama et al., 2023). In Spain, organic farming increased biomass and temporal heterogeneity of macrophyte communities but had no effect on their diversity, while at the same time rice yield decreased significantly (Martínez-Eixarch et al., 2017). Higher bird biomass was also reported from Spanish organic rice fields due to the presence of a larger biomass of prey items, such as fish, invertebrates, and macrophytes (Ibáñez et al., 2010). The recent meta-analyses of He et al. (2023) also suggested that organic farming generally increased the natural enemy abundance and diversity and reduced pest abundance in rice paddy ecosystems. Despite these partly ambiguous outcomes, organic management of rice production could harmonize wetland conservation and sustainable food production in other parts of the world, including the rice-growing regions of East-Central Europe; however, such studies in this area are entirely lacking.

In Europe, considerable efforts have been invested to restore the macrophyte vegetation of shallow lakes, because of their high biodiversity value and ecosystem services (Bakker et al., 2013; Hilt et al., 2018; Thomaz, 2023). Consequently, the identification of rice management variables, which are most favourable for certain macrophyte assemblages, could help support such conservation purposes in agricultural areas. Since macrophyte vegetation also includes many pernicious weed species that are very difficult to control and can significantly reduce rice yield, only selected groups of macrophytes should receive conservation priority. Determining the most favourable management regimes for non-harmful macrophytes could help optimize conservation strategies. Given the distinct environmental and management constraints in the different rice-growing regions of the world, regional research is also needed to develop tailored biodiversity measures.

P. Batáry
Faunistics and Wildlife Conservation, Department
of Agriculture, Ecotrophology, and Landscape
Development, Anhalt University of Applied Sciences,
Strenzfelder Allee 28, 06406 Bernburg, Germany

As a consequence of strong political pressure during the communist system, Hungarian rice cropping increased from about 7000 ha in 1946 to a peak between 50,000–90,000 ha in the 1950s (Bora, 1956; Csávás, 1962). This large surface of flooded paddy fields provided a great diversity of wetland plant species (Ubrizsy, 1961; Takács et al., 2013). Many of the once common aquatic plants that had become endangered due to the drainage of wetlands and river regulations during the previous centuries found a new home in the extensively flooded rice fields in the 1950s (Csávás, 1970). Nevertheless, in the 1960s this high floristic diversity started to decline dramatically due to the increasing use of herbicides and the gradual shrinkage of the rice-growing area. Today in Hungary, rice is cultivated on around 2300–3000 ha, approximately 10% of which is managed organically (Pinke et al., 2026). In contrast to the conventional systems, no herbicides are applied in organic fields, and instead of inorganic fertilizers, only supplementary, organic nutrients are permitted (Roszák, 2013). Consequently, organic farming can be expected to support a higher diversity of macrophytes in Hungarian paddies. Nevertheless, under certain circumstances, even conventional rice farmlands might support unique macrophyte communities (Pinke et al., 2014), whereas some of the management practices in organic farming are negatively associated with most aquatic plants (Pinke et al., 2026). In addition to comparing the conventional and organic systems, it is also essential to zoom in on the individual management practices and identify more concrete management variables with a great impact on species composition (e.g. crop rotation, time of flooding, etc.—cf. Martínez-Eixarch et al., 2017; Katayama et al., 2019; Corli et al. 2021). This can be used for providing more detailed management recommendations.

In the present study, we directly compare the species composition of the two types of farming, primarily focusing on species with conservation priority. We aim to answer the following questions: (1) Which weed species can be associated with either of the two management regimes? Do the weed flora of conventional and organic rice fields differ in their (2) composition and (3) conservation value? (4) Are there any variables that can override the effect of farming type for the valuable (wetland) species in the weed communities?

Materials and methods

Data collection

In July 2012, we surveyed 96 conventionally and 4 organically managed rice (*Oryza sativa* L.) fields located in the main Hungarian rice-growing district in the eastern part of the country (Fig. 1). In July 2014, we expanded the study with 38 further organically managed fields. Given the limited number of available rice fields and their aggregated distribution, the surveyed fields were often close to each other. This spatial arrangement reflects the natural clustering of rice cultivation in the region, which could potentially influence comparative results. The vegetation of the fields was sampled in two randomly located 100 m² (10×10 m) plots inside the fields (at least 10 m from the field margin). The abundance of plant species was estimated visually as a percentage of ground cover in each plot. For each field, we averaged the cover values of the species across the two plots. Macrophyte plant species were identified at the species level, whereas filamentous algae of taxonomically diverse origin were classified into a single group. All fields were on heavy clay soils with pH ranging between 6.9 and 7.9. The mean annual temperature and precipitation in the study area were 10.3 °C and 525 mm, respectively (Dövényi, 2010). During the field surveys, rice crops were in the flowering stage in all investigated fields, which also corresponds to the seasonal peak of the macrophyte vegetation in the region and throughout East-Central Europe. Accordingly, the identification of many aquatic plant species would have been difficult or impossible before or after this period. Altogether, seven different farms were involved in the study: we surveyed three conventional and three organic farms, and one farm had both conventionally and organically managed fields. Management information was obtained directly from the farmers in brief targeted interviews. We also measured water depth (referring to ‘water depth in July’) and water parameters, such as pH, temperature and conductivity (using Hanna Combo HI98129) at the centre of each plot, once during the fieldwork. The most important management and environmental variables collected during the study are listed in Table 1. For more information for understanding the rice cycle in Hungary see Pinke et al. (2014) and Pinke et al. (2026).

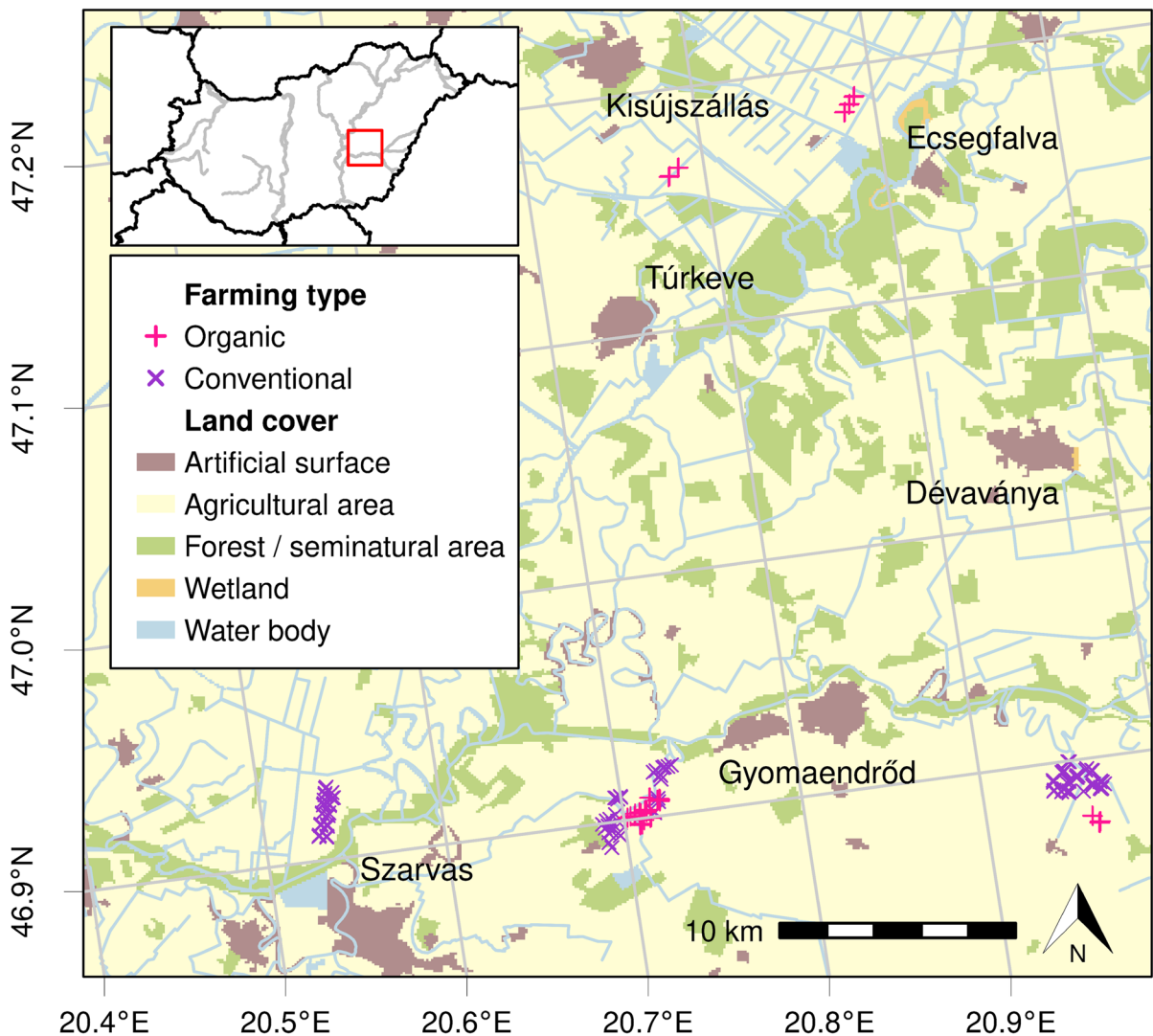


Fig. 1 The distribution of the surveyed rice fields in East Hungary

From the recorded taxa, we created three conservation priority groups: (i) non-harmful macrophytes, (ii) charophytes, and (iii) red-listed species (Table S1). These three groups have a nested structure, i.e. groups (ii) and (iii) were parts of group (i), which contained all macrophyte species, except for species listed as most troublesome weeds (as listed by Ujvárosi (1973) and Izsó and Giricz (2018), including species of *Echinochloa*, *Bolboschoenus*, *Cyperus*, and *Typha* genera, weedy rice, and filamentous algae), and terrestrial arable weeds (i.e. *Cirsium*, *Hibiscus*, *Polygonum*, and *Xanthium* species). In this sense, non-harmful macrophytes

correspond to “neutral weeds” which according to Esposito et al. (2023) coexist with crops and do not negatively affect crop yield and quality. The other two conservation priority groups contained species of particular conservation interest: group (ii) included the charophyte species from genera *Chara* and *Nitella*, whereas group (iii) embraced five red-listed species (*Alisma gramineum* Lej., *Elatine alsinastrum* L., *E. hungarica* Moesz., *E. triandra* Schkuhr., *Najas minor* All. according to Király (2007). In terms of taxonomic nomenclature, we followed Király (2009).

Table 1 Overview of variables related to weed management, cultural practices, and environmental factors in conventionally and organically managed rice fields, including the units and ranges of continuous variables and the values of categorical variables

Variable (unit)	Range / Values	
	Conventional	Organic
<i>Weed management</i>		
Herbicides		
Penoxsulam (g ha ⁻¹)	0–40	–
Azimsulphuron (g ha ⁻¹)	0–20	–
Pendimethalin (l ha ⁻¹)	0–1.65	–
Hand weeding (times)	0–1	0–1
<i>Cultural</i>		
Previous crop	Wheat, Indian wild rice, lucerne, red clover, sunflower	Cereal, fallow, lucerne, white mustard
Years after last rotation	1–4	1
Years after conversion to organic farming	–	1–15
Amount of fertilizer (kg ha ⁻¹)		
N	58–81	–
P ₂ O ₅	0–52	–
K ₂ O	0–60	–
Plant nutrition		
Foliar amendments (meso- & microelements) (l ha ⁻¹)	–	0–10
Organic manure (kg ha ⁻¹)	–	0–2500
P & K supplementary nutrients (kg ha ⁻¹)	–	0–300
Sowing type	Surface, soil	Surface, soil
Time between sowing and flooding of the fields (days)	1–15	4–15
Tillage type	Soil inversion; loosen	Soil inversion; loosen
Tillage depth (cm)	15–20	15–25
Farm holding size (ha)	180–2000	350–4500
Field size (ha)	3.6–8.6	4–6
Crop cover (%)	25–100	5–90
Water depth (cm)		
May	3–5	4–6
June	10–16	14–20
July	7–36	3–24
<i>Environmental</i>		
Altitude (m)	84–95	87–98
Water parameters		
pH	7.1–9.4	7.4–9.7
Temperature (°C)	20.3–30.8	21.5–29.9
Conductivity (µS cm ⁻¹)	300–1266	180–845

Statistical analysis

We performed different types of analysis that responded to the four research questions raised in the introduction.

- (1) The association between the occurrence or cover values of each species and each of the two types of farming was tested by point-biserial correlation (De Cáceres and Legendre, 2009), which is identical to the Phi coefficient (Chytrý

- et al., 2002) for the presence/absence data. The observed correlations were compared with the random expectation that species distribution across the fields is independent of the field management type by randomization test (i.e. reshuffling organic/conventional labels). Analysis was done in the *vegan* R package (Oksanen et al., 2011).
- (2) We also investigated whether the two types of farming differ in their total species composition by permutational multivariate analysis of variance (PERMANOVA; Borcard et al., 2011). Analysis was done by the *adonis* function in the *vegan* R package (Oksanen et al., 2011) with 9999 permutations. Variability in species composition between the two management systems was compared by analysis of multivariate homogeneity of group dispersions (Anderson, 2006) using the *betadisper* algorithm in the *vegan* package, which compares the mean distance of the plots from the group centroid, a multivariate analogue of variance. Hellinger distance matrices (Anderson, 2001), i.e. Euclidean distances of species cover values after Hellinger transformation (Legendre and Gallagher, 2001), were used in both analyses. To visualize the results, principal coordinate analysis was done using the same distance matrix.
 - (3) Considering that quantile regression is a more robust, comprehensive, and flexible method than the commonly used mean regression analyses (Cade and Noon, 2003; Koenker, 2014), we applied quantile regression to compare the proportions of conservation priority groups of the two farming types. If the response variable is nonlinearly influenced (e.g. limited) by many (partly unmeasured) factors, then changes in the mean response can easily be masked by the unmeasured factors. In such cases, changes in upper quantiles of the response variable can offer a better representation of the effect, since the response variable cannot be more than some upper limit set by the studied factor. While quantile regression is still relatively little used in ecology, it has been increasingly applied in recent years. Notable applications include studying plant-abiotic interactions (Agarwal et al., 2019), predicting plant invasion scenarios (Sofaer et al., 2022), using policy tools through urban planning (Wang et al., 2024), and investigating aquatic plant communities (Liu et al., 2020). The total cover and the species richness (species number) of the selected conservation priority groups were compared using farming type (i.e. organic or conventional) as a categorical independent variable. Regression models were fitted using the *quantreg* package (Koenker, 2023).
 - (4) To identify variables which can potentially confound (co-explain) the effect of farming type on the selected conservation priority groups, we used decision tree (also known as classification and regression trees, CART) models by using the *partykit* package (Hothorn and Zeileis, 2015). Decision trees have a relatively simple and transparent structure, which makes interpreting patterns easy and straightforward (Breiman et al., 1984). In these models, the collected variables (Table 1) served as explanatory predictors, and the response variables were the total cover and the species richness (species number) of the selected conservation priority groups. As our main purpose was to identify the most important predictor, only the first splits in the regression trees were established. We carried out this analysis separately with each of the six response variables (*species numbers* and *cover values* of the three target groups, i.e. non-harmful macrophytes, charophytes, and red-listed species) and an additional “synthetic” response variable. This synthetic variable was defined as the first principal component of the six correlating variables, thus unifying common information of the six variables into a single variable, which we call “botanical conservation value” hereafter (Fig. 2). In addition, we also tested the combined effect of the most important explanatory predictor revealed by the decision trees and farming type on conservation value using two-way ANOVA.
 - (5) To assess if the differences in conductivity can be ascribed to the NPK content of the applied fertility amendments, we estimated the NPK content of organic manures using a simple nutrient calculator (British Columbia, 2025) and combined the resulting values with the PK values of the supplementary nutrients applied in the organic fields. Then, the association between NPK values (applied either in conventional or organic fields)

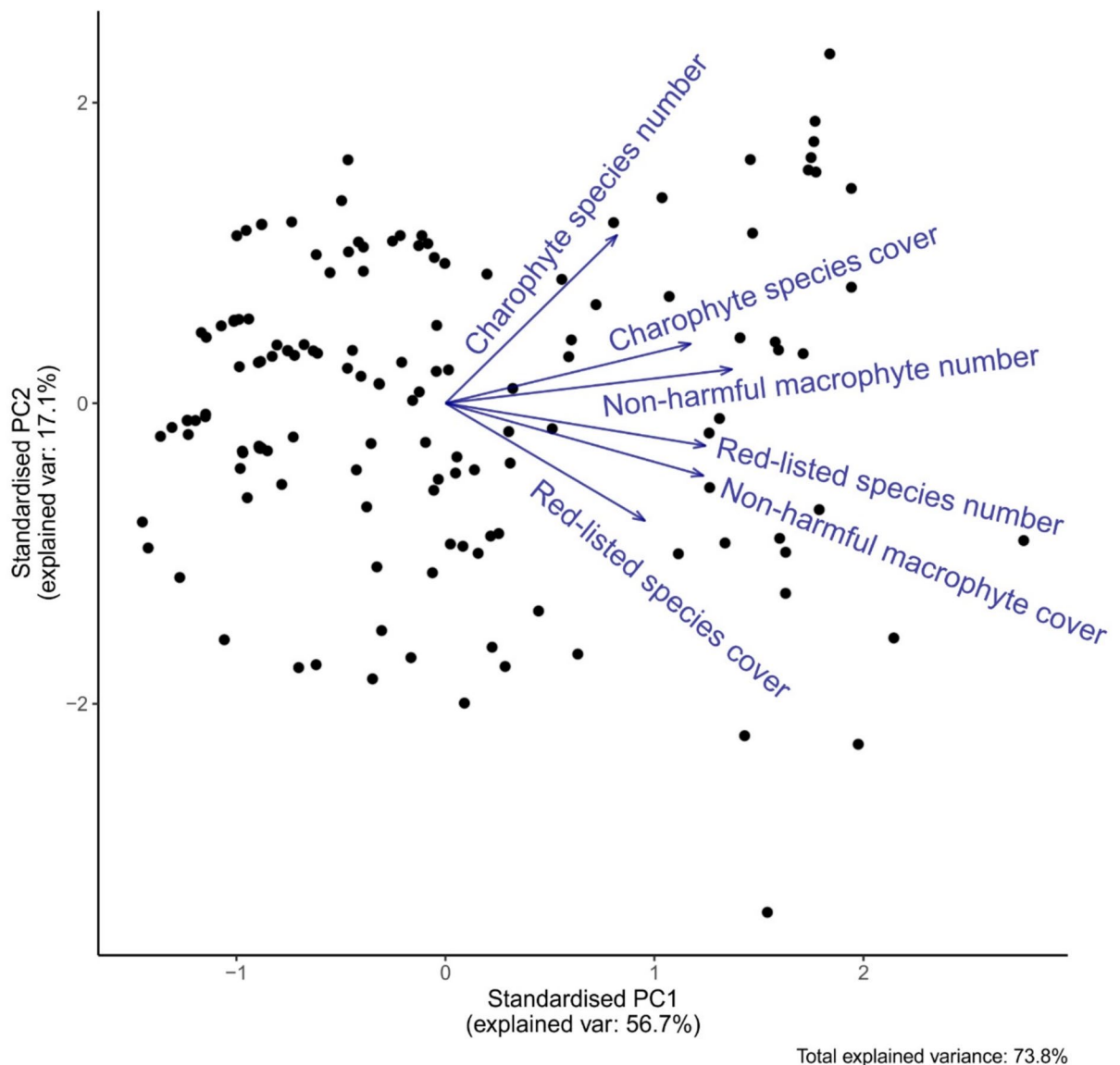


Fig. 2 Synthetic botanical conservation value, defined as the first principal component of the numbers and cover values of non-harmful aquatic plants, charophytes, and red-list species,

explains 56.7% of the total variation of the six variables. (The two axes together explain 73.8%)

and water conductivity was measured using Spearman's rank correlation.

The entire statistical analysis was conducted in the R environment (R Core Team, 2024).

Results

- (1) Along with the filamentous algae, 50 macrophyte species were recorded, 39 were found in conventional and 44 in organic fields (Table S1). Based

on cover values and occurrences, there were 19 species positively associated with organically managed fields, and 8 taxa (including filamentous algae) were associated with conventionally managed fields (Table 2).

- (2) According to the PERMANOVA, the two management types differ significantly in species composition ($F=13.526$, $P<0.001$) despite their remarkable overlap in the ordination space of the first two PCoA axes (Fig. 3). Nonetheless, the management type explained only the 9% of the total variance in the species data. The PER-

MANOVA test revealed that organic fields were significantly more diverse, which means that we found different levels of dispersion by farming types (*average distance to median: organic/conventional: 0.6575/0.5705*; $F=5.3165$, $P=0.022$).

- (3) The quantile regression models show that for three of the studied response variables (the *cover* and *number of non-harmful macrophytes*, and the *cover of charophytes*) there are no significant differences between the organic and conventional fields at the lowest quantile, suggesting that the species poorer organic and conventional fields

Table 2 Association between occurrence and cover values of each species and each of the two field types using point-biserial correlation. (Positive values indicate that the species are

more abundant/frequent in organic fields, negative values show that the species are more abundant/frequent in conventional fields)

Taxa	Cover		Presence/absence	
	Test statistic	P-value	Test statistic	P-value
<i>Alisma lanceolata</i> Withering	0.415 ****	<0.0001	0.495 ****	<0.0001
<i>Schoenoplectus mucronatus</i> (L.) Palla	0.376 ****	<0.0001	0.515 ****	<0.0001
<i>Chara vulgaris</i> L	0.363 ****	0.0001	0.313 ****	0.0003
<i>Schoenoplectus supinus</i> (L.) Palla	0.363 ****	<0.0001	0.555 ****	<0.0001
<i>Rumex stenophyllus</i> Ledeb	0.323 ****	<0.0001	0.548 ****	<0.0001
<i>Xanthium italicum</i> Moretti	0.310 ****	0.0004	0.322 ****	0.0006
<i>Ranunculus sardous</i> Crantz	0.278 ****	0.0023	0.293 ****	0.0022
<i>Chara fibrosa</i> C.Agardh ex Bruzelius	0.277 ****	<0.0001	0.375 ****	<0.0001
<i>Cirsium arvense</i> (L.) Scop	0.250 ****	0.0031	0.403 ****	<0.0001
<i>Alopecurus aequalis</i> Sobol	0.236 ****	0.0005	0.322 ****	0.0006
<i>Lindernia procumbens</i> (Krock.) Borbás	0.234 ****	<0.0001	0.395 ****	<0.0001
<i>Bolboschoenus planiculmis</i> T.V.Egorova	0.222 ****	<0.0001	0.648 ****	<0.0001
<i>Elatine alsinastrum</i> L	0.211 ****	0.0006	0.322 ****	0.0006
<i>Chara braunii</i> S.G.Gmel	0.207 **	0.0123	−0.071 ^{NS}	0.5013
<i>Najas gracillima</i> (A. Braun ex Engelmann) Magnus	0.186 **	0.0217	0.200 **	0.0216
<i>Najas minor</i> All	0.179 **	0.0207	0.073 ^{NS}	0.4606
<i>Persicaria amphibia</i> (L.) Grey	0.178 **	0.0010	0.240 **	0.0090
<i>Chara fragilis</i> Desv	0.103 ^{NS}	0.1988	0.262 ***	0.0033
<i>Potamogeton nodosus</i> Poir	0.081 ^{NS}	0.1777	0.193 **	0.0320
<i>Alopecurus geniculatus</i> L	−0.114 ^{NS}	0.2231	−0.114 ^{NS}	0.3136
<i>Butomus umbellatus</i> L	−0.125**	0.0409	−0.127 ^{NS}	0.1821
<i>Bolboschoenus glaucus</i> (Lam.) S.G. Smith	−0.132****	<0.0001	−0.482****	<0.0001
<i>Lemna minor</i> L	−0.138**	0.0397	−0.359****	<0.0001
<i>Echinochloa crus-galli</i> (L.) P.Beauv	−0.141**	0.0475	0.159*	0.0777
<i>Typha angustifolia</i> L	−0.187****	0.0005	−0.199**	2.29
<i>Oryza sativa</i> L. (weedy rice)	−0.262****	<0.0001	−0.409****	<0.0001
<i>Lemna aequinoctialis</i> Welw	−0.288****	<0.0001	−0.267***	0.0029
Filamentous algae	−0.289****	0.0004	−0.183*	0.0911

Bold letters indicate significant differences ($P<0.05$)

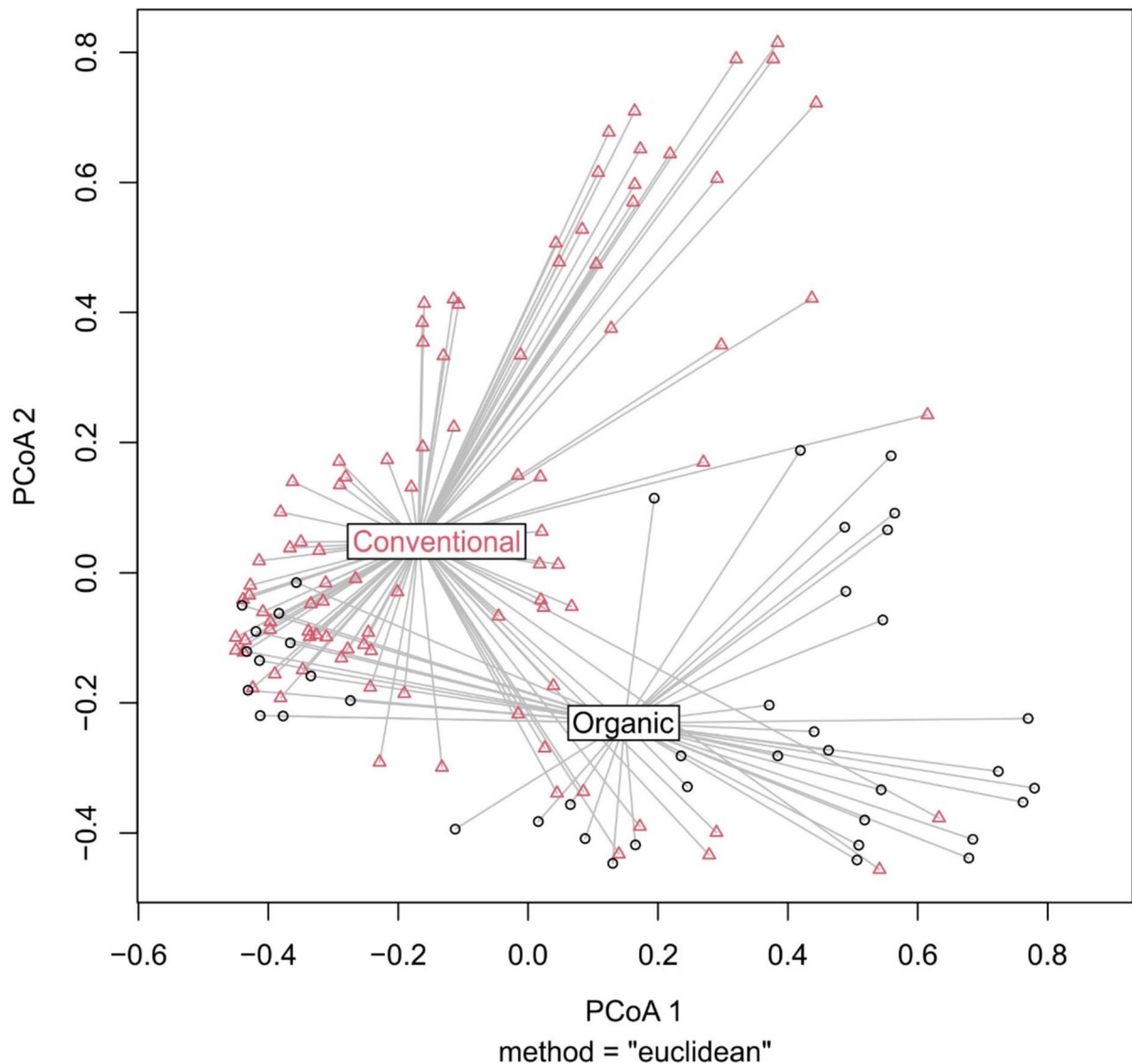


Fig. 3 PCoA ordination of community composition between the two types of farming

are very similar, but the “better” organic sites are different from the “better” conventional ones (Fig. 4). There is a similar pattern for the cover of red-listed species, but here the difference in the “better” sites is even smaller (confined to the highest quantile), with no significant difference between farming types in the “lower tail” of the sites’ distribution. And two response variables (the *number of charophytes* and *red-listed species*) display no clear difference between conventionally and organically managed fields over

the studied quantiles. (Fig. 4). All of these results indicate that although organic fields can hold a higher abundance of plant species with conservation value on average, there are no considerable differences between the less valuable fields of the two management types in terms of plant biodiversity value.

- (4) For four of the six main response variables (*cover & number of non-harmful macrophytes* and *red-listed species*), as well as for the synthetic botanical *conservation values*, the decision tree models

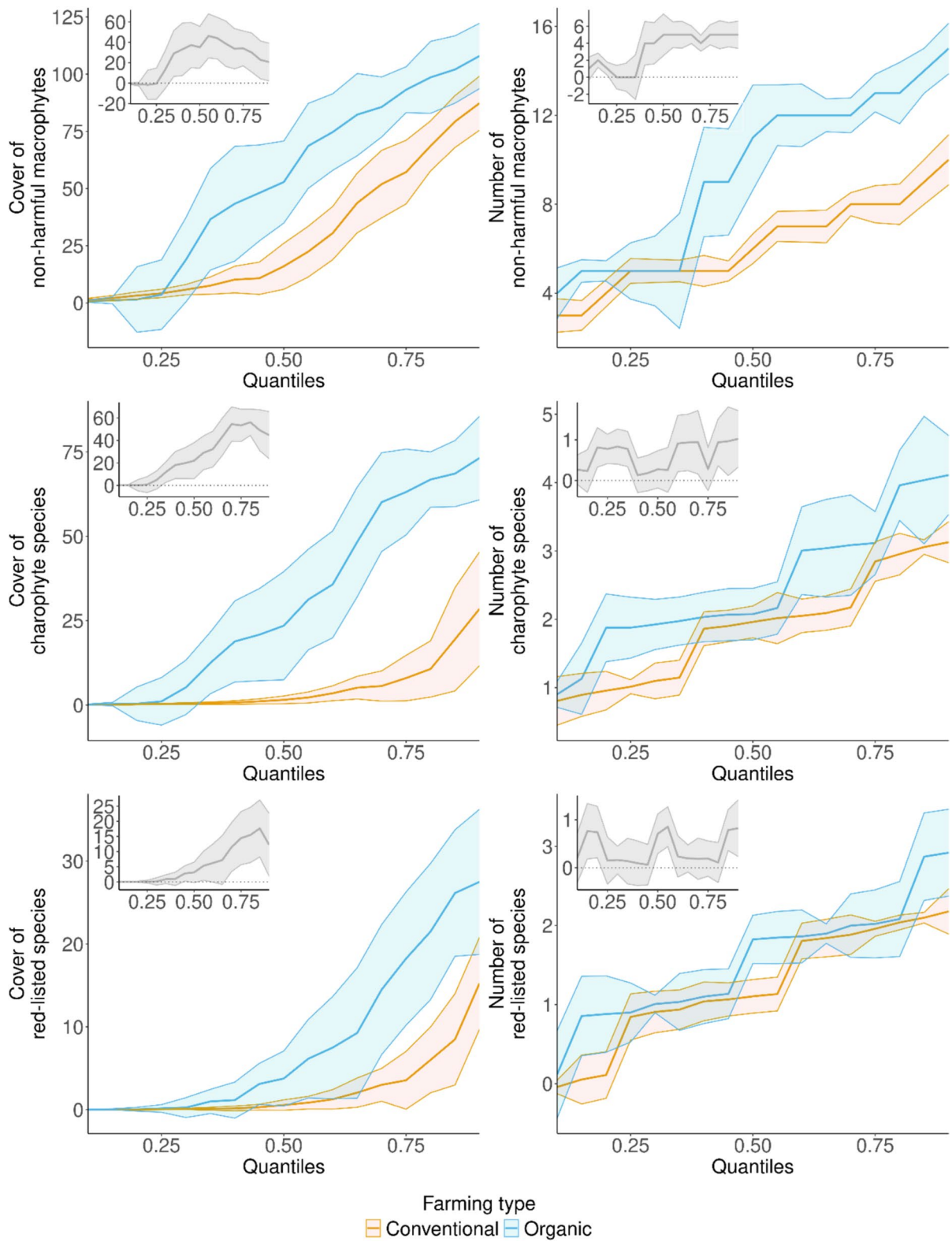


Fig. 4 Quantile regression on the association between cover and number of conservation priority groups of species and farming type. At a quantile q , proportion q of the observed values lower than or equal to the value plotted on the y-axis. Bold lines are the estimates, coloured stripes are the 95% confidence intervals. In the main figures, the values are the cover and number of species in the two management type categories. In the inset figures the values are the differences between the two management categories and the horizontal line represents zero difference, thus, where this line does not cross the grey stripe, the difference is significant at $\alpha = 0.05$ level

highlight water conductivity as the primary splitting variable, showing higher plant abundances in sites with lower water conductivity values (with the thresholds set at 501–475.5 $\mu\text{S cm}^{-1}$; Figs. 5 and 6). For *charophyte cover*, farming type was the most important explanatory factor, suggesting higher cover in organic fields; while for *charophyte number* the first split was determined by the previous crop, with lower species counts associated with Indian wild rice (*Zizania aquatica* L.) as the previous crop. The two-way ANOVA combining farming type and water conductivity indicated that the *conservation value* of the fields was higher at lower conductivity values, with organic fields exhibiting larger conservation values than conventional ones (Fig. 7). At higher conductivities there was no significant difference in the *conservation value* of the two farming types. The two variables together explained 44.24% of variation of the conservation value. Farming type and water conductivity alone explained 16.02–34.43%, respectively (3.21% of the explained variation were shared by the two variables).

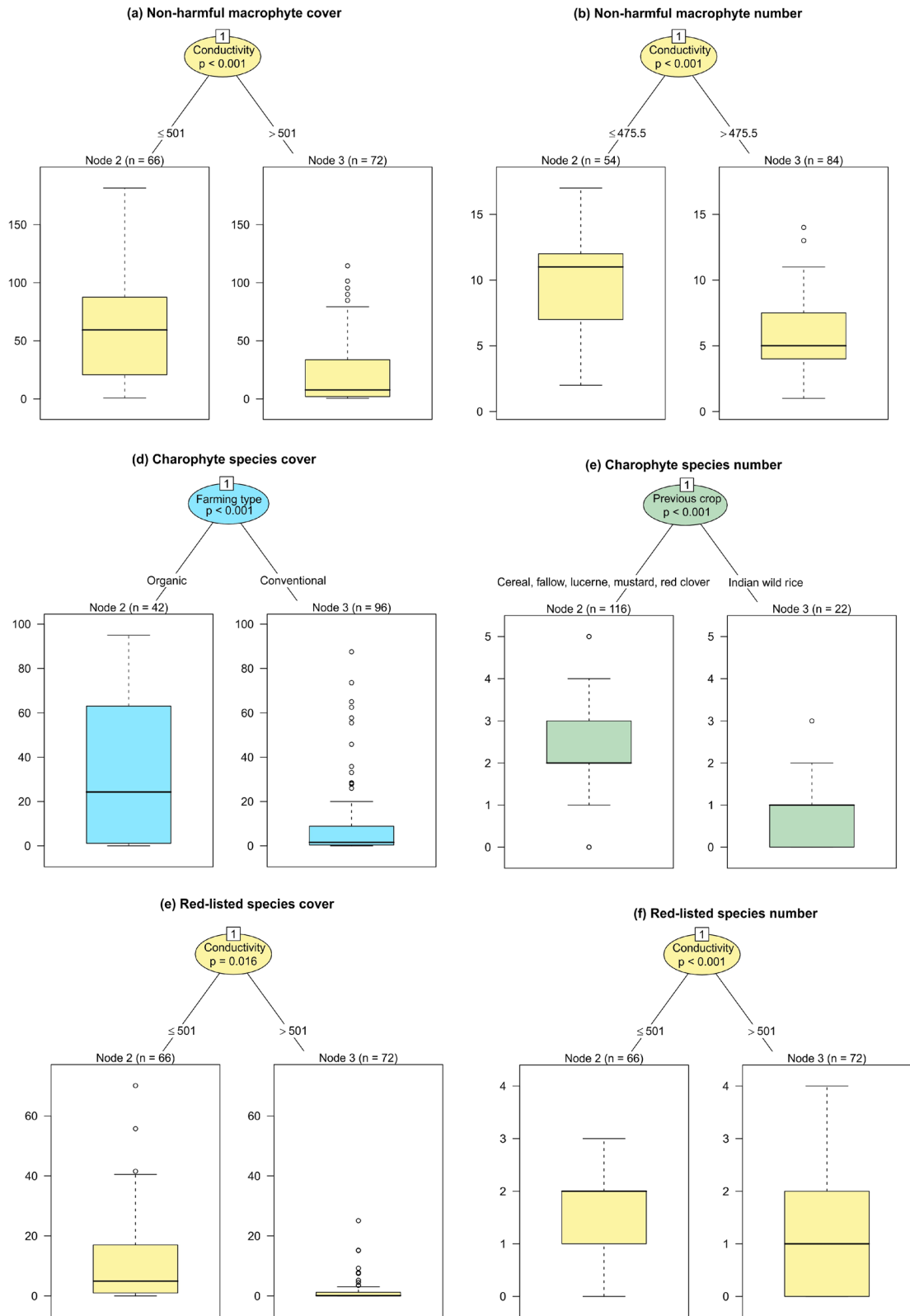
- (5) The rank correlation shows a strong positive correlation between water conductivity and NPK contents (particularly in the case of P & K) of the applied fertility amendments (Table 3).

Discussion

Our analyses revealed that 19 species were associated with the organically managed fields, and 8 taxa with the conventional ones (Table 2); and the two management systems differed significantly in their overall species composition (Fig. 3). As the investigated fields shared similar environmental conditions,

weed management and cultural variables between the two farming types could be the main drivers for the different patterns in individual species distributions. When the two farming types were analysed separately (Pinke et al., 2014, 2026), many of the species associated with either farming type during this study showed strong responses to management variables. This knowledge of their response to management variables eases the interpretation of their behaviour here. The lack of herbicides and fertilizers allowed a greater abundance of *Chara* and *Najas* species in organic fields, as they generally appeared susceptible to these agents (Pinke et al., 2014). In contrast, species that appeared tolerant of herbicides, such as *Lemma* species and *Echinochloa crus-galli* (L.) P.Beauv. (Pinke et al., 2014), were now positively correlated with the conventional fields. The divergent rotation system between the two farming types could be also responsible for the greater abundance of some troublesome weeds, like *E. crus-galli*, *Bolboschoenus glaucus* (Lam.) S.G. Smith, and weedy rice in the conventional fields. Namely, in organic management, a terrestrial shift crop must be inserted directly after each rice in the rotation, to hinder the propagation of aquatic and marsh weeds (Pinke et al., 2026). In contrast, in the investigated conventional fields, rice can have been cultivated in monoculture for up to four consecutive years, allowing the build-up of those weeds (Pinke et al., 2014). The positive correlation of typically dryland weeds, such as *Cirsium arvense* (L.) Scop. and *Xanthium italicum* Moretti, with organic farming can be because of the rotation system as well, as they have to survive only the shorter (one-year) flooding. Similarly, the characteristic plants of mud vegetation, e.g. *Schoenoplectus supinus* (L.) Palla, *Elatine alsinastrum*, and *Lindernia procumbens* (Krock.) Borbás were also more common in organic fields. They thrive when normally dry land gets intermittently flooded, but they do not tolerate long-term inundations (Molnár and Pfeiffer, 1999; Lukács et al., 2013; Altenfelder et al., 2016).

The present study focused more on the distribution patterns of species groups than on those of individual species. According to Albrecht (2003), in the case of arable weed communities, the proportion of species with high conservation value is more suitable for biodiversity assessments than many commonly used ecological indices. To implement this approach, we followed the theory of Esposito et al. (2023), i.e. we



◀**Fig. 5** Decision tree models of the numbers and cover values of non-harmful macrophytes, charophytes, and red-listed species recorded at the investigated rice fields. (Only the first splits are shown)

focused on “neutral weeds” (i.e. all species except the most pernicious weeds) as one of the key plant groups. These species, which we call “non-harmful macrophytes”, are supposed not to significantly affect the yield or quality of the rice crop. At the same time, they offer significant ecological advantages and can provide ecosystem services that were recently highlighted by Thomaz (2023) and Jiang et al. (2024). Charophytes, which are amongst the most endangered primary producers in aquatic ecosystems (Bellino and Baldantoni, 2023) and have special attention in bioindication in aquatic ecology (Schubert et al., 2018; Pukacz et al., 2024), were also the focus of our investigation as well as the most threatened red-listed species in Hungary (Király, 2007). Our results showed that organic fields bear a higher abundance of plant species from the selected groups described above on average, compared to that of conventional fields (Fig. 4). This concurs with the findings of similar investigations showing the positive impact of organic management on macrophyte vegetation in paddy ecosystems (Martínez-Eixarch et al., 2017; Katayama et al., 2019). Nevertheless, the quantile regression analyses allowed us to gain a deeper insight into the vegetation patterns. This suggested that the mean values of organic farming type were certainly pulled up by the best organic fields, and there were no remarkable differences between low quantiles of organic and conventional fields in terms of species groups of conservation interest. Similar results were obtained by Linke et al. (2014) in Brazil, who found equally impoverished macrophyte vegetation in both conventional and organic rice fields. This was probably because water management and soil tillage operations in organic fields were equally effective at weed control as herbicides were in conventional fields (Linke et al., 2014).

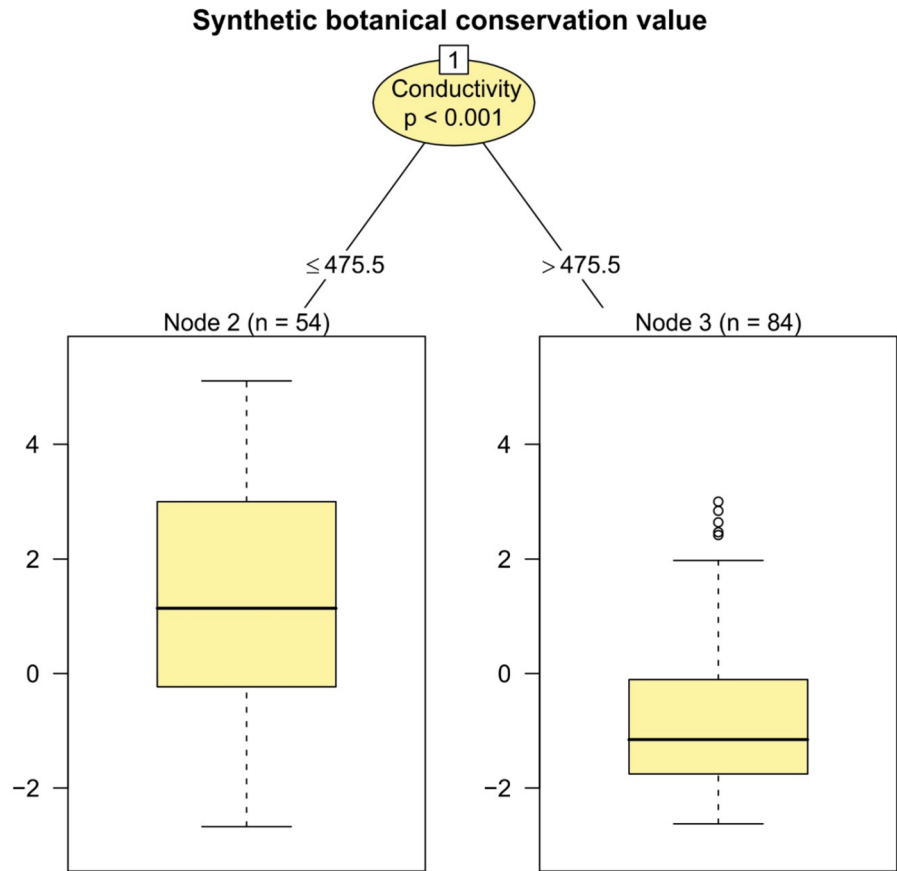
We also attempted to identify the predictors that seemed to override the impact of the farming type and levelled the proportions of species groups of conservation interest in the great amount of conventional and organic fields. Our analyses revealed that primarily the water conductivity could be responsible for this phenomenon, and lower water conductivity

(<475.5 $\mu\text{S cm}^{-1}$) was associated with higher proportions of non-harmful macrophytes and red-listed species (Fig. 5), as well as with higher synthetic botanical conservation values (Fig. 6). The effect of conductivity on the composition of aquatic plant species was also significant in conventional rice fields in Hungary (Pinke et al., 2014). Nonetheless, there are very few studies that would emphasize the key role of conductivity in shaping the weed flora of rice fields. This might indicate that conductivity was just a proxy of other (rarely measured) environmental variables, like, e.g. the nutrient content of the water. Nevertheless, the electric conductivity of water appeared to be highly relevant for aquatic vegetation in plenty of studies in natural water bodies. Amongst others, it was one of the most important drivers for macrophyte species composition in lakes in the Pannon Ecoregion (Lukács et al., 2015), and rivers, streams, ditches, and ponds in other regions of Central Europe (Svitok et al., 2016).

Our findings suggested that under certain circumstances, conductivity can overwhelm the impact of management factors. Nevertheless, conductivity appears to be a variable that does not control the occurrence of species in itself, but it is rather a composite factor that expresses complex, fundamental gradients of water chemistry (Navarro Law et al., 2024; Šolcová et al., 2024). It usually displays a strong correlation with parameters such as temperature, pH, alkalinity, total hardness, total dissolved solids, chemical oxygen demand, chloride, and iron concentration of water (Bhateria and Jain, 2016). The total dissolved solids are the materials dissolved in water, like bicarbonate, sulphate, phosphate, nitrate, calcium, magnesium, sodium, and organic ions, through which conductivity can be an indicator of the nutrient status, eutrophication, and water pollution (Rameshkumar et al., 2019; Wu et al., 2020). Consequently, increased anthropogenic pressure from urbanization failing sewage systems, and agriculture with fertilization runoff can result in an increased conductivity in surface waters (Alahuhta et al., 2013; Gyosheva et al., 2020; Banaś et al., 2023).

We observed a positive correlation between water conductivity and NPK contents of the applied fertility amendments (Table 3) in our research. As high-nutrient inputs tend to decrease weed community diversity (Jiang et al., 2024), the distinct nutrient status of the water in the rice fields is most likely

Fig. 6 Decision tree model of the synthetic botanical conservation value (defined by PCA in Fig. 2) recorded at the investigated rice fields. (Only the first split is shown)



underlying the strong influence of conductivity on the selected plant groups' abundances in our study. This could also explain why there were no significant differences between the organic and conventional management in terms of the synthetic botanical conservation value, in fields with higher conductivity (Fig. 7). In other words, the high-nutrient status could be the major reason why there were hardly any differences between the worst organic and worst conventional fields regarding conservation priority groups (Fig. 4). While N fertilizers were applied in all of the studied conventional fields, approximately 15% of the conventional fields did not receive any P or K fertilizers. Furthermore, about 24% of the organically managed fields received a relatively high amount of organic manure (2500 kg ha^{-1}), plus 14% of them received a supplementary P & K treatment ($\sim 300 \text{ kg ha}^{-1}$), and 90% of these fields were also treated with some foliar amendments containing meso- & microelements in addition (Table 1). Accordingly, some conventional fields may have had relatively low nutrient

status (allowing higher weed diversity), while a large share of the organic fields was probably exposed to high-nutrient concentrations (leading to the elimination of rare aquatic plants). This could be one of the main reasons why both the conventional and organic fields appeared to be so heterogeneous (Figs. 3, 4), and why conventional fields with low conductivity showed higher conservation value than organic fields with high conductivity (Fig. 7). It can be assumed that fields with the highest nutrient status independent of farming type could have the lowest cover and number of conservation priority groups (Fig. 4). Our assumption that organic manure can equally increase conductivity and can be equally harmful for macrophytes as inorganic fertilizers, is also supported by the findings of Cheng et al. (2017), indicating that organic matters increased conductivity to a significantly larger extent than PK and NPK fertilizers in paddy fields in a long-term experiment. This can be explained by the increased concentration of trace elements, micronutrients, and certain cations induced by

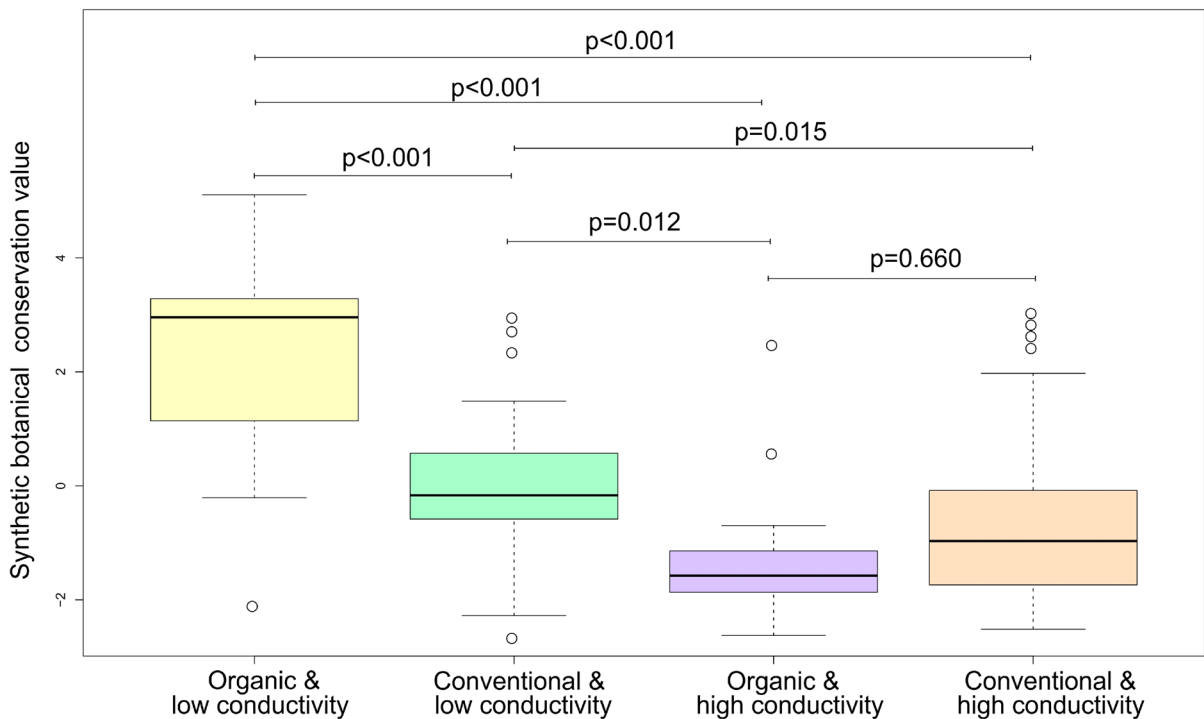


Fig. 7 Synthetic botanical conservation values (defined by PCA in Fig. 2) with the combined effect of farming type and low ($<475.5 \mu\text{S cm}^{-1}$) and high ($>475.5 \mu\text{S cm}^{-1}$) conductivity recorded at the investigated rice fields

Table 3 The association between the applied NPK values and water conductivity using Spearman's rank correlation. (In organic fields, NPK values of organic manures and P & K sup-

plementary nutrients were aggregated. In conventional fields, NPK values of inorganic fertilizers were used)

Nutrients	Organic fields		Conventional fields		All fields	
	rho	P-value	rho	P-value	rho	P-value
N	0.711	<0.0001	0.155	0.0315	0.340	<0.0001
P	0.748	<0.0001	0.606	<0.0001	0.695	<0.0001
K	0.748	<0.0001	0.606	<0.0001	0.715	<0.0001

manure applications relative to the inorganic nutrient treatments (Rayne and Aula, 2020). Tscharnkte et al. (2021) also highlighted that harmful overfertilization could occur not only with mineral fertilizers but also with manure in organic agricultural systems, leading to impoverished accompanying biodiversity.

Our study also indicated that for the group of charophytes, farming type and the previous crop could be more important than conductivity (Fig. 5). Nevertheless, a former study in the conventional Hungarian rice fields suggested that, amongst others, conductivity could also be important for this group of species

(Pinke et al., 2014). Charophytes appeared to be particularly sensitive to conductivity, and their abundance negatively correlated with this variable also in some recent studies investigating natural water bodies in western Poland (Pelechaty et al., 2015), Switzerland (Rey-Boissezon and Auderset Joye, 2015), and northeastern USA (Sleith et al., 2018). This interaction is most likely attributed also to the higher nutrient status, which is generally unfavourable for these species (Rodrigo et al., 2015; Murphy et al., 2018). In high-nutrient waters, charophytes usually disappear or are restricted to the niches, where light is not a

limiting factor (Schubert et al., 2018). Certain plants, which most densely covered extensive surfaces on the water (e.g. *Lemna* species and filamentous algae) were much more abundant in the conventional fields (Table 2), creating potentially adverse, light-poor circumstances for charophytes there, compared to those in organic fields. Accordingly, the farming type, which was indirectly influenced by light availability via nutrient status, was the most important predictor of charophyte cover. Our results also suggested that Indian wild rice (*Zizania aquatica*), as a preceding crop, also created harsh conditions for charophyte number in the subsequent rice (Fig. 5). This is most likely due to that Indian wild rice is usually grown in monoculture in 3-year periods, in the study area; it usually forms much denser and taller crop stands than Asian cultivated rice (*Oryza sativa*), with more limited light availability on the water surface, leading to the depletion of charophyte propagules.

The difference between the conventional and organic systems could also be linked to variations in the composition of aquatic plants related to the adjacent natural wetland areas (Linke et al., 2014; Maltchik et al., 2017). Nevertheless, we did not survey the natural wetlands, as most conventional and organic paddies are located in close proximity to each other, particularly in the southern part of our study area (Fig. 1). These paddies were flooded from the same irrigation canal systems, and even the fields located slightly further afield in the northern part of our study area were flooded from the same river system. Accordingly, we supposed that the conventional and organic paddies in our study are exposed to the same inflow of plant propagules, representing the same regional species pool. Furthermore, recent studies also suggest that distant wetland habitats can also significantly influence the floristic composition of rice fields via long-distance dispersal by migratory birds (Green et al., 2023; Peralta-Sánchez et al., 2023).

Finally, we also have to mention that the studied fields were clustered into relatively few (seven) farm holdings, and the differences between the farms can also explain a considerable share of the variation in our response variables (Fig. S1). This part of the variation may also be caused by unmeasured hidden variables that vary across the farms. However, the within-farm variation is also large, suggesting that this cannot be the dominant effect. Moreover, we also tried to include all relevant variables with possible

causal effects to avoid this effect. Accordingly, even if some part of the variation is related to farm-level hidden variables, this fact does not invalidate our main conclusion: the potential conservation value of organic farms is higher, but this potential is not always realized.

Conclusions

The organically managed rice fields had a distinct weed species composition compared to the conventional fields, most likely due to the lack of herbicides and fertilizers and their divergent rotation system. Although organic fields harboured a higher abundance of non-harmful macrophytes, charophytes, and red-listed species on average, a high proportion of organic and conventional fields hardly differed in the abundance of these groups. However, water conductivity appeared to moderate the impact of farming type on botanical conservation value, most likely as a result of high-nutrient inputs in a considerable part of the organic fields. Accordingly, it can be concluded that nutrient conditions, rather than the farming system per se, drive conservation value. To maintain diverse macrophyte vegetation in organic rice fields, the application of organic manure and supplementary nutrients should be avoided or greatly reduced. This study underscores the need for integrative farming practices that support conservation goals.

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Data availability The data sets are available from: <https://doi.org/10.5281/zenodo.21137795>.

Declarations

Conflict of interest Authors declare that they have no conflict of interest.

Ethical approval and consent to participate This is not applicable.

Consent to publish This is not applicable.

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