Pinke, G, Csiky, J., Mesterházy, A., Tari, L., Pál, R., Botta-Dukát, Z., & Czúcz, B. (2014). The impact of management on weeds and aquatic plant communities in Hungarian rice crops. Weed Research, 54(4), 388–397.

Abstract

This study assessed the cultural and weed-management factors influencing the weed communities of Hungarian rice fields. Hungary is situated at the northern limit of rice production with about 300 years history of rice culture. We surveyed the weed flora and 25 background variables in 100 active rice fields. Using a minimal adequate model containing 11 terms, 48.5 % of the total variation in weed species data could be explained. The net effects of 9 variables on species composition were significant. Crop cover was found to be the most important explanatory variable, which was followed by the herbicides penoxsulam & azimsulfuron, tillage depth, phosphorous & potassium fertilisers, years after last rotation, water depth in May, sowing type, pendimethalin and water conductivity. Filamentous algae, as the most abundant group of weeds, were positively associated with deep tillage, deep water, and surface sowing. *Echinochloa crus-galli*, one of the most troublesome grass-weeds was associated with low rice cover, shallow water and later years after crop rotation, while weedy rice favoured high crop cover, deep water and soil sowing. These findings can be used to design improved weed management strategies. The occurrence of red list species and charophytes in diverse micro-mosaic patterns deserves attention from a conservation perspective as well. The maintenance of these unique charophyte communities can be facilitated by shallow tillage without soil inversion.

Keywords: agroecology, *Oryza sativa*, weed vegetation, water management, tillage, macrophytes, filamentous algae, *Echinochloa*, *Lemna*, charophytes, weedy rice, paddy fields

Introduction

In Hungary the cultivation of rice might have been introduced already by the Turkish invaders in the 17^{th} century (Csapody, 1953), while according to other sources the first rice farms were established by Italian settlers in the 18^{th} century (Ruzsányi, 1992). Rice production was promoted by the socialist agriculture and its growing area increased dramatically, from about 20,000 hectares in 1940s to more than 80,000 hectares in 1950s. At this time rice was not treated with herbicides and these fields harboured a diverse accompanying flora and vegetation (Csapody, 1953; Ubrizsy, 1961). The advent of widespread chemical weed control in Hungarian rice farmlands from 1963 (Szilvássy, 2000) resulted in the decline of wetland weed species during the following decades (Takács *et al.*, 2013). In the 1970s rice was cropped on 20,000-28,000 hectares. Because of socio-economic reasons the harvested area dropped remarkably in the early 1990s, eventually stabilizing near 2,800 hectares during the first decade of the 21^{st} century (Faostat, 2013). Today's intensive rice farming practices typically produce a yield of 3.5-4.5 ton ha^{-1}during the ~120 day growing period (May–Sep) in Hungary.
Despite the recent decline in production tendencies, rice became an important stable and profitable crop in the regions of Hungary most suitable for rice cultivation. Nevertheless, probably due to the loss of the privileged status of a "major crop", there has been no comprehensive study about the weed vegetation of Hungarian rice fields since the 1960s. Nevertheless, information on weed communities and their relationship to major management and environmental factors is indispensable to enhance the effectiveness of weed management strategies in the Hungarian rice fields. Furthermore, these unique fields in Central-Europe provide an excellent opportunity for studying the connections between background variables and weed species composition in one of the most northern location of rice cultivation.

Recent Hungarian studies investigated the effect of weed-management, cultural and environmental factors on shaping the weed vegetation in dry land arable fields (Pinke *et al.*, 2011, 2012). In this study, working with similar methods, we assessed and rank the role of different factors influencing the weed species composition of Hungarian rice fields.

Materials and Methods

Data collection

100 land parcels were surveyed across active rice farmlands in eastern Hungary, in the Great Hungarian Plain, in the vicinity of the following settlements: Szarvas, Mezőtúr, Gyomaendrőd and Csárdaszállás, between Jul 25–30 2012. The parcels were separated by levees. Weed vegetation of the fields was sampled in two randomly located 100 m^2 plots inside the parcels (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 (200 plots in total). Macrophyte plant species were identified at a species level, while filamentous algae of taxonomically diverse origin were categorised into one group. During the survey in each sampling plot we measured water parameters as pH, conductivity, temperature and salt content (with Hanna Combo HI98129 instrument) and water depth (referring to 'water depth in July') as well as altitude (measured by a GPS receiver) (Table 1). The investigated farms are located in the relatively close proximity of one another, within a total range of 41 km (between 46º53′N–46º55′N and 20º31′E–20º58′E), and their irrigation systems share the same watershed. All fields were on heavy clay soils with pH ranging between 6.9-7.9. Mean annual temperature and precipitation in the study area were 10.3 ºC and 525 mm respectively (Dövényi, 2010). As the investigated fields share very similar environmental conditions, we rather focused on the effects of the diverse cultural and weed-management variables.

Crop management information was obtained directly from the farmers. The following active herbicide ingredients were used: penoxsulam (Viper, 20 g a.i. L^{-1}; Dow AgroSciences), azimsulfuron (Gulliver, 500 g a.i. Kg^{-1}; Dupont) and pendimethalin (Stomp 330, 33% a.i.; BASF). Hand weeding was applied only in four fields. Shift crops included wheat (*Triticum aestivum* L.), Indian rice (*Zizania aquatica* L.), lucerne (*Medicago sativa* L.), red clover (*Trifolium pratense* L.) and sunflower (*Helianthus annuus* L.). Shift crop refers here to the crops which directly preceded rice in the rotation. We also recorded the number of years after the last shift in the rotation for each parcel, which was between 1 and 4. Further variables recorded in the farmers' interviews were: the amount of fertilizers applied, date of sowing, seeding rate, time between sowing and flooding of the fields, the name of the cultivar, field size, maximum tillage depth, amount of flood water, and water depth in May and June. Altogether 4 weed-management, 17 cultural and 4 environmental variables were recorded during the survey (Table 1).

Table 1 near here

Preliminary variable selection

To make the data appropriate for a multivariate analysis, multicollinearity was checked by calculating variance inflation factors among the potential predictors (Fox & Monette, 1992). As we experienced high generalized variance inflation factors (GVIF), we had to identify first an effectively uncorrelated subset of predictors with maximum information content. We dropped all variables which were not considered as important for shaping the weed vegetation in rice fields (Bhagat *et al.*, 1996). As the dosage of P and K fertilisers applied by the farmers were highly correlated, we unified these two treatments into a single categorical variable with three levels (no, medium and high). Similarly, as there were strong correlations between penoxsulam, azimsulfuron and N fertiliser, we unified penoxsulam and azimsulfuron in one variable with three levels (penoxsulam, azimsulfuron, neither), and the variable N was dropped. Furthermore, we also turned pendimethalin and tillage into binary variables, since they were applied always in (almost) the same doses / depth. Altogether 11 variables survived this preliminary selection. The GVIF value of the remaining variables decreased below 2.7, which allowed us to treat them as independent.

Analysis

First, we performed a multivariate analysis to determine the relationship between background variables and community composition. For each field, we averaged the cover values of the species across the two plots. Mean cover values were then subjected to a Hellinger transformation (Legendre & Gallagher, 2001) and examined in a redundancy analysis (RDA), together with weed-management, cultural and environmental data (Borcard *et al.*, 2011). According to Legendre and Gallagher (2001), this procedure is able to relate multivariate species data to explanatory variables more accurately than the commonly applied canonical correspondence analysis (CCA), even if the species response curves are unimodal (owing to, e.g. long gradients). The number of explanatory variables was reduced by stepwise backward selection using a $P < 0.05$ threshold for type I error, which removed only two variables ('water depth in June' and 'water depth in July') leading to a minimal adequate model containing 9 terms (Table 2).

As a next step of the multivariate analysis, we assessed gross and net effects of each explanatory variable of the reduced model, according to the methodology of Lososová *et al.* (2004). The gross effect of a variable was defined as the variation explained by a 'univariate' RDA containing the studied predictor as the only explanatory variable. The net effect, on the other hand, was assessed as the significance of a similar partial RDA (pRDA) with the studied predictor still being the only constraining variable, but all the other variables of the reduced model were also involved as conditioning variables ('co-variables'), the effect of which was 'partialled out' (i.e. removed before the actual RDA). In the case of the net effects, model significances were assessed as type I error rates obtained by permutation tests. As the number of RDA axes depends on the degrees of freedom of the predictors, for most of the predictors there was only one constrained axis in the partial RDAs, except for the herbicides and the P& K fertilizers, where there were two. In these two cases both pRDA axes were tested separately (Leps & Smilauer, 2003). Based on the results, a common rank of 'importance' was established among all explanatory variables according to the R^2_{adj}-values of the net effects of the pRDA models. To demonstrate the responses of the weed species to the individual significant weed-management, cultural and environmental factors, in each case, we identified those 10 species (with >9 occurrences) that expressed the highest explained variation by the constrained axis in the partial RDA ("strongly associated" species).

In the RDA ordination diagrams of the reduced model, co-ordinates of continuous variables were calculated from their linear constraints, while categorical variables were transformed to 'dummy' indicator variables and these dummies were placed in the ordination space by weighted averaging.

To study the relationship between rice cover (dependent variable) and cultivar (independent variable), one-way ANOVA and Tukey post hoc tests were used. The conditions of ANOVA were checked graphically and no data transformation was needed.

The entire statistical analysis was performed in the R Environment (R Development Core Team, version 2.11.1) using the Vegan add-on package (vegan 1.17-2).

Results

Along with the filamentous algae, altogether, 39 macrophyte species were recorded. Filamentous algae were both the most dominant and frequent weed (Fig. 1). Macrophytes belonged to 15 families, with *Lemnaceae* (17.5%), *Characeae* (11.7%) and *Poaceae* (8.7%) showing the largest mean cover values. Submerged and floating aquatic plants had a great share in the total weed cover, 17.5% and 15%, respectively.

The full RDA model (comprising 11 explanatory variables) explained 48.5% of the variance, while the reduced model (comprising 9 explanatory variables) still explained 47.4% of the total variation in species data. According to the explained variance in the pRDA models, the most important predictor was rice cover, which was followed by penoxsulam & azimsulfuron, tillage depth, P & K fertiliser, years after last rotation, water depth in May, sowing type, pendimethalin and water conductivity (Table 2). The order of the variables according to their gross effects only slightly differed from this order. The responses (mean positions along the pRDA axis) of the weed species with the highest fit are listed in Table 3 for all predictors having just one constrained axis. In the case of the P & K fertilizers only the first constrained axis was significant. Fields treated with high doses of P & K fertiliser separate along this axis from those receiving medium or zero doses (Fig 2). Species which were sensitive for these fertilizers generally exhibited positive values on the first RDA axis. In the pRDA of the merged herbicide variable for penoxsulam and azimsulfuron both constrained axes were significant at 5% level, but there were no frequent (>9 occurrences) species strongly associated to the plots, where neither azimsulfuron nor penoxsulam was applied (figure not shown), probably due to the low number of such plots. Therefore, we repeated this pRDA analysis excluding these plots, thus reducing this variable to a binary variable of either penoxsulam or azimsulfuron treatment (Table 3).

Table 2, Table 3 near here

Fig 1, Fig 2, Fig 3 near here

In the multivariate RDA ordination of the species data, the first axis can be most related to the explanatory variables water depth in May and rice cover, while the second axis is strongly correlated with herbicide penoxsulam & azimsulfuron, P & K fertiliser, sowing type and years after last rotation (Fig. 3A). Most of the variance among the strongly associated species is concentrated along axis 2, with *Schoenoplectus supinus* (L.) Palla being associated to higher, whereas *Chara braunii* C.C.Gmelin to lower values (Fig. 3B).

There was a significant positive correlation between rice cover and seeding rate ($r=0.358$; $p<0.01\%$) and according to the ANOVA ($F=4.077$; $p<0.01\%$) cultivar significantly influenced rice cover as well. Tukey post hoc tests showed that the cultivar M-60 had significantly greater cover than the cultivars Fruzsina, M-225, while the difference between other cultivar pairs is not significant.

Discussion

Like in many aquatic plant communities (Borhidi *et al*. 2012) the studied rice weed vegetation was relatively poor in species, but was composed of plants of phylogenetically diverse origin and a great proportion of plant cover was attributed to floating and submerged growth types. Even though our work was based on a broad-scale survey, and not a field trial or controlled experiment, several of the studied management variables turned out to be significant determinants of weed community composition. The abundance of the most noxious species could be explained by crop management variables which can provide useful hints for future experimental studies and eventually inspire improved weed control strategies.

Cultural variables

In our study, rice cover was found to be the most important factor in shaping the weed vegetation. *Lemna aequinoctialis* Welw seems to be most tolerant for the shading effect of the crop canopy (Table 3). The shade tolerance of *Lemna* species is well known from natural water bodies as well. Because of their free floating nature, they cannot tolerate strong waves or currents, so they prefer the protective stands of other plant species (Borhidi *et al.*, 2012). This species was most abundant in the small gaps of the densest crop stands, similar to its presence in small gaps of natural reed beds (Borhidi *et al.*, 2012). On the contrary, *Chara vulgaris* L. was associated to places with a less developed crop canopy (Table 3), which seems to be in accordance with the known high light demand of many macrophytes (Bornette & Puijalon, 2011).

In our study both cultivar and seeding rate were strongly correlated with rice cover which is in accordance with other studies revealing that weed suppressive ability can be enhanced by growing weed-competitive cultivars (Toure *et al.*, 2011) or by using higher seeding rates (Chauhan *et al.*, 2011). In our survey the variety 'M-60', a Japonica-type variety of tall stature, large foliage and good tillering ability, had the highest crop cover.

Despite the relatively small difference between shallow and deep tillage (15 and 20 cm) its effect proved to be also significant, which can also be attributed to the fact that a shallow tillage was generally created with a disk-harrower or a cultivator, while deeper tillage was always performed by a plough. Harrowing and cultivating generally results only in mixing and loosening the topsoil, while ploughing is associating with soil inversion as well. Filamentous algae responded more strongly to deeper tillage, while the members of submerged stonewort communities (the species of *Chara*, *Nitella* and *Najas* genus) were associated with shallower tillage (Table 3). It is known that the vertical distribution of propagules in the soil can be influenced by tillage depth, which in turn, affects weed seedling emergence patterns (Chauhan & Johnson, 2009). Small oospores of charophytes (*Chara*, *Nitella*) tend to be unable to emerge from great depths (Bonis & Grillas, 2002), so their emergence could be hindered if their oospores are buried deeper into the soil. In order to save energy and to avoid harming the farm machinery in the extremely heavy clay soils, cultivation without ploughing is more popular among Hungarian rice farmers, which can generate favourable conditions for charophytes. The positive response of filamentous algae for deep tillage might potentially be explained with nutrients (e.g. plant residues) brought up from the inverted soil layers promoting algal blooms and setting back charophytes, which are highly P-sensitive (Borhidi *et al.*, 2012) at the same time. Filamentous algal mats and stonewort communities thus appeared to be antagonistic vegetation types in our study, which compete for dominance over the submerged vegetation zone, with tillage depth and soil nutrient status being the key factor determining the outcome of this competition.

In our study phosphorus and potassium fertilizers showed also significant effects on the weed species composition. *Persicaria lapathifolia* (L.) S. F. Gray and *Typha angustifolia* L. were associated with high amounts of fertilisers while *Nitella tenuissima* (Desv.) Kütz., *C. braunii*, *C. vulgaris* and *Najas gracillima* (A. Braun ex Engelm.) Magnus associated with lower (medium or zero) doses (Fig 2). Although our investigation did not reveal a direct correlation between filamentous algae and fertilization, it is a well known fact that higher phosphorous concentration can promote algal growth (Lundy *et al.*, 2012), while stonewort communities are very susceptible to increased P levels (Borhidi *et al.*, 2012). When the phosphorous concentration increases in shallow lakes, competition for light between phytoplankton and macrophytes leads to macrophyte limitation and even disappearance (Bornette & Puijalon, 2011). According to Lambert & Davy (2011) elevated nitrate concentration is also detrimental for charophytes, and Moss *et al.* (2013) showed that increased N loading is also associated with the loss of macrophyte communities. Other studies suggest that P is the nutrient with the greatest impact on the higher plant weed community structure of paddy fields (Huang *et al.*, 2013) and PK together influence most the species richness and diversity of the paddies (Wan *et al.*, 2012).

Our study showed that the most dominant weeds in Hungarian paddies are filamentous algae, forming dense stands at many places. At the beginning of rice growing season the light conditions in the paddies are favourable and if nutrients are also abundant, the developing algal mats can severely overwhelm the rice stands. Although cyanobacteria among filamentous algae could be regarded as a potential source of N for the flooded rice, dense algal mats can heavily reduce rice yield. Due to their N_2-fixing capacity they are broadly described as P-limited, and the application of either copper sulphate or herbicide mixes has only been minimally effective (Spencer *et al.*, 2009; Lundy *et al.*, 2012). The failure of these control methods was experienced also by Hungarian farmers. The persistence of algal mats during the progress of the vegetation season is depending also on unpredictable weather conditions, as usually only heavy showers are able to rout the algal carpet ultimately.

We found that water depth in May was also an important variable. This is in accordance with the observation of other researchers, namely water depth significantly affects weed species composition and densities (Caton *et al.*, 1999). We measured water depth also later in the vegetation season, but even though water levels in June and July exhibited a higher gradient length, only May levels turned to be significant. This suggests that water level could be most critical in the germination phase of the weeds. Setting up appropriate water levels was in fact the only effective strategy to combat *E. crus-galli* in the Hungarian rice cultures before the era of herbicides (Szilvássy, 2000), and this method is still in use in Hungary and other rice growing countries (Chauhan & Johnson, 2011). Our results support that *E. crus-galli* is associated with lower water depth, while weedy rice can tolerate higher values (Table 3), which is obviously due to the different ecological requirements of the obligate wetland species (helophyte) rice and the facultative wetland species (hygrophyte-mesophyte) *E. crus-galli* (Ubrizsy, 1961).

The variable 'sowing type' which describes whether rice was sown directly on the surface or 3-5 cm deep in the soil was also found significant in our study. The different reaction of weed seeds to the disturbance caused by the soil sowing operation might be a potential explanation to this relationship. Nevertheless, the fact that sowing type turned out to be a significant factor could also be attributed to a link between sowing type and water management in current Hungarian rice management practices. This relationship was captured in our data as a strong correlation between the variables 'sowing type' and 'time between sowing and flooding', which resulted in the omission of this second variable from our analysis. The time elapsed between sowing and flooding was generally 1-5 days for surface-sowing, while 12-15 days in the case of soil-sowing. This can lead to a second potential explanation for the significance of sowing type in determining the weed composition of the rice paddies. According to Bhagat et al. (1996) the delay in flooding generally encourages weed emergence, as most of the hygrophyte and mesophyte weeds cannot germinate under water. On the other hand the emergence of the helophyte weedy rice is not hindered by an early flooding, which seems to offer an explanation for the strong preference of weedy rice for surface sowing in our results (Table 3).

The number of years after the last shift in the rotation, which indicates how long rice has been being grown continuously in the same fields, proved also to be relevant. It is not possible to grow rice in endless monoculture under Hungarian circumstances, the maximum number of subsequent years of rice crop in the same field is 3-5 years. After that time a shift crop should be inserted into the rotation, partly due to the build-up of certain aquatic and marsh weeds (Csapody, 1953; Ruzsányi, 1992). In Table 3 we can see that weed species of a dryland character (e.g. *P. lapathifolia* and *Polygonum aviculare* L.) were mostly restricted to the first years after rotation, whereas aquatic weeds (e.g. *Lemna minor* L., *C. braunii*, or *E. crus-galli*) were more abundant in the later years.

Herbicides

The effects of the herbicides applied have proven to be significant as well. All of the three active ingredients are primarily targeted against *E. crus-galli*, because similarly to several other countries (e.g. Beltran *et al.*, 2012; Osca, 2013), this species is regarded as the most important yield-limiting factor in Hungarian rice farmlands. Penoxsulam is also considered effective against perennial species in the *Bolboschoenus* genera, while azimsulfuron has a wide-spectrum impact on broad-leaved weeds as well. In our study many aquatic plants appeared to be sensitive to pendimethalin, except for *L. minor*. Filamentous algae and weedy rice were most abundant in the fields treated with azimsulfuron; while penoxsulam treated plots seem to be affected most high cover values of *L. aequinoctialis* and *E. crus-galli* (Table 3). Azimsulfuron was found to be significantly effective against *E. crus-galli* in Italian rice-field experiments (Vidotto *et al.*, 2007), furthermore penoxsulam and pendimethalin are efficiently used against rice weeds in Asiatic countries as well (Jabran *et al.*, 2012).

Water conductivity

We measured several correlated water parameters in our study from which we only included conductivity into the analysis, as according to the findings of other researchers conductivity was one of the most important factors influencing the species composition of aquatic plant communities (Capers *et al.*, 2010). Water conductivity was also found to be an important variable in our study. Conductivity values are influenced both by ecological conditions and anthropogenic pollutants, as this variable is usually highly correlated with water alkalinity and both are related to ionic concentrations (Heegaard *et al.*, 2001). So water conductivity in rice fields could be greatly affected also by the applied fertilisers and its significance to species occurrences would require further water chemistry studies with more precise analytical sampling of chemical water properties.

Conservation aspects

Before the intensification of rice production flooded paddy fields provided a great diversity of wetland species (Ubrizsy, 1961). Our study indicates that these habitats might have a relatively high conservation value even today. During our survey the occurrences of four Hungarian red list species were recorded, they are: *Elatine triandra* Schkuhr, *E. hungarica* Moesz, *Najas minor* All. and *Alisma gramineum* Lej. (Király, 2007).).The occurrence of charophytes, which sometimes formed very dense grass-like submerged vegetation types, is also notable from a conservation perspective. In terrestrial communities, recurrent soil disturbances reduce the competitive fitness of perennials and create favourable conditions for pioneer plant communities (Dierschke, 1994). Stonewort communities, which usually exist in extended monodominant associations in shallow natural water bodies in Hungary (Borhidi *et al.*, 2012), are also only viable among pioneer aquatic conditions and usually decline as the process of succession continues (Moor, 1986). In the surveyed rice fields these communities were thriving in varying micro-mosaic patterns forming a unique charophyte diversity hotspot. Our results suggest that the existence of these aquatic communities is sustained by shallow tillage without inverting the soil layers. Organic farming techniques, which have recently started to infiltrate rice growing in Hungary, might improve the future persistence of these vegetation types in this region. It is worth mentioning that there are great efforts to restore macrophyte vegetation (involving charophytes) in European lakes because of its high biodiversity value and its great role in ecosystem stability (Bakker *et al.*, 2013). Future research addressing the effects of organic versus conventional rice farming on macrophyte vegetation could identify practices that would be most beneficial from conservation perspectives. The conservation importance of waterlogged arable land, including paddy fields in Central-Europe was also highlighted by Lukács *et al.* (2013), while in Japan Yamada *et al.* (2011) emphasised the importance for maintaining floristic diversity in paddies.

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Table 1 Units and ranges of continuous variables and values of categorical and binary variables

Variable (unit)	Range / Values
Weed-management	
Herbicides (g ha^{-1})	
Penoxsulam	0; 40 [3, 4]
Azimsulfuron	0; 18; 20 [3, 4]
Herbicides (L ha^{-1})	
Pendimethalin	0; 1.65 [3]
Hand weeding (times) [1]	0; 1
Cultural	
Cultivar [2]	Ábel, Byoriza, Fruzsina, Janka, Selenio, M-60, M-225, M-488
Shift crop [1]	Wheat, Indian rice, lucerne, red clover, sunflower
Years after last rotation	1-4
Amount of fertilizer (kg ha^{-1})	
N [1]	0; 58; 72; 76; 81
P_2O_5	0; 30; 52 [5]
K_2O	0; 16; 60 [5]
Date of sowing [1]	3-10 May 2012
Sowing type [1]	Surface, soil
Time between sowing and flooding of the fields (days) [1]	1-15
Seeding rate (kg ha^{-1}) [2]	180-225
Tillage depth (cm)	15 (shallow); 20 (deep) [3]
Field size (ha) [1]	3.6-8.6
Crop cover (%)	25-100
Amount of flood water (m^3 ha^{-1}) [1]	8000-10000
Water depth (cm)	
May	3-5
June	10-16
July	7-36
Environmental	
Altitude (m) [1]	84-95
Water parameters	
pH [1]	7.1-9.4
Temperature (°C) [1]	20.3-30.8
Salt content (ppm) [1]	149-632
Conductivity (µS cm^{-1})	300-1266

[1] variables not included into the analysis due to multicollinearity
[2] variables not included into the RDA analysis but their effect to crop cover was tested by ANOVA
[3] variables treated as binary variables
[4] variables combined under the name "herbicides"
[5] variables combined under the name "P & K fertilizers"

Table 2 Gross and net effects of the explanatory variables on the weed species composition identified using pRDA analyses with single explanatory variables

		Gross effect		Net effect			
Factors	d.f.	Explained variation (%)	R^2_{adj}	Explained variation (%)	R^2_{adj}	F	p-value
Rice cover	1	13.3	0.123	5.731	0.0476	9.5814	0.005
Penoxsulam & azimsulfuron	2	11.21	0.0915	5.299	0.0331	4.429	0.005
Tillage depth	1	5.148	0.0406	3.789	0.028	6.3345	0.005
P & K fertiliser	2	11.54	0.0948	4.131	0.0211	3.4525	0.01
Years after last rotation	1	5.706	0.0462	2.58	0.0158	4.3128	0.005
Water depth in May	1	8.23	0.0718	2.51	0.015	4.1961	0.005
Sowing type	1	3.426	0.0232	1.822	0.0081	3.0459	0.005
Pendimethalin	1	2.092	0.0097	1.567	0.0055	2.6196	0.015
Water conductivity	1	3.971	0.0287	1.464	0.0045	2.4477	0.0225

Table 3 Names, fit and score values of the ten species giving the highest fit along the first constrained axis in the partial- RDA models of the significant variables specified in Table 2

	Ax 1 score	Fit		Ax 1 score	Fit
Rice cover (+ high – low)			Herbicide (+ penoxsulam – azimsulfuron)		
Lemna aequinoctialis	0.501	0.192	*Lemna aequinoctialis*	0.256	0.049
Oryza sativa (weedy rice)	0.097	0.053	*Echinochloa crus-galli*	0.137	0.030
Nitella tenuissima	0.071	0.032	*Elatine triandra*	0.098	0.035
Persicaria lapathifolia	-0.011	0.015	*Chara fragilis*	0.056	0.077
Butomus umbellatus	-0.017	0.048	*Schoenoplectus supinus*	0.024	0.048
Typha angustifolia	-0.025	0.020	*Polygonum aviculare*	-0.014	0.097
Najas gracillima	-0.049	0.015	*Bidens frondosa*	-0.020	0.093
Bolboschoenus glaucus	-0.126	0.055	*Persicaria lapathifolia*	-0.032	0.113
Echinochloa crus-galli	-0.133	0.029	*Oryza sativa* (weedy rice)	-0.191	0.201
Chara vulgaris	-0.176	0.038	Filamentous algae	-0.251	0.061
Tillage depth (+ deep – shallow)			Water depth in May (+ high – low)		
Filamentous algae	0.251	0.060	Filamentous algae	0.252	0.061
Cyperus difformis	0.121	0.074	*Nitella tenuissima*	0.075	0.035
Typha angustifolia	0.027	0.023	*Oryza sativa* (weedy rice)	0.059	0.020
Persicaria lapathifolia	0.023	0.062	*Chara fragilis*	0.032	0.025
Typha latifolia	0.019	0.023	*Lindernia procumbens*	-0.046	0.107
Schoenoplectus mucronatus	0.017	0.054	*Najas gracillima*	-0.054	0.018
Nitella tenuissima	-0.097	0.060	*Najas minor*	-0.074	0.031
Chara braunii	-0.128	0.0751	*Elatine triandra*	-0.106	0.034
Najas gracillima	-0.181	0.2043	*Echinochloa crus-galli*	-0.126	0.025
Chara vulgaris	-0.288	0.101	*Lemna minor*	-0.186	0.103
Years after last rotation (+ high – low)			Sowing type (+ surface – soil)		
Chara braunii	0.193	0.169	Filamentous algae	0.165	0.026
Echinochloa crus-galli	0.165	0.044	*Oryza sativa* (weedy rice)	0.125	0.088
Lemna minor	0.158	0.074	*Nitella tenuissima*	0.074	0.034
Elatine triandra	0.151	0.069	*Chara fragilis*	0.041	0.043
Nitella tenuissima	0.069	0.030	*Utricularia australis*	0.027	0.036
Lindernia procumbens	0.040	0.082	*Bidens frondosa*	0.017	0.066
Polygonum aviculare	-0.012	0.077	*Najas gracillima*	-0.063	0.025
Schoenoplectus mucronatus	-0.014	0.037	*Najas minor*	-0.067	0.025
Typha latifolia	-0.027	0.045	*Elatine triandra*	-0.090	0.024
Persicaria lapathifolia	-0.035	0.139	*Chara vulgaris*	-0.139	0.023
Herbicide pendimethalin (+ yes – no)			Water conductivity (+ high – low)		
Lemna minor	0.142	0.06	*Nitella tenuissima*	0.194	0.239
Alisma lanceolata	-0.009	0.037	*Chara braunii*	0.125	0.071
Butomus umbellatus	-0.012	0.025	*Echinochloa crus-galli*	0.116	0.022
Utricularia australis	-0.026	0.033	*Utricularia australis*	0.070	0.239
Schoenoplectus supinus	-0.032	0.068	*Cyperus difformis*	0.031	0.005
Chara fragilis	-0.034	0.028	*Polygonum aviculare*	-0.003	0.006
Typha angustifolia	-0.051	0.084	*Butomus umbellatus*	-0.006	0.007
Najas minor	-0.086	0.042	Filamentous algae	-0.057	0.003
Nitella tenuissima	-0.105	0.069	*Elatine triandra*	-0.06	0.010
Chara vulgaris	-0.152	0.028	*Lemna minor*	-0.087	0.022

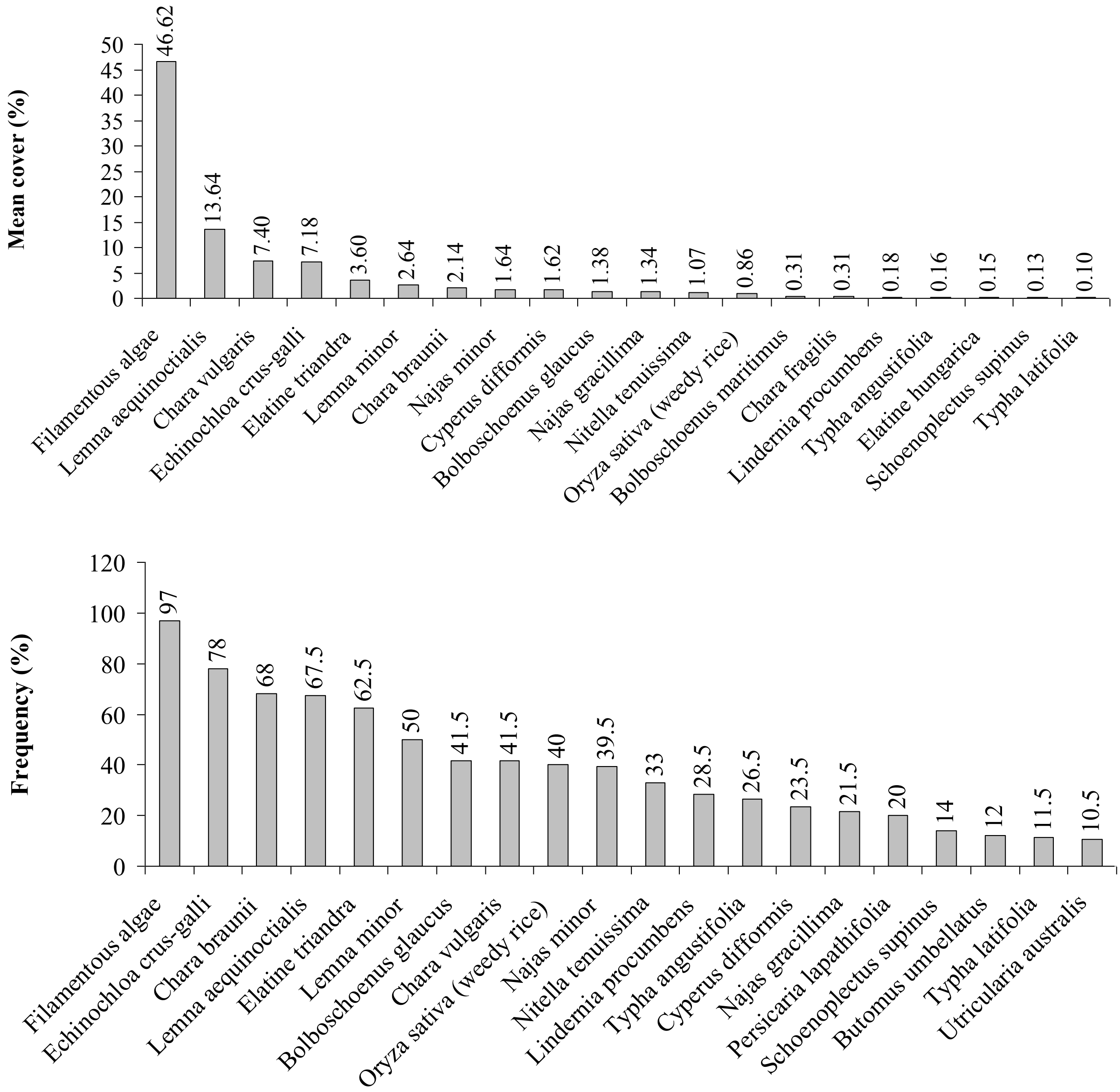

Fig. 1 The mean cover values (% of the surface covered) and the frequency of occurrence (% of the fields surveyed) of the twenty most dominant/frequent weed species

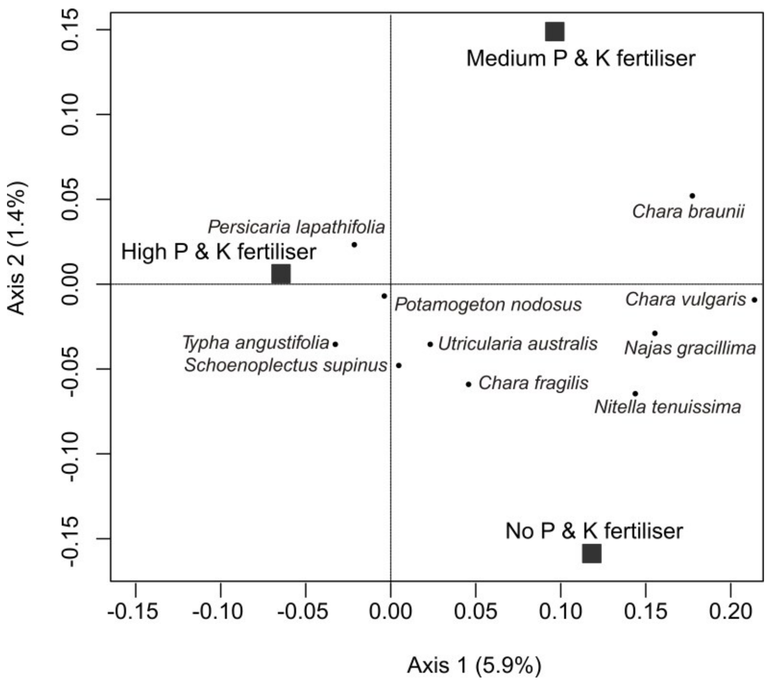

Fig. 2 Ordination diagram of the partial RDA model containing the explanatory variable P & K (phosphorous and potassium) fertiliser. The 10 species with the highest weight on the first two RDA axes are presented. Note that only the first axis is significant at 5% level.

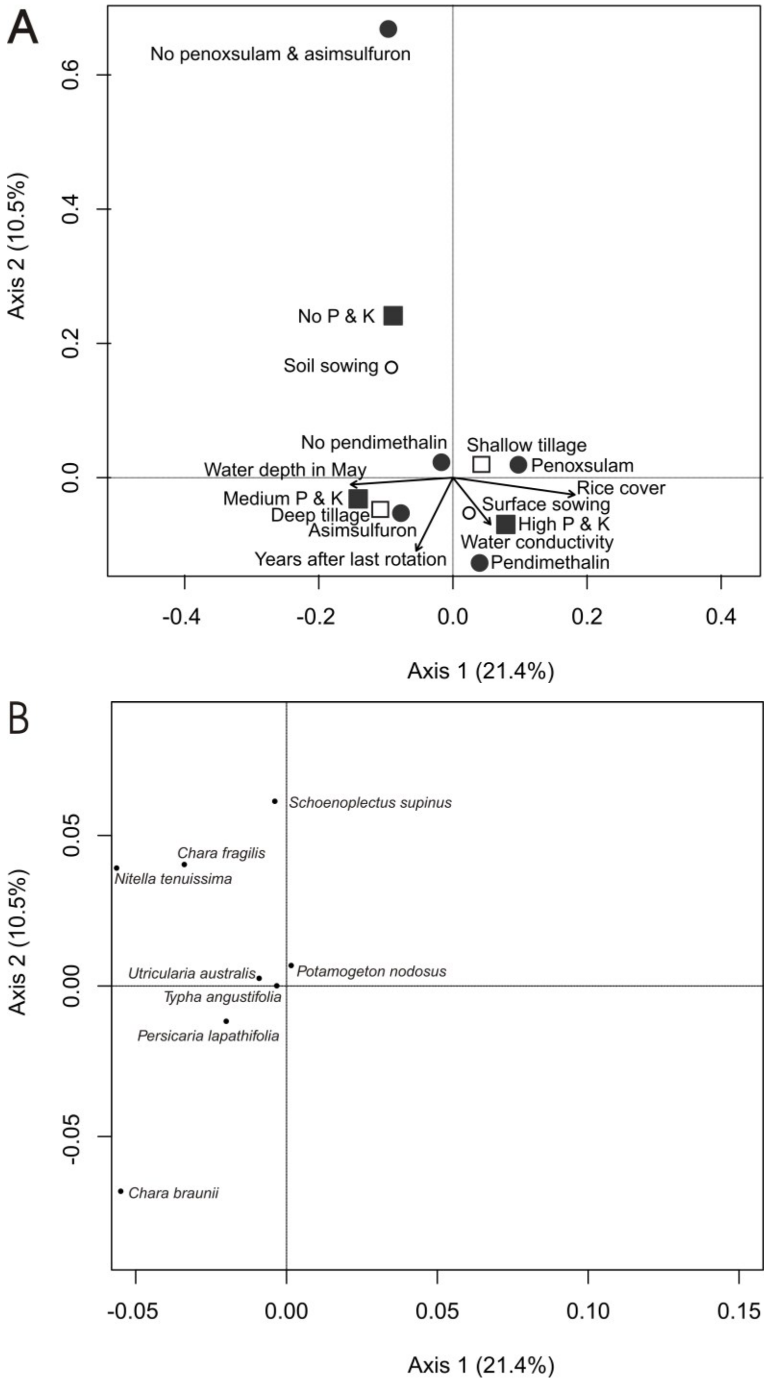

Fig. 3 Ordination diagrams of the reduced RDA model containing the 9 significant explanatory variables for (A) the variables and (B) the species. Only the species with the highest weight on the first two RDA axes are presented. Empty circle = sowing type; filled circle = herbicide; empty square = tillage depth; filled square = P & K fertiliser.