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ORIGINAL RESEARCH PAPER

Weed vegetation of arable land in Slovakia: diversity and species composition

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* Corresponding author. Email: jana.majekova@savba.sk**Abstract**

Arable fields are among the most widespread habitats in Slovakia, but recently, there have been no studies regarding species composition and structure of weed vegetation in these fields. Therefore, we studied the structure of arable weed vegetation and detected α - and β -diversity. The dataset of 507 phytosociological relevés in different crop types contains 407 plant taxa in 46 plant families. Native plants dominated over aliens, archaeophytes dominated over neophytes, and 14 plants belonged to invasive taxa. The most common species in the dataset were *Tripleurospermum perforatum*, *Cirsium arvense*, and *Viola arvensis*. Weeds were mostly therophytes, b- and a-euhemerobic, competitors, and ruderals, reproducing by seeds and pollinated by insects. The β -diversity of weed vegetation decreased with elevation and temperature and was higher in the Pannonicum than the Carpathicum region. The highest β -diversity was established in fodder+fallow fields, followed by that in cereals and root-crop fields, and the smallest diversity was found in stubble. Beta-diversity increased from spring to summer and slightly decreased again in fall. Detrended correspondence analysis indicated that the major compositional turnover of weed vegetation was related to light, temperature, moisture, and elevation. Weed vegetation constitutes an important habitat in the landscape that provides refuge to many threatened plants, and this vegetation has important functions in the agro-ecosystem food chain.

Keywords

alien taxa; alpha diversity; beta diversity; Central Europe; threatened plants; segetal vegetation

Introduction

Arable weed vegetation, also known as segetal vegetation, is a complex system that has developed over millennia from the time when man first began to cultivate crops in agricultural fields. Segetal vegetation originated in the Neolithic period, more than 5,000 years ago, so this type of vegetation is closely related to human activity. Humans caused the formation of weed vegetation and participated in its expansion and distribution [1]. Human impact is still very significant across many agricultural techniques: intensive soil cultivation, seed cleaning, and herbicide and fertilizer applications. But vegetation of arable fields is affected not only by man but also by many environmental factors. Vegetation cover is remarkably dynamic, with its composition and beta diversity changing with climate, elevation, seasonality, and soil type [2].

Weed vegetation is rich in different plant groups [3] and is composed of native and non-native plants [4]. Agriculture in Europe expanded from the south to the north; with cereal crops (e.g., wheat, rye, and barley) from Asia reaching new areas by migration, and accompanied by weed admixtures. Archaeophytes came to Europe before the fifteenth century [5]. Many thermophilous archaeophytes common in their original range became specialized in Central Europe and still remain fairly rare [1,2,6]. Many of them are included in the red lists of European countries [7–9]. Neophytes with mostly American

origin were then introduced after 1500, and these are also commonly distributed in arable fields [5]. This biotope therefore represents a meeting point of highly specialized plants together with species with wide ecological amplitude [6]. Weed vegetation is highly dynamic because of species' ability to respond to different disturbances [10]. Species are altered during the vegetation season, but also, continual change occurs throughout the years. Some species decrease or become extinct while others increase, and new species have been introduced anthropogenically [2,4,11–13].

Fields are a valuable element in the country. On the one hand, they increase plant diversity of the area, and on the other hand, they are also important to fauna diversity. Many insect-pollinators are linked specifically to weed species. Weed seeds are also an important food source for farmland birds, and indirectly provide food through their associated insects. Many birds feed on seeds and green plant parts of weeds and also on cereal seeds [7,14–16]. Fields also provide a niche for rodents, mollusks, and other vertebrates or invertebrates. Arable fields are one of the most widespread habitats in Central Europe [10]. In Slovakia, almost half of the total land area is used agriculturally and is mainly concentrated in the warm southern areas [17]. The area of the Slovak Republic is highly diverse and comprises different geographical and climatic regions, and various geological bedrock and soil types; elevations vary from lowlands in the south to mountains in the central and northern region. This also diversifies arable weed vegetation which widely varies in different areas of the country [18]. Lowlands are typical with intensively managed broad-scale fields; conversely hilly regions are typical with small extensively managed fields. Although several authors have focused on weed flora and vegetation and classified Slovak arable plant communities [18–20], there is still insufficient research regarding weed vegetation structure and β -diversity in Slovakia, although these have been broadly studied in other European countries [4,10,21–26].

Therefore, the aims of our study were: (i) analyzing species composition and α - and β -diversity in weed vegetation in Slovak arable fields, (ii) comparing selected species traits (life forms, reproduction, ecological strategy, pollination, hemeroby, floristic region) in different crop fields, and (iii) analyzing the main environmental gradients in species composition of weed vegetation.

Material and methods

The dataset

Field sampling was undertaken throughout Slovakia from April to November in 2002–2008 (Fig. 1). A total of 507 phytosociological relevés were recorded according to the Zürich-Montpellier school [27,28] using the 9-degree scale of abundance and dominance: r (very few individuals), + (few individuals), 1 (abundant; cover <5%), 2m

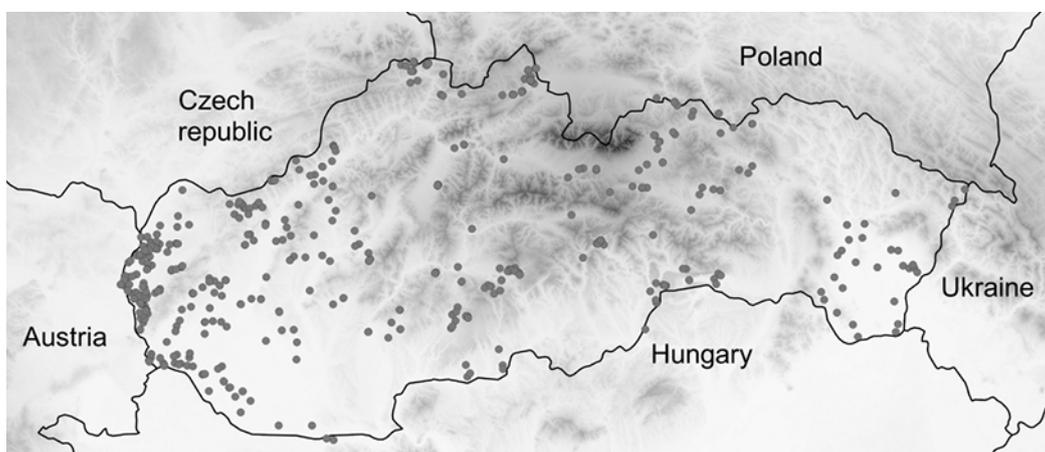


Fig. 1 Location of the weed vegetation relevé plots in Slovakia.

(very abundant; cover <5%), 2a (cover 5–12.5%), 2b (cover 12.5–25%), 3 (25–50%), 4 (50–75%), 5 (75–100%) [29]. Plot size was mainly 10 × 10 m in broad-scale fields and 5 × 10 m in fine-scale private fields. Relevés were made only on those fields where weed cover was at least 25%, and the vegetation type was of the *Stellarietea mediae* class [19]. Each plot was sampled only once in the weed vegetation optimum. Relevés were sampled in arable land in different crop types and at different elevations.

Biological and ecological species traits

For the comparison of the weed vegetation diversity in different crops, we analyzed the selected biological and ecological species traits taken mostly from the BiolFlor database [30]. The following attributes were compiled for each species:

- The reproduction types were listed in five categories: reproduction by seeds, mostly by seeds and rarely vegetatively, by seeds and vegetatively, mostly vegetatively and rarely by seeds, and vegetatively.
- The strategy types were listed in seven categories: competitors, competitors/ruderals, competitors/stress-tolerators, competitors/stress-tolerators/ruderals, ruderals, stress-tolerators, and stress-tolerators/ruderals.
- Pollen vectors were divided into three categories: by wind, selfing with pseudocleistogamy, cleistogamy and geitonogamy, and by insects.
- Hemeroby was listed in six categories: ahemerobic, oligohemerobic, mesohemerobic, b-euhemerobic, a-euhemerobic, and polyhemerobic.
- Floristic regions were divided into six categories: circumpolar, Europe, Asia, Africa, America, Australia.
- Life forms as determined by Dostál and Červenka [31] use the Raunkiaer classification: therophyte, hemicryptophyte, chamaephyte, geophyte, hydrophyte, and phanerophyte, including both nano- and macrophanerophytes.

When a taxon exhibits more than one category of species traits, the taxon is considered representative of each of these categories. Plant taxa nomenclature follows Marhold [32], IUCN threat categories follow Eliáš et al. [33], and the taxa origin and invasiveness are according to Medvecká et al. [34].

Vegetation traits

We studied β -diversity of weed vegetation along five major gradients:

- Crop type was divided into four groups according to the following agricultural practice: cereals, including wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), rye (*Secale cereale*), oats (*Avena fatua*), triticale (\times *Triticosecale rimpaui*), rape (*Brassica napus*) and mixed crops. Root-crops (row-crops), including potatoes (*Solanum tuberosum*), maize (*Zea mays*), sunflowers (*Helianthus annuus*), beets (*Beta vulgaris*), and vegetables. Field stubble was assessed after cereal harvesting, and finally, the fodder crops (lucerne – *Medicago sativa* and clover – *Trifolium pratense*) were merged with fallow in recently abandoned fields because they had received only minor agricultural management for several years.
- Season classifications corresponded to the relevé date, and this was divided into three groups: before the end of May, the period from June to July, and from the beginning of August.
- Elevation was also divided into the three vegetation belts [35]: lowlands up to 200 m a.s.l, the colline belt from 201 to 500 m, and submontane, above 501 m.
- Climatic regions were divided into three groups; warm, moderately warm, and moderately cool [36].
- Phytogeographical regions of the studied plots were too fine-scaled and required generalization into two regions: Pannonicum and Carpathicum (including Carpathicum occidentale and C. orientale; cf. [37]).

Data analyses

Before analyses, bryophytes, cultivated crops, and taxa determined only at the genus level were excluded from relevés. The main species composition gradients were analyzed by detrended correspondence analysis (DCA, with a gradient length of 5.448, square-root transformation, and no down-weighting of rare species) using the CANOCO 4.5 program [38]. For ecological interpretation of the ordination axes, the average unweighted Czech indicator values (CIV for light, temperature, moisture, nutrients, and soil reaction) [39] for the relevés, elevation, and Shannon–Wiener’s index of diversity [40] were plotted onto the DCA ordination diagram as supplementary environmental data. Spearman correlation coefficients were calculated between CIV, elevation, Shannon–Wiener index, and the first two DCA ordination axes. After multiple correlations, Bonferroni correction was applied to control the familywise error by setting critical values of α as 0.0056 (0.05/9 variables). The ecological indicator values and the diversity index for four delimited crop types were then compared on Box–Whisker plots. Significant differences were tested by one-way ANOVA and subsequent Tukey HSD post hoc test ($p < 0.01$) using STATISTICA software. Only indicator values with significant differences were plotted.

To access β -diversity, the dataset was partitioned along five gradients for crop type, season, elevation, and the climatic and phytogeographical regions. The β -diversity for each gradient was calculated by mean Sørensen dissimilarity with 500 bootstrap samples taken from relevés in each partition [21] using the JUICE 7.0 program [41], and the results were presented as Box–Whisker plots. Significant differences were tested by one-way ANOVA and subsequent Tukey HSD post hoc test ($p < 0.01$) using STATISTICA software.

Results

Alpha diversity and species composition

The dataset of 507 phytosociological relevés from different crop types consisted of 407 plant taxa; 25 of these were bryophytes, and 35 taxa were determined only to the genus level. Of the 19 crop plants, 13 were “volunteers” (self-set plants from the previous year’s crop that are considered weeds in the current crop): *Avena sativa*, *Brassica napus*, *B. oleracea*, *Cucurbita pepo*, *Helianthus annuus*, *Hordeum vulgare*, *Medicago sativa*, *Pisum sativum*, *Secale cereale*, *Solanum tuberosum*, *Trifolium pratense*, *Triticum aestivum*, and *Vicia sativa*.

In the analyzed dataset, dicotyledons (85%) prevailed over monocotyledons (15%). Therophytes (50%) were the most represented life form, followed by hemicryptophytes (39%); other life forms were poorly represented (Fig. 2A). The most frequent reproduction type (Fig. 2B) was by seeds (66%), followed by the combined type – by seeds and vegetatively (24%). Species were mostly competitors and ruderals (Fig. 2C) and pollinated by insects (47%) and selfing (44%; Fig. 2D). Hemerobic species were quite frequently encountered (Fig. 2E), where b-euhemerobics comprised 27%, a-euhemerobics 26%, and mesohemerobics 22% of total species; a-euhemerobics are typical species in arable fields. European (47%) and Asiatic species (36%) prevailed in our dataset (Fig. 2F). These figures were very similar in all studied crops.

Identified species were from 46 plant families, with the most abundant being Poaceae (46%), Asteraceae (37%), Fabaceae (25%), Caryophyllaceae (22), and Scrophulariaceae (22%). The Poaceae family was the most abundant in the categories of cereals and fodder+fallow fields, whereas Asteraceae species were most abundant in root-crops and stubble fields.

Determination of the origin of recorded species established that natives representing 53% of recorded species prevailed over the 43% alien species, and the remaining 4% were species of uncertain origin (Tab. 1). Archaeophytes (33%) were much more abundant than neophytes (10%), and naturalized species were the most frequent aliens (Fig. 3). Invasive species consisted mainly of neophytes, with 11 species; *Amaranthus retroflexus*, *Ambrosia artemisiifolia*, *Aster lanceolatus*, *Bidens frondosa*, *Conyza canadensis*,

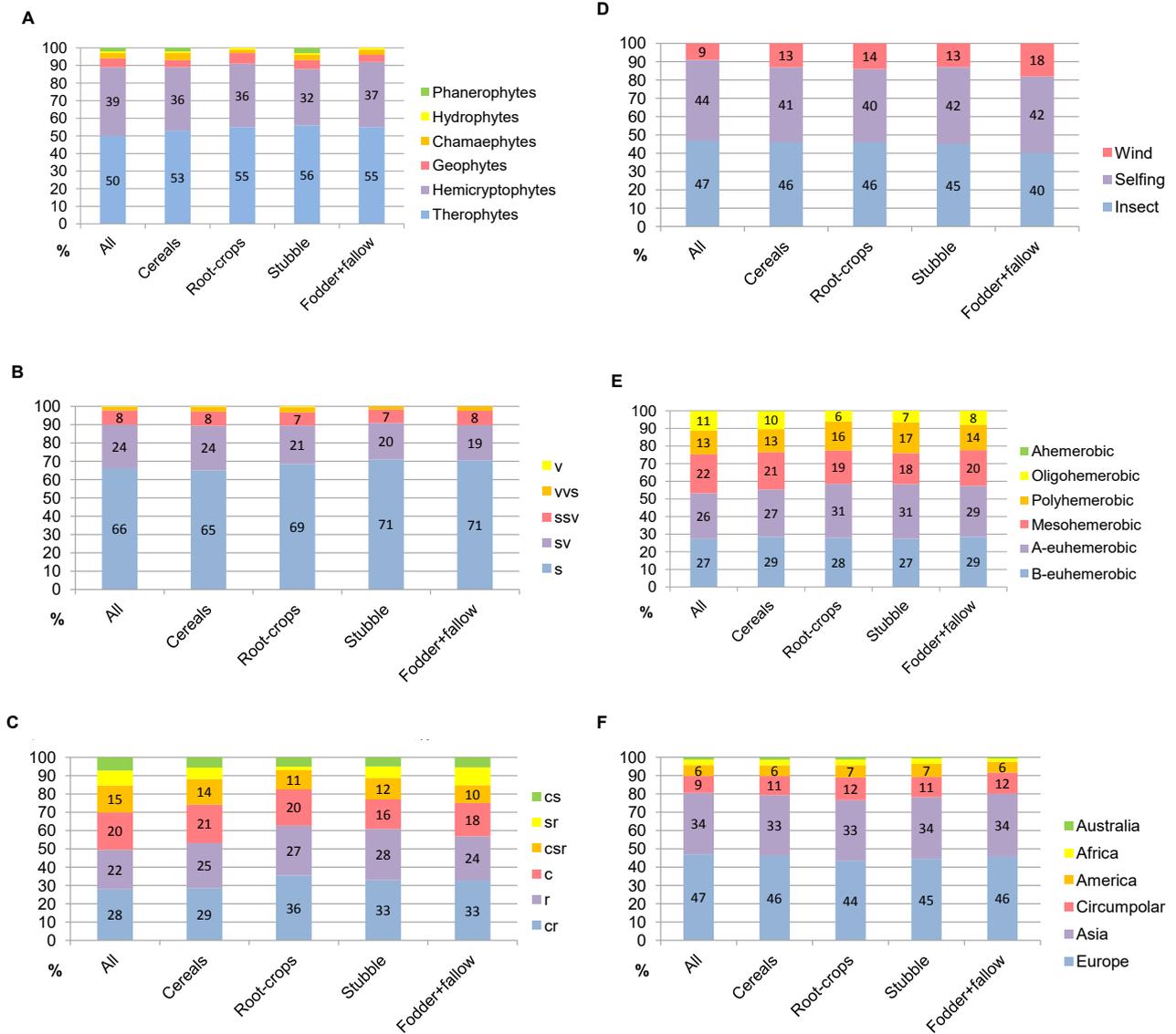


Fig. 2 Species traits of weed vegetation in arable land in Slovakia: (A) life forms; (B) reproduction types; (C) strategy types; (D) pollen vectors; (E) hemeroby; (F) floristic regions. Reproduction type: s – by seed; ssv – mostly by seed, rarely vegetatively; sv – by seed and vegetatively; vvs – mostly vegetatively, rarely by seed; v – vegetatively. Strategy type: c – competitors; cr – competitors/ruderals; cs – competitors/stress-tolerators; csr – competitors/stress-tolerators/ruderals; r – ruderals; s – stress-tolerators; sr – stress-tolerators/ruderals).

Tab. 1 Representation of native and alien species in weed vegetation.

	No. species/relevé		Species/relevé (%)		Cover (%)		Species pool	
	Mean	SD	Mean	SD	Mean	SD	No.	%
Native	7.4	4.9	31.8	13.1	29.5	21.7	182	53.4
Archaeophytes	11.2	4.6	52.3	13.2	51.8	23.4	113	33.1
Neophytes	1.7	1.3	7.7	5.9	12.4	20.2	34	10.0
Uncertain	1.7	1.0	8.2	5.7	11.0	15.4	12	3.5

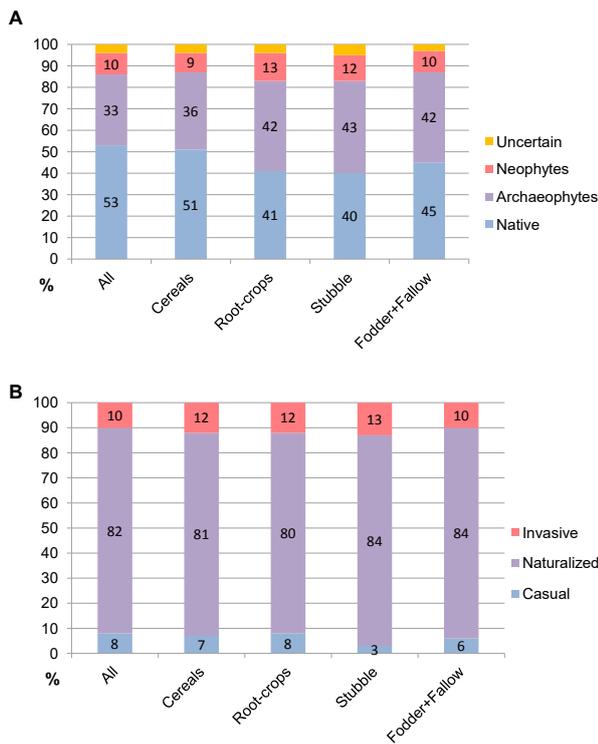


Fig. 3 Representation of (A) native and alien (archaeophytes, neophytes) species, and (B) different invasion status of aliens (casual, naturalized, invasive) in weed vegetation in arable land in Slovakia.

Galinsoga parviflora, *G. urticifolia*, *Matricaria discoidea*, *Negundo aceroides*, *Solidago gigantea*, and *Stenactis annua*. The following three species were invasive archaeophytes: *Apera spica-venti*, *Cardaria draba*, and *Echinochloa crus-galli*. *Apera spica-venti* had the highest frequency (33%), followed by *Echinochloa crus-galli* (24%) and *Conyza canadensis* (18%). The majority of invasive species (64%) belonged to the family Asteraceae. Four recorded aliens are included in the Slovak law decree of invasive species [42]: *Ambrosia artemisiifolia*, *Fallopia ×bohemica*, *Solidago gigantea*, and *Negundo aceroides*. The alien species mostly originated from Europe (39%) and Asia (35%) with less from Africa and America.

Weed vegetation structure revealed that archaeophytes were the most abundant species group in relevés, and these also had the highest cover (Tab. 1); archaeophytes were followed by natives, and neophytes were less abundant. The average number of species per relevé was similar in almost all crop types (23–25), except for fodder+fallow, which had fewer species than other crops (19). The highest species pool was in cereals (270 species), followed by root-crops (188), fodder+fallow (173), and stubble (170). The Shannon–Wiener diversity index was similar in cereals, root-crops, and stubble, and was significantly lower in fodder+fallow fields (Fig. 4). Native species were the most abundant in cereals, archaeophytes in stubble, and neophytes in root-crops (Fig. 3).

The most frequent taxa in the entire dataset were *Tripleurospermum perforatum* (74%), *Cirsium arvense* (70%), *Viola arvensis* (70%), *Fallopia convolvulus* (69%) and *Chenopodium album* agg. (65%). The most frequent taxa varied between crops (Tab. 2). *Viola arvensis* exhibited an 83% frequency in cereals, while *Chenopodium album* agg. dominated root-crops and stubble with frequencies of 94% and 82%, respectively, and *Capsella bursa-pastoris* exhibited an 82% frequency in fodder+fallow.

Thirty of the recorded weed taxa were included in the Red list of Slovakia (Tab. 3). From them, archaeophytes representing 57% and 43% were native plants, and majority were therophytes (83%). Most grew in cereals (21 taxa), then in fodder+fallow (13), stubble (10), and the least were found in root-crops (four). Only *Cyanus segetum* grew in all crops. Rare and threatened plants were from 15 plant families, and the most abundant were from the Scrophulariaceae family (23%).

Environmental indicator values

Ecological differentiation of weed vegetation of studied crop types is shown in the ordination diagram (Fig. 5) where the axis of the highest variability (Axis *x*) was positively correlated with CIV for light (0.57) and temperature (0.55). On the right side of the diagram, relevés from stubble fields with light- and temperature-demanding species which are tolerant to dry conditions were plotted (e.g., *Conyza canadensis*, *Digitaria sanguinalis*, *Setaria pumila*, *Stachys annua*; Fig. 6) since these plots are exposed to light after cereal harvesting. Cereals with species not so strictly light- and temperature-demanding are depicted mainly in the left side of the diagram. Species were ordered from early spring annuals on the left through summer species, to species with their optimums in fall on the right side of the diagram. The second axis (Axis *y*) positively correlated with indicator values for moisture (0.71), nutrients (0.47), and with elevation (0.51). Weed vegetation of root-crops (with nutrients-demanding species *Galinsoga parviflora* and *G. urticifolia*) occurring on humid and nutrient-rich soils at higher elevations are depicted in the upper part of the ordination chart. Relevés of fodder+fallow fields did not contain species with specific requirements, and they were scattered throughout the diagram.

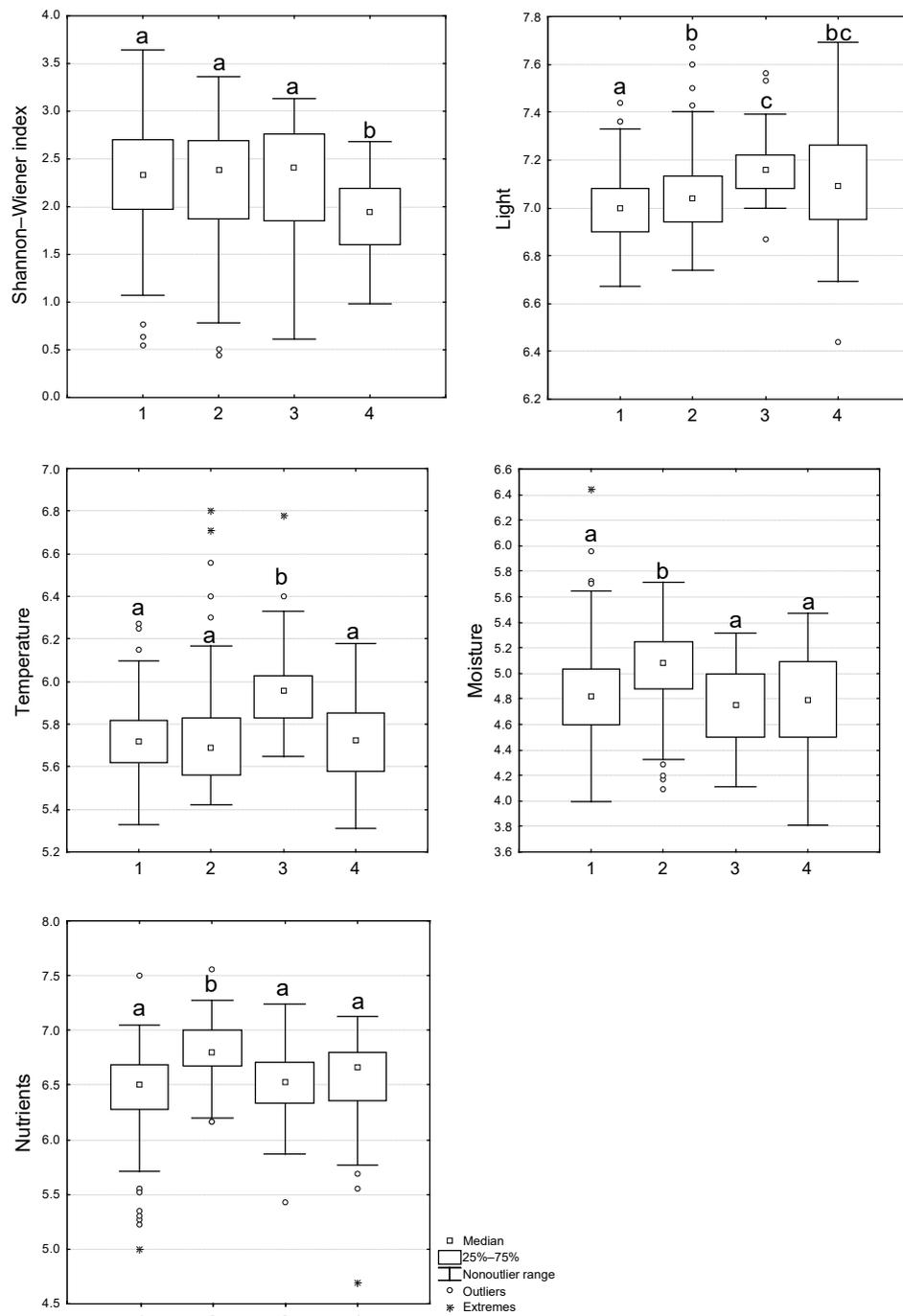


Fig. 4 Comparison of the Shannon–Wiener index of diversity and selected Czech indicator values for studied crop types: 1 – cereals; 2 – root-crops; 3 – stubble; 4 – fodder+fallow.

Results of the ordination analysis were also confirmed by statistical comparison of mean Czech indicator values, which showed significant differences between the crop types, especially in requirements for light, temperature, moisture, and nutrients (Fig. 4). Statistically, cereals included less light-demanding species, species with the highest requirements for temperature occurred in stubble fields, and root-crops hosted species most demanding of moisture and nutrients.

Beta diversity

The effects of crops, seasons, elevation, climatic, and phytogeographical regions on β -diversity are shown in Fig. 7. Weed vegetation occurring in low elevations up to 200

Tab. 2 The most frequent taxa in all relevés and different crops.

	Crop*				
	All	Cer	Root	Stub	F+f
Number of relevés	507	270	113	74	50
<i>Tripleurospermum perforatum</i>	74	80	56	77	76
<i>Cirsium arvense</i>	70	66	82	81	44
<i>Viola arvensis</i>	70	83	58	64	42
<i>Fallopia convolvulus</i>	69	72	75	68	40
<i>Chenopodium album</i> agg.	65	53	94	82	42
<i>Capsella bursa-pastoris</i>	63	63	69	42	82
<i>Stellaria media</i>	61	68	58	35	68
<i>Polygonum aviculare</i> agg.	58	60	51	78	32
<i>Elytrigia repens</i>	57	51	68	53	64
<i>Galium aparine</i>	49	62	52	14	22
<i>Veronica persica</i>	47	46	49	51	42
<i>Convolvulus arvensis</i>	44	40	58	57	20
<i>Apera spica-venti</i>	33	52	5	4	34
<i>Sonchus arvensis</i>	31	28	50	30	6
<i>Persicaria lapathifolia</i>	25	16	53	26	8
<i>Echinochloa crus-galli</i>	24	9	52	47	8
<i>Taraxacum</i> sect. <i>Ruderalia</i>	33	20	38	58	56
<i>Anagallis arvensis</i>	32	30	11	80	18
<i>Setaria pumila</i>	19	3	23	76	8
<i>Lactuca serriola</i>	18	11	4	42	54

Only taxa with a minimum 50% frequency in any column are shown. Taxa are arranged in decreasing frequency, with frequencies over 50% marked in bold. Shaded cells indicate the highest frequency in the column.

* Cer – cereals; Root – root-crops; Stub – stubble; F+f – fodder+fallow.

m a.s.l. had the highest β -diversity, which decreased sharply with increasing elevation. The highest β -diversity was detected in warm climatic regions and the lowest diversity in moderately cool climatic regions. Considering phytogeographical regions, β -diversity was much higher in the Pannonicum than in the Carpathicum region. Diversity was low in the spring, increased in the summer (June–July), and slightly decreased again in fall. The highest β -diversity was in fodder+fallow fields, followed by cereals and root-crops, and the lowest diversity was found in stubble.

Discussion

Alpha diversity and species composition

Arable fields are biotopes rich in plant species [3]. The Slovak Republic lies in the middle of the climate gradient of weed species richness [43]. As human-made habitats support the immigration of alien species [5], both native and alien plants play an essential role in arable weed vegetation structures. Arable land is one of the most invaded habitats by alien plants in Central Europe [3,44,45]. Although Pyšek et al. [4] found native species were the most abundant in Czech fields, followed by archaeophytes and neophytes, Chytrý et al. [44] noted species decline from archaeophytes through natives to neophytes. Similar to Pyšek et al. [4], in our dataset, archaeophytes were more represented than natives in species numbers and cover in relevé plots, and neophytes were the fewest present.

Tab. 3 The recorded red list plants in different crop fields.

Taxon	IUCN status	Cereal	Root-crop	Stubble	Fodder+fallow
<i>Adonis aestivalis</i>	LC	+			+
<i>Agrostemma githago</i>	CR	+			
<i>Ajuga chamaepitys</i>	NT			+	+
<i>Aphanes arvensis</i>	EN	+		+	
<i>Bifora radians</i>	CR				+
<i>Bolboschoenus maritimus</i>	NT			+	
<i>Bromus commutatus</i>	LC	+			
<i>Bromus secalinus</i>	EN	+			
<i>Cyanus segetum</i>	LC	+	+	+	+
<i>Centaurium pulchellum</i>	NT			+	
<i>Cerastium dubium</i>	NT	+			+
<i>Euphorbia virgata</i>	LC	+			
<i>Filago minima</i>	NT				+
<i>Hibiscus trionum</i>	LC		+		
<i>Kickxia elatine</i>	LC	+		+	
<i>Kickxia spuria</i>	LC	+	+	+	
<i>Lolium temulentum</i>	CR	+			
<i>Lythrum hyssopifolia</i>	LC	+		+	
<i>Misopates orontium</i>	NT	+		+	
<i>Myosurus minimus</i>	NT	+			+
<i>Papaver argemone</i>	EN	+			+
<i>Papaver dubium</i> subsp. <i>austromoravicum</i>	NT	+			
<i>Pulicaria dysenterica</i>	NT			+	
<i>Ranunculus arvensis</i>	NT	+			+
<i>Rumex stenophyllus</i>	NT	+			
<i>Spergula morisonii</i>	VU				+
<i>Veronica agrestis</i>	CR	+	+		+
<i>Veronica anagalloides</i>	VU				+
<i>Veronica triloba</i>	VU	+			
<i>Veronica triphyllos</i>	NT	+			+
Total	30	21	4	10	13

Generally, archaeophytes were much more abundant than neophytes in arable fields [1,13,44,46]. Some authors noted that archaeophytes are common in cereal fields but are poorly represented in root-crop fields where neophytes are more abundant [4,10]. The dominance of naturalized species in our dataset corresponds with the results of Sádlo et al. [3].

Weed vegetation is mainly composed of annual plants that rapidly respond to disturbances from intensive agricultural management [7,10,21,46–49]. This would correspond to the dominance of ruderal strategists in arable fields [10,46], but in our dataset, competitors/ruderals were most abundant, followed by ruderals. Slovak fields were enriched with numerous hemicryptophytes and species of another strategy type, which spread onto arable land from neighboring habitats (e.g., grasslands, forests, ruderal habitats).

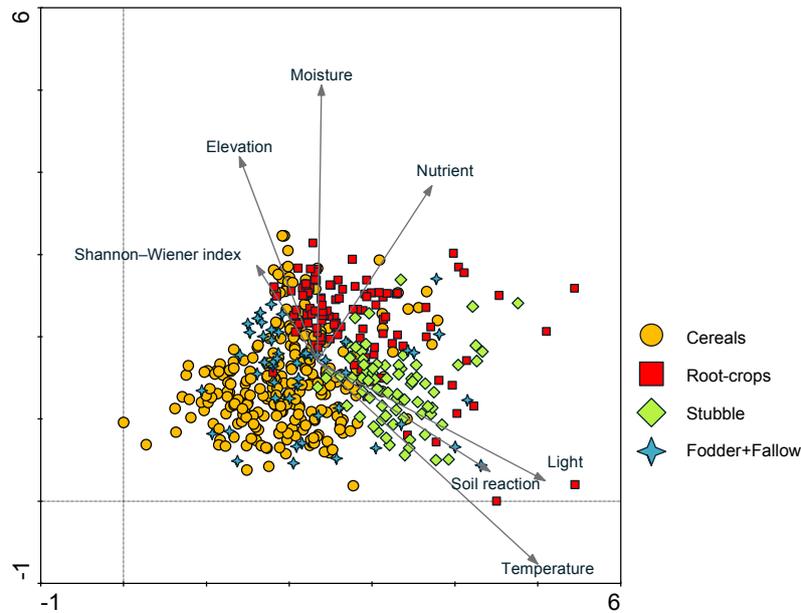


Fig. 5 Detrended correspondence analysis (DCA) of weed vegetation with Czech indicator values and elevation plotted onto a DCA diagram as supplementary variables.

Asteraceae is the most common family in weed vegetation throughout Europe [1,26,49,50]. It seems that our results slightly differed from these authors, because Poaceae held the first place in Slovak fields. This finding is the result of the differentiation of Cichoriaceae and Asteraceae families in our study; if we merged these two families, Asteraceae would be the most abundant family in the overall dataset and also in a majority of crop types. The dominance of the Asteraceae family in weed vegetation is related to being one of the most widespread families in Europe [1,26,49] and globally, and to its ancient origin [1,51]. These plants, bearing attractive inflorescences, are interesting for many insects [51] and this fact corresponds with a broad representation of insect pollinators in Central European fields [7,46,49]. Moreover, the Asteraceae family is remarkably successful in terms of dispersal and establishment and is also the most abundant family of alien or invasive floras worldwide [52,53]. Species from this family are successful invaders not only in anthropogenic biotopes [54] but also in natural ones [55]. The family also hosts species most involved in pollenosis; one of which is *Ambrosia artemisiifolia* [56]. While in neighboring Hungary, the most ragweed-polluted country, *Ambrosia* is the most noxious invasive weed [57], we recorded a frequency of only 4% in our dataset. The reason for this finding may be different climates and altitudes in both countries. *Ambrosia* distribution in Slovakia has an increasing trend over the years due to spreading along highways, roads, and railways, and due to agricultural activities [58,59]. It is possible that in the future *Ambrosia* invasion will be a major problem in Slovak fields, as it is spreading from south to north.

The most abundant weed species in our dataset were mostly taxa with circumpolar and Eurasian distribution [30], which is in accordance with other studies [7,49]. Some of these (e.g., *Tripleurospermum perforatum*, *Viola arvensis*, *Fallopia convolvulus*, *Chenopodium album* agg., *Capsella bursa-pastoris*, *Stellaria media*) are characteristic species of annual synanthropic vegetation in Slovakia [19]. Species occurrence in various countries and crops differs slightly. In Czech fields, *Viola arvensis* and *Chenopodium album* had the highest constancy [26,47,60]; *Chenopodium album* was the most abundant in root-crop fields [48]. In German and Moravian studies, *Stellaria media* had the highest abundance [12,13]; in the northwestern Balkans the most abundant species was *Convolvulus arvensis* [6]; in Denmark, the most abundant species was *Capsella bursa-pastoris* [61] and in the southnorthern gradient of Europe, *Tripleurospermum perforatum*, *Papaver rhoeas*, *Chenopodium album*, *Elytrigia repens*, and *Viola arvensis* prevailed [43]. In addition, Glemnitz et al. [62] recorded that *Polygonum aviculare*, *Fallopia convolvulus*, *Cirsium arvense*, and *Chenopodium album* occur in weed vegetation independent of climatic conditions. The species *Cirsium arvense*, *Tripleurospermum perforatum*, and *Fallopia*

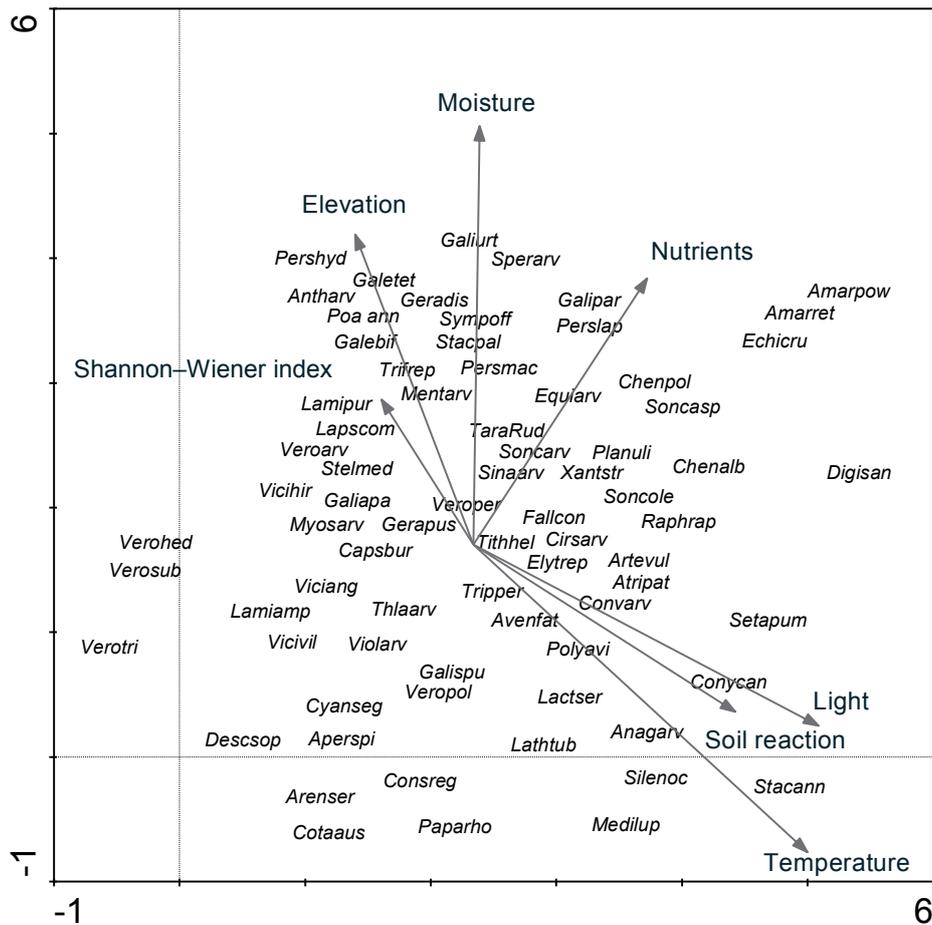


Fig. 6 Detrended correspondence analysis (DCA) ordination diagram of species with Czech indicator values and elevation plotted onto a DCA diagram as supplementary variables. Only species with weights of analysis greater than 7% are presented: Amarpow – *Amaranthus powellii*; Amarret – *Amaranthus retroflexus*; Anagarv – *Anagallis arvensis*; Antharv – *Anthemis arvensis*; Aperspi – *Apera spica-venti*; Arensr – *Arenaria serpyllifolia*; Artevul – *Artemisia vulgaris*; Atripat – *Atriplex patula*; Avenfat – *Avena fatua*; Capsbur – *Capsella bursa-pastoris*; Chenalb – *Chenopodium album* agg.; Chenpol – *Chenopodium polyspermum*; Cirsarv – *Cirsium arvense*; Consreg – *Consolida regalis*; Convarv – *Convolvulus arvensis*; Conycan – *Conyza canadensis*; Cotaaus – *Cota austriaca*; Cyanseg – *Cyanus segetum*; Descsop – *Descurainia sophia*; Digisan – *Digitaria sanguinalis*; Echicru – *Echinochloa crus-galli*; Elytrep – *Elytrigia repens*; Equiarv – *Equisetum arvense*; Falcon – *Fallopia convolvulus*; Galebif – *Galeopsis bifida*; Galetet – *Galeopsis tetrahit*; Galiapa – *Galium aparine*; Galipar – *Galinsoga parviflora*; Galispu – *Galium spurium*; Galiurt – *Galinsoga urticifolia*; Geradis – *Geranium dissectum*; Gerapus – *Geranium pusillum*; Lactser – *Lactuca serriola*; Lamiamp – *Lamium amplexicaule*; Lamipur – *Lamium purpureum*; Lapscom – *Lapsana communis*; Lathtub – *Lathyrus tuberosus*; Medilup – *Medicago lupulina*; Mentarv – *Mentha arvensis*; Myosarv – *Myosotis arvensis*; Papparho – *Papaver rhoeas*; Pershyd – *Persicaria hydropiper*; Perslap – *Persicaria lapathifolia*; Persmac – *Persicaria maculosa*; Planuli – *Plantago uliginosa*; Poa ann – *Poa annua*; Polyavi – *Polygonum aviculare* agg.; Raphrap – *Raphanus raphanistrum*; Setapum – *Setaria pumila*; Silenoc – *Silene noctiflora*; Sinaarv – *Sinapis arvensis*; Soncarv – *Sonchus arvensis*; Soncasp – *Sonchus asper*; Soncole – *Sonchus oleraceus*; Sperarv – *Spergula arvensis*; Stacann – *Stachys annua*; Stacpal – *Stachys palustris*; Stelmed – *Stellaria media*; Sympoff – *Symphytum officinale*; TaraRud – *Taraxacum* sect. *Ruderalia*; Thlaarv – *Thlaspi arvensis*; Tithhel – *Tithymalus helioscopia*; Trifrep – *Trifolium repens*; Tripper – *Tripleurospermum perforatum*; Veroarve – *Veronica arvensis*; Verohed – *Veronica hederifolia*; Veroper – *Veronica persica*; Veropol – *Veronica polita*; Verosub – *Veronica sublobata*; Verotri – *Veronica triphyllos*; Viciang – *Vicia angustifolia*; Vicihir – *Vicia hirsuta*; Vicivil – *Vicia villosa*; Violarv – *Viola arvensis*; Xantstr – *Xanthoxalis stricta*.

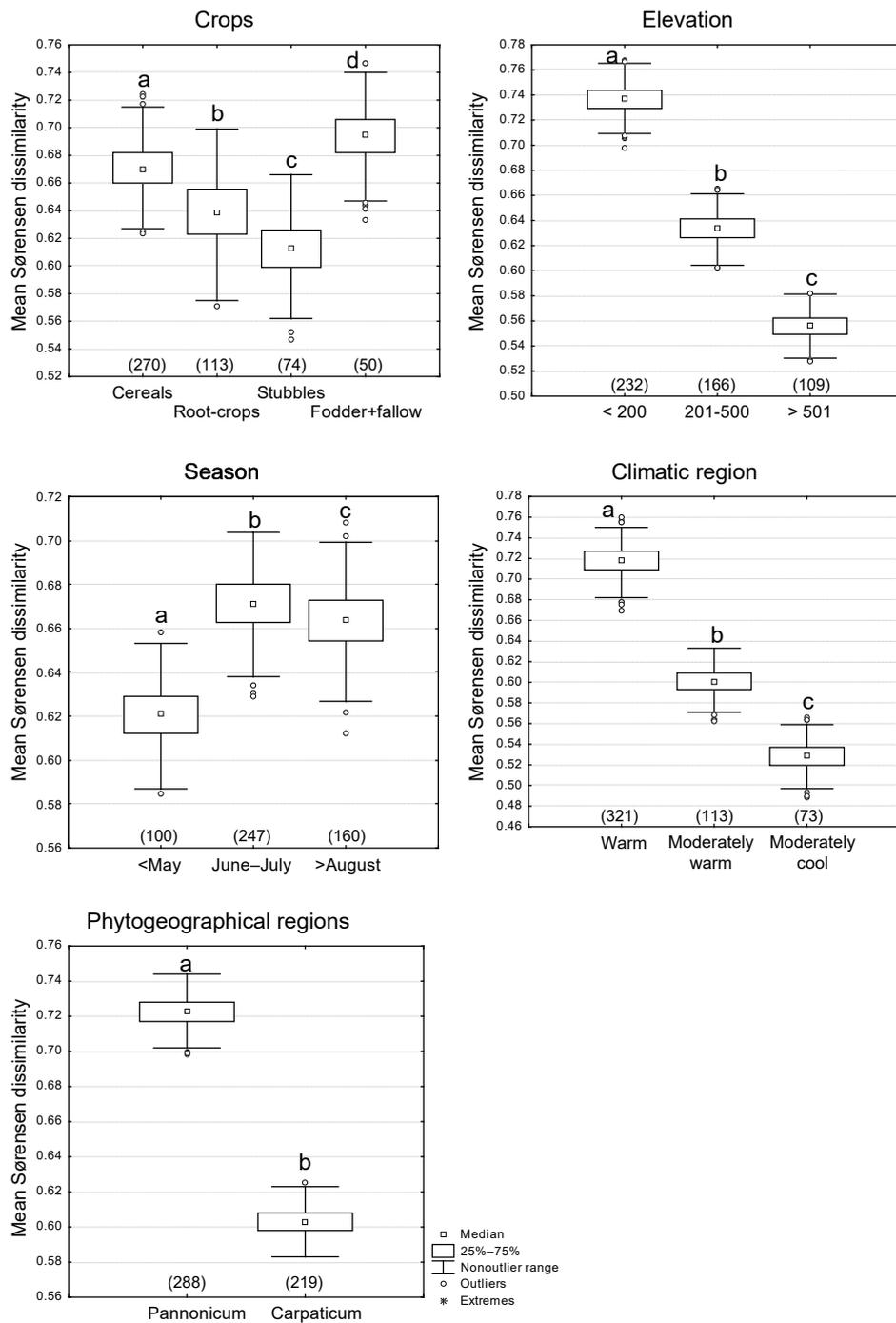


Fig. 7 Beta diversity along the five major gradients (crop type, elevation, season, climatic regions, and phytogeographical regions); numbers in brackets depict the number of relevés in each group.

convolvulus have the broadest habitat range in the Czech Republic [3]. Some perennials such as *Cirsium arvense*, *Elytrigia repens*, and *Equisetum arvense* that also often grow in arable fields are considered highly noxious species [63].

Arable fields host numerous rare plants included in the red lists of various European countries [7,8,26,63,64]. Holzner [2] demonstrated that segetal species at the limits of their ranges are more sensitive and less vigorous than in their distribution centers. For example, *Caucalidion* species have become extinct in many parts of Northern, Western, and Central Europe due to changes in agricultural management. Many other authors pointed out declines or extinction of some segetal species, mainly specialists [2,4,11–13]. Extensively cultivated fields, field margins, and short-abandoned fields provide refuges for survival of rare species, mostly archaeophytes. Moreover, weeds support many other species, principally insects and birds, providing valuable food sources

and nesting habitats. Several weeds are insect-pollinated, and a group of insect species is dependent on particular weeds to complete their life cycles. Weeds are also crucial as host plants for insects that are eaten by birds, but weeds themselves play a notable role in farmland bird diets. For example, *Stellaria media* and species of Poaceae, Polygonaceae, and Chenopodiaceae are of particular importance for farmland birds [14–16].

Arable fields and weed vegetation represent a valuable biotope in the country and play an essential role in supporting biological diversity. In Slovakia, this biotope is overlooked, and there is no effort to conserve weed species and vegetation, although in some countries it has been discussed, and some measures were proposed [14,15,63].

Environmental indicator values

The most important gradients in species composition of weed vegetation in Slovakia were connected with climate, elevation, and amounts of nutrients in the soil. Climate is closely related to elevation; with increasing elevation, temperatures decrease and moisture increases. Lososová et al. [21] revealed that elevation with associated climatic factors is the most important gradient in species composition in Central Europe. Elevation does not play a significant role in the composition of weed communities in areas with uniform lowland relief [7]. Šilc [24] determined crop types are the main factor in weed vegetation of Slovenia, but he emphasized that crop type influences weed species composition more in Southern Europe than in Central and Northern Europe. In the Balkans, the most important parameter in weed vegetation was phytogeography, and the second most important was crop type [24].

Based on the ordination diagram, diversity (expressed by the Shannon–Wiener index) of weed vegetation increases with elevation. Slovak lowlands are characterized by intensive agriculture with broad-scale fields and widespread use of herbicides. These fields would be a suitable biotope for thermophilous archaeophytes, but due to agrotechnical management, they are rare here. Agriculture in the highlands is less intensive; small-scale private fields mostly occur here, and weed vegetation is rich in species – both native and alien. The α -diversity increases by penetrating species from the surrounding vegetation; due to higher humidity, fields are also suitable for hygrophilous species such as *Persicaria hydropiper*, but fields are also invaded by neophytes (e.g., *Galinsoga parviflora* and *G. urticifolia*). A similar pattern in Central European weed vegetation was also observed by Lososová et al. [21], where species richness was greater at higher elevations. By contrast, β -diversity decreases with altitude which corresponds to our results.

The spectrum of weed species in arable fields is largely dependent not only on environmental conditions but also on human impact. Herbicide use, fertilization, changes in crop rotation, and field merging are of significant importance in species composition. Some studies have dealt with weed flora and vegetation in extensively and intensively managed fields. The diversity and biomass of weeds and also the occurrence of red list species was usually greater in extensively managed fields than in intensively managed fields [9,43,65,66].

Beta diversity

Beta diversity reveals the degree of difference between communities, and it is, therefore, a useful tool for comparing regions. This diversity decreased markedly with elevation and temperature in our study, and altitudinal β -diversity decreases in weed vegetation were particularly noted in other countries [21,23,26]. Although Lososová et al. [21], and Lososová and Cimalová [10] recorded higher β -diversity in root-crops than in cereals, Šilc et al. [25] reported the opposite trend. In addition, Fried et al. [23] determined that β -diversity was the highest in winter cereals compared with other crops, but our data established that it was the highest in fodder+fallow fields, followed by cereals, root-crops, and stubble. Beta-diversity also changes during the growing period; while Šilc et al. [25] reported the highest β -diversity in the summer, a finding similar to our results, Lososová et al. [21] recorded the highest diversity in the fall.

Cereal communities are well differentiated from root-crops in warm Slovak areas. This is noted in spring crop vegetation compared with winter crops, and especially evident at low elevations in the Pannonian region where weed vegetation varies widely. At higher elevation, the climate is colder but more humid, and this aids spring-cultivated crops. Thus, some communities retreat, and the vegetation become more uniform [67]. This effect provides the highest β -diversity in warm lowlands, and diversity was much higher in the Pannonian area than in the Carpathian area in our study. Holzner [2] also observed gradual impoverishment of weed vegetation with increasing elevations in the alps, thus confirming our results where the highest β -diversity occurred at the lowest elevations.

Conclusion

Weed vegetation on arable land in Slovakia remains species-rich and diverse, despite that a considerable part of the landscape is covered by large agricultural fields. Its structure and diversity are influenced by both agricultural management and environmental conditions [21,23,24]. Weed vegetation represents a crucial element in the country, hosting numerous plant species with entirely different histories. Weed vegetation provides refuge for threatened plants and fulfills important functions in agro-ecosystem food chains. Albrecht [63] highlighted that arable weeds are key species, the loss of which leads to changes in the biocoenosis via habitat and food chain relationships. Therefore, arable weed vegetation certainly deserves biodiversity conservation initiatives [7,63].

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