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Effect of Environmental, Soil and Management Factors on Weed Flora of Field Pea in South-East Hungary

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Abstract: Pea is a widely cultivated leguminous plant which also contributes to soil enrichment through nitrogen fixation and benefits crop rotations. However, large weed populations are a challenge for pea production, requiring effective management strategies. It is essential to highlight the influence of soil parameters, factors affecting the environment, and management practices on weed populations to develop effective weed control and maximize pea yield and ease of harvesting. In our study, a total of 31 pea fields were surveyed prior to harvest to determine the coverage of each weed species, with the aim of identifying the typical weeds in the study area. In addition, environmental, soil, and management factors were recorded for each field. Based on our hypotheses, these factors influence the weed composition, and these effects can be described by the dominance of weed species. In our study, summer annuals and geophytic perennials were common, with *Echinochloa crus-galli* and *Convolvulus arvensis* being most dominant. The analysis revealed that the year of data record, soil type, and farming system most significantly influenced weed composition. Weed species were observed to have varying responses to soil texture, salt concentration, and phosphorus content. The survey period, geographical factors, farming system, and tillage practices also played a role in determining weed flora. The findings suggest strong correlations between soil parameters and weed composition, highlighting the importance of soil management in weed control. The year of data collection had the greatest influence on weed infestation. Soil-related variables, such as soil type, also played a significant role. Farming systems had a smaller effect on weed composition. Comparing our results with previous country level weed surveys in Hungary, our results identified some unique characteristics in the weed flora of South-East Hungary.

Keywords: weed flora; weed survey; weed management; coverage of weed species; organic farming; conventional farming; soil management; *Pisum sativum*; redundancy analysis

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1. Introduction

Peas, of the genus *Pisum*, are one of the most widely cultivated leguminous plants in Hungary; they are grown in more than 100 countries around the world for seed, feed and food [1]. In Hungary, the area of cultivation (approx. 12 thousand hectares dry peas and 17 thousand hectares green peas) has been declining in recent years [2,3].

The most important use of peas is in animal feed, as they have very favorable nutritional values. They have a protein content of 21–25% and have high amounts of carbohydrates and digestible nutrients (86–87%). They are rich in amino acids and have a high content of lysine and tryptophan, which are less abundant in cereal grains. This makes peas a key ingredient in animal feed mixtures. Peas are also a good source of human protein and are consumed worldwide [4]. The climatic conditions in Hungary are favorable for pea production [5].

Peas are also useful crops for crop rotation because they leave a very favorable soil condition: they do not deplete the soil water and nutrient supply; early harvesting of peas allows sufficient time for tillage before sowing the next crop; and due to *Rhizobium* bacteria, they enrich the upper soil layer with nitrogen [6]. Beyond use as a main crop, peas can also be used as a green manure, second crop, and can increase the yield of roadside crops [4].

Field pea is mostly an early spring-sown crop in Hungary, and at the beginning of the growing season this crop develops together with winter annual and early summer annual weed species. Thus, the pea crop is easily weeded in the early stages of development due to late canopy closure [4]. Peas do not have the same shading density as cereals in the later growing period either, so they may also have a serious weed problem at harvest [5,7,8].

The most important winter annual species damaging pea crops include *Matricaria* spp., *Anthemis* spp., *Papaver rhoeas*, and *Galium aparine*. Among the most important members of the early summer annuals, *Sinapis arvensis*, *Raphanus raphanistrum* and *Avena fatua* are of concern. At the end of the growing season, after the leaves of peas have dried, the summer annuals weeds, *Chenopodium* spp., *Amaranthus* spp., *Echinochloa crus-galli*, *Solanum nigrum*, and the sunflower (*Helianthus annuus*), become dominant, while the most common perennial weeds are *Cirsium arvense*, *Convolvulus arversis,* and *Sorghum halepense*. During harvesting, the poisonous berries of *Solanum nigrum* may fall among the peas, causing quality damage [9,10].

The structure and nutrient content of the soil greatly influence the appearance and location of weeds [11]. The different physical and chemical properties of soil all interact. For example, a slight change in soil chemistry has a strong influence on the emergence and growth of weeds, too. Plants do not generally prefer more acidic soils, but some weeds may have an advantage over the crop under these conditions. The competitiveness of the cultivated crop can be improved by adding lime [12] and by organic and mineral fertilization [13].

Fertilization, as a factor affecting soil properties in the long term, has a crucial role in the development of weed flora and weed population and competition [14]. According to Häkansson [15], one such example is *Sinapis arvensis*, an important weed but formerly a major problem in acidic soils, whereas nowadays its importance has declined partly due to liming and fertilizer use.

Salinization is one of the most critical soil factors for crop yields. Salinization affects 20% of arable farmland globally, including 33% of irrigated farmland. Agricultural crops show a variety of adverse responses to salt stress and salinity adversely affects several different soil properties [16]. Salinity also determines morphological, physiological, and biochemical processes, including seed germination, plant growth, and water and nutrient uptake [17,18]. Thus, salinity as an ecological indicator plays a crucial role in habitat preference [19] as well as in all aspects of plant development, from germination to growth and reproduction [20].

Climate change is of paramount importance in agriculture, as weather factors have a profound impact on the development of all crops, including not only main crops but also weeds [21]. Sudden changes in weather stress main crops, making them more susceptible and less competitive against weeds [22]. Temperature, precipitation, humidity, and CO_2 concentration all play a crucial role in the geographic distribution of weeds, as they alter weed proliferation and competitive behavior in the crop [23,24]. Further northward expansion of several weeds such as *Amaranthus retroflexus*, *Setaria* spp., *Digitaria sanguinalis*, *Sorghum halepense* has been observed [25,26]. Milder and wetter winters tend to increase overwintering of annual weeds, but thermophilic annuals also grow with greater intensity and expand where summers are longer and warmer [27,28].

Precipitation patterns and the increasing droughts associated with climate change will alter the occurrence and spread of weeds, and thus their impact on crop production. Extreme weather conditions and drought-prone agricultural areas are expected to become more prevalent in the near future [29,30]. As a result, drought and flood seasons will become more frequent, which may also change the occurrence and further spread of weeds. Rainier years favor hydromorphic weed species, while in drier years C4 weeds are favored over C3 species [29].

Both crop rotation and soil tillage influence weed emergence. In general, reduced tillage systems, such as no-tillage, stratify the soil weed seed set closer to the soil surface, whereas intensive tillage provides a uniform distribution of weed seeds down to the tillage depth [31,32]. Weed species respond quite differently to different tillage regimes, with increasing cover of *Mercurialis annua*, *Panicum miliaceum,* or *Datura stramonium* and with decreasing cover of *Avena fatua*, *Cirsium arvense,* or *Anthemis austriaca* under reduced tillage [33].

Reducing the number of tillage operations and abandonment of soil rotation helps to reduce some weeds. The abundance of large seeded deep germinating weed species *Abutilon theophrasti*, *Xanthium* spp., *Datura stramonium* are declining. However, the incidence of small-seeded and broad-leaved weeds such as *Chenopodium album*, *Amaranthus retroflexus*, *Ambrosia artemisiifolia,* and annual grasses, e.g., *Echinochloa crus-galli* and *Setaria* species, has been observed [34]. In addition, it can promote the establishment and emergence of perennial weed species such as *Epilobium ciliatum*, *Poa trivialis*, *Cirsium arvense*, *Taraxacum officinale*, *Equisetum arvense*, and *Elymus repens* [35,36].

Weeds are the most damaging agricultural pest [37]. In recent years, the approvals of many pesticide active substances have been withdrawn or not renewed in the European Union. Herbicidal active substances and preparations are no exception [38]. The crop under study is a minor uses crop, which has not been previously managed by a wide range of herbicidal preparations. Due to the successive withdrawals of active substances, non-chemical weed control technologies and their effective application are becoming increasingly important. Furthermore, as these techniques are common practice in organic farming systems, the question of rethinking the management system may arise.

Field weed species show different adaptability to soil nutrients. They have fundamentally different nutrient requirements and are adapted to different nutrient supply levels [39]. *Rumex acetosella*, *Spergula arvensis*, and *Scleranthus annuus* tolerate Ca deficiency and are often referred to as acidophilic weeds, while *Chenopodium album*, *Stellaria media*, and *Tripleurospermum inodorum* prefer calcareous soils and are better able to use fertilizers than cultivated crops. The latter are also known as nitrophil weeds [40–42].

Weed infestations reduce yields by competing for moisture, nutrients, space, and light, and make harvesting peas more difficult. Weed control increases pea yield by an average of 63% [43,44], and pea yield loss ranges from 40–70% due to weed competition. In addition to herbicidal treatments, the weed suppressive ability of different cultivars plays a role in the above percentages [45]. Traits such as long stems, number of branches, leaf area, and rapid canopy development all influence the competitive effects of pea and weed interference. From the point of view of competitive ability, it is recommended to grow pea varieties with the largest, strongest growth habit and longer vines [46]. Timing is also an important factor. Early sown pea varieties are those that are less susceptible to weed infestation [47], but the extent of weed infestation can be reduced by higher seeding rates and the use of competitive varieties [48].

Since there are large differences in weed control between organic and conventional systems, conventional seeding rates are not appropriate for organic pea production. This is supported by results that show that increasing the seeding rate increases yield and plant competitiveness and reduces yield losses due to weeds. In organic farming systems, weed infestation can be effectively reduced by increasing the seeding rate [37,49]. The adjustment of the seeding rate to a higher seeding rate also plays a crucial role in the development of weed suppression. Several experiments involving pea stands confirm that weed suppression is improved in crops with higher stand density, resulting in lower weed infestation in plots with increased number of plants [50].

Based on the above, the hypotheses of our work were that soil, management, and environmental factors influence the weed composition of pea fields by affecting the ability of weed species to reproduce at different rates and that the influence of these factors can be described by the relative dominance of particular species, as indicators. Furthermore, the aims of the research included identifying the typical weeds in field pea in the study area and determining and comparing factors influencing the variation in weed flora.

2. Materials and Methods

2.1. Data Collection

The aim of our study was to examine the pre-harvest weed vegetation of pea fields. A total of 31 pea fields were examined between 2017 and 2020 in South-East Hungary (in the region of Gyomaendrőd and Szarvas cities; Figure A1) when weed vegetation was sampled between mid-June and late July depending on the pea maturity.

The study area is characterized by alluvial and meadow soils with poor water management and poor tillage resulting in high weed populations in general.

The surveyed fields were assessed in eight 1 × 1 m randomly placed quadrats. Each weed species was surveyed on the basis of coverage, i.e., the percentage of ground covered by aboveground plant parts [51]. The analyses were based on the field-level average for all species.

On all surveyed fields, soil and management variables and factors affecting the environment (named as 'environmental variables') were also recorded by soil analyses, other observations, or farmer interviews. Tillage was based on either ploughing to a depth of 30–34 cm or on loosening by shank ripper to a depth of 35–50 cm, depending on the field. Preceding crops within a three year period were classified into three groups, as winter crops (winter wheat, winter barley, spelt wheat, winter oil-seed rape), sprint row crops (maize, sunflower, oil-seed pumpkin) and spring dense crops (canary grass, spring pea), and the relative frequency (between 0 and 1) of these groups was calculated weighted by the years of production as 0.6 for previous crop #1, 0.3 for previous crop #2, and 0.1 for previous crop #3. Analysis included the relative frequency of these groups. (Tables 1 and A1) The cultivar, amount of seeds, and sowing date were also recorded but were excluded from the analyses as cultivar and amount of seeds was the same (Nanny and 150 kg ha^{-1}) and sowing data varied little (all pea plants were sown on the first week of March) for the surveyed fields.

2.2. Statistical Analyses

In the first step in the analysis, cover values of each species were aggregated within the eight plots from each field to calculate the average weed composition of the individual fields. These field averages were examined via statistical analyses. To demonstrate the importance of each species generally, both the average cover value and frequency (on field level) were calculated across all examined fields. The intercorrelations were assessed by calculating generalized variance inflation factors (GVIF) prior to the analysis in case of all of soil, environmental, and management factors. During this process, 'tillage depth' (highly correlated with tillage method); 'number of mechanical weed control applications', 'MCPB herbicides', fertilizer rates (N, P_2O_5, and K_2O) (all highly correlated with farming system where mechanical weed control and the abandonment of fertilizer use characterized organic fields, while fertilizer and herbicide [MCPB a.i.] use dominated in conventional fields.) and 'spring dense preceding crops' (highly correlated with other preceding crops) were removed from the analysis (Table 1). The rest of the variables showed only a limited collinearity, where the highest value of GVIF (adjusted by degree of freedom) was 4.11 [52].

The second step included the calculation of the Shannon diversity index [53] based on relative coverage of weed species of each field according to the following equation:

$$H\prime = -\sum \sum_{i=1}^{R} p_i \ln p_i$$

where R: number of species, p_i: proportion of coverage of individuals belonging to ith species in the sample.

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

Variable (Unit)	Range/Recorded or Calculated Values
Soil factors	
Soil type	Alluvial meadow soil, clay soil, loamy-clay soil
Soil texture (K_{Arany})	40–63
Soil pH (KCl) [B]	5.63–7.08
Soil properties (m/m %)	
Salt	0.03–0.11
Humus [B]	1.74–3.75
$CaCO_3$ [B]	0.08–2.91
Soil properties (mg kg^{-1})	
P_2O_5	40.7–420
K_2O [B]	253–546
Environmental factors	
Altitude (m, AMSL)	78–86
Latitude (°)	46.73990–46.97027
Longitude (°) [B]	20.42458–20.90111
Year	2017–2020
Management factors	
Tillage system	ploughing, loosening
Tillage depth (cm) [A]	30–50
Farming	conventional, organic
Nr. of mechanical weed control applications [A]	0–1
MCPB herbicide (g a.i. ha^{-1}) [A]	0–1200
Preceding crops [a]	
Wintering crops [B b]	0–1
Spring row crops [B c]	0–0.7
Spring dense crops [A d]	0–0.7
Amount of fertilizer (kg ha^{-1})	
N [A]	0–63
P_2O_5 [A]	0–22.5
K_2O [A]	0–22.5

[A] Variables not included into the analysis due to multicollinearity [B] Variables dropped during the backward selection process [a] Calculated by last three preceding crops: (precrop 1 × 0.6) + (precrop 2 × 0.3) + (precrop 3 × 0.1) [b] Winter wheat, spelt wheat, winter barley, winter oilseed rape [c] Maize, sunflower, oilseed pumpkin [d] Spring pea, canary grass.

Calculated indexes were analyzed together with the soil, management and environmental variables not eliminated in the first step by analysis of covariance (ANCOVA) [54] and by Pearson correlation (numeric variables) [55] in case of significant ($p < 0.05$) variables of ANCOVA.

In the third step, aggregated cover values were subjected to Hellinger transformation [56] and were examined in a redundancy analysis (RDA) together with the soil, management and environmental data, with the aim of describing the effect of explanatory variables on weed composition. The number of explanatory variables was decreased by stepwise backward selection using a $p < 0.05$ threshold for type I error, which resulted a minimal adequate model which contained nine independent variables (Table 1). In the next step of the multivariate analysis, the gross and net effects of each explanatory variable of the reduced model were estimated, based on methods of Lososová et al. [57]. In the case of most partial RDAs there was only one constrained axis, except soil type and year (date of record), where three and four constrained axes had to be tested. Based on the results, a common rank of 'importance' was settled among all explanatory variables according to the R^2 adj-values of the net effects of the partial RDA models. To show the connections between weed species and significant factors, for each pRDA model 10 species were identified that represented the highest explained variation in the constrained axis. The entire statistical analysis was conducted in the R Environment (R Development Core Team, version 4.1.3) using the Vegan add-on package (vegan 2.5-1).

3. Results

3.1. Weed Composition

According to Figure 1, more than half of the weed % cover was occupied by summer annuals (a total of 13.3%). Next to annuals, the % cover of geophyte perennials was next most important on the surveyed fields. The most abundant species with more than one percent coverage were *Echinochloa crus-galli* (summer annual; 6.0%), *Convolvulus arvensis* (geophyte; 4.5%), *Cirsium arvense* (geophyte; 1.7%), *Xanthium italicum* (summer annual; 1.6%), and *Hibiscus trionum* (summer annual, 1.4%). In addition to weed species, a range of crop volunteers also appeared, i.e., *Triticum spelta*, *T. aestivum,* and *Brassica napus* with coverage of 0.5%, 0.2%, and 0.1%.

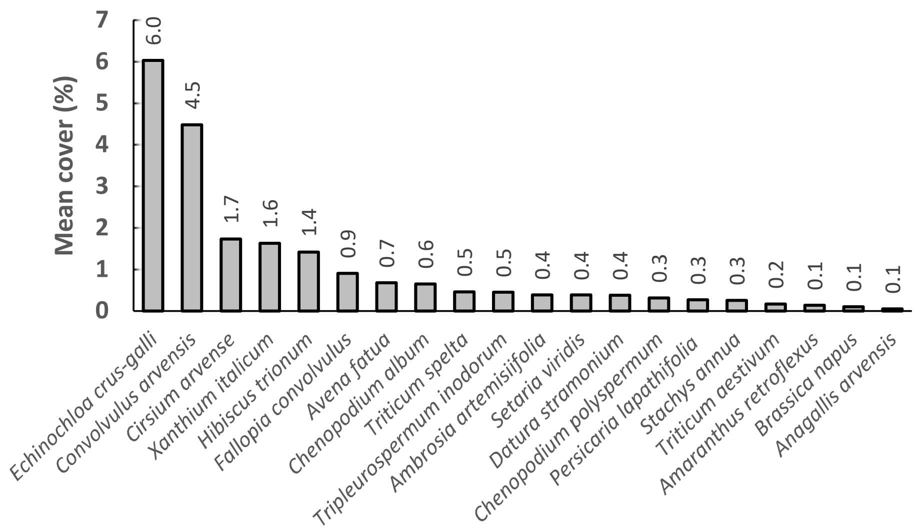

Figure 1. Mean % cover of most abundant weed species of surveyed pea fields.

As seen in the % cover values, the summer annuals and geophyte perennials were the most frequent weeds during surveys. Six of eight species with more than 50% frequency were annuals and two of them perennials with the highest frequency of *Echinochloa crus-galli* (74.2%), *Convolvulus arvensis* (67.7%), *Cirsium arvense*, *Chenopodium album*, *Setaria viridis* (all 64.5%). According to the analysis of % cover and frequency data together, it was apparent than some species (e.g., *Xanthium italicum*, *Hibiscus trionum*) had high % cover values but appeared only on a few fields, and conversely *Chenopodium album* was a general species on most fields with low % cover values (Figure 2).

3.2. Effect of Variables on Diversity

The analysis of covariance dedicated that diversity was affected only by a limited number of variables. However, a significant effect was detected for soil humus content ($p = 0.035$), soil K_2O content ($p = 0.042$), and frequency of spring row preceding crops ($p = 0.028$); the Pearson correlation did not show a significant relationship with diversity for any of these variables.

The small effect on diversity prompted us to analyze the impact on individual weed species in more detail.

3.3. Effect of Variables on Weed Composition

According to the redundancy analysis (RDA), the weed composition was mainly affected by the year of data record (15.6%), soil type (10.0%), and farming system (5.8%) but a total of nine factors were significant in our model. The total explained variation in order of all included soil, environmental, and management factors was 21.3, 23.0 and 8.8%, respectively (Table 2).

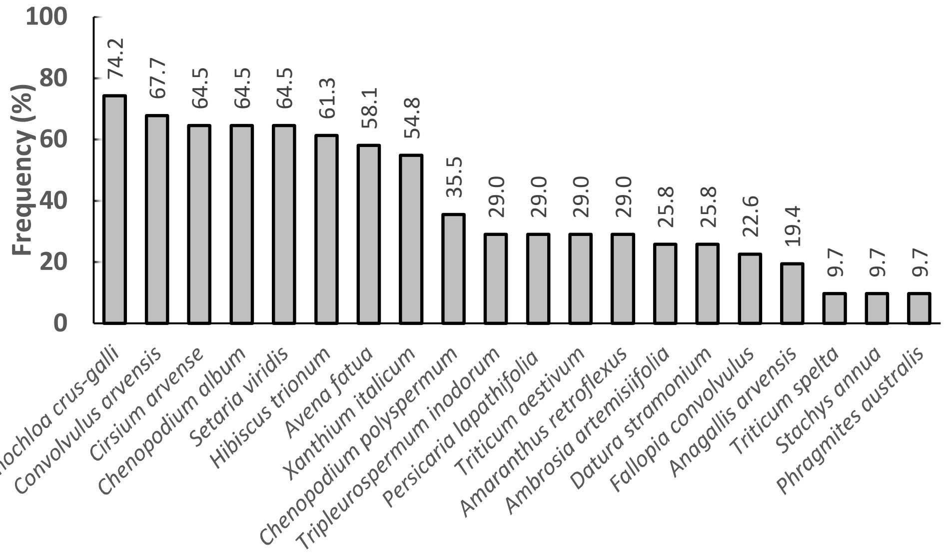

Figure 2. Most frequent weed species of surveyed fields.

Table 2. Effects of the explanatory variables on the weed composition.

Factors	df	Gross Effect		Net Effect			
		Explained Variation (%)	R^2_{adj}	Explained Variation (%)	R^2_{adj}	F	*p*-Value
Soil type	2	23.2	0.18	10.0	0.12	5.56	0.001
Soil texture (Arany)	1	20.0	0.17	2.9	0.03	3.20	0.002
Soil salt content	1	14.4	0.11	4.9	0.06	5.52	0.001
Soil P_2O_5 content	1	12.9	0.10	3.5	0.04	3.91	0.002
Year	3	29.4	0.22	15.6	0.18	5.82	0.001
Altitude	1	13.6	0.11	3.5	0.04	3.92	0.001
Latitude	1	14.9	0.12	3.9	0.05	4.38	0.002
Farming	1	23.5	0.21	5.8	0.08	6.44	0.001
Tillage	1	12.1	0.09	3.0	0.04	3.31	0.009

The soil preference of surveyed weed species varied widely. Alluvial meadow soil was highly preferred by *Xanthium italicum*, *Hibiscus trionum* and *Setaria viridis*; clay soils by *Tripleurospermum inodorum* and *Persicaria lapathifolia*; and *Convolvulus arvensis* was the most abundant on fields with loamy-clay soil.

The weed composition was also well differentiated by soil texture. Fields with hard ground featured higher % cover values for summer annuals (*Chenopodium* spp., *Echinochloa crus-galli*, *Tripleurospermum inodorum*) but *Xanthium italicum*, wheat species, and *Fallopia convolvulus* exhibited higher % cover values in the case of loose soils. The % cover of *Convolvulus arvensis* and *Hibiscus trionum* was most influenced by high salt concentration, but other species (e.g., *Fallopia convolvulus*, *Cirsium arvense*) preferred low salt content soils. High phosphorus content most influenced the % cover of *Hibiscus trionum* and *Amaranthus retroflexus*, but *Fallopia convolvulus* and winter wheat volunteers grew poorly in those fields (Table 3).

The survey periods exhibited varying levels of weed species dominance year by year. The most important species were *Stachys annua* and *Hibiscus trionum* in 2017, *Fallopia convolvulus* and *Chenopodium polyspermum* in 2018, spelt wheat volunteers and *Persicaria lapathifolia* in 2019, and *Echinochloa crus-galli* and *Datura stramonium* in 2020.

The surveyed area was relatively flat (altitude 78–86 m above mean sea level) but this factor also resulted in differences in weed composition. *Stachys annua* and *Triticum spelta* were more important on upland fields but *Cirsium arvense* and *Tripleurospermum inodorum* were frequent on low-lying fields.

Table 3. Names, score values, and fit of species giving the highest fit along the first constrained axis in the partial redundancy analysis (pRDA) models of soil variables in open-field pea experiment (Hungary, 2017–2020).

Species	Ax 1 Score	Fit	Species	Ax 1 Score	Fit
Alluvial meadow soil (+ high; − low)			Soil texture (Arany; + high; − low)		
Xanthium italicum	0.41	0.52	*Chenopodium album*	0.14	0.11
Hibiscus trionum	0.28	0.21	*Echinochloa crus-galli*	0.14	0.03
Setaria viridis	0.13	0.27	*Chenopodium polyspermum*	0.10	0.11
Avena fatua	0.11	0.15	*Tripleurospermum inodorum*	0.09	0.05
Triticum spelta	0.11	0.09	*Chenopodium hybridum*	0.02	0.05
Anagallis arvensis	−0.05	0.12	*Triticum aestivum*	−0.06	0.03
Chenopodium album	−0.13	0.10	*Avena fatua*	−0.09	0.10
Triticum aestivum	−0.17	0.25	*Fallopia convolvulus*	−0.11	0.02
Fallopia convolvulus	−0.33	0.22	*Triticum spelta*	−0.12	0.10
Convolvulus arvensis	−0.43	0.21	*Xanthium italicum*	−0.12	0.05
Clay soil (+ high; − low)			Salt content (+ high; − low)		
Tripleurospermum inodorum	0.23	0.32	*Convolvulus arvensis*	0.25	0.07
Persicaria lapathifolia	0.22	0.28	*Hibiscus trionum*	0.20	0.11
Chenopodium album	0.16	0.14	*Amaranthus retroflexus*	0.08	0.13
Triticum aestivum	0.14	0.17	*Phragmites australis*	0.06	0.21
Fallopia convolvulus	0.13	0.04	*Avena fatua*	0.05	0.03
Setaria viridis	−0.08	0.11	*Anagallis arvensis*	−0.05	0.10
Avena fatua	−0.10	0.11	*Chenopodium polyspermum*	−0.09	0.10
Hibiscus trionum	−0.14	0.05	*Tripleurospermum inodorum*	−0.11	0.07
Xanthium italicum	−0.15	0.07	*Cirsium arvense*	−0.13	0.06
Convolvulus arvensis	−0.23	0.06	*Fallopia convolvulus*	−0.23	0.11
Loamy-clay soil (+ high; − low)			Soil P_2O_5 content (+ high; − low)		
Convolvulus arvensis	0.57	0.38	*Hibiscus trionum*	0.16	0.07
Fallopia convolvulus	0.26	0.14	*Amaranthus retroflexus*	0.08	0.13
Triticum aestivum	0.09	0.07	*Avena fatua*	0.08	0.07
Anagallis arvensis	0.04	0.07	*Triticum spelta*	0.06	0.03
Setaria viridis	−0.08	0.12	*Setaria viridis*	0.05	0.05
Triticum spelta	−0.09	0.06	*Phragmites australis*	0.05	0.14
Persicaria lapathifolia	−0.17	0.17	*Ambrosia artemisiifolia*	0.05	0.04
Cirsium arvense	−0.19	0.12	*Chenopodium polyspermum*	0.04	0.02
Hibiscus trionum	−0.20	0.11	*Triticum aestivum*	−0.14	0.16
Xanthium italicum	−0.32	0.33	*Fallopia convolvulus*	−0.19	0.08

Approximately a 900 square kilometer large survey area (approx. 25 km by latitude and 36 km by longitude) was included in the data collection. In this landscape unit, the northern fields were more covered by *Stachys annua* and *Ambrosia artemisiifolia* but *Hibiscus trionum* and *Cirsium arvense* were more important in the south (Table 4).

Within the management variables, only farming system (with high collinearity to herbicide and fertilizer use and number of mechanical weed control applications) and tillage (collinearity to tillage depth) resulted in significant differences in weed flora.

Cirsium arvense, *Hibiscus trionum*, and *Chenopodium* spp. were the most problematic in organic fields, but conventional fields were infested mainly by *Convolvulus arvensis* and *Stachys annua*.

The abundance of *Tripleurospermum inodorum*, *Ambrosia artemisiifolia*, and *Fallopia convolvulus* was the highest in fields with the loosening type of tillage, whereas *Hibiscus trionum* and *Persicaria lapathifolia* appeared with higher frequency after ploughing (Table 5).

The ordination diagram of RDA of our experiment indicated a high correlation between soil texture, salt concentration, phosphorous content, and soil type; furthermore, latitude and altitude were also correlated with most soil parameters, but the effect of tillage seemed to have no correlation with these variables (Figure 3). The effects of farming systems and sampling year were less significant than the effect of soil parameters on weed composition.

Table 4. Names, score values and fit of species giving the highest fit along the first constrained axis in the partial redundancy analysis (pRDA) models of environmental variables in open-field pea experiment (Hungary, 2017–2020).

Species	Ax 1 Score	Fit	Species	Ax 1 Score	Fit
2017 (+ high; − low)			2018 (+ high; − low)		
Stachys annua	0.22	0.31	*Fallopia convolvulus*	0.51	0.55
Hibiscus trionum	0.21	0.12	*Chenopodium polyspermum*	0.13	0.22
Cirsium arvense	0.20	0.13	*Triticum aestivum*	0.13	0.14
Chenopodium hybridum	0.05	0.33	*Anagallis arvensis*	0.10	0.40
Calystegia sepium	0.04	0.23	*Amaranthus retroflexus*	0.09	0.17
Sinapis arvensis	0.04	0.24	*Phragmites australis*	0.05	0.15
Persicaria amphibia	0.02	0.10	*Lastuca serriola*	0.04	0.14
Trifolium repens	0.01	0.22	*Amaranthus albus*	0.01	0.14
Chenopodium album	−0.20	0.21	*Avena fatua*	−0.12	0.16
Echinochloa crus-galli	−0.33	0.19	*Convolvulus arvensis*	−0.33	0.13
2019 (+ high; − low)			2020 (+ high; − low)		
Triticum spelta	0.17	0.21	*Echinochloa crus-galli*	0.61	0.64
Persicaria lapathifolia	0.17	0.16	*Datura stramonium*	0.17	0.53
Tripleurospermum inodorum	0.16	0.15	*Avena fatua*	0.14	0.22
Brassica napus	0.06	0.14	*Ambrosia artemisiifolia*	0.07	0.06
Consolida regalis	0.04	0.14	*Bromus tectorum*	0.01	0.10
Rubus caesius	0.03	0.13	*Anagallis arvensis*	−0.04	0.07
Anagallis arvensis	−0.05	0.10	*Triticum aestivum*	−0.11	0.11
Datura stramonium	−0.09	0.14	*Persicaria lapathifolia*	−0.13	0.09
Chenopodium polyspermum	−0.13	0.22	*Tripleurospermum inodorum*	−0.13	0.11
Hibiscus trionum	−0.20	0.11	*Fallopia convolvulus*	−0.14	0.04
Altitude (+ high; − low)			Latitude (+ high; − low)		
Stachys annua	0.18	0.19	*Stachys annua*	0.17	0.19
Triticum spelta	0.12	0.11	*Ambrosia artemisiifolia*	0.10	0.13
Setaria viridis	0.08	0.10	*Triticum spelta*	0.09	0.06
Phragmites australis	0.05	0.11	*Setaria viridis*	0.06	0.07
Anagallis arvensis	0.03	0.04	*Anagallis arvensis*	0.04	0.06
Chenopodium album	−0.09	0.04	*Phragmites australis*	0.03	0.04
Chenopodium polyspermum	−0.11	0.16	*Chenopodium album*	−0.11	0.06
Hibiscus trionum	−0.13	0.05	*Chenopodium polyspermum*	−0.12	0.20
Tripleurospermum inodorum	−0.14	0.12	*Cirsium arvense*	−0.15	0.08
Cirsium arvense	−0.16	0.09	*Hibiscus trionum*	−0.18	0.10

Table 5. Names, score values and fit of species with the highest fit along the first constrained axis in the partial redundancy analysis (pRDA) models of management variables in open-field pea experiment (Hungary, 2017–2020).

Species	Ax 1 Score	Fit	Species	Ax 1 Score	Fit
Farming (+ organic; − conventional)			Tillage (+ loosening; − ploughing)		
Cirsium arvense	0.22	0.16	*Tripleurospermum inodorum*	0.15	0.13
Hibiscus trionum	0.21	0.12	*Ambrosia artemisiifolia*	0.14	0.29
Chenopodium polyspermum	0.15	0.29	*Fallopia convolvulus*	0.12	0.03
Chenopodium album	0.11	0.07	*Anagallis arvensis*	0.03	0.04
Persicaria lapathifolia	0.10	0.06	*Amaranthus retroflexus*	−0.05	0.04
Tripleurospermum inodorum	0.10	0.06	*Chenopodium polyspermum*	−0.05	0.03
Chenopodium hybridum	0.02	0.05	*Chenopodium album*	−0.07	0.02
Triticum spelta	−0.10	0.08	*Xanthium italicum*	−0.08	0.02
Stachys annua	−0.14	0.12	*Persicaria lapathifolia*	−0.10	0.06
Convolvulus arvensis	−0.23	0.06	*Hibiscus trionum*	−0.15	0.07

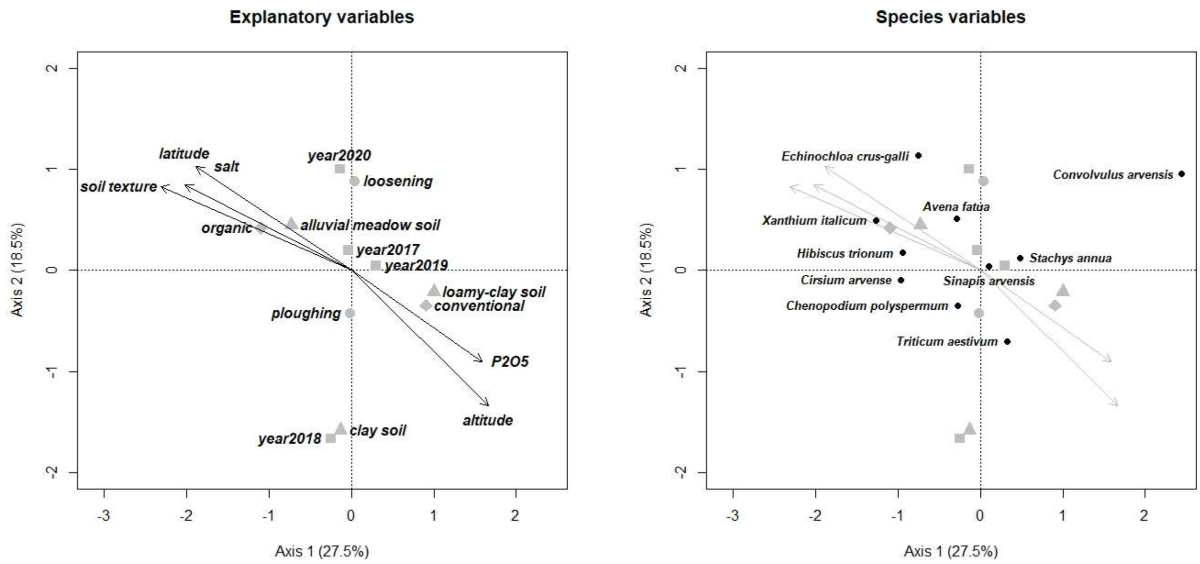

Figure 3. Ordination diagrams of the reduced redundancy analysis (RDA) model containing the significant explanatory variables for explanatory variables and species. (Arrow: numeric variable; triangle: factorial soil variable; square: factorial environmental variable; gray circle: factorial management variable; black circle: species).

Echinochloa crus-galli and *Xanthium strumarium* were frequently associated with high salt concentrations and organic farming but were less frequent in fields with higher phosphorous content and higher altitude. The effect of tillage was also indicated by the weed composition; *Triticum aestivum* and *Chenopodium polyspermum* were more abundant in ploughed fields, whereas *Echinochloa crus-galli* and *Convolvulus arvensis* preferred fields with the loosening type of tillage (Figure 3).

4. Discussion

The high total number of recorded weed species (38) illustrated the species richness of pea fields. The range of dominant weed species varied from field to field, but there were not clear relationships between the calculated diversity (Shannon) and the environmental, soil, and management variables.

The investigated areas were characterized by compacted soils with poor water management, unfavorable nutrient supply, and heavy weed infestations. In the studied production areas, it was particularly characteristic that unfavorable weather conditions during the sowing and emergence of peas might result in insufficient stocks, which was observed in both conventional and organic fields during the study period. These unfavorable growing conditions and improperly developing stands evidently provided space for emerging weeds in our current study.

In conventional farming, many herbicides can be used in pea culture, which can be effective against most weed species. On the other hand, in ecologically managed areas, post-emergence weed control is accomplished by possible weed harrowing and hoeing. In the course of the study, in some cases, % weed cover in organic areas was almost twice as much (18.1%) as in conventional areas (9.3%); these results were similar to those of Dorner [58] who demonstrated the weed cover of 9.8% on organic pea fields compared to 3.8% in conventional farming. This level of weed infestation seems high, but it may be tolerable in the case of a densely sown crop [59]. In addition to the weed cover, the weed flora also changed significantly by farming system (5.8% in RDA model), similar to previous works [60–62].

As the other significant management factor (3.0% in RDA model), the different tillage regimes (ploughing or loosening) also resulted in differences in weed composition. However, the loosening may result a near-surface layer with a high weed seedbank, where weed emergence is promoted regardless of the size of the weed seeds, and some of the seeds are ploughed into a deeper layer, so the germination of small seeded species is more restricted [31,63]. We found that the medium- (*Hibiscus trionum* [64], *Persicaria lapathifolia* [65], *Chenopodium* spp. [66]) and large-seeded (*Xanthium* spp. [67]) species were more reduced by ploughing in our study.

Examining the results further, it can be concluded that environmental factors had the greatest influence on weed infestation (23.1%). Of all the factors studied, the year of the survey (15.6%) had the greatest influence on weed infestation. In the case of survey periods, most of the difference can be explained by differences in rainfall [68]. In the survey area, the aggregated 20 year (2001–2020) average rainfall between January and June was 277 mm, compared to 184, 330, 328, and 293 mm between 2017 and 2020, respectively [69], and years with the most and least rainfall showed the largest differences. Similarly, Lososová et al. [57] found that increasing precipitation is one of the most determining factors in weed species composition associated with increasing altitude and decreasing temperature and soil condition. The effect of precipitation on weed vegetation has also been confirmed in a comparison of different European agroecological regions [70].

Soil-related variables were also prominent (21.3%), of which soil type (10.0%) had the greatest effect on weeds, similar to that described in [71]. However, the effect of soil type cannot be interpreted in isolation because it is related to other soil parameters [72]. High values of soil texture resulted in a high abundance of weed *Chenopodium* species; this effect was also detectable for Quinoa (*Ch. quinoa*) when clay-rich soil structure was combined with high nutrient (P, K) content [73]. The surveyed fields showed only a limited salinity, but weed composition was influenced by this factor, too, as assumed by Borhidi [19].

Field peas show higher weed infestation and weed biomass than other densely planted crops such as cereals [60,74]. Comparing our results with the results of the Sixth National Field Weed Survey on Hungary for winter wheat, for which the survey period was similar to our study, there were similarities between several species and cover values. For the top 20 weed species, six species were identical, including two weed species *Chenopodium album* and *Fallopia convolvulus*, which had cover values less than 0.2% different from each other. In addition, *Ambrosia artemisiifolia*, *Tripleurospermum inodorum*, *Convolvulus arvensis*, and *Cirsium arvense* were also found among the top 20 weed species in both studies [75]. On the other hand, the weed community of pea is more diverse and has higher evenness than cereals or pea-cereal intercropping [76].

There were also several differences between the results of our research and the Sixth National Field Weed Survey on Hungary for winter wheat. In our study, cereal (*Triticum aestivum* and *T. spelta*) and oilseed rape (*Brassica napus*) volunteers and several summer annuals, e.g., *Echinochloa crus-galli*, *Xanthium italicum*, *Hibiscus trionum*, *Avena fatua*, *Setaria viridis*, *Datura stramonium*, *Chenopodium polyspermum*, *Persicaria lapathifolia*, *Stachys annua*, *Amaranthus retroflexus*, and *Anagallis arvensis* were all prominent weeds. These results are in line with Dorner's research [58], in which the summer annual *Ambrosia artemisiifolia* was the most dominant. In contrast, in the Sixth National Field Weed Survey [75], the most prominent weeds of winter wheat included mainly winter annuals, e.g., *Stellaria media*, *Apera spica-venti*, *Veronica* spp., *Papaver rhoeas*, *Consolida* spp., *Galium aparine*, *Descurainia Sophia*, *Lamium* spp., *Capsella bursa-pastoris*, and *Anthemis arvensis,* but sunflower (*Helianthus annuus*) and *Lolium multiflorum* were also dominant.

Patterns in weed frequency seen in our results differed from those in Northern Europe, where *Viola arvensis*, *Chenopodium album*, *Stellaria media*, *Galeopsis* spp., and *Elymus repens* were present in most fields (44, 43, 42, 39, and 34%, respectively) [62].

5. Conclusions

The unique nature of the weed flora of peas in comparison to the weed flora of cereals is not clear. However, both cereals and field pea are generally densely planted crops, and they have a similar growing season. The many identified differences may be based on less % cover of field pea than cereals prior to harvest.

Since several factors influence the weediness of agricultural land simultaneously, it is essential to monitor and analyze these variables at the same time because some variables may have confounding or opposing effects on each other.

Although weed control is the cornerstone of plant protection in organic farming, the management systems differed mainly in the amount of weeds, whereas the weed flora differed less, despite the absence of herbicide use and different nutrient management methods.

During the data preparation, several variables were eliminated because of collinearity. Tillage depth was correlated with the tillage method; the number of mechanical weed control applications, amount of MCPB herbicides and fertilizers (N, P_2O_5, and K_2O) were highly correlated with the farming system; and spring dense preceding crops were highly correlated with other preceding crops. Additionally, several other factors did not have a significant effect on weed composition, such as soil chemistry, humus, $CaCO_3$ and K_2O content, longitude, and winter and spring row preceding crops. This elimination of various parameters in our analysis process suggests a need to survey these parameters on a longer gradient or limit the surveyed factors in further studies and have a greater focus on important key factors.

The year of the study and the soil parameters were found by the redundancy analysis to have the greatest effect on weed composition. The studied years differed most in terms of rainfall. However, variation in rainfall in the study years is consistent with variation in weed composition. The influence of this factor can only be demonstrated for the region under study or for a region like it. Likewise, the explanatory effect of soil variables can only be interpreted in areas characterized by similar soil parameters. The weed flora of different agroecological regions can vary considerably.

The effect of the extent of weed infestation and the weed flora on yield was not included in the research, although it is known that adequate management of weeds is largely responsible for the success of farming. In order to assess the usefulness of the soil, environmental, and management variables included in this research for farmer practice, further research should also examine the impact of these variables on yield.

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Appendix A

Table A1. Soil variables and measured values of sampling sites.

Nr of Field	Soil Type	Soil Texture	Soil Reaction	Soil Properties				
				Salt	Humus	$CaCO_3$	P_2O_5	K_2O
		[Arany]	[pH KCl]		m/m %		mg · kg^{-1}	
1	Loamy-clay soil	45	7.08	0.03	3.11	2.91	134	356
2	Alluvial meadow soil	52	6.85	0.06	2.21	0.42	57	312
3	Alluvial meadow soil	53	6.73	0.06	2.05	0.51	54	309
4	Alluvial meadow soil	57	6.87	0.07	1.74	0.63	46	268
5	Alluvial meadow soil	60	6.18	0.07	1.96	0.18	41	253
6	Alluvial meadow soil	60	6.27	0.07	1.90	0.25	45	282
7	Alluvial meadow soil	63	6.17	0.07	2.08	0.33	56	273
8	Alluvial meadow soil	52	6.25	0.11	2.19	0.10	132	494
9	Alluvial meadow soil	54	6.70	0.11	1.82	0.24	204	385
10	Loamy-clay soil	46	6.53	0.03	2.55	0.08	325	309
11	Loamy-clay soil	48	6.96	0.03	3.25	1.30	286	383
12	Clay soil	52	5.63	0.06	3.75	0.08	220	501
13	Loamy-clay soil	49	6.57	0.05	3.32	0.08	420	455
14	Alluvial meadow soil	55	7.03	0.09	2.20	0.38	136	375
15	Alluvial meadow soil	56	6.10	0.08	1.99	0.23	48	278
16	Alluvial meadow soil	63	5.96	0.07	1.94	0.35	41	268
17	Alluvial meadow soil	63	6.25	0.08	1.97	0.29	77	266
18	Clay soil	52	5.73	0.07	3.38	0.08	203	481
19	Clay soil	53	5.83	0.06	3.66	0.10	237	541
20	Loamy-clay soil	49	6.57	0.06	3.37	0.11	382	480
21	Loamy-clay soil	49	6.53	0.04	3.26	0.08	399	437
22	Loamy-clay soil	49	6.82	0.05	3.68	0.42	278	546
23	Loamy-clay soil	49	6.57	0.05	3.32	0.08	420	455
24	Alluvial meadow soil	57	6.95	0.06	1.98	0.65	68	274
25	Alluvial meadow soil	59	6.24	0.05	1.85	0.25	62	281
26	Alluvial meadow soil	57	6.97	0.09	2.89	1.66	338	295
27	Alluvial meadow soil	54	6.94	0.09	2.72	1.58	351	425
28	Loamy-clay soil	50	6.90	0.04	3.73	0.38	238	523
29	Loamy-clay soil	47	6.81	0.05	3.57	0.43	159	465
30	Loamy-clay soil	50	6.86	0.06	3.48	0.51	338	515
31	Loamy-clay soil	49	6.77	0.06	3.66	0.44	316	538

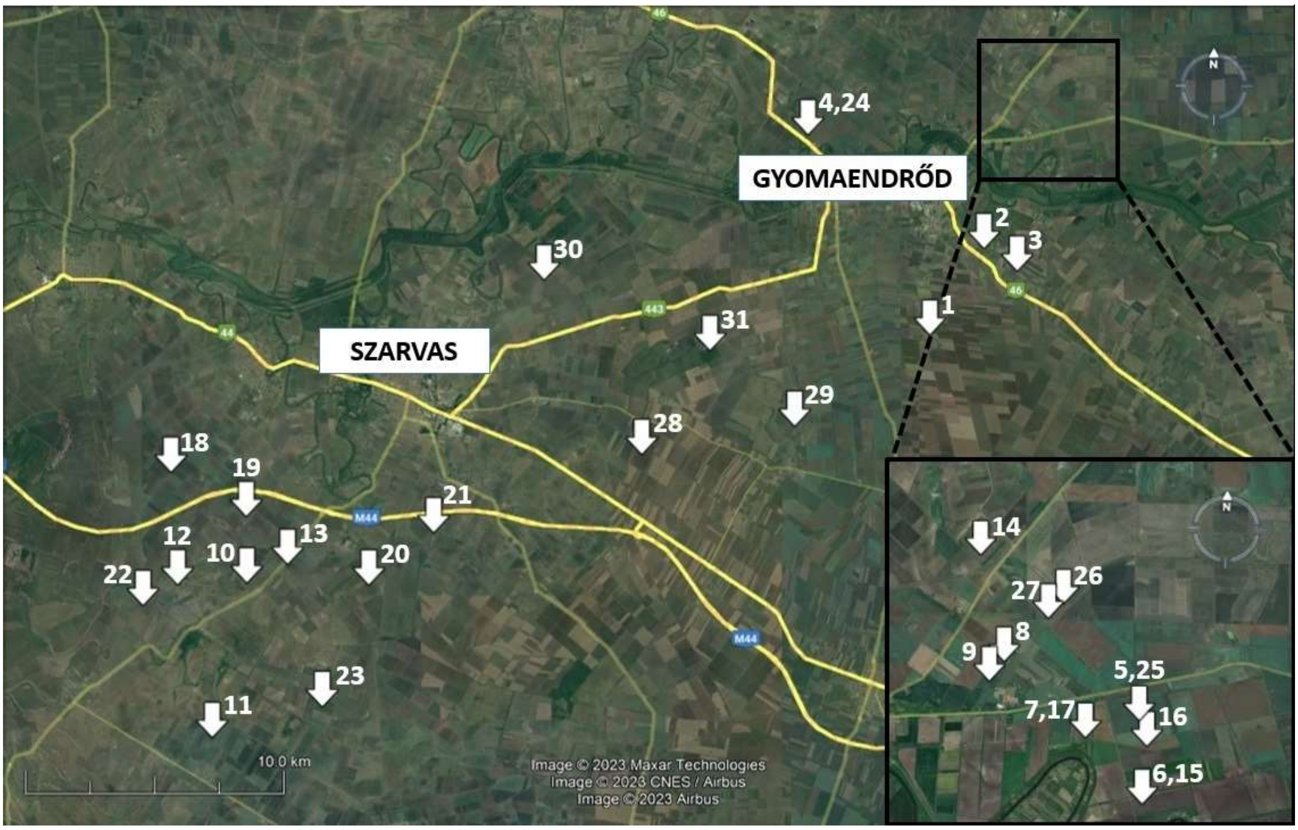

Figure A1. Location of fields in the survey area.

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