Hungarian University of Agriculture and Life Sciences

THE IMPACT OF ENVIRONMENTAL AND MANAGEMENT FACTORS ON WEED COMPOSITION IN MAIZE AND WINTER WHEAT IN EASTERN HUNGARY

Doctoral (PhD) dissertation theses

Erzsébet Tóth

Gödöllő

2025

Doctoral School

name: Agricultural and Food Sciences Doctoral School

research field: Crop and Horticultural Sciences

head: Dr. Kovács Melinda

Professor, Member of HAS

topic leader: Dr. Mihály Zalai

Associate professor, PhD

Hungarian University of Agriculture and Life Sciences

Plant Protection Institute

Department of Integrated Plant Protection

....

Approval of the head of
Doctoral School

Approval of the topic leader

1. INTRODUCTION AND OBJECTIVES

The structure of Hungarian arable crop production has undergone significant changes in recent decades due to both environmental and economic factors. Production is becoming increasingly unpredictable as a result of global market fluctuations, as well as the extremes in precipitation distribution and temperature anomalies associated with climate change (EUROPEAN ENVIRONMENT AGENCY 2024). A key to sustainable and efficient crop production is a thorough understanding and management of weed communities, especially in major crops such as maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.).

According to FAOSTAT data, wheat was grown on 244,036,272 hectares globally in 2023, while maize occupied 252,491,120 hectares. The two crops investigated also cover extensive areas in Hungary and are of strategic importance: based on 2024 data from the Hungarian Central Statistical Office, the maize sown area in Hungary amounted to 906,800 hectares, while that of winter wheat reached 874,600 hectares (KSH 2025). Wheat is primarily used as a raw material in the food industry, while maize is mainly used for fodder and industrial purposes (e.g. bioethanol).

Weed control is a particularly critical issue for both crops, as weed competition can cause substantial yield losses even at low cover levels (TEASDALE et al. 2010; FLESSNER et al. 2021; ADEUX et al. 2019). The continuously changing environmental conditions and growing weed management challenges require the re-evaluation of agronomic practices. The composition and cover of weed flora are shaped by a combination of factors, including soil physical and chemical parameters, climatic conditions, preceding crops, tillage methods, and the amount and type of nutrients applied. The weed vegetation of the two crops examined can also be clearly distinguished from an ecological perspective: in winter wheat, cold-tolerant species germinating in early spring typically dominate. In contrast, maize fields often exhibit a mass emergence of early-summer, heat- and light-demanding weeds, particularly during the spring emergence and early growth period.

The range of available herbicides is narrowing in both the European Union and Hungary, which makes effective weed control even more challenging (NEBIH 1,2 2025). Therefore, the use of non-chemical methods—such as mechanical weed control, crop rotation, and targeted tillage—is becoming increasingly important. The application of integrated weed management principles has become indispensable. For its effective implementation, accurate mapping of weed

vegetation and the identification of environmental and agronomic factors influencing weed dynamics are essential.

The aim of my doctoral research was to determine which environmental (primarily soil physical, chemical, and geographical) and management factors exert a decisive influence on weed vegetation in the investigated wheat and maize fields. The studies were conducted between 2018 and 2021, in three regions for maize and four regions for wheat, each differing in their characteristics. Particular attention was given to separating the effects of factors that are critical for weed control and distinguishing between variables that are manageable or non-manageable by farmers, thus contributing to the development of a targeted, site-specific weed management strategy. In both crops, my objectives included exploring the weed flora composition prior to weed control interventions, evaluating weed cover of each species and diversity, and examining their relationships with various environmental (soil and weather) and management (tillage, preceding crop, nutrient supply) variables. Weed surveys were conducted using a unified methodology, independently but in a comparable manner in the two crops. I evaluated the results using analysis of covariance (ANCOVA) and redundancy analysis (RDA). The following research questions guided the study:

• Which weed species are the most frequent and have the highest cover in winter wheat and maize in the studied regions?

• What levels of species richness, cover, and diversity characterize the weed flora of these areas, and how do these vary across regions, years, and production technologies?

• Which soil (e.g. humus content, pH, micro- and macronutrients), environmental (e.g. climatic characteristics, geographical coordinates), and agricultural (e.g. tillage, nutrient supply, preceding crop) variables most strongly influence the composition, species richness, and weediness of the weed flora in both crops?

•Can specific weed species be identified as indicators for certain farming systems or environmental conditions in the examined regions?

• To what extent do farmer-controlled factors (e.g. type of tillage, fertilisation, crop rotation) influence weed community structure compared with the effects of climate and region?

2. MATERIAL AND METHOD

Study conditions

My research was conducted between 2018 and 2021 in the eastern region of Hungary, covering the counties of Borsod-Abaúj-Zemplén, Szabolcs-Szatmár-Bereg, Hajdú-Bihar and Békés. Over the four-year study period, I analysed weed flora in maize and winter wheat. For more accurate evaluation, the study sites were divided into regions based on a classification that considered soil and geographical characteristics. Using administrative county boundaries would not have been appropriate, as such an approach may disregard environmental factors that directly influence production techniques and thus the development of weed flora.

The maize-related investigations were carried out in three distinct regions, across a total of 90 fields. The first region encompassed the Sajó–Hernád plain. The second region was established by combining several micro-regions with similar agroecological characteristics, including the Szoboszlói-Hajdúság, the Hajdúhát, the Löszös-Nyírség, and the Nagykállói-Nyírség. The third study unit was the Körös-menti plain (Figure 1).
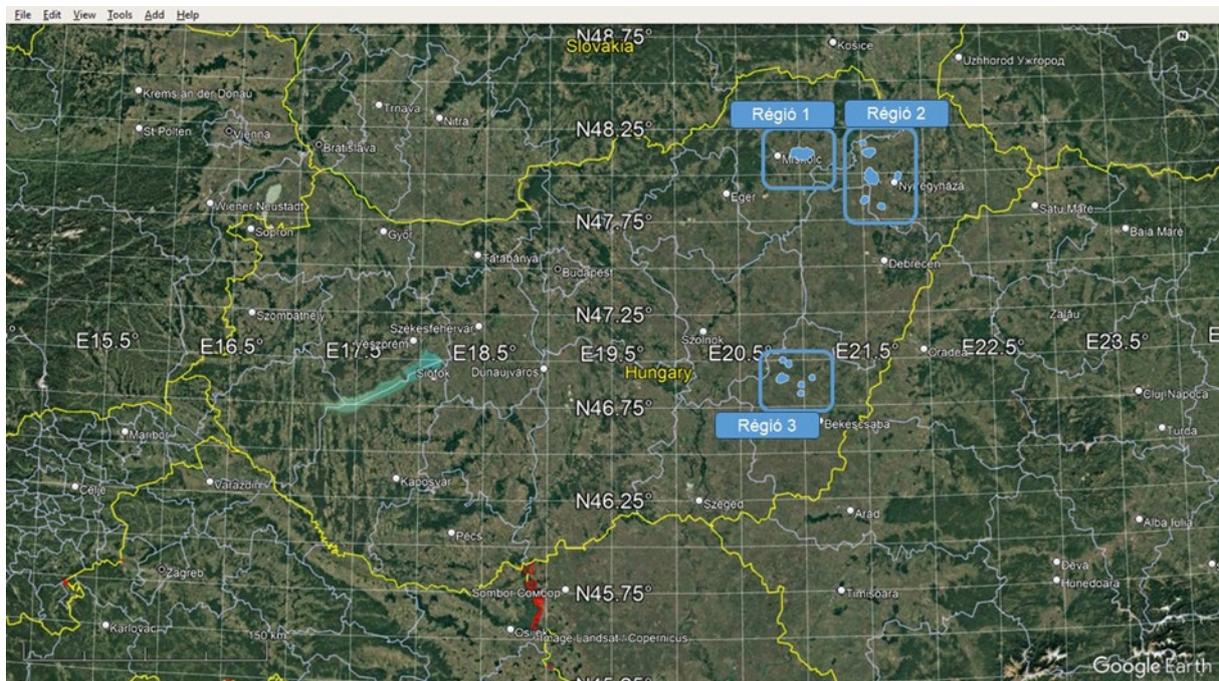

Figure 1. Locations of the maize surveys on the map of Hungary

(GOOGLE EARTH, 2025)

The weed surveys in winter wheat were conducted at 103 field sites, classified into four regions, following a similar approach to that used for maize, taking soil and geographical conditions into account. The first region consisted of the Harangod area and the Sajó–Hernád plain. Region 2a was formed by merging five micro-regions with similar characteristics: the Szoboszlói-Hajdúság, the Hajdúhát, the Löszös-Nyírség, the Nagykállói-Nyírség, and the Nyírbátori–Kisvárdai Nyírség. Region 2b represented the Rétköz area, while the third region comprised the Körös-menti plain (Figure 2).
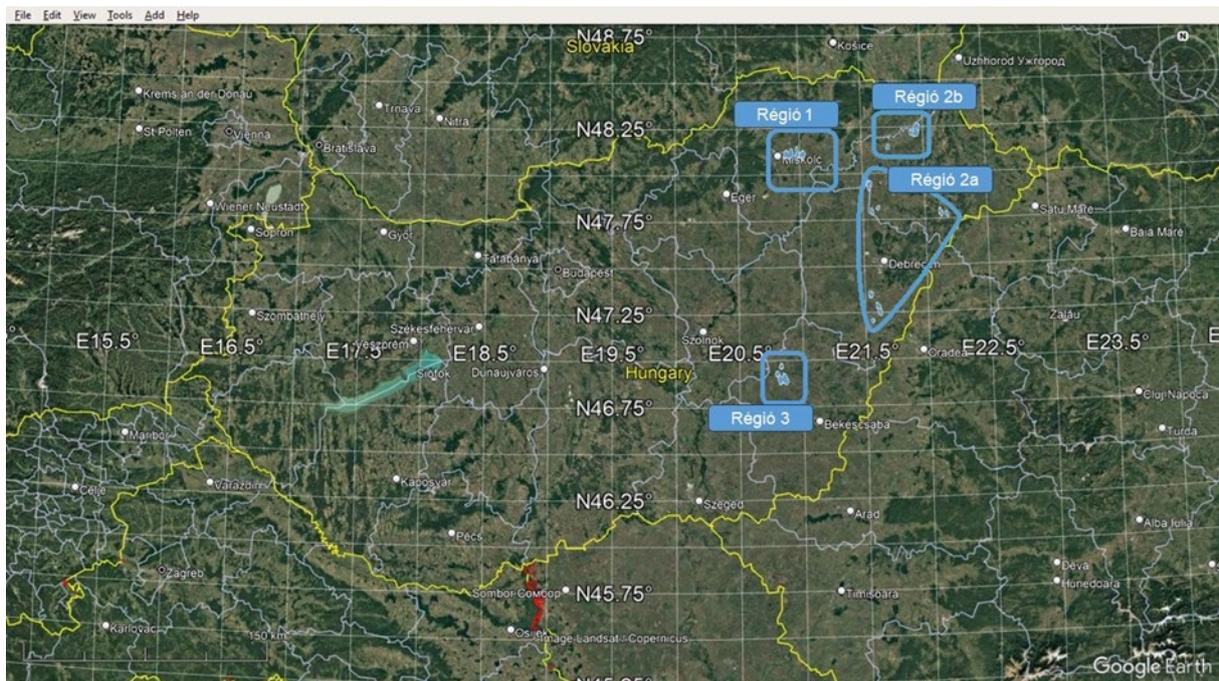

Figure 2. Locations of the winter wheat surveys on the map of Hungary
(GOOGLE EARTH, 2025)

Survey methods

To determine weed composition, all observed species (or genera) were recorded, along with their cover values—i.e. the proportion of soil surface covered by the aboveground parts of the weeds (VAN DER MAAREL et al. 2013). Sampling was carried out in eight randomly selected 1×1 m quadrats per field, keeping a minimum distance of 10 metres from the field edge (ZALAI et al. 2012). For all subsequent analyses, the average values per field were calculated. This sampling method is not suitable for documenting species occurring outside the quadrats, and such species were not included in any form in the analyses or evaluations. The exclusion of species outside the quadrats was necessary to ensure that every study in the thesis was based

on sampling areas of identical size and structure, thereby enabling reliable comparisons between fields.

Scientific names of weed species and genera were identified according to the EPPO database (EPPO 2025). In cases where species-level identification was not possible (e.g. *Consolida* spp.), plants were treated at the genus level. If a species encompassed multiple taxa (sensu lato), the polymorphic species name was used, for example in the case of *Veronica hederifolia*. The classification of weed species as life forms was determined based on UJVÁROSI (1973).

The timing of the weed surveys—between 19 March and 8 May in winter wheat, and between 8 May and 10 July in maize—was aligned with planned herbicide applications. In each case, data collection was carried out 1–8 days prior to herbicide treatment to ensure the most complete documentation of the weed vegetation. The surveys were conducted before any mechanical weed control took place. Due to this connection, the "survey timing" variable was included among the management variables.

In addition, soil-related ("soil variables"), environmental ("environmental variables"), and management ("management variables") factors influencing weed vegetation were recorded at each site. The soil variables included soil texture, soil pH, salinity, humus content, and concentrations of nitrogen, phosphorus, potassium, lime, sodium, magnesium, sulphur, copper, manganese, and zinc. Environmental variables recorded included the geographical coordinates (longitude and latitude), elevation above sea level (numeric variables), the year of the survey, and regional classification (categorical variables).

Field size was also recorded, based on the assumption that variations in the edge-to-area ratio may influence weed vegetation and weed control opportunities.

The preceding crop or vegetation of the three years prior to the study year was also documented. In the analyses, a weighted proportion of preceding crops was used, following the formula:

(preceding crop 1 × 0.6) + (preceding crop 2 × 0.3) + (preceding crop 3 × 0.1).

Accordingly, if a given preceding crop type had not occurred in any of the three previous years, its value for that field was recorded as "0", whereas if the same preceding crop occurred in all three years, the value was "1".

The type and depth of tillage applied before the study year were also recorded. In maize fields, three categories of tillage were distinguished: "shallow tillage" performed with a disc harrow or cultivator at a depth of 15–20 cm; "ploughing" at 20–35 cm; and "deep loosening" at 30–40 cm.

In wheat fields, four tillage types were identified: "disc tillage" (12–16 cm), "shallow cultivator tillage" (10–25 cm), "ploughing" (20–30 cm), and "deep loosening" (30–40 cm). In the statistical analyses, tillage type was treated as a categorical variable, while tillage depth was treated as a continuous variable.

The evaluation also included the amounts of nitrogen (N), phosphorus (P) and potassium (K) applied (in kg/ha of active ingredient) before the surveys in each growing season.

Applied mathematical and statistical methods

For the statistical and content-based evaluation of the results, weed cover data collected from maize and winter wheat fields were analysed separately for each crop.

Before beginning the statistical analyses, the weed cover values of the eight quadrats were averaged for each field to obtain field-level mean weed composition.

To assess the general importance of weed species, the untransformed mean cover and constancy (i.e. the proportion of fields in which the species occurred) were calculated for each species.

The field-level averages were then subjected to Hellinger transformation (BORCARD et al. 2011), which served as the basis for subsequent multivariate analyses.

To explore relationships among explanatory variables, generalized variance inflation factors (GVIF) and variance inflation factors derived from these (VIF = GVIF^(1/(2 df))) were calculated. The results indicated strong correlations between geographical variables (altitude, latitude, longitude) and regional classification, as well as between tillage type and tillage depth. Despite these correlations, all variables were retained in the statistical models in order to determine which of the correlated variable pairs had a greater explanatory effect. Moderate correlations were also observed between regional classifications and soil properties—an expected outcome, as the regions were partly defined based on edaphic characteristics.

However, apart from geographical variables and regional classification, all VIF values remained below 5 (FOX et al. 2016), indicating acceptable levels of multicollinearity.

To quantify weed diversity, the Shannon diversity index (H') was calculated for each field using untransformed cover values. The index was computed using the formula:

$$H' = -\sum_{(i=1)}^{R} p_i \ln p_i$$

where R denotes the total number of species in the field and p_i represents the proportion of total cover belonging to species i (SHANNON 1948).

The first analytical step was an analysis of covariance (ANCOVA), conducted to determine which environmental and management variables exert significant effects—based on separate ANCOVA models—on total weed cover, species richness, and the Shannon diversity index (CHAMBERS et al. 1992).

When ANCOVA results indicated significant effects for continuous variables, Pearson correlation coefficients were calculated to determine the strength and direction of the relationships (SOPER et al. 1917). The strength of correlations was interpreted according to the absolute value of the coefficients: 0–0.19: very weak; 0.20–0.39: weak; 0.40–0.59: moderate; 0.60–0.79: strong; 0.80–1.00: very strong.

For categorical variables showing significant effects in ANCOVA, pairwise comparisons of factor levels were performed using Tukey's post hoc test to identify statistically supported differences (KESELMAN et al. 1977).

The next analytical step involved redundancy analysis (RDA) to examine how soil, environmental, and management variables jointly influenced weed species composition (MUELLER-DOMBOIS 1976). To refine the model, backward selection was applied (SUTTER 1993), resulting in a simplified model consisting of ten explanatory variables for maize and nine for winter wheat. The RDA aimed to quantify the total (gross) and unique (net) contributions of each significant explanatory variable to variation in weed species composition (i.e. species occurrence variance). The ranking of variable importance was based on adjusted R² values derived from partial RDA models, representing the independent effects of each variable.

To further explore relationships between major explanatory variables and weed species, the ten weed species showing the highest variability along the axes generated by the RDA—both the full and partial models—were identified for each crop, excluding species that occurred in fewer than three fields.

For both crops, all statistical analyses were performed at a 95% confidence level using the R statistical environment (R Development Core Team, version 4.5.0), with the following R packages: car (v3.1–3), lattice (v0.22–7), MASS (v7.3–65), permute (v0.9–7), and vegan (v2.6–10).

3. RESULTS AND THEIR DISCUSSION

Weed Flora of Maize Fields

Between 2018 and 2021, a total of 51 weed species were identified in the surveyed maize fields. On average, the highest cover values were shown by *Echinochloa crus-galli* (2.0%), *Chenopodium album* (1.4%), *Portulaca oleracea* (0.9%), and *Hibiscus trionum* (0.8%). Together, these four species accounted for more than half (52%) of the total weed cover. Overall, the 20 most dominant species were responsible for 95% of the total weed cover. The average weed cover was 9.7%; however, the extent of weed infestation varied considerably among fields. The lowest recorded weed cover was 0.1%, while the highest value reached 37.5% (Figure 3).
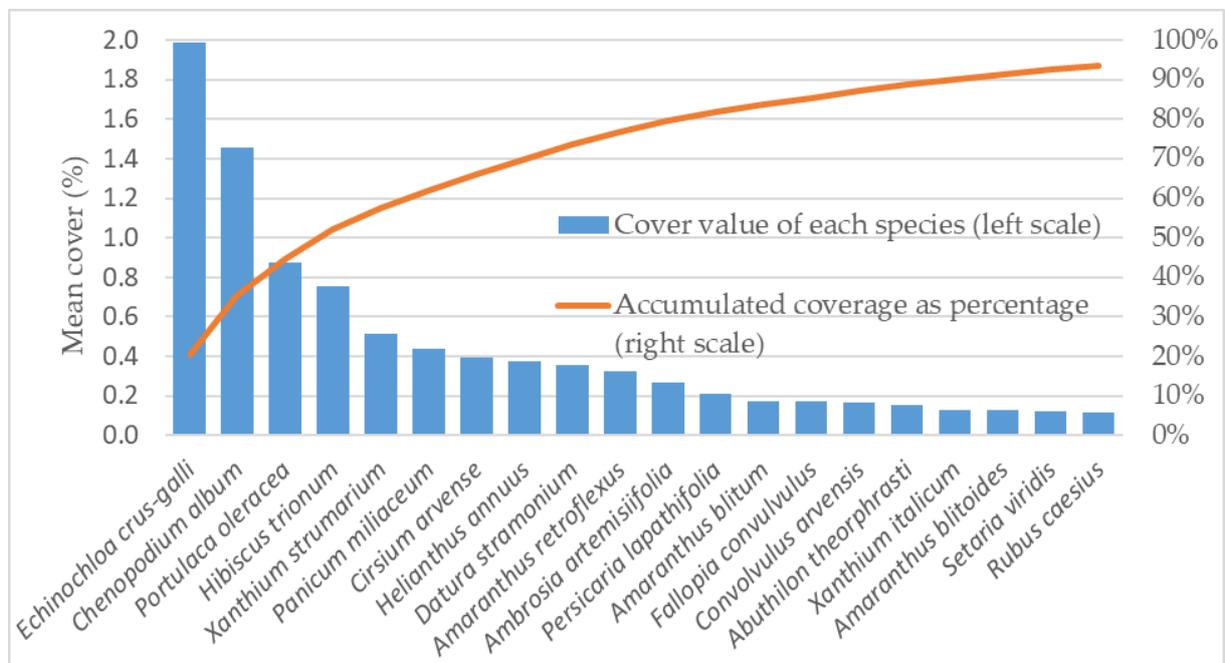

Figure 3. Average cover percentage of the most common weed species occurring in the surveyed maize fields

In most cases, I found a close relationship between weed cover and frequency of occurrence. This relationship is well illustrated by the dominance of *Echinochloa crus-galli* and *Chenopodium album*, followed by *Hibiscus trionum* and volunteer *Helianthus annuus*. At the same time, certain species such as *Convolvulus arvensis* showed high constancy values despite low cover, whereas *Portulaca oleracea*—which reached the third highest cover—occurred in only 21% of the surveyed fields. Some species, such as *Helianthus annuus*, exhibited high

occurrence rates even with moderate cover, while others—such as *Portulaca oleracea*—achieved considerable cover but were less frequently present.

Based on the results of the study, several soil, nutrient, and environmental factors influenced the weed vegetation of maize fields. Soil texture and pH showed medium to weak positive relationships with species richness and Shannon diversity, while humus content increased species number only slightly. Among macronutrients, soil phosphorus and potassium levels did not show notable effects, whereas nitrogen exhibited a negative correlation with diversity and species richness. Among meso- and micronutrients, several elements (zinc, sodium, magnesium, sulfur, copper, manganese) positively affected weed species number, diversity, or cover. Among environmental factors, altitude increased weed cover, while longitude reduced species richness. Differences were also observed between regions: Region 2 was less weedy than Regions 1 and 3. Of the surveyed years, 2019 showed the highest species richness, and differences in weed cover were detectable only between 2019 and 2020. Within-year variation showed that later surveys resulted in higher weed cover but lower diversity. Field size played no role, whereas tillage did: shallow tillage reduced species number and diversity. Fertilization results indicated that nitrogen and phosphorus fertilizers increased species richness and/or cover, while potassium fertilization had a beneficial effect on both cover and species number.

According to the results of the redundancy analysis, ten environmental and management factors significantly influenced the weed species composition of the maize fields, collectively explaining one-quarter of the total variance. Region had the strongest effect, followed by year, tillage method, and the amount of nitrogen applied. Soil-related factors—primarily humus content and zinc levels—also played noticeable, though smaller, roles. Notably, the combined effect of factors directly influenced by farmers was nearly equal to that of the environmental background factors.

The multivariate analysis revealed that humus-rich soils favoured the spread of *Chenopodium album*, *Amaranthus retroflexus*, and *Polygonum aviculare*, while the presence of certain *Amaranthus* species and ragweed decreased. Among micronutrients, zinc played an exceptionally important role: it increased, among others, the cover of white goosefoot and bindweed species, while other weeds—such as jimsonweed or various *Panicum* species—declined. Fertilization practices also had a substantial shaping effect: nitrogen supply increased the appearance of certain species (e.g. *Convolvulus arvensis*, *Xanthium italicum*), while

reducing others. Phosphorus fertilization particularly increased the occurrence of *Hibiscus trionum* and several annual weeds.

Weed composition varied considerably from year to year, with each study year elevating different species to dominant roles. Significant regional differences also emerged: in the nutrient-rich areas of Region 1, high-nutrient-demanding weeds were common, whereas Region 2 was generally poorer in nutrients and had a different species assemblage; Region 3, in turn, was characterized by species such as *Cirsium arvense* and *Datura stramonium*. The timing of weed surveys also affected species occurrence: some species were more common later in the season, while others were more frequent earlier. Field size also played a role, as larger fields favoured different species than smaller ones. The effect of the preceding crop was also detectable, particularly after wide-row cultures, which promoted the spread of several important weed species. The method of tillage strongly shaped species composition: deep loosening and ploughing favoured different species, while shallow cultivation resulted in a markedly different dominant weed flora. Overall, the RDA clearly showed that the spatial and temporal patterns of weed vegetation are intricately linked to soil characteristics, nutrient availability, and the agricultural practices applied.
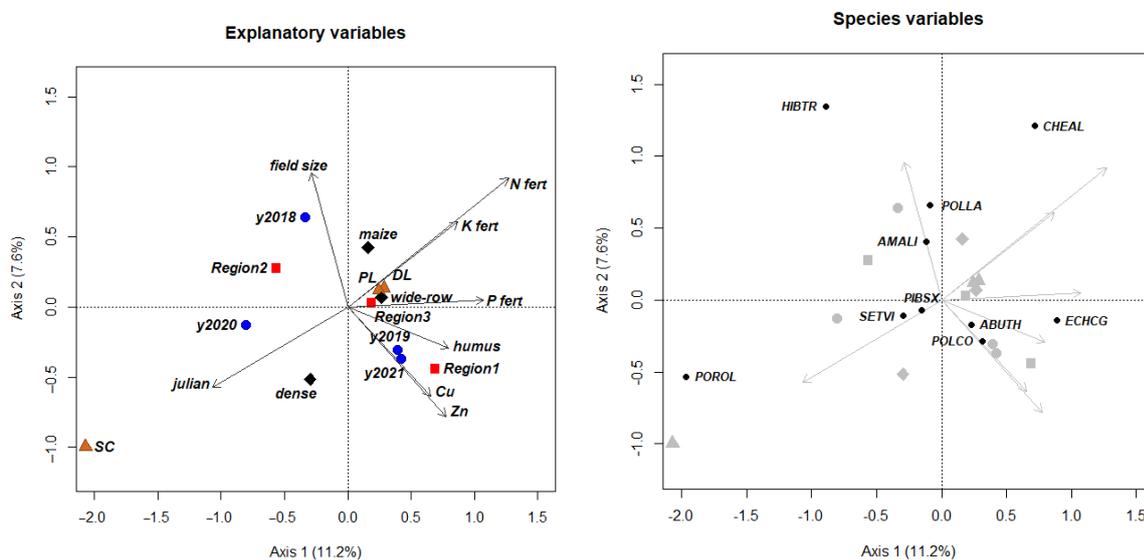

Figure 4. Ordination diagrams of the redundancy analysis (RDA), illustrating the connection between significant explanatory variables (left) and species (right). (Arrow, numeric variable; blue cycles, year; brown triangle, tillage method; red square, region; black diamond, preceeding crop; small black cycle, species; y2018–y2021, growing season between 2018 and 2021; DL, deep loosening; PL, ploughing; SC, shallow cultivation; maize, maize preceeding crop; wide-row, other wide-row

preceeding crops; dense, dense preceeding crops; humus, soil humus content; Cu, soil Cu content; Zn, soil Zn content; N fert, amount of N fertilizer; P fert, amount of P fertilizer; K fert, amount of K fertilizer; julian, date of weed survey ABUTH, *Abuthilon theophrasti*; AMALI, *Amaranthus blitum*; CHEAL, *Chenopodium album*; ECHCG, *Echinochloa crus-galli*; HIBTR, *Hibiscus trionum*; PIBSX, *Pisum sativum*; POLCO, *Fallopia convolvulus*; POLLA, *Persicaria lapathifolia*; POROL, *Portulaca oleracea*; SETVI, *Setaria viridis*).

Weed Vegetation of Winter Wheat Fields

In the surveyed winter wheat fields, a total of 47 different weed species were identified, with an average weed cover of 4.3%. However, the extent of weed infestation varied greatly among fields. The lowest recorded weed cover was below 0.1%, while the highest reached 54%. On average, the three most important weed species in the examined wheat fields were *Veronica hederifolia*, *Stellaria media*, and *Apera spica-venti*. These three species showed the highest average cover values, ranging between 0.5% and 1.3%. It was observed that the most frequent species were winter annuals, although summer annuals were also present in the fields. In addition, perennial weeds such as *Cirsium arvense* were also found (Figure 5).
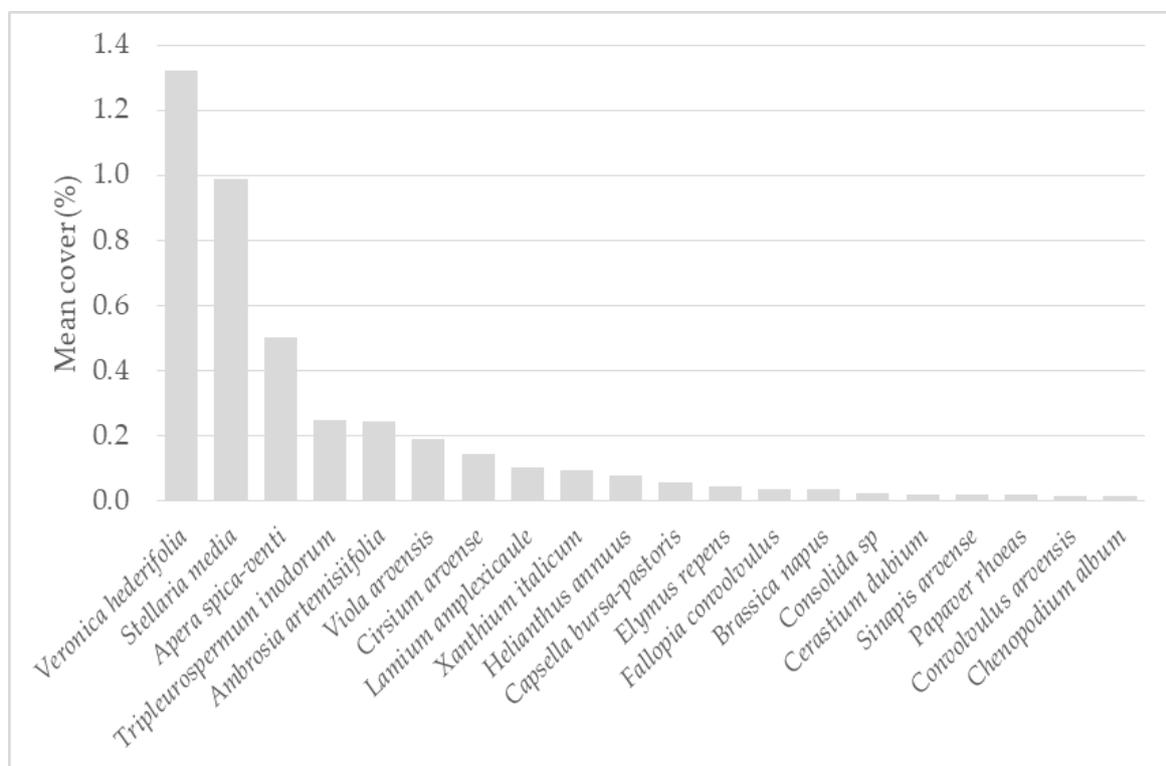

Figure 5: The Most Common Weed Species in the Surveyed Winter Wheat Fields and Their Average Cover Values (%)

In terms of occurrence frequency, *Stellaria media* showed the highest presence (43%). This was followed by *Veronica hederifolia*, *Tripleurospermum inodorum*, *Apera spica-venti*, *Helianthus annuus*, *Cirsium arvense*, and *Chenopodium album*, with occurrence rates of 27%, 27%, 23%, 23%, 22%, and 22%, respectively. Overall, however, 15 species displayed a frequency greater than 10%.

The relationship between occurrence frequency and average cover is illustrated in Figure 18. Five species were outstanding in terms of both cover and constancy: *Tripleurospermum inodorum*, *Ambrosia artemisiifolia*, *Apera spica-venti*, *Stellaria media*, and *Veronica hederifolia*.

Based on the results, soil factors had only a limited effect on total weed cover; however, they influenced species richness and weed diversity much more strongly. Total weed cover was increased only slightly by two soil elements—copper and zinc—while the effects of nitrogen and phosphorus contents were negligible. In contrast, weed community diversity was higher in soils that were heavier-textured, more alkaline, and richer in salts, and several nutrients (K, Na, Mg, S, Zn) positively affected species richness and the Shannon index.

Environmental and management variables were overall much more closely related to species richness and diversity than to total cover. Weed cover was mainly determined by the year, the type and depth of tillage, and the amount of applied nitrogen, although these effects were generally weak. The highest weed cover occurred in 2018 and under ploughing, while the lowest values were recorded in 2019 and under shallow cultivation.

Species richness was generally low, yet most environmental and management variables significantly influenced it. The highest species number occurred in Region 1, and 2018 also exhibited notably high species richness. Later survey dates likewise resulted in more species. Increasing tillage depth reduced species richness, and all forms of fertilization had a negative effect on species numbers.

The Shannon diversity index was also low, and among the geographical variables only latitude had a slight influence. In contrast, the year strongly shaped diversity, with much higher values in 2018 than in later years. The tillage system did not significantly affect the Shannon index,

and the effect of tillage depth was only minimal. Nitrogen fertilization did not influence diversity, but phosphorus and potassium fertilization increased it slightly.

Overall, variations in weed vegetation were shaped far more by environmental conditions and management practices—particularly year, region, tillage, and nutrient supply—than by the basic chemical properties of the soil.

Approximately 30% of the variance in species diversity was explained, with the largest proportion attributed to soil properties (especially nitrogen and magnesium content), regional differences, and seasonality. Together, these accounted for more than 60% of the total explained variance, exerting a considerably greater influence on weed flora structure than management factors. Nonetheless, tillage type remained a significant factor, exerting roughly three times the effect of tillage depth. Among previous crops, only spring row crops and some densely sown species had a detectable impact, while among fertilizers only potassium showed a significant effect.

Marked differences in weed species composition emerged between regions. Region 3 was characterized by the dominance of *Cirsium arvense* and *Xanthium italicum*, whereas Region 1 was characterized by *Stellaria media* and *Chenopodium album*. In Region 2A, *Consolida* species and *Raphanus raphanistrum* were more prevalent, while Region 2B was distinguished by the presence of *Viola arvensis* and *Elymus repens*. Differences also emerged between years: *Ambrosia artemisiifolia* and *Xanthium italicum* were prominent in 2018, while *Chenopodium album* and volunteer *Helianthus annuus* were characteristic of 2019. In 2020, *Tripleurospermum inodorum* and *Plantago lanceolata* dominated, whereas in 2021, *Elymus repens* and *Cannabis sativa* were typical. The most widespread species (*Stellaria media*, *Veronica hederifolia*, *Apera spica-venti*) displayed stable presence with year-independent patterns.

Tillage systems also produced clearly distinguishable weed species patterns: under deep loosening, *Veronica hederifolia* and *Fallopia convolvulus* were common; under disc tillage, *T. inodorum* and *X. italicum* dominated; ploughing favored *S. media* and *Viola arvensis*; whereas shallow cultivation was characterized by *Chenopodium album* and *Cannabis sativa*. Increasing nitrogen availability enhanced the presence of certain species such as *Veronica hederifolia*, while reducing that of *Stellaria media*. Both potassium and magnesium increased the presence of *S. media*, but created unfavorable conditions for *Cirsium arvense* and several other species.

Tillage depth also influenced weed occurrence: deeper tillage reduced the presence of *Cirsium arvense*, whereas shallow cultivation promoted the spread of *Tripleurospermum inodorum*. The influence of previous crops was overall limited, but certain spring crops facilitated the expansion of specific weeds (e.g., *T. inodorum*), while reducing others. Overall, species composition was primarily shaped by regional differences, soil properties, and the tillage system.
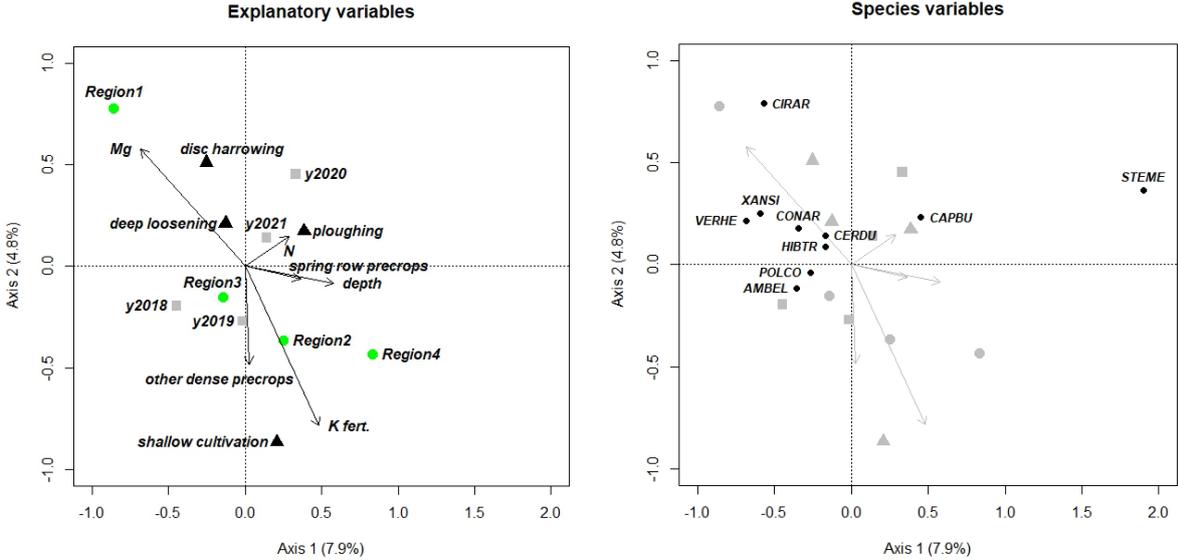

Figure 6. Ordination diagrams of the redundancy analysis (RDA) containing the connection between significant explanatory variables (left) and species (right). (Arrow, numeric variable; grey squares, year; black triangle, tillage system; green cycle, region; small black cycle, species; Mg, soil Mg content; N, soil N content; K. fert, Amount of K fertilizer; AMBEL, *Ambrosia artemisiifolia*; CAPBP, *Capsella bursa-pastoris*; CERDU, *Cerastium dubium*; CIRAR, *Cirsium arvense*; CONAR, *Convolvulus arvensis*; HIBTR, *Hibiscus trionum*; POLCO, *Fallopia convolvulus*; STEME, *Stellaria media*; VERHE, *Veronica hederifolia*; XANSI, *Xanthium italicum*)

4. CONCLUSIONS AND RECOMMENDATIONS

Conclusions and recommendations in maize

The weed vegetation of the surveyed maize fields showed a moderate but agronomically already risky level of infestation: the average weed cover was 9.7%, implying the possibility of yield loss. The species composition of the surveyed weed flora differed in several aspects from national patterns. While at the national level common ragweed is considered the most problematic late-summer weed in maize, its presence in the study area was only limited. In contrast, *Echinochloa crus-galli* proved to be the most frequent species, whereas nationally it only ranks third. *Chenopodium album*, *Hibiscus trionum* and *Datura stramonium* were dominant both nationally and locally. The region, however, also favoured weed species such as *Portulaca oleracea* and *Rubus caesius*, which are of lesser national importance.

The weed flora was determined by a few dominant species, especially *E. crus-galli*, *C. album* and *H. trionum*, which together accounted for half of the total weed cover. Several of the dominant species use C4 photosynthesis, which provides an advantage in summer, under high-light conditions. In the study area, the total cover of C4 species exceeded that of C3 species, reflecting their better adaptation to the climatic conditions.

Among soil-related factors, soil texture and pH showed a close relationship with species richness and diversity, confirming that the physical and chemical state of the soil fundamentally determines weed population structure. The dual effect of lime content—lower cover but higher diversity—suggests that competitive, high-biomass species may be suppressed, while more species with weaker competitive ability may establish. Micro- and mesoelements such as magnesium, manganese, sulfur and zinc showed positive relationships with weed diversity, highlighting the community-forming role of soil mineral composition. Humus content favoured nitrophilous species, including *C. album* and *Amaranthus retroflexus*, whereas *Ambrosia artemisiifolia* and *Amaranthus blitoides* occurred more frequently at lower humus levels. Copper and zinc strongly influenced the distribution of certain species, particularly those capable of phytoremediation (*H. annuus*, *X. strumarium*).

Among environmental factors, regional differences primarily affected cover and species richness, but had less effect on diversity. Interannual weather differences had a stronger influence than geographical regions: temperature and precipitation fluctuations significantly reshaped dominant species. Between 2018 and 2021, each year was associated with different

dominant weeds, although several species—such as *Veronica hederifolia*, *Stellaria media*, *Apera spica-venti*—showed stability across years. The timing of the survey also played an important role: later recording dates resulted in higher cover but lower diversity, which is consistent with the progression of the growing season.

Several management factors also had significant effects. Field size influenced species composition, as the poorly managed edges of smaller fields modified weed pressure. Although the previous crop did not directly affect cover or diversity, it caused marked differences in the distribution of dominant species due to differences in herbicide use and weed suppression capacity among crop groups. Tillage proved to be one of the strongest management factors: deeper tillage increased species richness and diversity, while the different tillage methods (deep loosening, ploughing, discing, shallow tillage) produced distinct species assemblages. Shallow tillage, for instance, was typical of *P. oleracea* and *S. viridis*, whereas deep loosening was associated with *C. arvensis* and *X. strumarium*.

Nutrient supply played a major role in shaping weed communities. High nitrogen levels decreased species richness while promoting the spread of nitrophilous species. The application of phosphorus and potassium increased species richness and the occurrence of several dominant species. Species-specific nutrient preferences were clearly visible, for example the high nitrate demand of *C. arvensis*, *X. strumarium* and *P. lapathifolium*, or the phosphorus preference of *H. trionum*.

Altogether, the explanatory variables accounted for 29.2% of the variance in species diversity. Of this, soil properties, region and seasonality accounted for more than 17%, representing more than 60% of the total explained variance. Among management factors, tillage method was the strongest determinant, with an effect more than three times that of tillage depth. Among previous crops and fertilizers, only potassium had a significant influence on weed composition.

Overall, changes in the weed flora were primarily shaped by environmental factors (climate, region, soil properties) and tillage, while nutrient supply and field size played secondary but species-specific roles. The results confirm that maize weed communities respond strongly to climatic and soil conditions, and although management interventions can modify species composition, the main patterns of weed communities are nevertheless determined by the environmental background.

Conclusions and recommendations in winter wheat

The weed vegetation of the surveyed winter wheat fields differed in several aspects from the results of national surveys. The most frequent species were *Veronica hederifolia*, *Stellaria media* and *Apera spica-venti*, whereas national averages identify *S. media*, *Ambrosia artemisiifolia* and *A. spica-venti* as the most significant weeds. *V. hederifolia* ranks only fourth on the national list, yet it played a dominant role in the present study. Other Carpathian Basin surveys—such as the assessments conducted in Mureș County—also reported different dominant species (*C. arvensis*, *V. persica*, *C. arvense*), confirming that the weed flora of wheat is strongly region-dependent.

The extent of weed cover averaged 4.3%, which is substantially lower than the national average of 16%. This can be attributed partly to geographical differences and partly to differing survey dates. From an agronomic perspective, the low weed cover is still acceptable, as intervention is generally justified above moderate levels of infestation (5–30%). The constancy of weed species (23–42%) was consistent with other national and international findings, indicating that the most important species not only had high cover values but also high occurrence frequencies. The similar ranking of species based on constancy and cover suggests that the dominant weeds were stable both spatially and in terms of abundance. The lack of species occurring at low frequency but high cover indicates that the weed flora of the surveyed fields was stable and only minimally affected by invasive processes.

In the analysis of soil factors, most parameters showed no significant relationship with weed cover or species richness. However, copper and zinc concentrations had a measurable effect on weed infestation. This partly aligns with other studies highlighting the influence of zinc and certain microelements on weed flora. Soil humus content showed no correlation with weed composition, which can be explained by the strong competitive ability of wheat and the low overall weed cover, limiting the influence of soil nutrient status.

Soil structure, texture, pH and salinity did affect weed diversity: heavier soils with higher pH supported richer species assemblages. No relationship was found between nitrogen or phosphorus and species richness, contradicting several earlier hypotheses. It is likely that intense competition allowed wheat to suppress weeds successfully, reducing the differentiating effect of nutrient availability. Potassium and several micro- and mesoelements, however, were associated with the development of species diversity.

Among environmental factors, year-to-year variation had the strongest influence on weed flora. In 2018—the wettest year—weed cover, species richness and the Shannon diversity index were all the highest. Thus, total rainfall and its distribution proved to be key determinants, while the effect of temperature was less evident. Geographical regions also significantly shaped weed composition and species richness, whereas individual geographical variables such as longitude, latitude or elevation showed no independent significant effects. The low Shannon diversity index indicates that the weed community was dominated by a few species, as reported in other studies as well. Latitude showed some influence, though to a lesser extent.

Among management factors, tillage method proved to be the strongest determinant. According to the RDA model, the effect of tillage method was more than three times greater than that of tillage depth. The highest weed cover was recorded under ploughing, while the lowest occurred with shallow cultivation. Discing and deep loosening produced intermediate values. These results indicate that the type and manner of soil disturbance had a greater impact than the depth of disturbance. Field size did not correlate with either weed cover or diversity, although other studies occasionally observed a slight decreasing trend in larger fields.

Of the previous crops, cereal predecessors proved beneficial, likely due to increased habitat stability. Long-term cultivation with similar technology promotes equilibrium in weed communities and the development of more stable niche structures. Other crop groups had only minor, weakly correlated effects. The timing of herbicide application was also related to species richness and diversity, though due to pre-treatment surveys, the direct effects of herbicides could not be detected.

Among macronutrients, phosphorus and potassium showed negative correlations with the Shannon index, while nitrogen had no effect. This partly contradicts previous literature suggesting that nitrogen fertilization reduces diversity. In the present study, due to low weed cover, nitrogen did not act as a selective factor.

A relationship was observed between tillage and previous crop, and the effects of tillage systems often outweighed the effects of tillage depth. The largest differences occurred between regions 1 and 4, attributable to geographical distance and site-specific conditions. Among weed species, *S. media* proved most sensitive to environmental factors, whereas *A. spica-venti*, despite its high cover, responded weakly to differences, indicating strong ecological plasticity.

Overall, the development of winter wheat weed flora is primarily determined by year-to-year variability, geographical region and tillage method. Soil factors—particularly microelements and structural properties—also play roles, while previous crop and tillage depth exert secondary but non-negligible influences. Based on the findings, the stability and diversity of weed communities in winter wheat are shaped mainly by long-term environmental and technological factors.

5. NEW SCIENTIFIC RESULTS

It is important to emphasize that the conclusions presented here apply exclusively to the geographical region investigated, which includes the arable lands of eastern and northeastern Hungary—specifically the counties of Borsod-Abaúj-Zemplén, Szabolcs-Szatmár-Bereg, Hajdú-Bihar and Békés.

1. I established that in maize cultivation within the study area, the most significant weed species belonged to the T4 and G3 life-form groups. Based on cover values, they were the following, in order of importance: *Echinochloa crus-galli*, *Chenopodium album*, *Portulaca oleracea*, *Hibiscus trionum*, *Xanthium strumarium*, *Panicum miliaceum*, *Cirsium arvense*, *Helianthus annuus*, *Datura stramonium* and *Amaranthus retroflexus*. I found that the most frequently occurring weeds (constancy %) in the examined maize fields also belonged to the T4 and G3 life-form groups, and the sequence of importance was as follows: *Echinochloa crus-galli*, *Chenopodium album*, *Portulaca oleracea*, *Hibiscus trionum*, *Helianthus annuus*, *Ambrosia artemisiifolia*, *Convolvulus arvensis*, *Amaranthus retroflexus*, *Xanthium strumarium* and *Cirsium arvense*.

2. I determined that in winter wheat, based on cover values, the most important weed species were *Veronica hederifolia*, *Stellaria media*, *Apera spica-venti*, *Tripleurospermum inodorum*, *Ambrosia artemisiifolia*, *Viola arvensis*, *Cirsium arvense*, *Lamium amplexicaule*, *Xanthium italicum* and *Helianthus annuus*. The most frequent species were overwintering annuals, although summer annuals were also present in the fields. In terms of occurrence frequency, the most prominent species were *Stellaria media*, *Veronica hederifolia*, *Tripleurospermum inodorum*, *Apera spica-venti*, *Helianthus annuus*, *Cirsium arvense*, *Chenopodium album*, *Capsella bursa-pastoris*, *Ambrosia artemisiifolia* and *Lamium amplexicaule*. I found that weed species employing C4 photosynthesis—such as *Echinochloa crus-galli*, *Chenopodium album* (C3–C4 intermediate type), *Amaranthus retroflexus* and *Portulaca oleracea*—proved particularly significant both in terms of cover and constancy in maize cultivation across the study sites.

3. I established that in both crops, soil variables exerted the strongest influence on weed species. They affected the Shannon diversity index and total weed cover to a lesser extent. The weed species composition in maize was most strongly influenced by soil humus and zinc content, whereas in winter wheat nitrogen and magnesium contents had the greatest impact.

4. Among environmental variables, I demonstrated that in both maize and winter wheat, the geographical location of the regions had a stronger effect on weed infestation than the year.

   In maize, I found that among management variables, tillage method and fertilizer use exerted the greatest influence on weed vegetation. In contrast, in winter wheat the effects of previous crop, tillage method and fertilizer use were outstanding among the management variables.

5. I established that in maize, significant indicator species included *Chenopodium album*, *Amaranthus retroflexus* and *Polygonum aviculare*, whose cover increased with rising humus content. High soil zinc levels favored the occurrence of *Chenopodium album*, *Convolvulus arvensis* and *Aristolochia clematitis*. *Convolvulus arvensis*, *Xanthium italicum* and *Persicaria lapathifolia* occurred more frequently under intensive nitrogen fertilization. Deep loosening increased the presence of *Xanthium strumarium*, *Lathyrus tuberosus* and *Cirsium arvense*. Ploughing favored the appearance of *Echinochloa crus-galli*, *Persicaria lapathifolia* and *Abutilon theophrasti*. Under shallow tillage, the dominant species were *Portulaca oleracea* and *Setaria viridis*. *Portulaca oleracea* and *X. strumarium* responded negatively to plough-based tillage.

6. In winter wheat I found that indicator species included *Veronica hederifolia* and *Fumaria schleicheri*, whose cover increased with rising soil nitrogen content. The occurrence of *Stellaria media* varied in response to soil potassium and magnesium content. *Veronica hederifolia* and *Fallopia convolvulus* were characteristic of deep loosening, *Tripleurospermum inodorum* and *Xanthium italicum* of discing, *Stellaria media* and *Viola arvensis* of ploughing, whereas *Chenopodium album* and *Consolida* spp. dominated under shallow cultivation.

7. I found that, in maize, significant indicator species were *Chenopodium album*, *Amaranthus retroflexus* and *Polygonum aviculare*, whose cover increased with rising humus content. High soil zinc content favoured the occurrence of *Chenopodium album*, *Convolvulus arvensis* and *Aristolochia clematitis*. *Convolvulus arvensis*, *Xanthium italicum* and *Persicaria lapathifolia* occurred more frequently under intensive nitrogen fertilization. Deep loosening increased the occurrence of *Xanthium strumarium*, *Lathyrus tuberosus* and *Cirsium arvense*. Ploughing favoured the appearance of *Echinochloa crus-galli*, *Persicaria lapathifolia* and *Abutilon theophrasti*. Under shallow tillage, the dominant species were *Portulaca oleracea* and *Setaria viridis*. *Portulaca oleracea* and *X. strumarium* responded negatively to plough-based tillage.

8. In winter wheat I found that indicator species included *Veronica hederifolia* and *Fumaria schleicheri*, whose cover increased with rising soil nitrogen content. The occurrence of *Stellaria media* varied in response to soil potassium and magnesium content. Deep loosening was characteristic for *Veronica hederifolia* and *Fallopia convolvulus*, discing for *Tripleurospermum inodorum* and *Xanthium italicum*, ploughing for *Stellaria media* and *Viola arvensis*, while shallow cultivator tillage was dominated by *Chenopodium album* and *Consolida* spp.

6. PUBLICATIONS OF THE AUTHOR RELATED TO THE TOPIC OF THE DISSERTATION

1. TÓTH, E. – DORNER, Z. – NAGY, J.G. – ZALAI, M. (2025): How weed flora evolves in cereal fields in relation to the agricultural environment and farming practices in different sub-regions of Eastern Hungary. Agronomy, 15: 1033. https://doi.org/10.3390/agronomy15051033

2. ZALAI, M. – TÓTH, E. – NAGY, J.G. – DORNER, Z. (2025): Regional patterns in weed composition of maize fields in Eastern Hungary: the balance of environmental and agricultural factors. Agronomy, 15: 1814. https://doi.org/10.3390/agronomy15081814

3. TÓTH, E. – ZALAI, M. (2019): The effect of soil type and preceding crop on the weed flora of maize and cereal fields in Békés, Borsod-Abaúj-Zemplén and Szabolcs-Szatmár-Bereg counties (A talajtípus és az előetemény hatása kukorica és kalászos táblák gyomflóra-összetételére Békés, Borsod-Abaúj-Zemplén és Szabolcs-Szatmár-Bereg megyében; In Hungarian with English abstract). Magyar Gyomkutatás és Technológia, 20 (2): 47-62.

4. TÓTH, E. – ZALAI, M. (2019): The effect of soil type and forecrop on the weed flora of maize and cereal fields in Békés, Borsod-Abaúj-Zemplén and Szabolcs-Szatmár-Bereg counties (A talajtípus és az előetemény hatása kukorica és kalászos táblák gyomflóraösszetételére Békés, Borsod-Abaúj-Zemplén és Szabolcs-Szatmár-Bereg megyében; In Hungarian). 65. Növényvédelmi Tudományos Napok, Budapest, pp. 71.

5. TÓTH, E. – ZALAI, M. (2020): The effect of soil type, geographical location and forecrop on the weed flora of cereal fields in Békés, Hajdú-Bihar, Borsod-Abaúj-Zemplén and Szabolcs-Szatmár-Bereg counties in 2019 (A talajtípus, a földrajzi elhelyezkedés és az előetemény hatása kalászos táblák gyomflóra-összetételére Békés, Borsod-Abaúj-Zemplén, Hajdú-Bihar és Szabolcs-Szatmár-Bereg megyében 2019-ben; In Hungarian). 66. Növényvédelmi Tudományos Napok, Budapest, pp. 75.

7. BIBLIOGRAPHY

1. Adeux, G., Vieren, E., Carlesi, S., Bárberi, P., Munier-Joalin, N., Cordeau, S. (2019): Mitigating crop yield losses through weed diversity. *Nat Sustain* 2, 1018–1026. p. https://doi.org/10.1038/s41893-019-0415-y

2. Borcard, D., Gillet, F., Legendre, P. (2011): *Numerical Ecology with R*; Springer: New York, NY, USA, 34–50. p.

3. Chambers, J.M., Freeny, A., Heiberger, R.M. (1992): Analysis of variance, designed experiments. In Statistical Models in S, 1st ed.; Chambers, J.M., Hastie, T.J., Eds.; Wadsworth & Brooks/Cole: Pacific Grove, CA, USA, 145–194. p.

4. European Environment Agency (2018) https://www.eea.europa.eu/hu/jelzesek/jelzesek-2018/cikkek/valtozo-etrendek-valtozotajak-2013 Lekérdezés időpontja: 2025.06.23.

5. FAOSTAT adatbázis https://www.fao.org/faostat/en/#data/QCL Lekérdezés időpontja: 2025.07.19

6. Flessner, M., Burke, I., Dille, J., Everman, W., VanGessel, M., Tidemann, B., Manuchehri, M., Soltani, N., & Sikkema, P. (2021): Potential wheat yield loss due to weeds in the United States and Canada. *Weed Technology* 35, 916 - 923. p. https://doi.org/10.1017/wet.2021.78.

7. Fox, J. (2016): Applied Regression Analysis and Generalized Linear Models, 3rd ed.; Sage Publications: Thousand Oaks, CA, USA, 342–358. p.

8. Központi Statisztikai Hivatal (2) A fontosabb növények vetésterülete. online elérhető: https://www.ksh.hu/s/kiadvanyok/a-fontosabb-novenyek-vetesterulete-2024-junius-1/index.htmlon07.19.2025) Lekérdezés időpontja: 2025.08.21

9. Keselman, H. J.; Rogan, J. C. (1977): The Tukey multiple comparison test: 1953–1976. *Psychological Bulletin*, 84, 1050–1056. p. https://doi.org/10.1037/0033-2909.84.5.1050

10. Mueller-Dombois, D., Ellenberg, H. (1976): Aims and methods of vegetation ecology. *Geographical Review* 66, 114-116. p.

11. NÉBIH Növényvédő szerek adatbázisa https://novenyvedoszer.nebih.gov.hu/Engedelykereso/kereso (letöltve: 2025.07.14.)

12. Ujvárosi, M. (1973): Gyomnövények. Mezőgazdasági Könyvkiadó Vállalat Budapest 833p.

13. Shannon, C.E. (1948): A mathematical theory of communication. *Bell Syst. Tech. J.* 27, 379–423. p.

14. Soper, H.E., Young, A.W., Cave, B.M., Lee, A., Pearson, K. (1917): On the distribution of the correlation coefficient in small samples. Appendix II to the papers of "Student" and R.A. Fisher. A co-operative study. *Biometrika* 11, 328–413. p.

15. Sutter, J.M., Kalivas, J.H. (1993): Comparison of Forward Selection, Backward Elimination, and Generalized Simulated Annealing for Variable Selection. *Microchemical Journal,* 47, 60–66. p. https://doi.org/10.1006/mchj.1993.1012.

16. Teasdale, J.R., Cavigelli, M.A. (2010): Subplots facilitate assessment of corn yield losses from weed competition in a long-term systems experiment. *Agron. Sustain. Dev.* 30, 445–453. p.

17. van der Maarel, E.; Franklin, J. (2013): Vegetation ecology: Historical notes and outline. *Weed Ecology* 2, 1-27.
18. Zalai, M., Dorner, Z., Kolozsvári, L., Szalai, M. (2012): A gyomfelvételezés pontosságát befolyásoló tényezők vizsgálata kukoricában. *Növényvédelem* 48 (10) p. 451-456.