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SC, LN, and JW conceived the idea, designed the computational framework and workflow of field experiment, and analyzed the data; SC and JW developed the theory, performed analytic calculations, and verified the analytic methods and the numerical simulations; LN and JW supervised the overall work and its findings; all authors discussed the results and contributed to the final version of the manuscript

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ORIGINAL RESEARCH PAPER

The effect of three soil tillage treatments on weed infestation in forage maize

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Abstract

This study assessed the impact of using soil tillage in maize crops on weed infestation intensity and weed species composition. A field experiment was established as a model example of livestock production management in drier climate conditions where maize was grown in seven-step crop rotation sequence: alfalfa – the first year, alfalfa – the second year, winter wheat, forage maize, winter wheat, sugar beet, and spring barley. Three soil tillage treatments were applied: conventional tillage (CT), minimum tillage (MT), and no-tillage (NT). An arithmetic method and multivariate analyses of ecological data were used. The highest weed infestation, mainly due to late spring species, was recorded in MT. Perennial and overwintering species were frequently observed in NT. Early spring weed species were abundant in CT. Different tillage treatments cause a significant change in the weed species spectrum in maize. A study of the relationship between tillage and the level of weed infestation requires long-term monitoring which will allow us to predict the intensity of weed infestation in particular locations.

Keywords

conventional tillage; minimum tillage; no-tillage; RDA analysis

Introduction

Increasing maize production is noticeable worldwide, even across Central Europe [1]. Given the fact that maize is considered as a wide-row crop [2] and its competitiveness is rather low, weed management is highly recommended [3]. In general, plenty types of weed infestation and different levels of losses caused by weeds have been reported by many authors [4,5]. The species composition of plant communities is often influenced by agricultural practice [6]. Some authors have noted an increasing occurrence of difficult-to-control weed species and overall change of weed species composition [6,7]. A weed community is also largely influenced by the seed bank formed in the soil [8]. There is one widely used measure designed to decrease weeds by burying directly their seeds called conventional tillage [9]. However, the interest in conservation agriculture systems is rapidly growing, mainly due to the economic and environmental benefits offered by these systems [10]. Additionally, this growing trend towards conservation tillage has mainly brought about the possibility of earlier sowing and reducing the risk of erosion by stubble retention, which has a positive influence on soil structure [11]. Each particular tillage treatment changes soil structure in different ways. This is due to the depth of tillage and degree of soil column disruption [12]. Some authors [13,14] have stated that the density and occurrence of particular weed species are influenced by crop rotation; in addition, these species have become and are an increasingly serious problem, especially in no-tillage. The increasing occurrence of perennial species due to the reduced tillage depth was also described [14] and their intense growth significantly threatens the quality of production and crop yield as well as the feasibility of some cultivation interventions [15]. Other authors [16,17] have confirmed that soil tillage, particularly minimum tillage, encourages the occurrence of late spring weed species. Furthermore, these species, particularly those that have similar emergence requirements as maize, have the potential to become very problematic weed species primarily in the case of no-tillage [18]. At the same time, many species formerly typical for arable land have not been able to survive the rapid intensification of agriculture within the last century and have significantly reduced or totally diminished their occurrence over the last decade. However, the average intensity of weed infestation has not changed significantly since 1990 [6]. Hence, effective weed control should be adopted in line with the change in weed species composition due to the implementation of reduced tillage. The aim of this study was to evaluate the effect of three soil tillage treatments on weed infestation in maize crops.

Material and methods

Experimental site

A field study was conducted at the Žabčice experimental station managed by the Mendel University in Brno (GPS 49.0117608N, 16.5908489E, Czech Republic). Experimental fields belong to a corn-producing area located at an altitude of 184 m a.s.l. The long-term average annual temperature is 9.2°C and annual total precipitation reaches 483.3 mm. The northwest wind prevails in this region, which causes the predominance of water evaporation over rainfall, subsequently creating a frequent water deficit. The soils were formed on Holocene and calcareous alluvial sediments. The gley process is caused by the continuous impact of ground water, which is currently situated at 1.80 m below the ground surface. The topsoil layer is clay-loam to loam and the thickness of the topsoil profile goes to a depth of 0.35 m. Moreover, the mean value of organic matter is 1.47% and pH reaches 5.46.

Design and crop management

A field trial, covering a total area of 2.3 ha, was established in 2004 as a model example of livestock production management in drier climate conditions. The size of one plot was 10 × 100 m for each tillage treatment (three) of each crop (seven) within the crop rotation.

Maize was grown in 7-step crop rotation sequence: (***i***) alfalfa (*Medicago sativa* L.) – the first year, (***ii***) alfalfa – the second year, (***iii***) winter wheat (*Triticum aestivum* L.), (***iv***) forage maize (*Zea mays* L.), (***v***) winter wheat, (***vi***) sugar beet (*Beta vulgaris* var. altissima L.), (***vii***) spring barley (*Hordeum vulgare* L.).

Three tillage treatments were used for each crop: conventional tillage (CT) – ploughing was carried out with a rotatable reversible plow to a depth of 0.2 to 0.24 m (medium deep) after harvesting the previous crop. Sowing was performed using sowing combinations, followed by rolling in spring. Minimum tillage (MT) – shallow tillage was performed after harvesting the previous crop and skimming was done with a chisel plow to a depth of 0.1 m. Sowing was carried out using sowing combinations in spring, followed by rolling. No tillage (NT) – the soil was not tilled after harvesting the previous crop and direct sowing was then carried out using sowing combinations, followed by rolling. It should be noted that only maize and sugar beet require pre-sowing soil preparation to a specific depth and the same industrial fertilizers were applied.

The seed rate for the maize variety 'Beautiful' was 80,000 seeds per hectare and the seed row width was 0.75 m. Maize was sown on April 25, 2013, then April 11, 2014, and April 16, 2015.

Methods of weed infestation assessment

Maize crops were evaluated before application of herbicides, whose active substances mainly included tembotrione, isoxadifen-ethyl, terbuthylazine, *S*-metolachlor, and mesotrione. According to BBCH scale, maize was at growth stages 17–19 and the specific evaluation dates were June 6, 2013, June 7, 2014, and May 30, 2015. Weed infestation was evaluated by numerical method where the number of individual weeds (every unwanted plant species occurring in maize crops) was counted in each tillage treatment (three) in the monitored maize plots on 1 m^2 in 24 replicates randomly selected within the typical growing season. The species nomenclature follows the *Key to the flora of the Czech Republic* [19].

The obtained data were analyzed using multivariate analyses of ecological data to reveal the effect of the applied tillage treatments on the weed species spectrum in maize crops. The objective of this method is to identify the structure and relationships in a complex data set encompassing many sampling units and variables. Data groupings are perceived, and similarities and differences are displayed in ordination diagrams. In our case, one grouping refers to weeds on individual plots (species composition, number of individuals) and the other grouping covers the soil tillage treatments. Before selecting the optimal analysis characterizing the correlation between groups, the length of gradient was identified by indirect gradient analysis (DCA). Based on the determined length of the gradient (3.509), the redundancy analysis (RDA) was selected for further processing. This analysis defines the spatial arrangement of particular weed species and their frequency in relation to the soil tillage treatments. A total number of 499 permutations were calculated in a Monte Carlo test. The collected data was processed by the computer program CANOCO 4.0 [20].

Results

Thirty-two various species of weeds were observed in the maize plots during the 3-year observation period. The average numbers of weeds found across treatments and years are shown in a table (Tab. 1). The results of RDA analysis are significant at the significance level $\alpha = 0.002$ for both canonical axes and are shown in Fig. 1. Weed species are displayed as the vectors and the analyzed treatments as points of different form and color. Following these results, identified weed species were divided into five groups. The first group occurred mainly in CT, represented by species as follows: *Anagallis arvensis* L., *Datura stramonium* L., *Chenopodium album* L., *Fallopia convolvulus* (L.) Á. Löve, *Lolium perenne* L., *Microrrhinum minus* (L.) Fourr., *Persicaria lapathifolia* (L.) Delarbre, and *Polygonum aviculare* L. Their occurrence was the highest or unique in this treatment. The second group was identified mostly in CT and MT: *Amaranthus* sp., *Echinochloa crus-galli* (L.) P. B., and *Chenopodium hybridum* L. The third group occurred especially in MT: *Euphorbia helioscopia* L., *Galium aparine* L., *Lamium amplexicaule* L., *Medicago sativa* L., and *Thlaspi arvense* L. The fourth group was recorded mainly in MT and NT. The species *Convolvulus arvensis* L., *Elytrigia repens* (L.) Nevski, and *Sonchus oleraceus* L. were uniquely found in MT and NT, while the species *Triticum aestivum* L., *Veronica polita* Fries, and *Viola arvensis* Murray were identified in an insignificant number also in CT. The fifth group contained such weeds as, e.g., *Cirsium arvense* (L.) Scop, *Geranium pusillum* Burm. Fil., *Malva neglecta* Wallr., and *Plantago major* L., which occur exclusively in NT.

The average number of weed individuals throughout the monitoring period was highest when MT was used (11.40 pieces m^{-2}) and species *Echinochloa crus-galli* occurred most often here; however, this species was the most represented one across all tillage treatments. *Amaranthus* sp. and *Chenopodium hybridum* were among other frequently represented weed species that infested maize crops to a large extent, but their occurrence gradually decreased during the monitoring period. On the contrary, the increasing occurrence of *Convolvulus arvensis* was observed, although its presence was found only in MT and NT. The lowest weed infestation (9.61 pieces m^{-2}) was observed in NT. According to the interpretation of the statistical results, it is clear that the intensity of weed infestation was significantly influenced by year. Furthermore, the results showed that the particular soil treatment and year created certain conditions affecting differently the intensity (number of weeds) of weed infestation during the monitored period. Therefore, we can assume that the soil tillage treatments changed the soil properties and also created different conditions for weed emergence depending on

Tab. 1 The average number of weed individuals and species identified in maize (pieces m^{-2}).

Weed species	Soil tillage			Year		
	NT	MT	CT	2013	2014	2015
Amaranthus sp.	0.24	1.58	1.00	1.78	0.64	0.40
Anagallis arvensis	0.11		0.49	0.49	0.11	
Capsella bursa-pastoris	0.31	0.03		0.21	0.10	0.03
Cirsium arvense	0.56			0.51		0.04
Convolvulus arvensis	1.50	1.10		0.71	0.90	0.99
Datura stramonium			0.07	0.06	0.01	
Echinochloa crus-galli	2.92	5.65	5.68	4.89	6.14	3.22
Elytrigia repens	0.01					0.01
Erodium cicutarium	0.25	0.03		0.18	0.01	0.08
Euphorbia helioscopia	0.07	0.18	0.08	0.19	0.14	
Fallopia convolvulus	0.17	0.11	0.58	0.57	0.22	0.07
Galium aparine	0.01	0.18	0.01	0.13	0.03	0.06
Geranium pusillum	0.06					0.06
Chenopodium album	0.21	0.58	0.81	1.32	0.22	0.06
Chenopodium hybridum	0.25	0.74	0.72	1.28	0.40	0.03
Lamium amplexicaule		0.06		0.04	0.01	
Lolium perenne			0.04		0.04	
Malva neglecta	0.04					0.04
Medicago sativa		0.07	0.01		0.07	0.01
Microrrhinum minus			0.06	0.04	0.01	
Persicaria lapathifolia	0.01		0.47	0.36	0.04	0.08
Plantago major	0.50			0.44	0.06	
Polygonum aviculare	0.13	0.32	0.44	0.56	0.08	0.25
Robinia pseudoacacia			0.01		0.01	
Solanum nigrum	0.17	0.01		0.13	0.06	
Sonchus oleraceus	0.01					0.01
Stellaria media	1.11	0.08		0.96	0.01	0.22
Thlaspi arvense	0.01	0.10		0.08	0.03	
Triticum aestivum	0.33	0.22	0.04	0.22	0.10	0.28
Veronica persica	0.33	0.22	0.22	0.35	0.38	0.06
Veronica polita	0.19	0.06	0.06	0.24	0.01	0.06
Viola arvensis	0.11	0.08		0.17	0.03	
Number of species	4.08	3.54	3.90	5.53	3.43	2.57
Number of individuals	9.61	11.40	10.81	15.89	9.88	6.06

NT – no-tillage; MT – minimum tillage; CT – conventional tillage.

the weather. These circumstances influence not only the intensity of weed infestation, but also the occurrence of individual weed species.

Discussion

Significant changes are observable in the weed species spectrum under different tillage treatments in maize crops. The main differences were identified between NT and the other tillage treatments. NT rather supports the occurrence of perennial and cool season

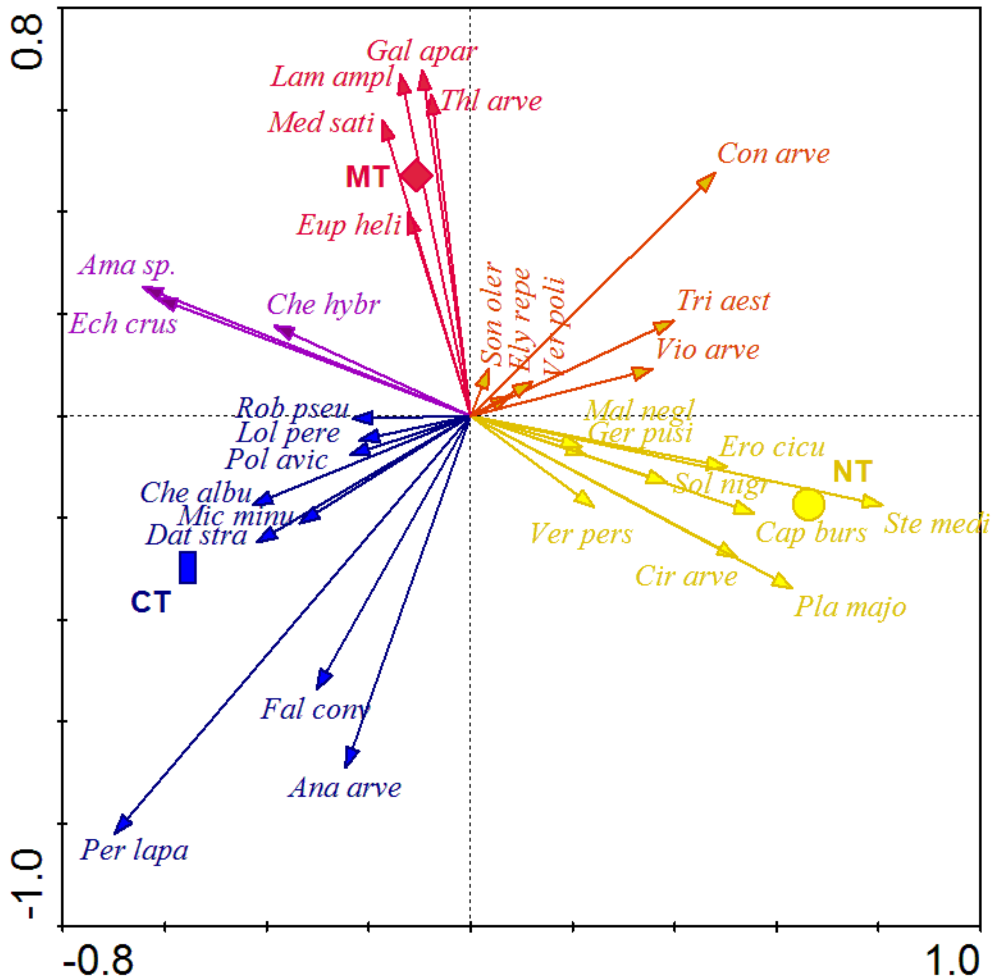

Fig. 1 RDA ordination diagram showing relationships between tillage treatments and weed species in maize crops (trace = 0.361, *F* ratio = 5.905, *p* value = 0.002). Note: CT – conventional tillage; MT – minimum tillage; NT – no-tillage. Legend: *Ama* sp. – *Amaranthus* sp.; *Ana arve* – *Anagallis arvensis*; *Cap burs* – *Capsella bursa-pastoris*; *Cir arve* – *Cirsium arvense*; *Con arve* – *Convolvulus arvensis*; *Dat stra* – *Datura stramonium*; *Ech crus* – *Echinochloa crus-galli*; *Ely repe* – *Elytrigia repens*; *Ero cicu* – *Erodium cicutarium*; *Eup heli* – *Euphorbia helioscopia*; *Fal conv* – *Fallopia convolvulus*; *Gal apar* – *Galium aparine*; *Ger pusi* – *Geranium pusillum*; *Che albu* – *Chenopodium album*; *Che hybr* – *Chenopodium hybridum*; *Lam ampl* – *Lamium amplexicaule*; *Lol pere* – *Lolium perenne*; *Mal negl* – *Malva neglecta*; *Med sati* – *Medicago sativa*; *Mic minu* – *Microrrhinum minus*; *Per lapa* – *Persicaria lapathifolia*; *Pla majo* – *Plantago major*; *Pol avic* – *Polygonum aviculare*; *Rob pseu* – *Robinia pseudoacacia*; *Sol nigr* – *Solanum nigrum*; *Son oler* – *Sonchus oleraceus*; *Ste medi* – *Stellaria media*; *Thl arve* – *Thlaspi arvense*; *Tri aest* – *Triticum aestivum*; *Ver pers* – *Veronica persica*; *Ver poli* – *Veronica polita*; *Vio arve* – *Viola arvensis*.

annual species (*C. arvense*, *P. major*). Predominantly late spring species (*D. stramonium*, *Ch. album*) were observed in MT, and mainly early spring species (*A. arvensis*, *F. convolvulus*) occurred in CT. Therefore, we can assume the increasing occurrence of persistent weed species with the increased popularity of soil conservation tillage (MT, NT). There was a gradual decrease in the number of weeds during the monitored years. This decline is evident in most of the weed species found. An increase in the numbers of individuals was observed only with respect to the species *E. crus-galli*. The influence of weather conditions and effective weed control in the previous crops could have led to the reduction in the weed spectrum. The species *E. crus-galli* was the most frequently represented weed species among all tillage treatments. Nevertheless, its presence was the highest in CT and MT. Some authors [21] also found that emergence of *E. crus-galli* was stable in treatments with different tillage depths during their research. According to Chauhan and Johnson [22], this weed can become a serious problem in NT. Furthermore, there is a high ability to compete successfully for resources [23]. Chauhan [24] claims that the emergence and growth of *E. crus-galli* may be reduced by shade and quantity of biomass residue, yet this option should be also combined with different strategies.

Convolvulus arvensis was the second most frequently occurring weed species in NT. This perennial weed is characterized by a fragile root system that can easily be damaged, but regenerates quickly [25]. The experiment of Rusu et al. [26] showed the highest population of *C. arvensis* in MT. Kobayashi et al. [27] found an increasing frequency of perennial weeds in NT, while according to Demjanova et al. [28] perennial weeds are suppressed significantly in CT. Management using NT, together with predominant cereals in crop rotation, can enhance the density of *C. arvensis* and create a prevalent weed problem [29]. Summer weeds *Amaranthus* sp. were observed in each of our tillage treatments, more significantly in MT and CT. According to Cimalová and Lososová [30], *Amaranthus* species were more frequently observed in relatively dry and warm lowland conditions of the Czech Republic. In the research of Nakamoto et al. [31], weed biomass in maize was significantly higher under MT, but the occurrence of the most dominant species *A. retroflexus* varied and responded to different treatments and years. *Robinia pseudacacia* is not a typical weed species; in our experiment, only seedlings occurred due to adult individuals growing near the experimental station. Tillage and crop rotation sequences are two primary practices often used as a weed control system and with the increasing popularity of MT and NT, management of problematic weeds is more expected [32]. Our results show that conservation tillage treatments (MT, NT) compared with conventional one support the occurrence of perennial weed species (e.g., *C. arvense*, *C. arvensis*, and *P. major*), and generally there is higher species diversity. MT creates conditions for higher weed infestation, where species as *Amaranthus* sp., *C. arvensis*, and the significantly dominant species *E. crus-galli* prevail. NT showed lower weed infestation, but the composition of the present weed species spectrum has changed considerably. Maize belongs to widely used crops with high yield potential. However, it is also a crop with low competition ability against weeds. The specificity of the maize crop structure offers a possibility for spreading new weed species, and thus maize also represents a certain risk of spreading alien weed species. Recognizing the importance and effect of tillage treatments can lead to an improvement in strategies for weed management.

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Wpływ trzech systemów uprawy gleby na występowanie zachwaszczenia w uprawie kukurydzy pastewnej

Streszczenie

W badaniach określano wpływ systemu uprawy gleby w uprawie kukurydzy pastewnej na zachwaszczenie i skład gatunkowy chwastów. Doświadczenie polowe zostało założone jako wzorcowe dla gospodarstwa specjalizującego się w produkcji zwierzęcej w strefie klimatu suchego, gdzie kukurydza była uprawiana w 7-letnim płodozmianie, który obejmował w pierwszym i drugim roku lucernę, a następnie pszenicę ozimą, kukurydzę pastewną, pszenicę ozimą, buraki i jęczmień jary. Zastosowano trzy systemy uprawy gleby: uprawę tradycyjną (CT), uproszczoną (MT) i bezorkową (NT). Zachwaszczenie określano stosując analizę danych ekologicznych oraz analizy wielowymiarowe. Największe zachwaszczenie (głównie w odniesieniu do gatunków chwastów późno wiosennych) zanotowano, gdy kukurydza uprawiana była w systemie uproszczonym. Gatunki wieloletnie i zimujące były często obserwowane w NT. Gatunki chwastów wczesnowiosennych licznie występowały w CT. Różne systemy uprawy istotnie wpływają na kompozycję gatunkowej chwastów w uprawie kukurydzy. Określenie relacji pomiędzy systemami uprawy a poziomem zachwaszczenia wymaga prowadzenia długoterminowego monitoringu, który pozwoli na przewidywanie intensywności zachwaszczenia w poszczególnych lokalizacjach.