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Initial Weed and Maize Response to Conservation Tillage and Liming in Different Agroecological Conditions

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Abstract: Conservation tillage (CT) is an effective tool for maintaining crop productivity under adverse climate conditions, while its adoption is conditioned by the possible negative response of crop weed. Research with CT and liming (L) was conducted at different experimental sites on acid soils (ES 1 and ES 2) to determine the maize weediness and yield. The tillage treatments used were ST (conventional tillage), CTD (deep loosening), CTS (shallow loosening), and liming; Ly (CaO) and Ln (no CaO). The weediness assessment was conducted at the V7 and R5 maize growth stages. Weed density (WD), biomass (WB), weed coverage (WC), and species density (WSN) were determined. The highest WD was recorded on ES 2 in V7, and WB, WC, and WSN were significantly higher at CTS in R5 compared to ST. Liming affected the decrease of WD and WC in V7 and WB, WC, and WSN in R5. The average maize yield on ES 2 was 36% higher compared to ES 1. CTS resulted with the highest yield at ES 1, while at ES 2, it was similar to ST. Liming application significantly increased the maize yield. The given results indicated the positive impact of CT and L on crop productivity in different agroecological conditions, despite the increased weediness.

Keywords: weed occurrence; maize yield; conservation tillage systems; CaO application; site properties

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1. Introduction

Agriculture is nowadays highlighted as one of the most vulnerable domains under the negative influence of climate change [1,2]. Finding effective measures to mitigate and adapt agricultural production to climate change with an emphasis on sustainability and productivity is a key task for the current and upcoming food safety production strategy.

Conservation agriculture, with its basic principles (permanent soil cover, minimal soil disturbance, and proper crop rotation) [3,4], is one of the most effective ways to adapt crop production to the present shifting and seasonal changes in average temperatures and precipitation amount in various agroecological conditions, with conservation tillage as the main tool [4–6]. Conservation tillage tends to offer numerous benefits for soil quality improvement, water conservation, yield stability, the reduction of labor costs, and increasing biodiversity [7–9]. The sustainability of implementation and wide general integration of conservation tillage in agriculture production depend mainly on the extent of expected changes in the weed community, the use of herbicides, and the development of effective weed management [10–12]. In spite of the numerous advantages of conservation agriculture on the agroecosystem, weed management in most cases requires chemical control measures with the use of glyphosate [13] and modified weed management by farmers [12].

Weeds are common and widely present in segments of crop production and crop fields, and their presence results from the interactions of agricultural production measures and environmental and ecological elements. Weed abundance can be conditioned by different management strategies, including soil tillage, crop rotation, liming and fertilization, and herbicide use, and it is site specific [14–17] with a pronounced variation and simple and prompt alternation to new environmental and agricultural conditions [18,19]. Despite various and numerous weed management strategies, the damage they cause to agricultural crops is serious and can reach up to 80% yield loss [20,21]. The diverse results of many studies indicate the different possibilities of changes in weed abundance when conservation tillage systems are included [22–28]. Lower soil tillage intensity in conservation systems can lead to the extensive dominance of perennial weed species [29–31] but also to a greater occurrence of annuals [32,33], higher total weed densities, biomass and weed coverage [25,26,31], and an increase in the weed species number [26,34,35]. However, some studies pointed out that reduced soil tillage does not always bring increased weediness [27,34,36]. The impact of conservation soil tillage on weed occurrence also depends on specific agroecological conditions combined with weed management strategies [10], whereby increased weediness does not always lead to yield loss, and many studies confirmed that conservation tillage improves soil properties and crop yields, which are at the same or a higher level compared to conventional tillage [37–40]. Conservation tillage with its numerous positive effects on soil properties and degradation prevention also has a positive effect on acidic soils [41,42].

Weeds and crops react differently to soil acidity, which significantly affects the accessibility of plant nutrients, soil structure, aeration, etc. [43–45], and liming is a common procedure for reducing the soil acidity level [44–46], which changes weed community characteristics and the ecological conditions of plant growth and reduces crop weediness [47,48]. It can be assumed that liming allows more favorable conditions for crop growth, which are more competitive with weeds and thus lead to weed suppression. Weed competition with agricultural crops for common resources (light, water, and nutrients) is the most important biotic agent that causes yield loss, and as for maize, a reduction of about 37% is reported on the global scale [49].

This research was conducted with the main goal to compare weediness and maize yield on different soil tillage systems and liming treatments in two different agroecological areas in the initial period of transition to CA.

We hypothesized that, in different agroecological conditions, conservation soil tillage combined with liming would increase maize weediness without reducing maize yield.

2. Materials and Methods

2.1. Study Areas

The experiment with conservation tillage and liming was carried out in two different agroecological areas in Croatia. One field experiment was set up in the eastern part of Croatia (central Pannonian sub-region) in Čačinci, experimental site ES 1 (17°86′36″ E, 45°61′32″ N, 111 m a. s. l.) on Stagnosol (Table 1).

Table 1. Selected soil properties on investigated experimental sites: Čačinci (ES 1) and Križevci (ES 2).

Experimental Site	ES 1	ES 2
Soil type/ST	Stagnosol/SCL	Gleysol/S
Sand, silt, clay (%) (0–40 cm Sd)	12.34, 54.97, 32.68	7.70, 82.13, 10.17
pH $_{KCl/H20}$	4.09/5.65	5.00/6.40
Hy (cmol$^{(+)}$ kg^{-1})	7.90	2.45
AL P_2O_5 (mg 100 g^{-1})	10.37	10.81
AL K_2O (mg 100 g^{-1})	15.63	9.39
SOM (%)	2.8	1.7

ES 1—experimental site Čačinci, ES 2—experimental site Križevci, ST—soil texture, sand—(2–0.05 mm), silt—(0.05–0.002 mm), clay—(<0.002 mm), SCL—silty clay loam, S—silt, Sd—soil depth; Hy—hydrolytic acidity, SOM—soil organic matter.

The area is characterized by a moderate climate with average precipitation that decreases from east to west (688–729 mm), with average air temperatures ranging from 10.7 to 11.1 °C [50]. The second field experiment was set up in the western part of Croatia (western

Pannonian sub-region) in Križevci, experimental site ES 2 (16°33′32″ E, 46°01′38″ N, 141 m a. s. l.), with an average amount of precipitation ranging from 865 to 891 mm and an average annual temperature from 10.1 to 10.6 °C [50] on Gleysol. Soil types (Table 1) were determined according to the IUSS Working Group [51].

2.2. Experiment Set Up and Design

The experiment started in 2021 at both experimental sites (ES 1 and ES 2) and was set up as a split plot design in three replications, in which the main treatment was soil tillage and the sub-treatment was liming. The size of the basic plot was 160 m^2 (tillage treatment), and the size of the sub-treatment plot was 80 m^2 (liming). Tillage included three different tillage treatments: conventional tillage (ST) (plowing up to 30 cm in depth); deep conservation tillage (soil loosening up to 30 cm in depth) with a minimum soil surface coverage of 30% of crop residues (CTD); shallow conservation tillage (shallow soil loosening up to 10 cm in depth) with a minimum soil surface coverage of 50% of crop residues (CTS). Liming treatments were liming (according to the recommendation for neutralizing the pH soil reaction) [52,53] (Ly) and treatment without liming (Ln).

2.3. Weather Conditions over the Experimental Period

The maize vegetation period was characterized by a marked lack of precipitation at both experimental sites throughout May and June (Figures 1 and 2). The recorded amounts of precipitation in those months were significantly lower compared to the multi-year average (1984–2013) with above-average air temperatures.

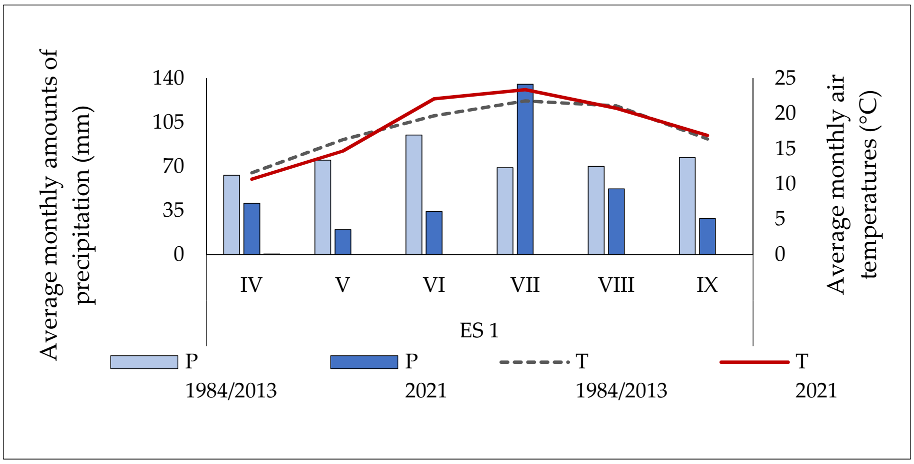

Figure 1. Weather conditions during the maize vegetation period (April–September 2021) and multi-year average (1984–2013) at ES 1 (experimental site Čačinci). T, temperature (°C); P, precipitation (mm).

In May, the amount of precipitation was about 75% less than the long-term average (Figures 1 and 2), and in July, only 3.5 mm of rain was recorded at ES 2, on which the unfavorable weather conditions continued until the end of the maize vegetation with a continuous lack of precipitation (Figure 2). An excessive amount of precipitation in July was present at ES 1, almost 50% more in comparison to the multi-year (1984–2013) average (Figure 1). Average air temperatures deviated from the multi-year average at both experimental sites in June and July (Figures 1 and 2), while in April and May, they were slightly lower compared to average values (Figures 1 and 2).

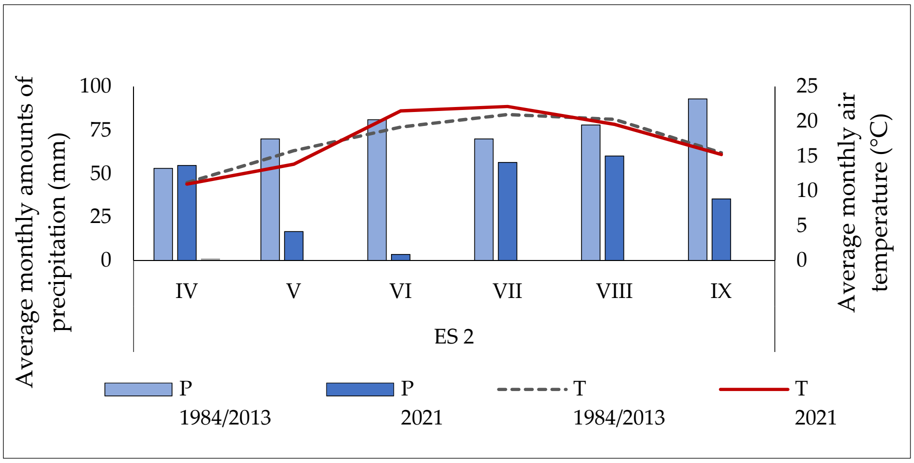

Figure 2. Weather conditions during the maize vegetation period (April–September 2021) and multi-year average (1984–2013) at ES 2 (experimental site Križevci). T, temperature (°C); P, precipitation (mm).

2.4. Sample Collection and Analysis

Soil samples for the selected chemical and physical analysis were taken before the beginning of the research. A soil probe was used for soil sampling in a depth of 0–30 cm to determine chemical soil properties (Table 1). Sampling for the determination of physical soil properties (percentage of sand, silt, and clay) was conducted at a depth of 0–40 cm from the surface horizon, after which the soil samples were prepared for laboratory analysis [54].

Soil pH was measured from soil suspension in H_2O in a ratio of 1:5 (w/v) and in 1 mol dm^{-3} KCl with a pH meter [55]. Hydrolitic acidity was measured by the titration method with Ca-acetate [43], and ammonium lactate-acetic acid was used for plant available P and K extraction [56], which were then determined with flame spectrophotometric analysis. Soil organic matter (SOM) was obtained using measurements of organic carbon with sulphocromic oxidation [57]. The pipette method with wet sieving and sedimentation after dispersion with sodium pyrophosphate [58], according to USDA-NRCS, were used for texture analysis [59]. Before establishing the experimental fields, the initial state of the weediness of the experimental areas was determined. A weed survey was performed twice during the maize vegetation period, and it included the determination of following:

- Weed density (WD) [60];
- Weed biomass (aboveground) (WB) [60];
- Weed coverage (WC) [61];
- Weed species identification [62];
- Weed species number (WSN).

The weed density (total number of weeds per unit area) was established on each investigated plot by counting all classified weed species on the randomly selected area of 0.25 m^2 in four repetitions. The total weed coverage was determined by visual assessment within the same sampling area, after which weed species were clipped on the ground level for aboveground biomass evaluation, separated by different types of species and dried at 60 °C, lasting 48 h for dry aboveground measurement. First, weed sampling was carried out in the V7 maize growth stage (seven fully developed lives with visible collars) according to the leaf collar method [63], which fits up to 42 days after emergence (DAE) at ES 1 (June 21) and 36 DAE at ES 2 (June 22). The second weed observation was made in the R5 maize growth stage (dent stage) [58], which implied 129 DAE at ES 1 (September 16) and 126 DAE at ES 2 (September 20).

2.5. Field Management

Liming material (CaO) was applied manually (evenly on each investigated plot) in summer 2020 in recommended amounts for both experimental sites after winter wheat harvest at ES 1 and on the meadow, which was present at ES 2. Applied amounts of CaO were calculated using the ALRxp computer program for fertilizer recommendations [52,53].

Plowing with KUHN Multi-master 121 plow and loosening with Maschio Artiglio magnum 300/7 loosener at both experimental sites were carried out in autumn 2020. In the spring of 2021, the winter furrow (for ST treatment) was closed with a spike-tooth harrow combined with a hollow roller modified for the research purposes (Agromerkur) at ES 1 until, at ES 2, there was no need for winter furrow closing. Pre-sowing soil preparation for maize seeding was performed with one pass of a spike-tooth harrow combined with a hollow roller (Agromerkur) (ES 1 and ES 2). The fertilization was performed in an optimal amount calculated with the ALRxp computer program for fertilizer recommendations [52,53] (Table 2). The recommended amounts of nutrients were added in autumn prior to basic soil tillage (NPK, 0:20:30; and UREA, 46% N) and in spring with pre-sowing soil preparation (KAN, 27% N). Mineral fertilizer was applied using the mineral fertilizer spreader Gaspardo Primo EW/ISOBUS.

Table 2. Total applied amounts of NPK and CaO according to recommendations.

Experimental Site	Fertilization			Liming
	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	N (kg ha^{-1})	CaO (kg ha^{-1})
ES 1	150	225	170	4375
ES 2	150	225	168	1046

ES 1, experimental site Čačinci; ES 2, experimental site Križevci.

Maize sowing was performed with a no-till seeder Gaspardo Mirka 8R on May 6 at ES 1 and May 10 at ES 2, with a seeding rate of 78. 000 seeds ha^{-1}, and the used hybrid was OS 378, FAO 350. After the manual harvesting of the investigated sub-treatment plot, the rest of the experimental area was harvested using a combine (John Deere S770) with a crop residue cracker adapter. The yields were recalculated with the standard moisture content (14%). Weed control was carried out uniformly in both experimental sites and in all treatments with HARDI Commander 3300 L sprayer. *Glyphosate* (360 g L^{-1}) was applied in the pre-sow treatment in a dosage of 1.5 L ha^{-1}. Post-em *Tembotrione* (44 g L^{-1}) application in a dosage of 2.25 L ha^{-1} was conducted when maize was in the V4 growth stage (four fully emerged leaves with leaf collars visible).

2.6. Statistical Analysis

The influence of different tillage systems and different liming levels at different agroecological experimental sites on weed density, weed biomass, weed coverage, weed species number, and maize yield was tested by the factorial ANOVA design with the experimental site, soil tillage, and liming as given factors. Mean values that were significant according to the performed F-test were compared using the LSD test at a $p < 0.05$ level of significance for the observed factors. The Statistica software package, version 14.0.0. (TIBCO Software Inc., Palo Alto, CA, USA), was used to conduct the ANOVA analysis [64].

The data of the total number of perennial and annual weed species were square root transformed according to the formula: $y = \sqrt{x+1}$, where y stands for the transformed data of the total number of perennial and annual weed species and x represents the original data.

3. Results

3.1. Selected Soil Properties on Investigated Experimental Sites

Determined soil types at the investigated areas were Stagnosol (ES 1) and Gleysol (ES 2) (Table 1), both hydromorphic with characteristic occasional or constant excess wetting of a part of the profile or the entire solum [60]. The soil texture was determined as silty clay loam (ES 1) and silt (ES 2), and soils were moderately acidic (pH (H_2O) = 5.65, ES 1) and weakly acidic (pH (H_2O) = 6.40, ES 2) [41], with a soil organic matter content under 3% on ES 1 and below 2% on ES 2 (Table 1). The measured content of plant-available P and K at experimental sites indicated a poor supply of these nutrients at both experimental sites and values of Hy (Table 1) highlighting the need for obligatory liming in medium quantities for ES 2 and large quantities for ES 1 [43,52].

3.2. Weed Species Occurrence

Prior to the experiment, the initial state of weed species occurrence was carried out by visual assessment in the middle of September 2020 on both experimental sites. A typical residual weed flora of stubble (after winter wheat harvest) [62] at experimental site Čačinci (ES 1) was established. Identified main weed species were *Ambrosia artemissifolia* L., *Anagalis arvensis* L., *Capsella bursa pastoris* (L.) Med., *Calystegia sepium* (L.) R. Br., *Chenopodium album* L., *Cirsium arvense* (L.) Scop., *Plantago major* L., and *Stellaria media* (L.) Vill. At experimental site Križevci (ES 2) the composition of the initial weed flora was determined by the floristic composition of the meadow, which consisted of perennial forage grasses and perennial forage legumes (*Lolium perenne* L., *Dactylis glomerata* L., *Trifolium pratense* L., *Medicago sativa* L., and *Lotus corniculatus* L.). During the research, a total of 17 weed species divided into 10 weed families were identified in the maize for both investigated experimental sites, of which ten were annual and seven were perennial weed species (Table 3).

Table 3. Weed species recorded on the investigated experimental sites (ES 1) and (ES 2).

		Annual Weed Species		**Experimental Site**	
Weed family	Scientific name	Common name	EPPO Code	ES 1	ES 2
Asteraceae	*Ambrosia artemisiifolia* L.	Common ragweed	AMBEL	p	np
Chenopodiaceae	*Chenopodium polyspermum* L.	Many-seeded goosefoot	CHEPO	np	p
Polygonaceae	*Fallopia convolvulus* (L.) Á. Löve	Black-bindweed	POLCO	p	np
Poaceae	*Echinochloa crus-galli* (L.) PB.	Barny grass	ECHCG	p	p
Oxalidaceae	*Oxalis fontana* Bunge	Lemon clover	OXAST	np	p
Polygonaceae	*Polygonum lapathifoilum L.*	Pale smartweed	POLLA	p	np
Poaceae	*Setaria glauca* (L.) PB.	Pearl millet	PESGL	p	np
Poaceae	*Setaria viridis* (L.) PB.	Green foxtail	SETVI	p	p
Asteraceae	*Xanthium strumarium* L.	Common cocklebur	XANST	p	np
Fabaceae	*Vicia sativa L.*	Common vetch	VICSA	np	p
		Perennial Weed Species			
Convolvulaceae	*Calystegia sepium* (L.) R. Br.	Hedge bindweed	CAGSE	p	p
Asteraceae	*Cirsium arvense* (L.) Scop.	Creeping thistle	CIRAR	p	p
Convolvulaceae	*Convolvulus arvensis* L.	Field bindweed	CONAR	p	np
Apiaceae	*Daucus carota L.*	Wild carrot	DAUCA	np	p
Lamiaceae	*Mentha spicata* L.	Spearmint	MENSP	p	np
Boraginaceae	*Symphytum officinale* L.	Common comfrey	SYMOF	np	p
Fabaceae	*Trifolim pratense L.*	Red clover	TRFPR	np	p

ES 1, experimental site Čačinci; ES 2, experimental site Križevci; p, weed species present; np, weed species not present.

The number of weed species was similar at both experimental sites (11 at ES 1 and 10 at ES 2). Weed species common to both experimental sites were *E. crus–galli*, *S. viridis*, *C. sephium*, and *C. arvense* (Table 3). The most numerous weed species at ES 1 were *A. artemisiifolia E. crus-galli* and *C. sepium* or *S. viridis*, *S. officinale*, and *C. sepium* (L.) on ES 2. A slightly higher number of annual weed species was recorded on ES 1 (seven weed species) compared to ES 2 (five weed species), while the number of perennials weed species was almost identical (four at ES 1 and five at ES 2) (Table 3).

3.3. Maize Weediness in V7 Growth Stage (Seven Fully Developed Lives with Visible Collars)

Experimental site properties had a significant impact ($p < 0.05$) on weed density (WD) and weed coverage (WC) in the V7 maize growth stage. Weed density was over 80%

higher on ES 2 compared to ES 1 (Table 4), with confirmed significant differences that also existed in the case of weed coverage, which was also higher at ES 2. All indicators of maize weediness were significantly influenced by soil tillage. Conventional soil tillage treatment (ST) resulted in weed density being about 70% higher compared to CTS and almost 80% higher compared to CTD, while the treatments of conservation tillage systems did not significantly differ among themselves (Table 4). Maize weediness was most pronounced on CTS treatment in terms of weed aboveground biomass (WB), weed coverage (WC), and weed species number (WSN), with significant statistically differences ($p < 0.05$) compared to conventional tillage (ST). Weed aboveground biomass was 77% higher with CTS treatment compared to ST and 82% higher compared to CTD treatment, on which the weed biomass and weed coverage had the lowest values on average. The average number of weed species was the lowest with ST treatment, with significant differences ($p < 0.05$) in relation to conservation tillage treatments. Liming had the effect of reducing weed occurrence in maize. All investigated parameters of weediness were on average lower with the liming application; however, significant differences existed just in the case of weed density and weed coverage. Weed density was over 40% higher with Ln (no liming) compared to Ly (liming) and weed coverage was 26% higher.

Table 4. The influence of experimental site properties, soil tillage, and liming on weed density, weed aboveground biomass, weed cover, and weed species number.

V7	ES		T			L		
	ES 1	**ES 2**	**ST**	**CTD**	**CTS**	**Ly**	**Ln**	**Average**
WD (m^{-2})	7.83 ^{b}	53.33 ^{a}	59.25 ^{a}	13.66 ^{b}	18.83 ^{b}	22.44 ^{b}	38.72 ^{a}	30.58
$F_{(WD)}$	42.83			17.18		5.48		
WB (g m^{-2})	6.07	6.82	3.19 ^{b}	2.45 ^{b}	13.70 ^{a}	5.25	7.64	6.44
$F_{(WB)}$	n.s.			29.34		n.s.		
WC (%)	15.66 ^{b}	22.16 ^{a}	16.50 ^{b}	11.25 ^{b}	29.00 ^{a}	16.05 ^{b}	21.77 ^{a}	18.91
$F_{(WC)}$	7.81			20.51		6.05		
WSN (m^{-2})	1.77	1.94	1.00 ^{b}	2.00 ^{a}	2.58 ^{a}	1.72	2.00	1.85
$F_{(WSN)}$	n.s.			8.14		n.s.		

V7 maize growth stage (seven fully developed lives with visible collars), ES (experimental site), ES 1 (experimental site Čačinci), ES 2 (experimental site Križevci), T (soil tillage), ST (conventional tillage), CTD (deep conservation tillage), CTS (shallow conservation tillage), L (liming), Ly (with liming), Ln (no liming), WD (weed density), WB (weed aboveground biomass), WC (weed coverage), WSN (weed species number), $F_{(WD)}$ (F test for WD), $F_{(WB)}$ (F test for WB), $F_{(WC)}$ (F test for WC), $F_{(WSN)}$ (F test for WSN), n.s. (not significant). Values with different letters in the same line differ significantly at $p < 0.05$.

Significant interactions were confirmed among experimental sites and soil tillage treatments in relation to weed density (WD) (Figure 3). Weed density on conventional soil tillage treatment (ST) differed significantly regarding the experimental sites. Weed density with ST treatment on ES 1 was over 30 times smaller compared to ES 2. Looking at other soil tillage treatments on different experimental sites, no statistically significant differences were found.

Significant interactions were found for weed coverage (WC) and the following: experimental site and soil tillage (Figure 4), experimental site and liming (Figure 5), and soil tillage and liming (Figure 6).

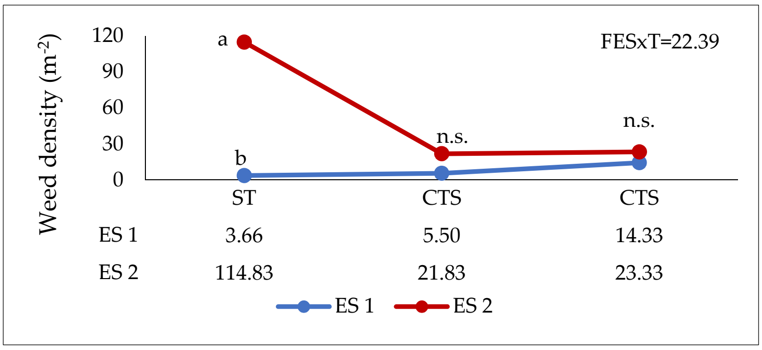

Figure 3. The influence of the experimental site and soil tillage on weed density (WD) in the V7 maize growth stage (seven fully developed lives with visible collars). ES 1 (experimental site Čačinci), ES 2 (experimental site Križevci), ST (conventional tillage), CTD (deep conservation tillage), CTS (shallow conservation tillage), F_{ESxT} (F-test for experimental site and tillage interaction), n.s. (not significant). Values with different lower case differ significantly at $p < 0.05$.

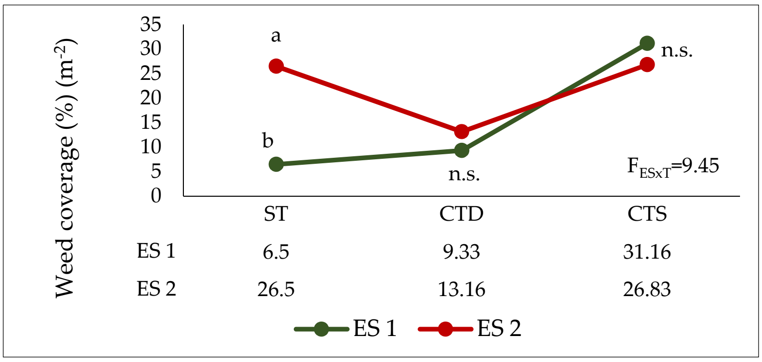

Figure 4. The influence of experimental site and soil tillage on weed coverage (WC) in the V7 maize growth stage (seven fully developed lives with visible collars). ES 1 (experimental site Čačinci), ES 2 (experimental site Križevci), ST (conventional tillage), CTD (deep conservation tillage), CTS (shallow conservation tillage), F_{ESxT} (F-test for experimental site and tillage interaction), n.s. (not significant). Values with different lower case differ significantly at $p < 0.05$.

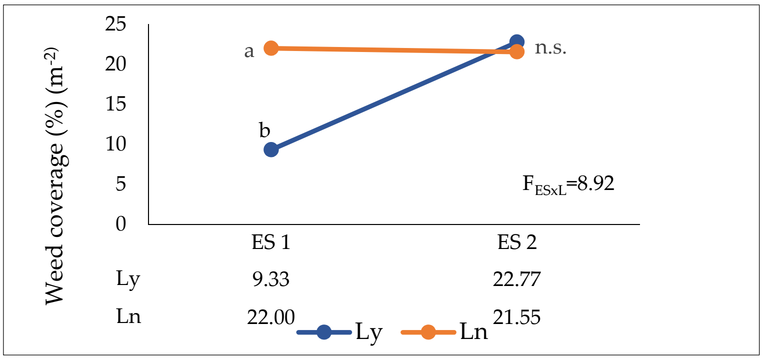

Figure 5. The influence of the experimental site and liming on weed coverage (WC) in the V7 maize growth stage (seven fully developed lives with visible collars). ES 1 (experimental site Čačinci), ES 2 (experimental site Križevci), Ly (with liming), Ln (no liming), F_{ESxL} (F-test for experimental site and liming interaction), n.s. (not significant). Values with different lower case differ significantly at $p < 0.05$.

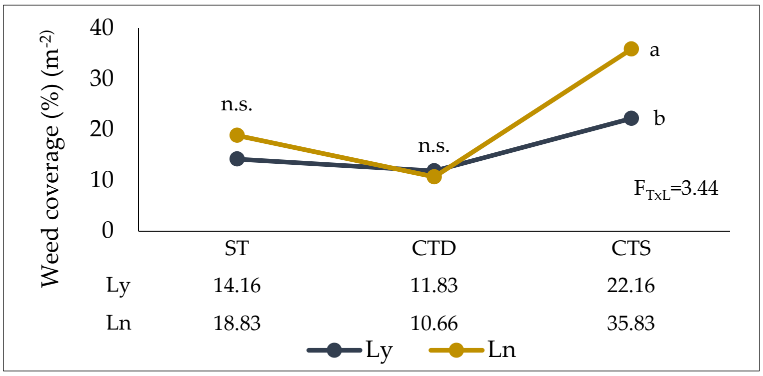

Figure 6. The influence of soil tillage and liming on weed coverage (WC) in the V7 maize growth stage (seven fully developed lives with visible collars). ST (conventional tillage), CTD (deep conservation tillage), CTS (shallow conservation tillage), Ly (with liming), Ln (no liming), F_{TxL} (F-test for tillage and liming interaction), n.s. (not significant). Values with different lower case differ significantly at $p < 0.05$.

Conventional soil tillage (ST) on the experimental site Križevci (ES 2) resulted in weed coverage that was four times greater (26.5%) compared to ES 1 at a significant level ($p < 0.05$) (Figure 4). However, significantly notable weed coverage was found on ES 1 with treatment without liming (Ln) and was 58% higher compared to Ly treatment (Figure 5).

Shallow conservation soil tillage (CTS) treatment resulted in the highest weed coverage with Ln liming treatment (35.83%) with statistically significant differences ($p < 0.05$) compared to Ly treatment (22.16%) (Figure 6).

3.4. Maize Weediness in R5 Growth Stage (Dent Stage)

Weed density (WD), weed aboveground biomass (WB), and weed coverage (WC) varied significantly among different experimental sites in R5 maize growth stage. Weed density was 64% higher for ES 2, while WB and WC had lower values. Measured weed biomass was five times higher for ES 1 compared to ES 2, whereas weed coverage was higher by 54%. The number of weed species was also higher for ES 1 but without statistically proven significance (Table 5).

Table 5. The influence of experimental site properties, soil tillage, and liming on weed density, weed aboveground biomass, weed coverage, and weed species number.

R5	ES		T			L		Average
	ES 1	**ES 2**	**ST**	**CTD**	**CTS**	**Ly**	**Ln**	
WD (m^{-2})	14.50 ^{b}	39.77 ^{a}	24.66	29.00	27.75	26.27	28.00	27.13
$F_{(WD)}$	41.18			n.s.		n.s.		
WB ($g\ m^{-2}$)	98.89 ^{a}	19.54 ^{b}	36.00 ^{b}	56.71 ^{ab}	84.80 ^{a}	45.52 ^{b}	72.82 ^{a}	59.18
$F_{(WB)}$	42.69			5.41		5.04		
WC (%)	46.05 ^{a}	21.16 ^{b}	20.58 ^{b}	29.66 ^{b}	50.58 ^{a}	27.00 ^{b}	40.22 ^{a}	33.60
$F_{(WC)}$	23.10			11.77		6.52		
WSN (m^{-2})	2.16	1.77	1.5 ^{b}	1.66 ^{b}	2.75 ^{a}	1.5 ^{b}	2.44 ^{a}	1.96
$F_{(WSN)}$	n.s.			6.63		9.63		

R5 maize growth stage (dent stage), ES (experimental site), ES 1 (experimental site Čačinci), ES 2 (experimental site Križevci), T (soil tillage), ST (conventional tillage), CTD (deep conservation tillage), CTS (shallow conservation tillage), L (liming), Ly (with liming), Ln (no liming), WD (weed density), WB (weed aboveground biomass), WC (weed coverage), WSN (weed species number), $F_{(WD)}$ (F test for WD), $F_{(WB)}$ (F test for WB), $F_{(WC)}$ (F test for WC), $F_{(WSN)}$ (F test for WSN), n.s. (not significant). Values with different letters in line differ significantly at $p < 0.05$.

Soil tillage treatments significantly ($p < 0.05$) affected weed aboveground biomass (WB), weed coverage (WC), and weed species number (WSN). The highest WB was obtained with the shallow conservation tillage system (CTS), which differed for 58% in relation to conventional tillage (ST). The conservation tillage systems CTD and CTS did not significantly differ among themselves according to the achieved weed biomass.

Shallow conservation tillage also led to an average increase of weed coverage and weed species number in regard to ST and CTD. Weed coverage was 60% higher, and the weed species number was 66% higher, with CTS compared to ST, which was not significantly different from CTD. All investigated parameters of maize weediness were, on average, lower when liming was applied.

Liming had a statistically significant effect on weed aboveground biomass (WB), weed coverage (WC), and weed species number (WSN), which were higher with Ln treatment (no liming) compared to Ly (liming). Measured values of WB, WC, and WSN were higher by 48%, 33%, and 39% compared to Ly treatment with the existence of a statistically significant difference (Table 5).

By analyzing the collected data of maize weediness in the second sampling (R5), significant interactions were found among soil tillage and liming for weed density (WD) (Figure 7), while a significant interaction of experimental site and liming existed concerning weed aboveground biomass (WB) and weed coverage (WC) (Figure 8).

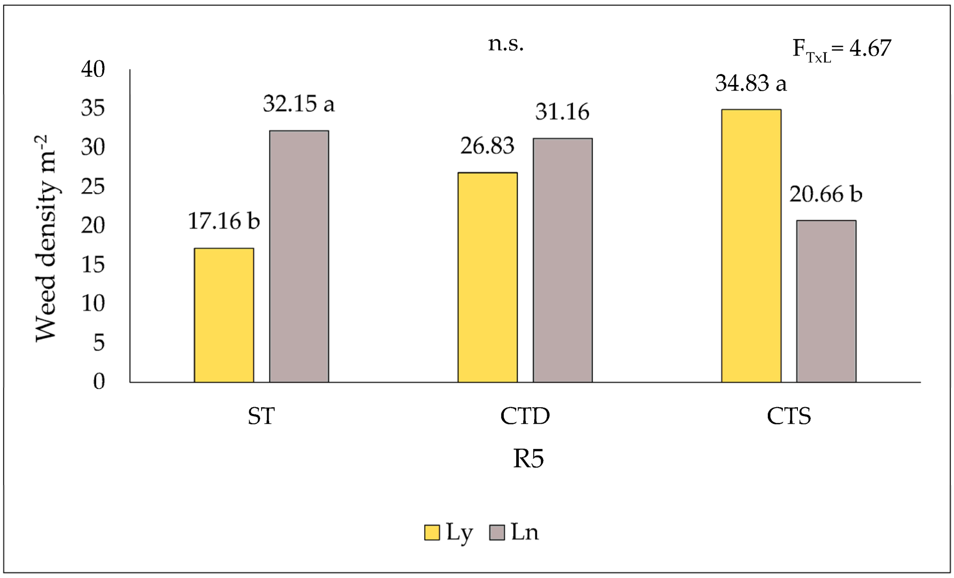

Figure 7. The influence of soil tillage and liming on weed density (WD) in the R5 maize growth stage (dent stage). ST (conventional tillage), CTD (deep conservation tillage), CTS (shallow conservation tillage), Ly (liming), Ln (no liming), F_{TxL} (F-test for tillage and liming interaction), n.s. (not significant). Values with different lower case differ significantly at $p < 0.05$.

The highest weed density (WD) was recorded with the shallow conservation tillage system (CTS) with liming application (Ly), which was 40% higher in relation to Ln. On the contrary, the conventional soil tillage (ST) liming treatment resulted in a 47% greater weed density with Ln compared to Ly (Figure 7).

Liming application led to a significant reduction of weed aboveground biomass (WB) and weed coverage (WC) for ES1 (Figure 8). WB was significantly lower ($p < 0.05$) with Ly in comparison to Ln, for which the obtained weed biomass was 44% higher and the equal percentage increase was noted for weed coverage with Ln for ES 1.

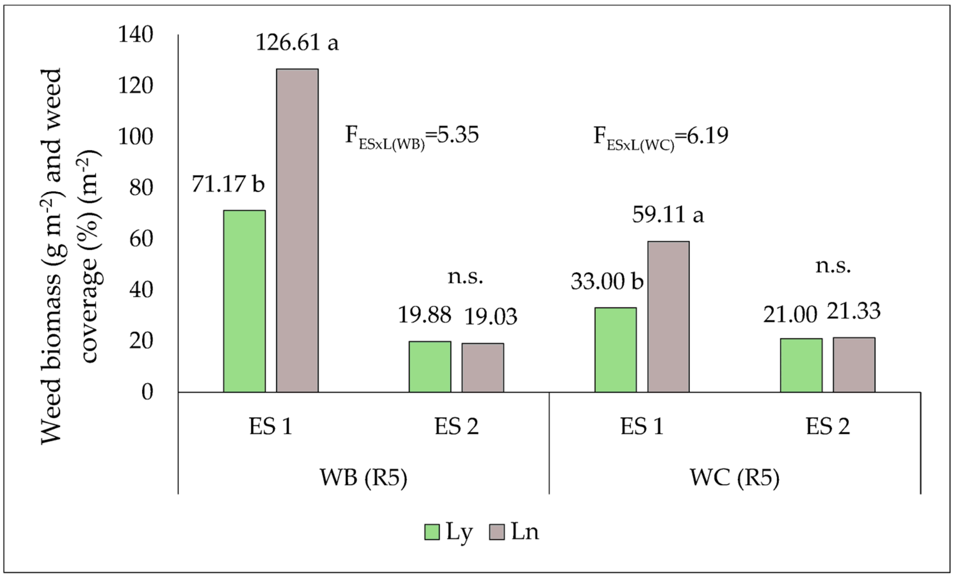

Figure 8. The influence of soil tillage and liming on weed aboveground biomass (WB) and weed coverage (WC) in the R5 maize growth stage (dent stage). ES 1 (experimental site Čačinci), ES 2 (experimental site Križevci), Ly (liming), Ln (no liming), $F_{ESxL(WB)}$ (F-test for experimental site and liming interaction at weed aboveground biomass), $F_{ESxL(WC)}$ (F-test for experimental site and liming interaction at weed coverage), n.s. (not significant). Values with different lower case differ significantly at $p < 0.05$.

3.5. Incidence of Perennial and Annual Weed Species in Maize

The average number of perennial and annual weed species in different soil tillage systems is shown in Figure 9. The average weed number indicates a higher incidence of perennial weed species for the conservation soil tillage systems CTD and CTS.

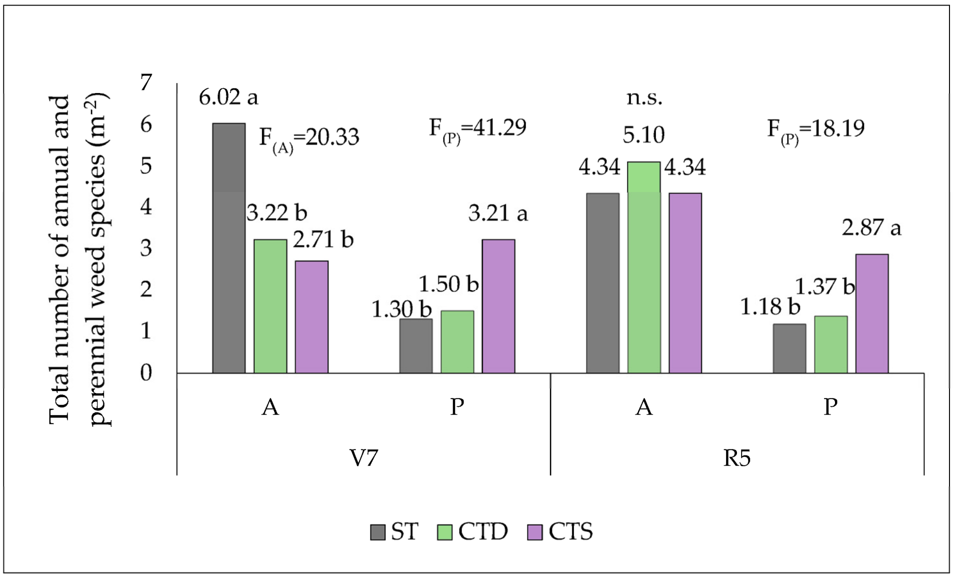

Figure 9. Total number of perennial and annual weeds for different tillage systems. P (perennial weed species), A (annual weed species), V7 maize growth stage (seven fully developed lives with visible collars), R5 maize growth stage (dent stage), ST (conventional tillage), CTD (deep conservation tillage), CTS (shallow conservation tillage), $F_{(A)}$ (F-test for annual weed species), $F_{(P)}$ (F-test for perennial weed species), n.s. (not significant). Values with different lower case differ significantly at $p < 0.05$.

The highest average perennial weed occurrence according to the number of perennial weeds was present for the shallow conservation tillage system (CTS), which was 3.21 m^{-2} in the first observation (V7) and 2.87 m^{-2} in the second observation (R5). Then, the CTD treatment followed with a slightly lower number of perennial weeds (1.50 m^{-2} in V7 and 1.37 m^{-2} in R5), and conventional tillage (ST) was last, for which the presence of perennial weeds was the lowest. Statistically significant differences ($p < 0.05$) were found in the number of perennial weeds among shallow conservation tillage (CTS) and CTD and ST.

The highest average number of annual weeds (6.02 m^{-2}) was recorded for the conventional soil tillage system (ST) in the first observation (V7), while in the second (R5), no statistically significant differences were found in the number of annual weeds with regard to the soil tillage system (Figure 9).

3.6. Maize Yield

The achieved maize yield was significantly influenced by all the investigated factors; experimental site (ES), tillage (T) liming (L), and statistically significant interactions among ES and T are presented in Table 6. The influence of different agroecological conditions was pronounced, and the yield differed significantly depending on the experimental site. The average maize yield for the experimental site Križevci (ES 2) was 36% higher compared to the experimental site Čačinci (ES 1), and a significant influence of soil tillage highlighted the shallow conservation system (CTS), which recorded the highest average maize yield (11.18 t ha^{-1}).

Table 6. The influence of the experimental site (ES), soil tillage (T), liming (L), and interaction (ESxT) on maize yield (t ha^{-1}).

T	ES 1	ES 2	T Mean	F
ST	8.47 ^{d}	13.56 ^{a}	11.01 ^{B}	F_T = 984
CTD	8.01 ^{e}	12.34 ^{b}	10.18 ^{C}	
CTS	8.80 ^{c}	13.55 ^{a}	11.18 ^{A}	
ES mean	8.43 ^{B}	13.15 ^{A}		F_{ES} = 57,019
L mean	Ly = 10.84 ^{A}	Ln = 10.74 ^{B}		F_L = 30
		F_{ESxT} = 127		

ES 1 (experimental site Čačinci), ES 2 (experimental site Križevci), T (tillage), ST (conventional tillage), CTD (deep conservation tillage), CTS (shallow conservation tillage), L (liming), Ly (liming), Ln (no liming), F_{ES} (F test for experimental site), F_T (F test for tillage), F_L (F test for liming), F_{ESxT} (F test for experimental site and tillage interactions). Values with different lower or upper case differ significantly at $p < 0.05$.

The liming application significantly affected the average maize yield, which was statistically significantly higher ($p < 0.05$) for Ly (liming) compared to Ln (no liming). The interaction of the experimental site and tillage (ES x T) led to variations in the maize yield that ranged from the lowest (8.01 t ha^{-1}) for ES 1 using deep conservation tillage (CTD) to the highest (13.56 t ha^{-1}) for ES 2 using conventional soil tillage (ST).

The maize yield achieved using shallow conservation tillage systems (CTS) was statistically significantly higher ($p < 0.05$) than conventional tillage (ST) for the experimental site Čačinci (ES 1), while for Križevci (ES 2), CTS resulted in a maize yield in range with ST.

4. Discussion

4.1. Soil Properties

Hydromorphic soil types [51] in the investigated experimental sites (ES 1-Stagnosol) and (ES 2- Gleysol) were characterized with unfavorable physical, chemical, and biological properties [65]. Moderate acidic (ES 1) and weakly acidic (ES 2) soil reactions with soil organic matter content under 3% for ES 1 and below 2% for ES 2 pointed to a certain limitation of these soils for intensive crop production, which was also affected by the low level of soil fertility (poor supply of plant-available P and K). The need for reducing the soil acidity level stemmed from the obtained values of hydrolytic acidity (ES 1, 7.90; ES 2, 2.45), which indicated obligatory liming in large quantities for ES 1 and medium quantities for ES 2 [43,46,52].

4.2. Weed Species Composition during the Research

The usual composition of maize weed flora for the researched agroecological areas was recorded during the experiment [66]. Grassy annual weed species, *E. crus galli* and *S. viridis*, detected at both experimental sites are defined as the most common and competitive weeds in maize, with a high adaptability level to different environmental conditions [66]. The pronounced presence of the broadleaf perennial species *C. sepium*, frequent in maize, was noticeable in both experimental areas, which is probably a consequence of the suitable soil conditions for the development of this weed. Moist soil with clay silt and silty loam soil texture favors *C. sepium*, which is resistant to dry periods at the same time [67,68]. Of numerous weed species, *S. officinale* was specific only to the experimental site Križevci (ES 2), which is probably the result of favorable soil texture (silt). The mentioned weed species is an indicator of moderately moist soil, tolerates occasional stronger wetting and drying, and is widespread in soils of a lighter texture with variable humidity [62]. *F. convolvulus* appeared only at the experimental site Čačinci (ES 1) in soil with a higher clay content, which is consistent with [69], and the site-specific occurrence of certain weed species was also confirmed by Pätzold et al. [70].

Ecological indices for soil acidity, which represent a significant factor for weed growth, classify the majority of identified weed species for both experimental sites in a weekly acidic or neutral soil class (pH 4.5–7.5) with wide ecological amplitude [62]. Although specific soil reactions can be a limiting factor for weed development [64], warm season weeds can appear in a relatively wide pH range (4.8–6.4) [71], and the optimal pH for many weed species is about 5.5 [72]. The occurrence of certain weed species is probably conditioned by pedoclimatic specificities of experimental sites and the high ability of weeds to adapt to various environmental factors.

4.3. Maize Weediness

Different pedoclimatic conditions of the investigated areas had a significant influence on the maize weediness indicators. The greater average weed occurrence in terms of weed density and weed coverage for the experimental site Križevci (ES 2) in the first observation (V7 maize growth stage) was a possible result of the present weather conditions. Weather conditions were highlighted as the dominant factor affecting weed emergence [73], and the variation in environmental factors was cited as more important than tillage systems in terms of the impact on weed species diversity and weed density [74]. The optimal amount of precipitation at the very beginning of maize vegetation enabled the emergence and development of weeds, whose competition was more pronounced in later dry conditions, especially in June with a marked lack of precipitation with above-average temperatures. Although unfavorable weather conditions have a negative influence on weed species development [65], drought stress during maize vegetation increased weed competition, despite requiring similar abiotic conditions as agricultural crops [75]. Weeds show better physiological resistance to drought with the excessive use of water that allows them to grow in conditions of pronounced lack of water in the soil [76].

Maize weediness had a dynamic increase among two observations, with the exception of weed density, which was higher for ES 2 during the first sampling, and different weed densities of various soil types were also confirmed by Ervio [69], while Salonen [77] found variation in weed biomass between other soil types. Excessive amounts of precipitation in July at the experimental site Čačinci (ES 1) led to a significantly higher weed biomass (WB) and weed coverage development (WC) compared to ES 2. This is probably the result of soil waterlogging caused by weak infiltration because of the common impermeable layer on poorly draining Stagnosol, which leads to a lack of oxygen in the soil [78]. In the specified environmental stress conditions, weed competition is more pronounced compared to crops [76] due to their marked adaptability to different unfavorable conditions [79].

Tillage intensity is an important factor that influences the level of weediness, which, in conservation and conventional tillage systems, depends on the plant production system, soil, and climatic conditions. Tillage had a significant effect on maize weediness throughout the vegetation season, with the exception of weed density in the R5 maize growth stage. A significantly higher average weed density with conventional tillage in the V7 maize growth stage may be the result of the weed seed incorporation into deeper soil layers that provide more moisture for weed germination and development when insufficient soil moisture is present [80], as in the case of this research when there was a lack of precipitation in May. In conventional tillage systems, the seeds are distributed more or less evenly throughout the soil layer, while in reduced systems, a large part of the seed is concentrated on the surface of the soil [81].

The influence of soil tillage on weed density is variable, which has been confirmed by various studies [29,81,82], and it is also visible from this research where the influence of soil tillage on average weed density in the second sampling (R5) was not recorded. Higher weed densities using conventional tillage were confirmed by Shrestha et al. [83]. Onwards, plant residues on the soil surface in conservation tillage can have a suppressive effect on weed emergence by changing the physical environment at the very beginning of the maize vegetation, while later in the growing season, by conserving soil moisture and nutrient release, they can stimulate the growth of weeds [84]. Shallow conservation tillage (CTS) resulted in the highest average weed aboveground biomass (WB), weed coverage (WC), and weed species number (WSN) compared to conventional tillage in maize vegetation, with a noticeable trend of increasing the level of weediness during the growing season, which is consistent with [23,24,28]. Significantly higher weed biomass in reduced tillage compared to conventional tillage, with an increasing trend from the beginning of the vegetation season to the later stages, was also proven by Hofmeijer [28], while the increase in weed coverage and weed species number was also confirmed with previous research [31,35,85]. Reduced tillage can lead to increased incidence and the development of perennial weeds [28,30]. The average occurrence of weeds with respect to the life cycle differed among soil tillage systems in this research. By reducing the intensity of soil tillage, the average number of perennial weeds increased through maize vegetation. Shallow conservation tillage (CTS) had the highest average incidence of perennial weeds, and a greater perennial weed density using reduced soil tillage compared to conventional was confirmed with previous research in maize [29,86]. More pronounced changes in weed composition and the appearance of perennial weeds can be expected with longer conservation tillage implementation [24], which also applies to the increasing biodiversity [34].

Significant experimental site and soil tillage interactions were present in the case of weed density (WD) and weed coverage (WC), which were significantly higher using conventional soil tillage for the experimental site Križevci (ES 2). According to Derksen [10], agroecological conditions and soil tillage are important factors that influence weed occurrence with emphasis on annual grasses. Greater weediness using conventional soil tillage for ES 2 was probably conditioned by the soil type (Gleysol) and a lighter soil texture (silt), which enabled the better emergence and development of weeds. Additionally, the most numerous weed species for ES 2 using conventional tillage was *S. viridis*, and a greater incidence of annual grasses associated with plowing that are site-specific has been previously reported [25,70].

Weed occurrence in agricultural fields is mainly affected by anthropogenic activity, and various soil improvement management is directly aimed at reducing weediness. The liming of acidic soils, along with a positive effect on the chemical, physical, and biological soil properties can also affect the reduction of weediness of agricultural crops [48] and thus can have a positive effect on increasing crop productivity [87]. In this research, liming performed on moderately acidic (ES 1) and weakly acidic (ES 2) soils had a positive influence on average weediness decreasing. All investigated weediness indicators were, on average, lower with the liming application with the existence of an increasing trend in the level of weediness during the growing season. The statistically significant influence of liming on the reduction of weediness in the V7 maize growth stage was determined for weed density (WD) and weed coverage (WC), while later in maize vegetation (R5), liming had a significant effect on weed aboveground biomass (WB), weed coverage (WC), and weed species number (WSN). It can be assumed that liming positively influenced the competitive ability of maize, which led to an average reduction in weediness similar to the findings of Skuodiene [47], in which weed species number, weed density in the earlier vegetation crop growth stage, and weed biomass in the maturity stage of the crop were significantly lower in limed soils. Contrary to the above, few research studies have reported a greater diversity of weed species and a higher weed density and biomass caused by different liming treatments [88,89]. Significant experimental site and liming interactions were recorded during maize vegetation, where lower average weed coverage was determined for the experimental site Čačinci (ES 1) with liming application, as well as lower weed biomass, but only at the R5 maize growth stage. The positive influence of liming on the soil property improvement was more pronounced in moderate acidic Stagnosol, which led to a decrease in the competitive ability of weeds compared to maize. Liming can have a contrasting effect on weediness, which may depend on the specific weed species and soil properties. By reducing soil acidity, liming can make it less suitable for some weed species development, which was confirmed by Stephenson et al. [72], indicating that the optimal pH for many weed species is about 5.5. Liming led to lower weediness using the shallow conservation tillage system (CTS), which significantly decreased weed coverage in the V7 maize growth stage and weed density in R5. This was probably caused by the positive impact of conservation treatment in acid soil management [41], since it has a positive effect on the soil structure and biological activity, while plant residues additionally protect the soil and reduce weediness, which is additionally expressed with the liming application and its positive influence of chemical, physical, and biological soil properties. The positive influence of conservation tillage on the soil pH reaction was proven by the research of Ligowe et al. [42], which reported higher soil pH values when conservation tillage was applied, which is why the positive influence of liming was additionally pronounced for CTS soil tillage treatment and reducing weed competition.

4.4. Maize Yield

Agroecological conditions, agricultural management, genetic background, and other often limiting factors in different agroecological regions are key factors for maize yield formation [90]. The experimental sites had a significant impact on the final average maize yield in this research. Maize vegetation during the research was followed with variable weather conditions with unfavorable rainfall and temperature patterns. A pronounced lack of precipitation with above-average high temperatures was present in the critical early growth stage of maize for both experimental sites (ES 1 and ES 2) and continued until the late vegetative growth stage (tasselling/silking), in which the optimal temperature and available water are of great importance for the grain formation [90]. However, sufficient soil moisture in Križevci (ES 2) led to better conditions for maize sowing due to the water supply from April, and the emergence and initial growth of maize was better for ES 2. Adverse weather conditions continued through July for the experimental site Čačinci (ES 1), with an excessive amount of rain that resulted in soil waterlogging. This was caused by weak infiltration due to the impermeable layer present in poorly draining Stagnosol, which leads to a lack of oxygen in the soil [78]. Waterlogging can cause a significant stagnation in growth and reduction in yield depending on the duration [91], in particular, to the sensitivity of maize with insufficient oxygen concentrations, which prevent optimal root function. The amount of precipitation at the experimental site Križevci (ES 2) in July was slightly above average, and in August, the lack of precipitation was expressed at both investigated sites. Variable environmental conditions at the research sites, along with specific soil properties, resulted in a significantly lower average maize yield for the experimental site Čačinci

(ES 1). Despite varying weather conditions, maize yields were satisfactory for ES 1 and above average for ES 2, which was probably conditioned with luxury fertilization that was conducted for both poor supplied soils. Optimal nutrient supply (N, P, K) strongly affects the maize yield when drought is present [92,93] through water-use efficiency increasing, stomatal regulation, and photosynthesis activity [94,95]. Moreover, it is likely that weed pressure during maize vegetation did not interfere significantly with the final maize yield.

Yield differences with respect to soil tillage treatments confirm maize sensitivity to changes caused by soil tillage [96]. The reduction in soil tillage intensity and depth resulted in the highest average maize yield for the shallow conservation tillage (CTS), which is in line with Sime et al. [97], who reported a 14–19% higher maize yield under a conservation tillage system compared to a conventional system, and similar was cited by much other research [39–41].

Conservation tillage has a broad effect on the soil water regime and water availability of plants [98], which had a positive effect on the maize yield increase in adverse weather conditions during the research. Residue management in conservation tillage systems stands out as an important factor affecting root development, water and nutrient availability, and yield increase, with pronounced positive effects in drier environmental conditions [99,100].

At the experimental site Čačinci (ES 1), the highest maize yield was obtained using CTS soil tillage, with a significant difference ($p < 0.05$) compared to ST, while at Križevci (ES 2), there were no significant differences among CTS and ST. This is probably a consequence of site-specific soil properties, where the positive impact of conservation treatment in acid soil management [41] was pronounced for ES 1, which had higher soil acidity. Higher average maize yields for both experimental sites using CTS compared to CTD indicated the importance of higher soil cover (50% for CTS), which significantly affects water conservation and greater water use efficiency while reducing water losses [101], especially in drier conditions on heavy or light soils. Deep conservation tillage CTD had the lowest average yield, and a maize yield decrease in deep reduced tillage has been confirmed before [98].

Liming application led to an increase in the average maize yield due to many positive effects on soil properties, which allowed more favorable conditions for crop growth [44–46]. The proven liming effect refers to improving the rooting systems, availability and uptake of nutrients, the water supply, and thus, better drought resistance, which were probably reflected by the increase of maize yield in this research. Crops showed better drought resistance under liming treatment, and higher maize yields with the liming application were also reported by several researchers [41,53,102,103].

Although the changes in the weed flora in conservation systems were already recorded after the first year of research in some previous studies [104], as well as an increased corn yield with the application of liming [53], future research will certainly contribute to a better understanding of the conservation system influence on crop productivity and the implementation of adapted and specific measures in weed control that should be based on the reduced use of herbicides.

Furthermore, the comparability of the results of the one-year experiment in different agroecological conditions with long-term research can contribute to a better understanding and greater acceptance of the transition to CA by farmers.

5. Conclusions

Soil tillage and liming affected the level of maize weediness under different agroecological conditions in the conducted one-year research. The reduction of soil tillage intensity led to an average increase in weed pressure. Weed aboveground biomass (WB), weed coverage (WC), and weed species number (WSN) were the highest using shallow conservation soil tillage (CTS), with a larger average number of perennial weeds.

Liming affected the reduction of all investigated weediness parameters during the maize growing season, including average weed density (WD) and WC in the V7 maize growth stage, and (WB), (WC), and (WSN) in the R5 maize growth stage.

The obtained average maize yield was site-specific and influenced by soil tillage and liming. The highest average maize yield was recorded for experimental site ES 2, using conservation (CTS) soil tillage and with liming application (Ly). Shallow conservation tillage (CTS) resulted in the highest average maize yield for ES 1, while for ES 2, it was similar to conventional (ST).

The preliminary results of the conducted research indicate an increase in maize weediness with conservation soil tillage implementation, with the opposite effect of liming, but without a negative impact on maize yield, which confirms the given hypothesis.

The presence of satisfactory maize yields, despite adverse environmental conditions, indicates the benefits of conservation tillage as an effective tool for the adaptation and mitigation of negative abiotic factors of crop productivity and the possibility of its implementation in different agroecological conditions.

However, the pronounced influence of agroecological conditions with varying levels of weediness and maize yield indicate the need for continued research.

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