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Straw Mulch Effect on Soil and Water Loss in Different Growth Phases of Maize Sown on Stagnosols in Croatia

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Abstract: Soil and water loss due to traditional intensive types of agricultural management is widespread and unsustainable in Croatian croplands. In order to mitigate the accelerated land degradation, we studied different cropland soil management strategies to obtain feasible and sustainable agro-technical practices. A rainfall simulation experiment was conducted at 58 mm h^{-1} over 30 min on 10 paired plots (0.785 m^2), bare and straw covered (2 t ha^{-1}). The experiment was carried out in maize cultivation (Blagorodovac, Croatia) established on Stagnosols on slopes. Measurements were conducted during April (bare soil, after seeding), May (five-leaves stage), and June (intensive vegetative growth) making 60 rainfall simulations in total. Straw reduced soil and water losses significantly. The highest water, sediment loss, and sediment concentrations were identified in tillage plots during May. Straw addition resulted in delayed ponding (for 7%, 63%, and 50% during April, May and June, respectively) and runoff generation (for 37%, 32%, and 18% during April, May and June, respectively). Compared with the straw-mulched plot, tillage and bare soil increased water loss by 349%. Maize development reduced the difference between bare and straw-mulched plots. During May and June, bare plots increase water loss by 92% and 95%, respectively. The straw mulch reduced raindrop kinetic energy and sediment detachment from 9, 6, and 5 magnitude orders in April, May, and June, respectively. Overall, the straw mulch was revealed to be a highly efficient nature-based solution for soil conservation and maize cultivation protection.

Keywords: agriculture systems; clay–loam soil; artificial rainfall; nature-based solutions; soil conservation

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1. Introduction

Soil is an irreplaceable resource, as it continues to provide habitat for 95% of the world's produced food. Besides enabling food security, soils are multi-functional. Soils sequester carbon; recycle nutrients; regulate and filtrate water; provide habitat support, cultural services, raw materials and food; remediate contaminants; control flooding, erosion, pests, and disease; and increase biodiversity [1]. If the soils are properly managed, many soil ecosystem outcomes are accomplished. In this context, Viana et al. [2] highlighted that UN Sustainable Development Goals (SDGs) should consider adopting innovative forms of sustainable practice to increase efficiency, build resilience, and mitigate the impact of agriculture. Besides tillage, nutrient management is vital to increase soil productivity and reduce yield variability in vulnerable environments [3]. This approach supports several SDGs, such as zero hunger (SDG 2), climate action (SDG 13), and ensuring sustainable consumption and production patterns (SDG 12); regardless, water and food security are threatened under climate change [4].

Soils are endangered by several degradation processes. Loss of organic matter, crusting, soil compaction, soil acidification, nutrient imbalance, pollution, salinization, and erosion appear as signs of agricultural intensification. Conventional agriculture practices have devastating impacts on the environment and are a major cause of land degradation, biodiversity loss, and climate change [5]. Between 60 and 70% of soils in the European Union are unhealthy [6], while at least one third of land globally is considered moderately to highly degraded [7]. Despite these risks, the importance of food security is still critical, and food production will increase in the future. Possible food crises accelerated by warfare [8] or population growth [9] are the major factors in future soil disturbance. It is expected that an increase of approximately 25–70% above current production levels may be necessary to meet 2050 crop demand [10,11], and this will increase the area subjected to agricultural soil degradation.

Maize production is one of the most important cereals both for human and animal consumption; it is grown for grain and forage. Among the main crops produced, maize is certainly one of the most important crops for humanity. According to the FAO [12], maize production covers 205 million ha, making this crop, alongside wheat, one of the most important for farmer income [13]. Maize cultivation is organized in a wide diversity of soils and environments. In addition, different crop and soil management practices occur in maize cultivation; from dominantly no-tillage and other conservation-tillage systems of production in developed countries, to conventional tillage systems which occur in low-development countries with a prevalence of smallholders [13]. This diversity of management also has powerful implications for soil condition, quality, and soil degradation. Conventional agricultural practices, such as ploughing or excessive agrochemical use, are a major threat to soil system sustainability. Bare soils, for instance, are a generator of sediment, nutrient loss, and diffuse pollution [14]. In addition, previous works revealed that soils under maize are highly vulnerable to soil erosion and sediment transport on silty [15], loam [16], clay–loam [17], or sandy soils [18] in different environments. Since the cultivation of maize is in wide rows, the plant cover is not significant, making it a ineffective crop for raindrop interception.

Several erosion control measures are used in different agricultural landscapes: reduced tillage and/or no-tillage management, suitable crop rotations, mulching, cover crops, strip and/or contour cropping, and terracing [19]. Recently, nature-based solutions (NBS) have become popular measures to control and reverse land degradation. Their introduction to practical crop production is essential for sustainable development [20]. Application of organic mulch materials is one example of a NBS for restoring degraded ecosystems and delivering vital ecosystem services, since it has a positive/neutral effect on several land degradation processes in agricultural soils [21]. Therefore, this strategy should be considered a primary practice to halt soil erosion; furthermore, it supports major EU policy priorities, in particular the European Green Deal, Biodiversity strategy and Climate adaptation strategy. Globally, mulching has been tested as a solution for controlling soil erosion [14,22–24]. However, the precise contribution of mulching at particular maize growing stages for controlling soil erosion has not been singled out as a separate variable. This topic is especially important due to reports indicating that a single high-magnitude rainstorm can be responsible for 93% of the total annual soil losses [25]. Besides the favourable impact on hydrological response, organic mulch application has other benefits for the soil system as well. Mulch was proven to improve soil structure; conserve soil moisture; reduce soil compaction; and increase soil organic matter, infiltration, nutrient concentration, and cycling [26–29]. Despite all mentioned positives, in countries with poor agricultural sectors, a clear tradition about conservation practices is missing, so the use of mulch in practical crop production is rare and its impact in most agricultural systems is not well understood. Maize cropping systems in Central Europe have mostly focused on testing the effects of different tillage directions or no-tillage implementation in recent decades, thanks to pioneers who developed new strategies in soil conservation. However, most of the mentioned research focused on the effect of tillage systems and crops on yearly soil erosion proportions [30–33], without considering the effect of single rainstorms on different crop cultures in especially vulnerable growth stages.

New challenges are confronting Croatian croplands, resulting from the potential for organic residues in agricultural production to improve soil systems and ensure more sustainable management. Therefore, the aim of this work is to (1) investigate the use of straw mulch as an NBS to reduce soil and water loss in maize cropping systems, (2) to determine the critical stages of maize development when the soil degradation is greatest, and (3) to assess the short-term impact of straw mulch on soil health. We hypothesize that organic mulching will preserve soil quality and promote the recovery of soil services in poor-quality stagnosols on slopes.

2. Materials and Methods

2.1. Location, Climate and Soil

The experiment was set up in the municipality of Dežanovac, in the southern part of Bjelovar-Bilogora County, continental Croatia (Figure 1). Bjelovar-Bilogora County is a large Croatian rainfed cropland production zone, with maize, wheat, barley, soybean, and rapeseed being the dominant crop cultures. The study area is characterized by gentle hills area with dominantly silty soils developed on loess [15]. The studied plot has been arable land for more than two centuries, with conventional agricultural practices located at 129 m a.s.l. on a 9° slope. The climate is temperate continental, with an average rainfall of 889 mm, but with erratic distribution, particularly in the spring and autumn, when most of the high-intensity rains occur. The mean annual temperature is 10.7 °C, ranging from −0.4 °C in January to 20.6 °C in July [15]. Soil is silty stagnosol with low organic matter concentration and poor structure, which makes this soil type prone to compaction and erosion [34]. General soil properties are presented in Table 1.

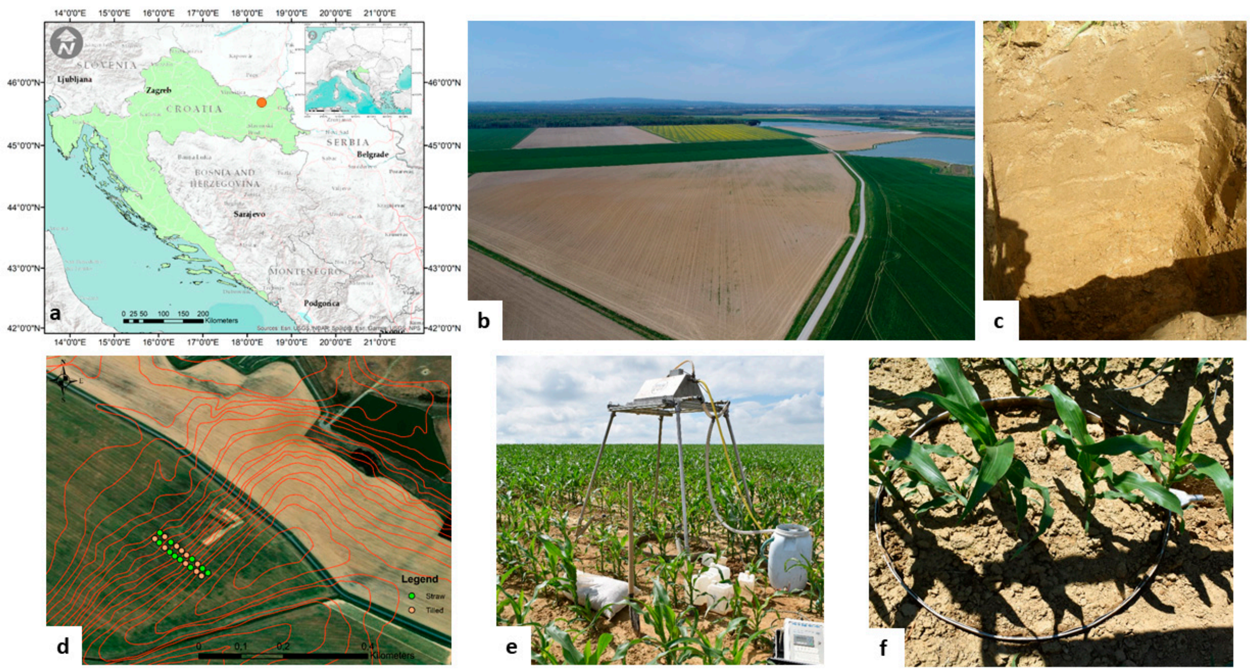


Figure 1. (**a**) Study site Location, (**b**) view of the study site, (**c**) soil profile, (**d**) sampling strategy, (**e**) rainfall simulator during installation, and (**f**) view of the plot size and shape.

Table 1. Soil profile characteristics of the study site. Values following ± indicate standard deviation.

Horizons	Ap + Eg	Eg + Btg	Btg
Depth range (cm)	0–24	24–35	35–95
pH in KCl (*w*/*w* 1:2.5)	4.21 ± 0.15	4.20 ± 0.18	4.81 ± 0.23
Organic matter (g kg^{-1})	16 ± 3.3	14 ± 4.2	6 ± 3.8
Available P_2O_5 (g kg^{-1})	172 ± 18	65 ± 4	244 ± 24
Available K_2O (g kg^{-1})	308 ± 6	123 ± 8	502 ± 12
Clay (<0.002 mm) (g kg^{-1})	235.8 ± 9.0	241.3 ± 6.9	230.3 ± 11.7
Silt (0.02–0.002 mm) (g kg^{-1})	291.2 ± 42.1	273.4 ± 7.2	289.0 ± 39.9
Fine sand (0.2–0.02 mm) (g kg^{-1})	465.1 ± 47.9	479.8 ± 8.4	476.1 ± 40.5
Coarse sand (2–0.2 mm) (g kg^{-1})	7.9 ± 1.4	5.6 ± 1.0	4.6 ± 1.1
Texture classification	Clay Loam	Clay Loam	Clay Loam

The annual management consists of ploughing during October or November, followed by disking or cultivation in spring (April or March) prior to sowing. Maize is usually fertilized with urea 46% (150 kg ha^{-1}), NPK 7:20:30 (400 kg ha^{-1}), and calcium ammonium nitrate (KAN) 27% (300 kg ha^{-1}). Farmyard manure or slurry was not part of the regular management, while organic residues are regularly incorporated in soil by tillage interventions. The preceding culture was winter wheat, and straw was mixed with soil during primary tillage. Maize was sowed by a JD 750A planter (John Deere, Moline, IL, USA) on 15 April 2020 (73,000 grains ha^{-1}; inter row spacing 70 cm, sowing depth 4 cm), and herbicide application ("Adengo", dosage 0.44 L ha^{-1}) was performed on 9 May. Inter-row cultivation intervention was not performed during 2020.

2.2. Experimental Design and Field Observations

The experimental setup consisted of 10 paired plots (Figure 1), named straw and bare (control). Each paired plot consisted of two plots of 0.785 m^2 (metal ring of 1 m diameter), with a 3 m distance between them. The bare plot is a control treatment. The surface of this area is without vegetation due to conventional tillage management (tilled), while the straw plot was manually covered with 2 t ha^{-1} of barley straw; the mulch covered approximately 80% of the topsoil (straw).

Rainfall simulation experiments were carried out during the three growth stages of maize during April (after seeding—VE stage), May (five leaves—V3 stage), and June (intensive vegetative growth—V5 stage) by using a pressurized type of rainfall simulator (UGT Rainmaker, Müncheberg, Germany). In total, 60 rainfall simulation experiments (10 per treatment, 20 per growing stage) were performed using a rainfall intensity of 58 mm h^{-1} for a duration of half an hour; storms such as that simulated have a return ratio in the area of research every 7 years [35]. Plots were established in non-traffic areas, and a plastic vessel was used above the plots to ensure calibration before the simulation commenced. Before each rainfall simulation experiment, soil samples (0–10 cm depth) were collected in the close vicinity of a circular metal ring used for overland flow collection. Samples were collected using soil cores (for bulk density—BD, water holding capacity—WHC, and soil water content—SWC) and by shovel for soil structural characteristics (mean weight diameter—MWD, and water stable aggregates—WSA). A photo of the plot surface and measurement of inclination were noted to obtain vegetation/mulch cover and slope, respectively. Finally, a chronometer was used to determine the time to ponding (TP) and time to runoff generation (TR). To collect the overland flow during rainfall simulation experiments, a plastic canister was connected to the metal ring (plot) for the collection of overland flow. The collected surface flow was weighed and filtered to obtain runoff and soil loss (SL) after drying on a filter paper. Sediment concentration (SC) was calculated by dividing the mass of SL by the mass of the runoff [36].

2.3. Laboratory Analysis

Soil cores were weighted before and after wetting for determination of WHC, and dried in an oven at 105 °C for 48 h and weighed obtain the BD and SWC, according to Black's method in [37]. Undisturbed soil collected by shovel and stored in rectangular boxes was used for gentle hand preparation of soil aggregates, following instructions of Dıaz-Zorita et al. [38], before soil aggregates were subjected to dry sieving for the duration of 30 s to obtain aggregate size fractions [39] and calculate MWD. A 4 g amount of the size fraction 0.4–0.5 mm diameter was used for soaking to obtain WSA, following the method of Kemper & Rosenau [39].

2.4. Statistical Analyses

The normality of data distribution was assessed with Shapiro–Wilk test ($p > 0.05$). Several variables did not respect the Gaussian distribution, so they were normalized with a Box–Cox transformation. A two-way ANOVA was used to identify significant differences among plots and growth stages. If significant differences were found (at $p < 0.05$), the Tukey HSD post-hoc test was applied. A principal component analysis (PCA) (based on the correlation matrix) was performed on Box–Cox data to identify the intrinsic relationships between the variables. Data analyses were carried out with Statistica 12.0 (StatSoft, Tulsa, OK, USA) [40]. Figures were elaborated with Plotly [41] to present the original data.

3. Results

3.1. Management and Growth-Stage Impact on Soil and Hydrological Response

Results of straw and growth-stage impact on soil are presented in Table 2. BD ranged from 1.15 g cm^{-3} to 1.59 g cm^{-3} in tilled plots, and from 1.29 g cm^{-3} to 1.57 g cm^{-3} in straw plots. BD was significantly lower in WE and W3 stage compared with the cropland W7 stage in tillage plots. WHC and SWC of the soils ranged from 28.70% to 44.00%, and from 20.20% to 34.90%, respectively. SWC was significantly higher in the tilled plots than in the straw plots at W3 stage. Temporal patterns reveal significantly higher SWC at W3 stage than in the other stages in tillage plots, while in straw plots, the W7 stage showed significantly lower SWC than at other stages.

Table 2. Results of two-way ANOVA analysis considering soil properties. Different letters after mean values in the columns represent significant difference at $p < 0.05$. Capital letters show statistical difference between stage growth. Lower case letters show statistical differences between treatments. Abbreviations: WE—after seeding; V3—five leaves stage; V5—intensive vegetative growth; BD, bulk density; SWC, soil water content; WHC, water holding capacity; MWD, mean weight diameter; WSA, water-stable aggregates.

Growth Stage	Treatment	BD (g cm^{-3})		SWC (%)		WHC (%)		MWD (mm)		WSA (%)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
VE	Tilled	1.35 Ba	0.11	27.61 Aa	1.50	40.84 Ba	1.50	3.51 Aa	0.20	24.51 Aa	4.57
	Straw	1.38 Aa	0.06	28.47 Aa	2.53	41.44 Aa	1.46	3.52 Aa	0.15	26.04 Aa	3.68
V3	Tilled	1.43 Ba	0.05	33.05 Aa	1.23	38.69 Aa	3.60	3.32 Aa	0.23	21.50 Aa	4.52
	Straw	1.45 Aa	0.07	29.07 Aa	1.43	40.05 Ab	0.80	3.31 Aa	0.22	24.61 Aa	5.24
V5	Tilled	1.46 Aa	0.08	25.80 Aa	1.57	39.23 Ba	1.56	2.88 Ba	0.12	24.92 Aa	4.52
	Straw	1.45 Aa	0.07	25.36 Aa	3.54	39.44 Ba	2.63	2.85 Ba	0.27	28.03 Aa	5.24

MWD and WSA varied between 2.23–3.91 mm and 13.16–35.26%, respectively. At W7 stage, MWD was significantly lower in both treatments than at WE and W3 stage. The highest WSA was marked at W7 stage in both treatments. In all cases, no significant difference was identified.

The mean TP in the tilled plots was found to be 126.4 s, with a maximum value of 360 s and a minimum value of only 5 s (Table 3). In straw plots, the mean was found to be 189.7 s, with a maximum value of 420 s and a minimum value of only 20 s. TP was significantly higher in the WE stage, compared to the W3 stage in both treatments, while the absolute values were higher in straw plots than in tilled. For TR, the values of 360 s were registered in tilled plots, reaching 780 and 60 s as maximum and minimum values, respectively. In straw plots, TR mean was 510 s, reaching 1800 and 120 s as maximum and minimum values, respectively. TR was significantly higher in the WE and W7 stages, compared to the W3 stage in both treatments, while the absolute values were higher in straw plots than in tilled. The runoff values ranged from 7.34 to 32.98 m^3 ha^{-1} (mean 20.16 m^3 ha^{-1}) in the WE stage, from 67.50 to 129.35 m^3 ha^{-1} (mean 98.42 m^3 ha^{-1}) in the W3 stage, and from 55.48 to 108.73 m^3 ha^{-1} (mean 82.10 m^3 ha^{-1}) in the W7 stage. In all growth stages, a significantly higher runoff was identified in tilled plots. In both treatments, significantly lower runoff was identified during WE stage than during other stages.

Table 3. Results of two-way ANOVA analysis considering overland flow properties. Different letters after mean values in the columns represent significant difference at $p < 0.05$. Capital letters show statistical difference between stage growth. Lower case letters show statistical differences between treatments. Abbreviations: WE—after seeding; V3—five-leaves stage; V5—intensive vegetative growth; PT, time to ponding; RT, time to runoff; SC, sediment concentration; SL, sediment loss.Growth stage.

	Treatment	TP (s)		TR (s)		Runoff (m^3 ha^{-1})		SC (g kg^{-1})		SL (kg ha^{-1})	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
VE	Tilled	234 Aa	71.8	456 Aa	158.0	33.0 Ba	14.0	18.5 Aa	11.8	639.5 Ba	662.1
	Straw	252 Aa	73.8	720 Aa	434.5	7.3 Bb	7.8	11.2 Aa	7.5	74.5 Bb	64.6
V3	Tilled	35 Ba	37.2	192 Ba	97.2	129.3 Aa	28.4	25.4 Aa	8.3	3283.8 Aa	1292.6
	Straw	95 Ba	83.2	282 Ba	113.3	67.5 Ab	37.7	8.8 Ab	2.9	586.5 Ab	314.3
V5	Tilled	110 Aba	35.5	432 Aa	132.1	108.7 Aa	40.7	18.4 Aa	5.6	2030.2 Aa	1108.2
	Straw	222 ABa	85.1	528 Aa	205.5	55.5 Ab	43.9	16.5 Aa	28.1	418.5 Ab	229.4

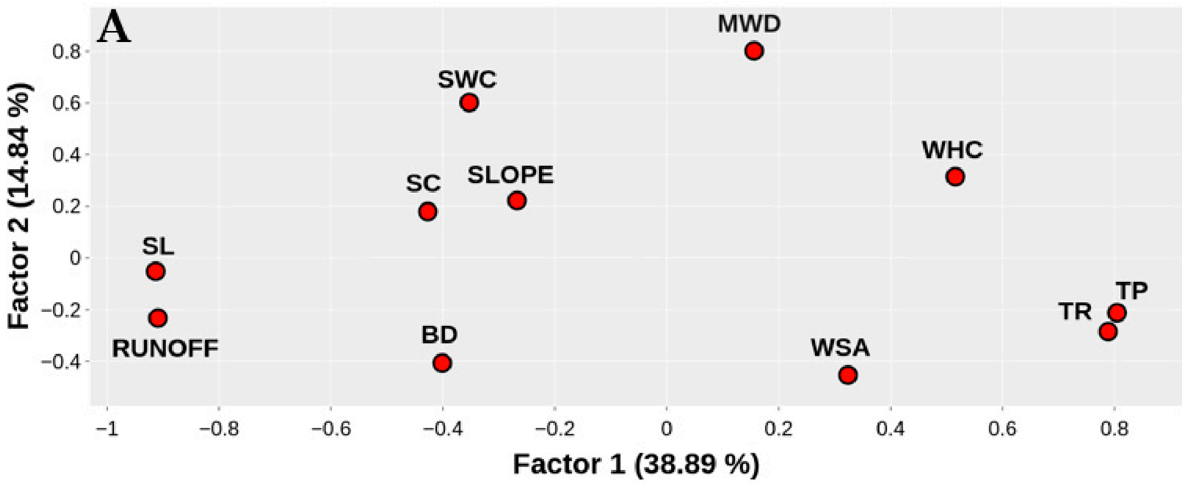
SC values ranged from 5.13 g L^{-1} to 41.46 g L^{-1} in tilled plots and from 4.45 g L^{-1} to 95.65 g L^{-1} in straw plots. SC showed different results, exhibiting significantly higher SC values in tilled plots in comparison with straw plots during the W3 stage. Temporal trends indicate non-significant behavior among growth stages at both treatments. The SL values ranged from 201.85 to 5067.29 kg ha^{-1} (mean 1984.48 kg ha^{-1}) in the tilled plots, and from 0.00 to 1047.77 kg ha^{-1} (mean 359.83 kg ha^{-1}) in the straw plots. Significant differences were observed at all growth stages among treatments. Tilled plots show significantly higher SL in every growth stage. Among growth stages, soil losses were significantly lower at WE than at W3 and W7.

3.2. Interrelation of the Variables

The first four factors explained 71.4% of the total variance. Factor 1 explained 38.89%, Factor 2 explained 14.84%, and Factors 3 and 4 explained 9.22% and 8.46%, respectively. Factor 1 had high positive loadings in WHC, TP, and TR, and high negative for runoff, SL, and SC (Table 4). Factor 2 had high positive loadings for SWC and MWD, and high negative loadings for WSA. Finally, Factor 3 and Factor 4 had high negative loadings in BD and slope, respectively. The intersection between Factor 1 and Factor 2 shows that runoff, SL, BD, SC, slope, and SWC are inversely related to the majority of the other variables, especially to the TP, TR, WHC, WSA and MWD (Figure 2A). The land management practices and time of measurement had different impacts on studied variables in tilled and straw treatments. The variability is lower in the W7 stage compared with the WE and W3 stages (Figure 2B).

Table 4. Loadings matrix considering the first four factors extracted from the Principal Component Analysis. Eigenvalues retained in each factor are in bold.

Variable	Factor 1	Factor 2	Factor 3	Factor 4
Slope (°)	−0.267470	0.222276	0.305639	**−0.670179**
Bulk density (g cm^{-3})	−0.401055	−0.406840	**−0.423273**	0.007005
Soil water content (%)	−0.352835	**0.601550**	−0.341593	0.063127
Water holding capacity (%)	**0.515545**	0.314809	0.154563	−0.369870
Mean weight diameter (mm)	0.156117	**0.801851**	−0.132513	0.244787
Water stable aggregates (%)	0.323820	**−0.453285**	0.072216	0.350031
Time to ponding (s)	**0.804425**	−0.212584	0.100781	−0.121820
Time to runoff generation (s)	**0.788527**	−0.285131	0.189527	−0.096806
Runoff (m^3 ha^{-1})	**−0.909082**	−0.232817	−0.032220	−0.163268
Sediment concentration (g L^{-1})	**−0.426888**	0.179558	0.717140	0.398189
Sediment loss (kg ha^{-1})	**−0.913082**	−0.051735	0.324428	0.073881



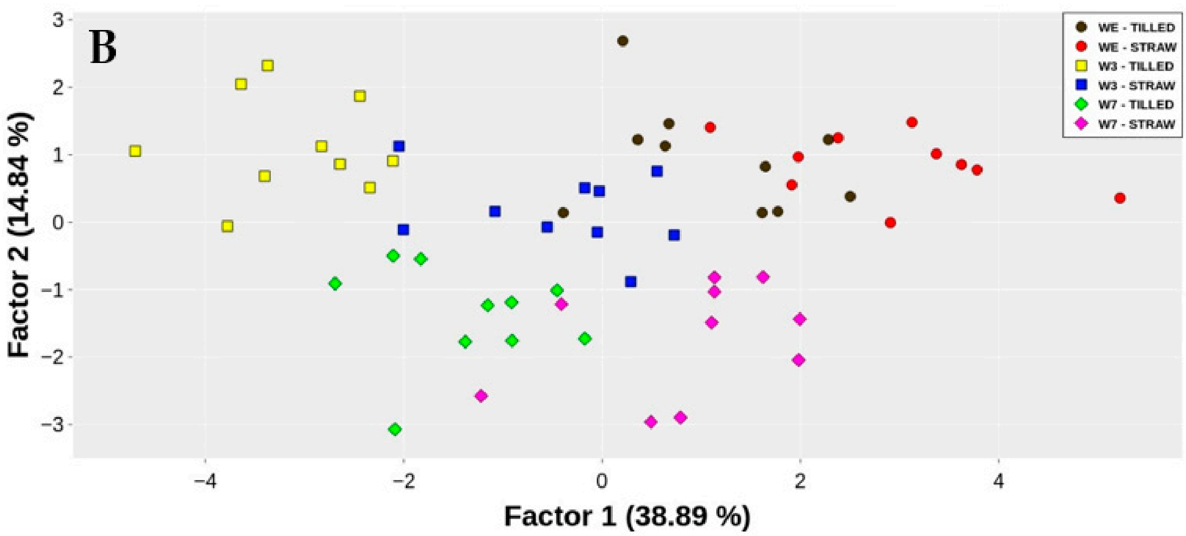


Figure 2. Relation between Factor 1 and Factor 2: (**A**) variables and (**B**) cases. Abbreviations: BD indicates bulk density; SWC, soil water content; WHC, water holding capacity; MWD, mean weight diameter; WSA, water stable aggregates; TP, time to ponding; TR, time to runoff generation; SC, sediment concentration; SL, sediment loss; SWC, soil water content. WE—after seeding; V3—five leaves stage; V5—intensive vegetative growth.

4. Discussion

4.1. Soil Properties

The results revealed that different land management partially changed some soil properties. The soil compaction between treatments was not significantly different at any growth stage. This is in agreement with the observations of previous studies. Dugan et al. [14] did not find difference between mulched and tilled treatments in the first few months after mulch application in hazelnut orchards. Similar results were noted in studies of Mulumba & Lal [42] and Głąb & Kulig [43] in croplands, indicating that a longer period of mulch application is needed, or the dosage of mulch application is too low to create a positive effect on soil compaction [21,44]. However, such criteria are not always solid, since there is proof that under reduced or no-tillage systems, mulching can decrease BD in the intermediate period [43,45]. The present study was performed under conventional tillage management; a long period with a high mulch application dose is needed. Tilled plots showed an increase in compaction over time, while in straw plots, the highest compaction was determined at the W3 stage of maize. The temporal increase of the compaction can be attributed to soil consolidation and tractor traffic. Moreover, the soil on the research site is silty with poor physical and chemical characteristics [34], which makes it very susceptible to consolidation and compaction [15]. Other findings also reported a significant increase in soil compaction under natural conditions in a few months after tillage interventions [46–48].

WHC, WSA, and MWD was not affected by treatment during all three growth stages. This can be attributed to the short duration of mulching practice and the low dosage of straw in the experiment. Usually, mulch decomposes in the soil and gradually increases the soil organic matter concentration, which improves the soil's ability to hold water [49]. The current dosage of 2.5 t ha^{-1} of mulch is too low, which is also confirmed in the study of Nzeyimana et al. [44]. However, the gradual increase of aggregate stability over time on straw plots indicates the positive impact of straw mulch on soil structural characteristics, as is proved in other works [45,50], despite the fact that MWD decreased on both treatments in the W7 stage. This reduction is very likely due to the structural deterioration by kinetic energy from rainfall, which easily breaks the artificial tillage-created clods [47]. Jordán et al. [51] in their study of 11 years of straw application also did not detect a significant increase in MWD, even in treatment with mulch dose of 16 t ha^{-1}.

SWC in the studied area showed high values. It is known that the effects of mulching on soil moisture depend on precipitation and climatic factors. Mulch effect on water conservation is usually more marked in arid and semiarid conditions, since mulching influences the soil moisture regime by controlling the surface evaporation rate [52]. Such conditions were absent during the research period, since the precipitation was normal and the high temperatures were not as high as those during summer. Therefore, positive mulch impact on soil moisture conservation by reducing the evaporation rate was absent in studied plots. Moreover, during the W5 stage, the tillage plots showed higher SWC than straw plots. The unusual finding could be explained by the recent heavy rain that fell just before the rainfall simulation experiment was performed. Precipitation on bare soil completely entered the soil, while in straw plots, some parts remained on the cover. This is not an uncommon occurrence, as other studies [53–55] have also showed similar or higher SWC in wet conditions on straw or no-tillage plots compared with bare conventional plots. However, it is important to further investigate this finding in future research to gain a better understanding of its implications.

4.2. Hydrological Behaviour

Soil erosion in cropland under wide-row spring cultures such as maize is recurrent and considerable during intense rainfall events. The main factors responsible for the high sediment yields in continental Croatia are poor structural stability of the stagnosol under conventional agricultural management and the lack of vegetation cover under frequent and intense tillage, which are common in this region [15,56]. The absence of strong crop rotations and lack of cover crop prevalence of wide-row cash crops like maize, potato, sugar beet and soybean, together with the lack of farmyard manure application, increases the rate of erosion because these management practices result in greater sediment detachment in croplands [57].

The usual strategies to fight soil erosion involve soil conditioning to improve soil structure, using mulches, cover crops, no-tillage systems, contouring, grass margins, and wide crop rotations with a prevalence of high-density crops and perennial grasses, which effectively decrease runoff and soil and nutrient loss, as is proven in other works [30–33,35] on similar pedological, geomorphological, and environmental conditions. Nevertheless, the main strategy to reduce soil erosion in Croatia is tillage direction in conventional systems, which significantly reduces the soil and nutrient losses if performed across the slope, or using no-tillage [58,59], since other agricultural conservation practices are rarely used in agricultural systems in Croatia and other Central European countries [60–63]. Moreover, the majority of these unused strategies for reducing soil erosion are impractical or expensive because of the time and labour involved, or the treatment and origin of the materials, which often need to be transported or manufactured (i.e., mulches, farmyard manure, lime, gypsum, biochar). Farmers also have an issue with structural problems, such as small land parcels, poor economic strength, limited access to special machinery for conservation tillage, or not having the knowledge to implement conservation management [57,64–66]. Coupled with high input prices, slow administration, and low market food prices, this creates a challenging business environment [67].

Our research has shown the early maize development stage has a large effect on soil erosion and hydrological processes in sloped croplands at the pedon scale. By using a high rainfall-intensity rainfall simulation with use of a rainfall simulator on almost-bare soil in the early stage of maize development, and by studying runoff generation development and measuring soil losses under bare and straw-mulched soil, the present study demonstrated that runoff coefficients depended on a management decision: a straw mulch cover. The study site was situated on stagnosols under conventional agriculture on a slope with an average of 9°, where high runoff and sediment discharges were already confirmed in a long-term study [31]. However, the step forward achieved in this work was obtaining the conservation potential of straw mulch as a nature-based solution to mitigate soil degradation in conventionally managed soils. Straw cover delays TP and TR, and significantly decrease runoff and SL in WE, W3 and W7 maize stages. This has also been reported by other authors in other European dry farming areas [65,68,69]. Our results indicate that farmers should use straw in the early development stages of maize cultivation because it contributes to reducing runoff and soil loss. However, in the later development stages of maize, it did not reduce the overall erosion under high-magnitude rainstorms. This is because the crop canopy is still relatively small for protecting the soil during V3 and V7 maize stages. Other works confirm the need for greater crop cover to obtain a significant reduction of soil loss [70,71]. Similar loss under the same pedological conditions were reported by Kisić [35] under wide-row cultures such as maize or soybean.

The measurements carried out in Central Croatia simulated high-magnitude storms and showed that croplands under maize can lose as much as 5.1 t ha^{-1} of soil in 30 min when measured at the plot scale, which makes conventional soil management practices on stagnosols unsustainable. Soil loss under straw-covered plots are six magnitude orders lower. Such results indicate that conventional tillage negatively affects soil sustainability. Tillage has been recognized as a major cause of soil erosion since agriculture was developed and acts as a driving factor for an acceleration of soil loss in agricultural landscapes [72]. Our rainfall simulation experiments prove that such hydrological behavior on stagnosols occurs mostly because the straw cover is embedded in the soil and acts as a barrier. Soil cover protects the soil from raindrop impacts and is a key factor in controlling erosion, and the present study results confirm this idea. Our study agrees with other research, e.g., in Austria, where mulch tillage in silt–loam croplands seems to be responsible for 20–55% lower runoff and 73–91% lower soil loss in comparison with conventional tillage [73]. In clay soil, Nishigaki [74] reported a 47% lower erosion rate on mulched cropland in comparison with bare plots. These findings confirm the fact that mulch on the soil surface plays a key role in soil conservation in the early maize development stage in the studied area. In each growth stage, we can notice a clear trend—a delay in the time to ponding and time to runoff generation with a straw cover. As a result, more rain infiltrates in the soil profile, which confirms the runoff behavior in the current study (Table 3).

4.3. Interrelations between Properties

The effectiveness of soil management, maize growing stage, and related properties are shown in the PCA results. The grouping of the variables in PCA indicates that BD, SWC, SL, slope, SC, and runoff are positively associated, and they are inversely associated with the opposite group, consisting of WSA, MWD, WHC, TP, and TR. Such results prove the fact that soil aggregation and compaction dominate the soil erosion response [38]. Soil pores are crucial for controlling infiltration, and bigger and more stable aggregates are responsible for lower compaction levels [75]. Positive interrelation between BD, SWC, SL, and runoff in our study reveals that compaction levels modify soil pore characteristics, which increases the overland flow and sediment loss. Compaction usually increases soil loss and runoff generation [75] and decreases aggregate size [38], as shown in the present study. Topsoil BD and SWC had a negative effect, while MWD and WSA had positive effects on ponding time and runoff time. On bare soil, lower BD through higher porosity contributed to accelerating the duration required for ponding. This was expected because soil compaction reduces water infiltration, while larger and more stable aggregates reduce runoff generation and soil loss [76].

Finally, a negative relationship between WSA, MWD, and SWC may be explained by cohesion forces. When aggregates are dry, their stability is higher [77]. Cohesion forces hold aggregates until SWC increases. However, when soil has a high SWC, it indicates a high proportion of small and medium pores in the total porosity, since the water cannot fill the pores of large dimensions. Such soil behavior clearly indicates that SWC is an important factor in unsustainable soil erosion in the later stages of maize development in the present experiment (Tables 2 and 3), despite the fact that maize canopy cover is higher at W3 and W7 stages in comparison with WE stage. Soil management had a significant impact on runoff rates and soil erosion risk after a simulated high-intensity storm. The soil and water loss in maize croplands in Central Croatia are not sustainable when they are conventionally tilled unless mulching is also performed.

5. Conclusions

Soil management had a significant impact on runoff rates and soil erosion risk after a simulated high-intensity storm. The soil and water loss in maize croplands in Central Croatia are not sustainable when traditionally tilled. Fast soil re-compaction after tillage intervention modifies soil structural and hydraulic properties, which in turn decreases the time to runoff generation and increases water and sediment loss. Although later maize growing stages had higher canopy cover, the physical status of the soil and the soil water content increases the erosion rate to an unsustainable level in comparison with mulched plots. Straw mulch in all studied maize growing stages is a significant measure for controlling soil and water loss. These findings show that from a soil erosion perspective, the conservation management strategies in maize croplands in Croatia need to be developed. An efficient reduction of runoff and soil erosion in early maize growth stages should be achieved through straw mulching, or by developing other soil conservation measures. It is crucial to increase land-use sustainability. The present study contributes to better soil use management in Croatian croplands.

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