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Soil management strategies for mitigating degradation and enhancing sustainability in sloped Stagnosols under maize cultivation – first results**

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A b s t r a c t. Conservation tillage management on rainfed croplands aims to improve the soil's physical environment, reduce soil erodibility, and enhance conservation. However, transitioning from plowing to conservation tillage can present challenges, particularly regarding soil compaction and erosion-runoff dynamics. This study comprehensively evaluates soil degradation in an area characterized by maize cultivation in Croatia on Stagnosols extremely prone to compaction and erosion. During 2024, the impacts of plowing, chisel, and subsoiling were monitored, considering soil properties, erosion, and element losses. Nine experimental plots (100 m × 8 m) were established, each equipped with a runoff and sediment collection system. Soil erosion and sediment transport were monitored throughout the maize growing season. The results reveal significantly reduced sediment concentrations by 49.1% at chisel plots compared to plowing plots, while subsoiling led to a 77.7% reduction. The highest sediment loss occurred under plowing, while chisel decreased soil loss by 73.4% and subsoiling by 95.9%. Nutrient losses followed a similar pattern. The sediment collected from plowing plots was significantly enriched with nutrients and heavy metals, compared to bulk soil, highlighting the role of soil erosion rates in nutrient depletion and pollution. In contrast, subsoiling showed no significant differences between sediment and bulk soil concentrations, reinforcing its role in reducing fine particle detachment and nutrient loss. Subsoiling significantly reduced bulk density and penetration resistance at 10-30 cm depth. The highest water-holding capacity was determined under subsoiling, *i.e.* it was 7.6% greater than under plowing, contributing to better soil moisture retention. The highest maize biomass yields were found ($p > 0.05$) under subsoiling (25.06 t ha^{-1}); they were 11 and 19% greater than in the plowing and chisel treatment, respectively. Subsoiling significantly improves soil structure, minimizes erosion, and reduces nutrient losses, making it a viable conservation strategy for sloped agricultural landscapes. The substantially reduced sediment transport under subsoiling indicates that deep loosening enhances soil stability and infiltration, providing long-term benefits for sustainable soil management and water quality protection on Stagnosols.

K e y w o r d s: soil erosion, conservation tillage, soil fertility, climate resilience, sustainable agriculture, sediment pollution, soil health, environmental impact

1. INTRODUCTION

Soil degradation, particularly manifested by erosion and compaction on sloping terrains, is a critical environmental concern that affects agricultural productivity and ecosystem stability. The combined effects of erosion, compaction, and nutrient depletion undermine soil productivity, disrupt water balance, and contribute to environmental pollution. This problem is particularly pronounced in poorly drained soils (*e.g.* Albeluvisol, Gleysol, Luvisol, Planosol, Stagnosol, Solonchak, Solonetz, Vertisol), highly prone to compaction and erosion, which poses significant challenges for sustainable agricultural management (Houšková and Montanarella, 2008; IUSS-WRB, 2022). Given the

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increasing pressures of climate change and intensive practices, developing effective soil management strategies is essential to mitigate degradation and enhance long-term soil functionality.

Soil degradation due to management practices is a widespread global challenge threatening agricultural productivity and environmental sustainability (Kopittke *et al.*, 2024). Intensive farming practices, deforestation, and climate change have accelerated the depletion of fertile topsoil and reduced the ability of croplands to produce high yields. Globally, millions of hectares of arable land are affected by yearly erosion, leading to nutrient loss, decline in soil organic matter, and reduced water retention (FAO, 2021). Similarly, soil compaction caused by heavy machinery and continuous cropping restricts root growth, decreases porosity, and increases runoff, further intensifying land degradation (Sonderegger and Pfister, 2021; Zhang *et al.*, 2024). Recognizing these threats, international initiatives such as the European Commission's Soil Strategy (European Commission, 2021), the United Nations Land Degradation Neutrality (LDN) framework, the UN Decade on Ecosystem Restoration, and the Sustainable Development Goals (SDGs) aim to combat soil degradation through sustainable land management practices, conservation agriculture, and reforestation efforts (UNCCD, 2019). In addition, the European Union has implemented the Soil Mission under the Horizon Europe program, investing €1 billion to enhance soil health through innovative research and policy frameworks (Panagos *et al.*, 2022). The introduction of the Soil Monitoring Law (European Commission, 2023) in 2023 is another significant milestone in ensuring long-term soil resilience and sustainability. These policies emphasize the urgent need to restore degraded soils, improve land resilience, and ensure long-term food security in the face of increasing climate variability.

Soils filtrate water, sequester carbon, and ensure nutrient cycling, a crucial process for maintaining environmental balance and agricultural sustainability (Kopittke *et al.*, 2024). Healthy soils are crucial for food security as they contribute to biodiversity, support plant growth, and increase resilience to extreme climate events. Degraded soils impair agricultural productivity, exacerbate erosion, and lead to the loss of arable land, jeopardizing the global food supply (Kalantari *et al.*, 2023). Effective soil management is, therefore, crucial for ensuring long-term agricultural viability and mitigating climate change impacts. Conservation tillage practices, including chisel plowing and subsoiling, have emerged as promising alternatives to conventional plowing, offering potential benefits in reducing soil compaction, enhancing infiltration, and curbing erosion (Kisic *et al.*, 2017; Weidhuner *et al.*, 2021).

Despite extensive research on soil degradation, most studies focus on soil physical (Botta *et al.*, 2006; Hartmann *et al.*, 2008; Araya *et al.*, 2011; Salem *et al.*, 2015; Jug *et al.*, 2024) and chemical properties (Cai *et al.*, 2014; Büchi *et al.*, 2017; Jug *et al.*, 2019; Du *et al.*, 2021; Fang, 2021), hydrological response, or erosion processes (Basic *et al.*, 2004; Kisic *et al.*, 2017; Preiti *et al.*, 2017; Chalise *et al.*, 2020; Yadav *et al.*, 2024) in isolation, without integrating these key factors under different tillage systems. While numerous studies (Kagabo *et al.*, 2013; Kurothe *et al.*, 2014; Bogunovic *et al.*, 2018; Abidela Hussein *et al.*, 2019; Carretta *et al.*, 2021; Weidhuner *et al.*, 2021) assess the impact of tillage on soil structure, compaction, and carbon content, fewer (Chalise *et al.*, 2020; Klik and Rosner, 2020; Fang, 2021; Dugan *et al.*, 2022) investigate the relationship between tillage practices and nutrient and/or pollutant losses due to erosion. Even more scarce are studies that simultaneously analyze soil physical and chemical properties, erosion rates, and the elemental composition of both soil and eroded sediments. This comprehensive approach is crucial for understanding how tillage influences soil degradation and how it affects nutrient depletion and potential environmental pollution. Accordingly, this study provides a more integrated perspective on soil degradation processes in sloped Stagnosols by incorporating in situ soil property measurements, erosion monitoring, and portable X-ray fluorescence (pXRF) analysis for elemental composition. This approach is often overlooked in tillage management studies. Although Stagnosols are widely known for forming in flat areas, in many regions such as the Pannonian Basin, these soils are also well represented on hilly terrain due to millennia of erosion and landscape evolution. Consequently, sloped Stagnosols are not uncommon and are frequently threatened by surface runoff and erosion under conventional tillage.

The main aim is to provide valuable insights into the sustainability of different tillage practices, close critical knowledge gaps, and support the development of more effective soil protection strategies. The results of the integrative strategy could help farmers, soil scientists, and policymakers develop effective soil conservation strategies. The specific objectives of this study were: (i) to evaluate the impact of conventional plowing, reduced tillage, and subsoiling on key soil physical and chemical properties; (ii) to determine the extent of soil degradation, including compaction and erosion-induced losses, under different management practices; (iii) to assess the potential for environmental pollution due to erosion-induced sediment transport; (iv) to provide insights into the most sustainable soil management approach for mitigating soil degradation in sloped Stagnosols under maize cultivation.

2. Materials and methods

2.1. Location, soil, and climate

This research was conducted on annual cropland in Pannonian Croatia (45°32'N; 16°56'E, 119 m a.s.l.) near Kaniška Iva (Fig. 1). The surrounding area predominantly includes annual cropland and forest (*Quercus robur* L.

Fig. 1. Site photo of the study area.

– *Carpinus betulus* L. association) land use. The area is characterized by a gentle hilly topography, with an average slope of 13% and a land cover mainly represented by croplands and surrounded by natural forests in minor parts with orchards. In the last 40 years, the fields were used for arable farming with usual crops, such as maize, winter wheat, barley, soybean, rapeseed, and triticale. The soil is loamy Dystric Stagnosol (IUSS-WRB, 2022), corresponding to a Pseudogley in the Croatian soil classification system. A detailed morphological description and profile image of the same soil type in similar geomorphological and land use conditions is available in Bogunović *et al.* (2023). The topsoil is slightly acidic, poor in organic matter, and rich in potassium, with a moderate phosphorus supply (Table 1). The clay, silt, and sand contents in the topsoil are 152, 521, and 327 g kg^{-1}, respectively, while a channel network bounds the fields.

Table 1. Basic soil properties on the experimental field in Kaniška Iva

Property	Horizon		
	Ap (0-27 cm)	Eg (27-40 cm)	Bg (40-102 cm)
pH (in KCl)	6.22 (6.61)	5.7 (4.4)	6.5 (4.9)
Organic matter (%)	2.1	0.4	-
Total N (%)	0.09	0.02	-
P_2O_5 (mg kg^{-1})	130	68	16
K_2O (mg kg^{-1})	323	96	70
Sand (g kg^{-1})	327	251	219
Silt (g kg^{-1})	521	492	512
Clay (g kg^{-1})	152	257	269
Texture	Silt loam	Loam	Clay loam

The climate conditions (1996-2023) can be considered humid, with 915.3 mm of rain annually (Fig. 2). The highest precipitation occurs during September (110.3 mm), while the lowest occurs during February (58.7 mm) and March (58.3 mm). The annual average temperature was 12.0°C. January (1.4°C) was the coldest month, while July (22.4°C) was the warmest month.

2.2. Experimental design, treatments, and management

Three distinct soil management strategies were examined: conventional plowing (LS Variomat, Kverneland, Norway) up to 30 cm depth, reduced tillage using a chisel (Tiger MT, Horsch, United Kingdom) to a 30 cm depth, and loosening *via* a subsoiler (TERRASTRIP ZN 8-70/75, Bednar, Czech Republic) up to 60 cm depth. Each tillage treatment was applied (April 29, 2024) in three replicates, resulting in nine plots with a length of 100 m and a width of 8 m. After primary tillage, all plots were uniformly leveled and prepared using a Swifter SE wide seedbed cultivator (Bednar, Czech Republic) to ensure a consistent seedbed layer across treatments. Tillage on all treatments was up and down to the slope direction. To ensure accurate data

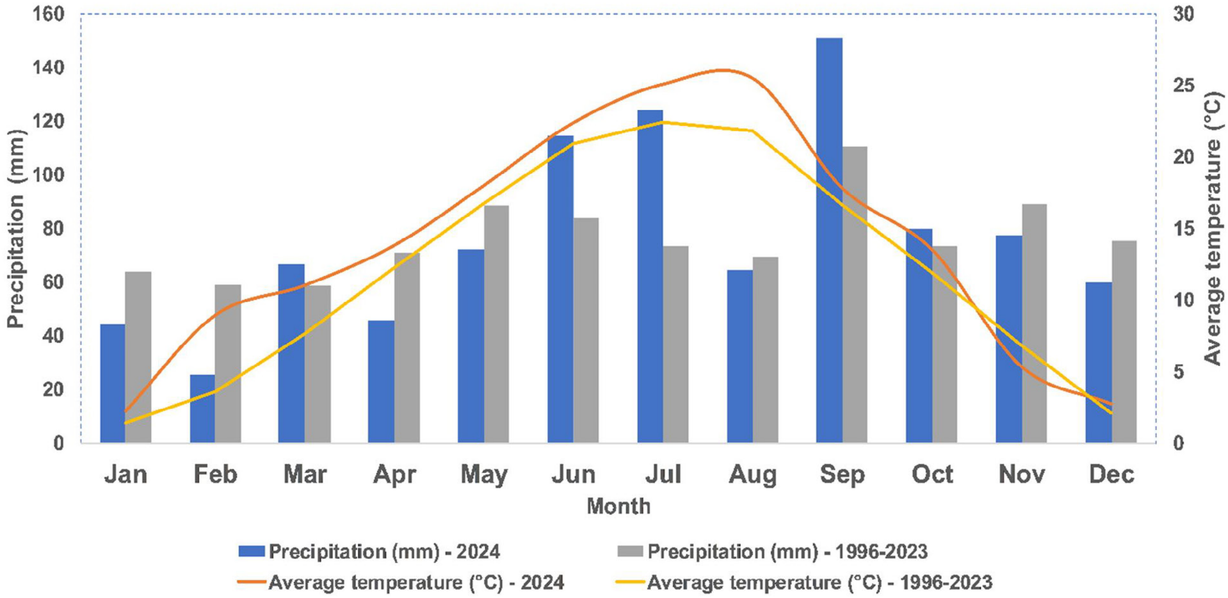

Fig. 2. Experimental site's monthly precipitation and average temperatures in 2024 and 1996-2023.

Fig. 3. Tillage management, equipment installation, and aerial view.

collection, all experimental plots were fenced off with barriers extending 10 cm into the soil and 20 cm above the soil to minimize external disturbances and facilitate precise measurement of soil and water loss due to erosion (Fig. 3). Fenced plots enclose a catchment area of 20 m^2. Collector tanks have been installed at the foot of the slope and are connected to the fenced plot collector to store the overland flow after rainfall.

Maize (variety DKC5911, Dekalb, Croatia) was sown on April 30, 2024. Fertilization was carried out with urea 46% (400 kg ha^{-1}), NPK 8:20:28 (250 kg ha^{-1}), and KCl 60% (200 kg ha^{-1}). Weeds were suppressed with herbicides, meaning inter-row cultivation was absent in 2024. Organic fertilizers were not applied. Maize was sown by a JD 750A planter (John Deere, USA) at a seeding density of 75 000 grains ha^{-1} (inter-row spacing 70 cm, sowing depth 4 cm), and herbicide application ("Adengo," active substances: tembotrione 90 g L^{-1}, isoxaflutole 225 g L^{-1}, safener: cyprosulfamide 150 g L^{-1}; formulation: suspension concentrate; dosage 0.44 L ha^{-1}) was performed after sowing.

2.3. Soil and sediment sampling, field measurements, and physical property analysis

Soil sampling was conducted in two periods: during maize emergence (spring) and post-harvest (fall). For each plot, core soil samples were collected from 0-10 cm and 10-30 cm depth from the bottom and the upper slope. In each treatment, twelve core samples were taken (108 per period, totaling 216 samples during 2024). Additionally, undisturbed samples were collected from the same topographic positions, considering a shallower depth (0-10 cm), to obtain the soil structural characteristics. These samples were stored in plastic rectangular boxes to avoid mechanical damage by compression or distortion, as suggested in Díaz-Zorita *et al.* (2002) and Kemper and Rosenau (1986). Disturbed samples for soil chemical properties were collected by hand-held probes from the same positions as undisturbed samples. At the same time, along with soil sampling, the penetration resistance measurements were carried out using a hand-pushed cone penetrometer (Penetrologger, Eijkelkamp, Giesbeek, The Netherlands). Soil resistance measurements were done using a 1 cm^2 cone base area shaped with a 60°-point angle. The penetrometer resistance data were grouped at 0-10 and 10-30 cm depth intervals before performing statistical analysis.

The physical analysis included bulk density (BD), soil water content (SWC), water-holding capacity (WHC), aggregate stability, and size. The WHC, SWC, and BD were determined using the core sampling method (Grossman and Reinsch, 2002) after capillary wetting the cores and oven-drying them at 105°C for 48 h. The aggregates were gently prepared by hand before we performed the dry sieve tests. Aggregate size fractions were determined by weighing each fraction after 30 seconds of sieving from sieve sizes: <0.25, 0.25-0.4, 0.4-0.5, 0.5-0.8 mm, 0.5-1.0, 1.0-2.0, and 2.0-4.0 mm. From this data, the calculation of mean weight diameter (*MWD*) was performed using the Eq. (1):

$$MWD = \sum_{i=1}^{n} xi\ wi, \quad (1)$$

where: *xi* is the mean diameter of any particular size range of aggregates separated by sieving, and *wi* is the weight of aggregates in that size range as a fraction of the total dry weight of soil used. Size fraction 0.4-0.5 mm diameter was used to obtain water-stable aggregates (*WSA*) following the wet-sieving method proposed by Kemper and Rosenau (1986) and to calculate their percentage using the Eq. (2):

$$WSA = \frac{Wds}{Wds+Wdw} 100, \quad (2)$$

WSA is the percentage of stable water aggregates, *Wds* is the weight of aggregates dispersed in a dispersing solution (g), and *Wdw* is the weight of aggregates dispersed in distilled water (g).

Maize biomass yields were obtained by cutting and weighing in the field. A sample from each plot was taken to obtain the water content after drying at 105°C for 3 days. Biomass yields were presented as dry mass.

2.4. Monitoring soil erosion and sediment transport

The amount of rainfall received in different months during 2024 is presented in Fig. 2. The total rainfall received in 2024 was 924.4 mm, which was higher than the long-term average rainfall (915.3). The amount of rainfall received at the experimental site during the spring, summer, and fall seasons were 250.1, 306.2, and 223.6 mm, respectively. There were eight erosive monitoring dates in the maize cropping period during 2024: May 5, 22, 29; June 14, 23; July 10, 26; and August 21. Generally, rainfall during the maize cropping season falls several days in a row, after which we collect the samples and clean the equipment.

Erosion monitoring research was carried out using collection tanks installed at the base of each plot to capture sediment and runoff water. The runoff was determined in situ by measuring the height level in the tanks. After runoff homogenization in the tanks obtained by a paddle mixer, a subsample was collected in plastic canisters (5 L) and taken into the laboratory to determine the soil loss (SL) and sediment concentration (SC). The subsample canisters were weighed, and runoff was filtered on the filter paper. After drying the filter paper, we obtained the SL in the canister by subtracting the mass of the sediment and filter paper from the mass of the filter paper. The sediment concentration was calculated by dividing the SL mass by the runoff mass. Sediment concentrations were then used to compute the total SL volume at each event, considering the total volume of water collected in the tank. These measurements provided critical insights into erosion severity across different management practices. Sediment composition was analyzed to determine elemental concentrations and total loss of elements during erosion.

2.5. Assessment of chemical properties

Disturbed soil samples were milled and sieved (2 mm mesh) after air-drying in the laboratory for a week at room temperature of 20°C. Sediments were gently removed from the filter paper using a spatula and homogenized using a mortar with a pestle. Soil and sediment chemical properties were assessed by measuring total carbon and nitrogen content using an elemental CHNS analyzer following the norm ISO 13878 (1998). The heavy metal and nutrient concentrations were determined with a portable X-ray fluorescence (pXRF) spectrometer (VantaTM XRF analyzer C Series) (Olympus, Waltham, MA, USA, 2019). Soil and sediment samples were transferred into a plastic cylinder with a protective thin foil on the bottom and a plastic lid on the top. Afterwards, the cylinder was set into the workstation and run for the analyses with the pXRF. The sample was exposed to X-ray beams for 120 s. For element characterization, we used *Geochem* calibration. With the use of a pXRF analyzer, total concentrations of phosphorus (P), potassium (K), copper (Cu), lead (Pb), and zinc (Zn) were determined.

The accuracy and precision of the analyses were verified using the reference materials ISE 989, ISE 851, and ISE 869 of the Wageningen Evaluating Programmes for Analytical Laboratories (WEPAL). The results were within acceptable limits, with an accuracy (recovery) of less than 3% and a precision (RSD) of less than 3%.

2.6. Statistical analysis

First, the data were checked for normality with the Kolmogorov-Smirnoff test. Afterwards, different analysis procedures were used in this work. A factorial analysis of variance (ANOVA) was applied to compare the effects of different soil management treatments on soil parameters. Factors used for soil properties were season (spring, fall), depth (0-10 and 10-30 cm), and treatment (plowing, chisel, subsoiling). One-way ANOVA was used to determine erosion characterization and maize biomass yield. Two-way ANOVA was used to determine the offsite pollution under different soil management methods, and we tested the treatment and season effect. Fisher's *post hoc* test was used to determine significant differences between treatments at a 95% confidence level in all cases. Statistical analyses were computed with the Statistica 12.0 software package (Statsoft, 2015).

3. RESULTS

3.1. Soil physical properties and biomass yields

Factorial ANOVA revealed significant treatment and treatment × depth × season interaction effects on BD, PR, SWC, and WHC (Table 2a). Bulk density was significantly lower in the subsoiling treatment ($p<0.05$) compared to the plowing and chisel treatments, respectively (Table 2b). Similar results were obtained in the spring and fall measurements. Penetration resistance in the spring was significantly higher in the chisel than subsoiling treatment at 10-30 cm depth. In the fall, a significantly higher PR was recorded under plowing than in the other treatments. The treatments had significantly decreased ranks at 10-30 cm depth: plowing > chisel > subsoiling. Seasonal effects were significant ($p<0.001$) for SWC and WHC, with higher values recorded in the fall (Table 2). During the spring treatments, the following significantly different order of SWC was found:

Table 2. a) Results of factorial ANOVA analysis for bulk density (BD), penetration resistance (PR), soil water content (SWC) and water holding capacity (WHC) in the spring and fall of 2024; b) mean bulk density, penetration resistance, soil water content and water holding capacity according to the management practice, season, and soil depth

a)	BD	PR	SWC	WHC
Treatment	***	***	*	**
Season	n.s.	n.s.	***	***
Depth	*	***	n.s.	n.s.
T × D	**	*	n.s.	*
T × S	*	*	***	*
D × S	n.s.	n.s.	*	n.s.
T × D × S	*	*	*	*

b)	BD						PR					
	Spring			Fall			Spring			Fall		
Depth (cm)/ Treatment	0-10	10-30	x̄	0-10	10-30	x̄	0-10	10-30	x̄	0-10	10-30	x̄
Plowing	1.50a	1.57a	1.53a	1.50	1.60a	1.55a	0.36	1.10ab	0.73	0.44	1.42a	0.93a
Chisel	1.50a	1.53a	1.51a	1.50	1.55a	1.53a	0.40	1.29a	0.85	0.27	0.93b	0.60b
Subsoiling	1.41b	1.39b	1.40b	1.44	1.44b	1.44b	0.23	0.87b	0.55	0.35	0.36c	0.35b
	SWC						WHC					
Plowing	31.0a	32.6a	31.8a	33.2	33.7	33.5	40.8	39.6	40.2	42.8b	41.4b	42.1b
Chisel	28.8ab	29.8b	29.3b	33.1	32.9	33.0	40.4	38.9	39.7	43.3ab	42.1b	42.7b
Subsoiling	26.9b	27.5b	27.2c	34.1	35.2	34.6	40.8	41.1	41.0	45.4a	45.1a	45.3a

Statistical significances at ***$p<0.001$, **$p<0.01$ and *$p<0.05$; n.s. – non-significant at a $p<0.05$. Different letters represent significant ($p<0.05$) differences between management practices.

Table 3. a) Results of factorial ANOVA analysis for mean weight diameter (MWD) and water-stable aggregates (WSA) in the spring and fall of 2024; b) mean values of mean weight diameter and water stable aggregates according to the management practice and season

a)		MWD			WSA	
Treatment		n.s.			n.s.	
Season		***			***	
T × S		*			*	
(b)		MWD			WSA	
Season/ Treatment	Spring	Fall	x̄	Spring	Fall	x̄
Plowing	3.30bB	4.22aA	3.76a	59.3aA	54.5aB	56.9a
Chisel	3.59aB	4.20aA	3.90a	59.6aA	53.7aB	56.6a
Subsoiling	3.35abB	4.21aA	3.78a	58.5aA	55.3aB	56.9a

Statistical significances at ***$p<0.001$ and *$p<0.05$; n.s. – non-significant at a $p<0.05$. Different letters represent significant ($p<0.05$) differences between management practice (lowercase) and seasons (uppercase).

plowing > chisel > subsoiling. Stratified by depths, SWC was significantly higher under plowing than subsoiling. In the fall, subsoiling demonstrated superior WHC, significantly higher than plowing. Stratified by depths, subsoiling recorded significantly higher WHC than plowing.

Table 3 presents MWD and WSA data. In the spring, the chisel treatment recorded significantly higher MWD than plowing. In the fall, the treatments showed nonsignificant differences. At the beginning of the experiment, the chisel treatment had the highest WSA in the spring, while the subsoiling had the lowest value. Subsoiling increased the percentage of WSA in the fall, compared to the other treatments, indicating improved soil structure.

Biomass yields showed no statistically significant differences between the tillage management practices (Fig. 4). The subsoiling management resulted in the highest mean biomass yield at 25.06 t ha^{-1}. Plowing exhibited 11% lower biomass (22.30 t ha^{-1}) than subsoiling, while chisel had the lowest biomass yield at 20.34 t ha^{-1}, representing a 19% decrease compared to subsoiling and an 8.8% reduction relative to plowing.

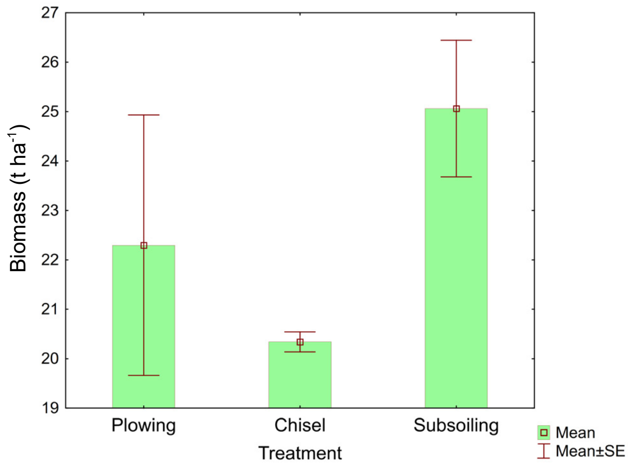

Fig. 4. Biomass maize yields in 2024.

3.2. Erosion monitoring data

To assess the impact of soil management strategies on water and soil losses, runoff (Table 4), sediment concentration (Table 5), and sediment loss (Table 6) were measured following the major precipitation events during the 2024 growing season. The highest runoff values (Table 4) were consistently observed under conventional plowing, followed by chisel plowing, while subsoiling showed the lowest runoff volumes. From the average yearly point of view, the plowing plots exhibited significantly higher runoff than the chisel and subsoiling plots. Moreover, the subsoiling management showed significantly lower runoff than the other two tillage strategies. Plowing produced the highest runoff rates in individual events, with values ranging from 165.7 to 382.7 m^3 ha^{-1}, accumulating a total of 4452.6 m^3 ha^{-1} across all events. This highlights the reduced infiltration capacity and increased surface water generation associated with conventional tillage. Chisel management resulted in intermediate runoff levels, with average values ranging from 113.3 to 199.2 m^3 ha^{-1} and a cumulative runoff of 2458.2 m^3 ha^{-1}, suggesting moderate improvement in water infiltration compared to plowing. Lastly, subsoiling was the most effective at reducing runoff, with values as low as 109.1 m^3 ha^{-1} during peak events, accumulating only 984.5 m^3 ha^{-1} overall (a 77.9% reduction compared to plowing). This aligns with the improved soil porosity and infiltration potential under deep loosening practices. The variability indices, standard deviation, and coefficient of variation indicate that subsoiling exhibited more variability in runoff, particularly during high-intensity rainfall events, reflecting its dynamic response to soil moisture retention and infiltration.

Table 5 presents sediment concentrations (g L^{-1}) measured under the plowing, chisel plowing, and subsoiling treatments. On average, plowing resulted in the highest sediment concentration (47.5 g L^{-1}), followed by chisel (24.2 g L^{-1}), while subsoiling had the lowest values (10.6 g L^{-1}), with statistically significant differences among all the

Table 4. Runoff (m^3 ha^{-1}) for the three replicate plots at each rainfall event and, in total, for the plowing, chisel, and subsoiling management treatments

Date	Treatment	Mean	Sum	Minimum	Maximum	Std. dev.	CV	SE
22.5.2024	Plowing	361.4a	1084.3	347.8	374.5	13.4	3.7	7.7
	Chisel	148.0b	444.0	113.3	180.3	33.6	22.7	19.4
	Subsoiling	54.6c	163.8	40.6	64.2	12.4	22.8	7.2
14.6.2024	Plowing	226.0a	677.9	219.6	230.8	5.7	2.5	3.3
	Chisel	180.9b	542.7	173.1	185.2	6.8	3.7	3.9
	Subsoiling	97.8c	293.4	89.6	109.1	10.1	10.3	5.8
10.7.2024	Plowing	346.5a	1039.5	337.7	351.2	7.6	2.2	4.4
	Chisel	165.6b	496.9	129.7	199.2	34.8	21.0	20.1
	Subsoiling	41.9c	125.6	6.0	74.8	34.5	82.4	19.9
26.7.2024	Plowing	373.5a	1120.5	361.0	382.7	11.2	3.0	6.5
	Chisel	161.2b	483.5	121.6	192.8	36.3	22.5	20.9
	Subsoiling	56.3c	168.9	44.8	64.6	10.3	18.3	5.9
21.8.2024	Plowing	176.8a	530.4	165.7	190.1	12.4	7.0	7.2
	Chisel	163.7a	491.0	143.2	179.5	18.6	11.4	10.7
	Subsoiling	77.6b	232.8	69.6	88.9	10.1	13.0	5.8
Average	Plowing	296.8a	4452.6	165.7	382.7	83.2	28.0	21.5
	Chisel	163.9b	2458.2	113.3	199.2	26.4	16.1	6.8
	Subsoiling	65.6c	984.5	6.0	109.1	25.6	39.0	6.6

Different letters at each time event in tripled rows (plowing, chisel, and subsoiling) mean statistically significant differences according to ANOVA, p value <0.05 level. CV – coefficient of variability, SE – standard error. Note: On May 5, May 29 and June 23, 2024, no overland flow data could be retrieved due to collector tanks malfunctioning.

Table 5. Sediment concentration (g L^{-1}) for the three replicate plots at each rainfall event and, in total, for the plowing, chisel, and subsoiling management treatments

Date	Treatment	Mean	Minimum	Maximum	Std. dev.	CV	SE
22.5.2024	Plowing	48.8a	34.0	73.1	21.2	43.5	12.3
	Chisel	64.5a	54.8	73.7	9.5	14.7	5.5
	Subsoiling	27.8a	12.2	54.7	23.4	84.1	13.5
14.6.2024	Plowing	45.8a	41.5	49.5	4.0	8.8	2.3
	Chisel	22.5b	3.1	53.5	27.1	120.4	15.6
	Subsoiling	5.2b	3.2	8.1	2.6	50.3	1.5
10.7.2024	Plowing	60.3a	55.2	70.5	8.8	14.6	5.1
	Chisel	6.1b	2.3	12.1	5.3	85.6	3.0
	Subsoiling	4.5b	3.0	7.2	2.3	51.6	1.4
26.7.2024	Plowing	30.8a	19.4	42.2	11.4	37.1	6.6
	Chisel	19.5ab	5.4	34.4	14.5	74.6	8.4
	Subsoiling	6.5b	5.2	7.8	1.3	20.2	0.8
21.8.2024	Plowing	51.9a	44.2	59.4	7.6	14.6	4.4
	Chisel	8.4b	2.9	12.9	5.1	60.2	2.9
	Subsoiling	9.2b	5.1	12.0	3.6	39.4	2.1
Average	Plowing	47.5a	19.4	73.1	14.3	30.1	3.7
	Chisel	24.2b	2.3	73.7	25.1	103.9	6.5
	Subsoiling	10.6c	3.0	54.7	12.8	120.2	3.3

Different letters at each time event in tripled rows (plowing, chisel, and subsoiling) mean statistically significant differences according to ANOVA, p value <0.05 level. CV – coefficient of variability, SE – standard error.

Table 6. Sediment loss (t ha^{-1}) for the three replicate plots at each rainfall event and in total for the plowing, chisel and subsoiling management treatments

Date	Treatment	Mean	Sum	Minimum	Maximum	Std. dev	CV	SE
22.5.2024	Plowing	19.5a	58.6	13.6	30.3	9.4	47.9	5.4
	Chisel	10.5b	31.6	9.6	11.0	0.8	7.7	0.5
	Subsoiling	1.4c	4.2	0.8	2.5	0.9	64.4	0.5
14.6.2024	Plowing	11.3a	33.9	10.4	12.4	1.0	8.9	0.6
	Chisel	4.5b	13.4	0.6	11.0	5.6	126.0	3.3
	Subsoiling	0.5b	1.6	0.3	0.9	0.3	61.1	0.2
10.7.2024	Plowing	23.5a	70.5	20.7	28.2	4.1	17.4	2.4
	Chisel	1.1b	3.2	0.3	2.1	0.9	86.3	0.5
	Subsoiling	0.1b	0.4	0.04	0.2	0.1	64.4	0.1
26.7.2024	Plowing	12.4a	37.1	7.3	17.5	5.1	41.5	3.0
	Chisel	3.0b	9.1	0.9	4.5	1.9	61.6	1.1
	Subsoiling	0.4b	1.1	0.2	0.5	0.1	33.3	0.1
21.8.2024	Plowing	10.5a	31.5	8.4	12.2	1.9	18.4	1.1
	Chisel	1.3b	4.0	0.5	1.9	0.7	53.3	0.4
	Subsoiling	0.7b	2.2	0.4	1.1	0.4	49.0	0.2
Average	Plowing	15.4a	231.6	7.3	30.3	6.9	44.7	1.8
	Chisel	4.1b	61.3	0.3	11.0	4.3	104.1	1.1
	Subsoiling	0.6c	9.6	0.04	2.5	0.6	93.6	0.2

Different letters at each time event in tripled rows (ploughing, chisel and subsoiling) mean statistically significant differences according to ANOVA, p value <0.05 level. CV – coefficient of variability, SE – standard error.

treatments ($p<0.05$). The highest variability recorded was under chisel plowing, while subsoiling consistently maintained low sediment concentrations across all events.

Sediment loss (t ha^{-1}) closely followed the runoff trends, with plowing exhibiting the highest soil erosion rates, while subsoiling significantly reduced sediment detachment and transport (Table 6). Plowing resulted in the highest soil loss, averaging 15.4 t ha^{-1} across the season, with a maximum of 30.3 t ha^{-1} recorded in May. The total sediment loss under plowing was 231.6 t ha^{-1}, reflecting the vulnerability of conventionally plowed soils to erosion. Chisel plowing reduced sediment losses by 73.4% compared to plowing, with an average of 4.1 t ha^{-1}, accumulating 61.3 t ha^{-1} for the season. The highest sediment loss at the chisel plots occurred in May, reaching 11.0 t ha^{-1}, while the lowest values were recorded at the beginning of July. Lastly, subsoiling significantly reduced sediment transport by 95.9% compared to plowing. The total seasonal sediment loss was 9.6 t ha^{-1}, ranging from 0.04 and 2.5 t ha^{-1}, depending on individual events, which emphasizes the effectiveness of deep loosening in maintaining an artificial pore network and reducing erosion susceptibility.

3.3. Soil and sediment chemical properties

The results represented in Figs 5-7 confirm the profound impact of soil management on soil degradation and potential pollution risks. The soil management practices significantly influenced the chemical properties of soil and sediment. Soil sediments exhibited significantly higher pH, N, P, K, Cu, and Zn values than the soil (Figs 5-7). Furthermore, the treatment effect was generally statistically justified. Sediments had significantly higher pH than the soil in all treatments. Sediments from the plowing and chisel plots had significantly higher P and Zn concentrations than the soil. When observing C, N, and Cu, the sediments at the plowing treatment had significantly higher concentrations than the soil.

The treatment effect was significant in the case of pH, C, N, P, Cu, and Zn. The pH of sediments was significantly higher at chisel than at subsoiling. Soil pH was significantly higher at chisel than at the other treatments. Sediment C was significantly more concentrated at plowing than in the other treatments (Fig. 5). Soil C and N concentrations were significantly higher in the chisel than other treatments. Also, sediment N concentrations were significantly higher at plowing than in the subsoiling treatments.

Sediment P concentrations were significantly higher at plowing and chisel than in the subsoiling treatments (Fig. 6). In the soil, P concentrations were significantly lower at plowing than in the other treatments. Similar trends were observed in the case of sediment and soil K, but the relationships were insignificant in all cases ($p<0.05$).

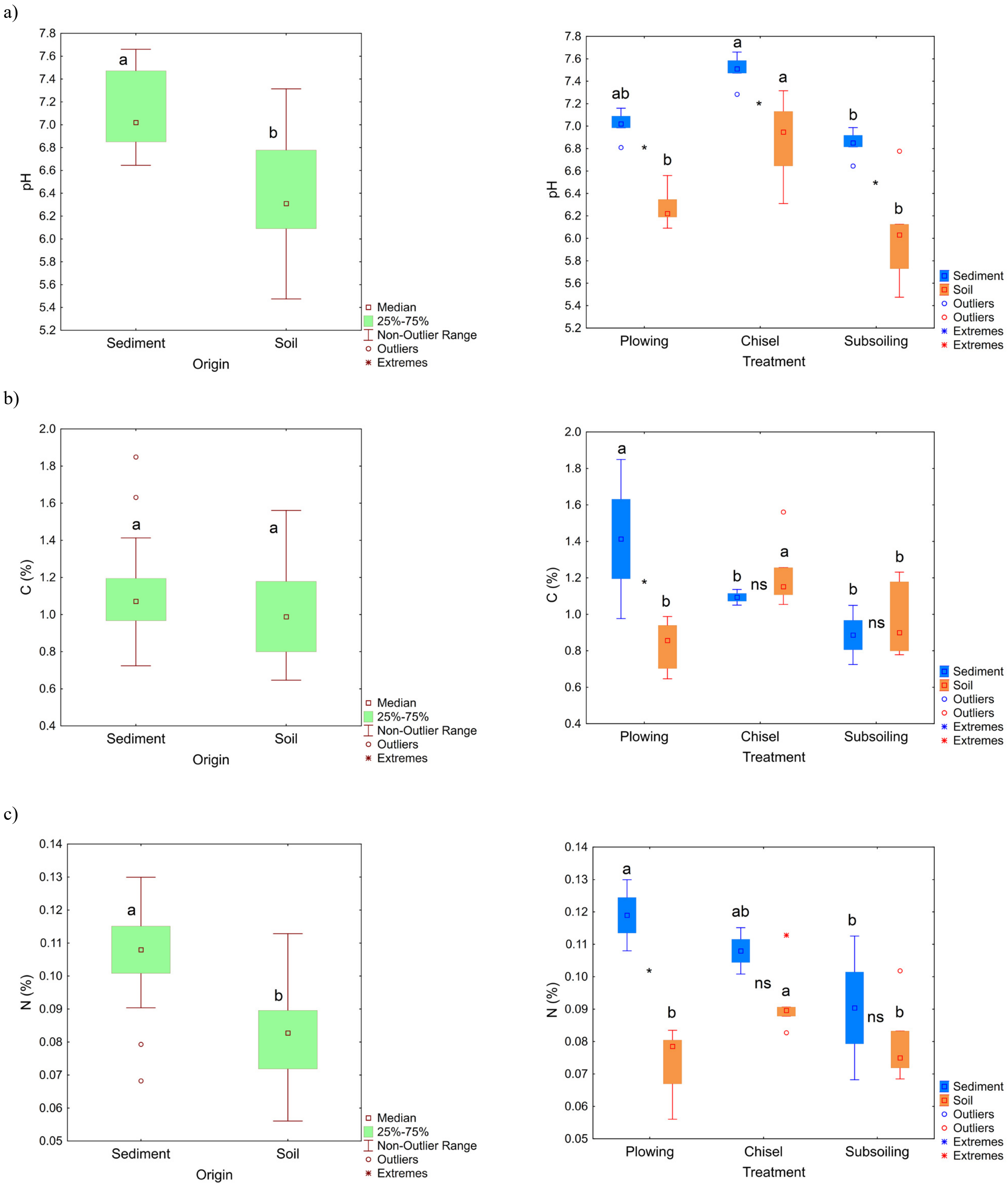

Fig. 5. Soil and sediment box plots of single and interaction effects of: a) pH, b) carbon, and c) nitrogen during the studied period. Different letters between same-coloured boxplots indicate significant differences at a $p<0.05$. Symbol * indicates significant differences between soil and sediments in each treatment; ns indicates not significant.

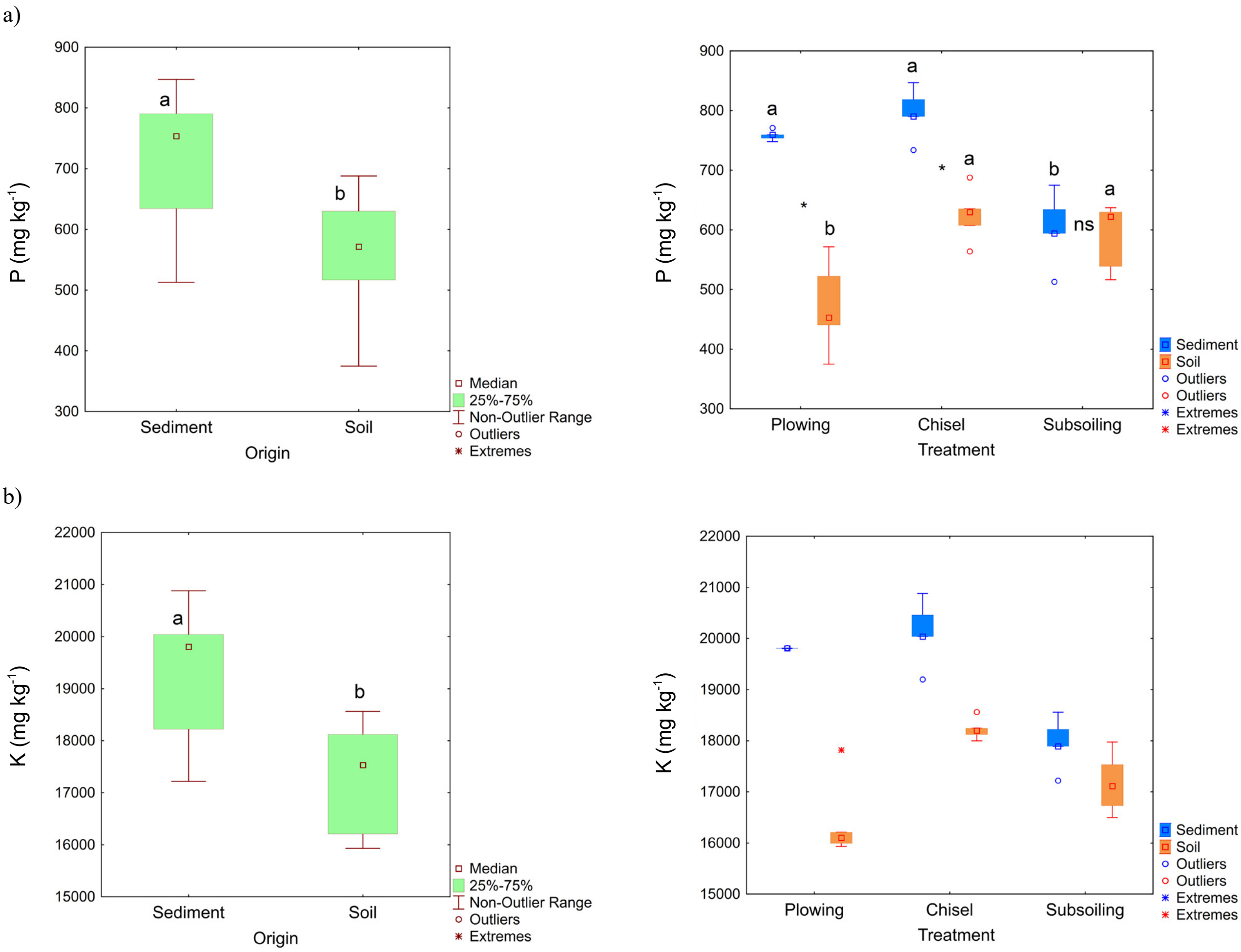

Fig. 6. Soil and sediment box plots of single and interaction effects of: a) phosphorus, and b) potassium during the studied period. Different letters between same-coloured boxplots indicate significant differences at a p<0.05. Symbol * indicates significant differences between soil and sediments in each treatment; ns indicates not significant.

Soil Cu was significantly higher in the chisel than subsoiling treatment (Fig. 7). Sediment Zn concentrations were significantly higher in the chisel treatment than under the other two treatments, while subsoiling showed significantly lower Zn concentrations than the other treatments.

The chemical properties of the soil varied significantly across the different soil management practices, with plowing resulting in the highest nutrient depletion, while subsoiling demonstrated the most effective nutrient conservation. The statistical analysis ($p<0.05$) confirmed significant differences in C, N, P, K, and trace element concentrations among the treatments (Table 7). Soil C and nitrogen N losses were significantly higher under plowing than conservation tillage methods. The highest annual C depletion was recorded in plowed plots (3 384 ± 235 kg ha^{-1}, $p<0.001$), whereas subsoiling retained the most C, with a minimal annual loss of 5.91 ± 1.07 kg ha^{-1}. Nitrogen losses followed a similar pattern (plowing: 278.35 ± 22.8 kg ha^{-1}, subsoiling: 9.16 ± 0.84 kg ha^{-1}), confirming the significant impact of tillage intensity on nutrient depletion.

Phosphorus and K (Table 7) exhibited the highest losses under plowing, while subsoiling retained the highest nutrient levels. The highest heavy metal concentrations in the sediment were determined in the plowed plots, whereas subsoiling minimized these losses. The statistical groupings between the treatments highlight significant differences ($p<0.05$) in trace element transport, emphasizing the role of plowing in accelerating heavy metal runoff.

4. DISCUSSION

Land uses of natural *Quercus robur-Carpinus betulus* forests and grasslands play a crucial role in the ecosystem conservation of the central Pannonian hilly environment on predominant silty soils developed on loess (Bašić, 2013). However, land use changes to croplands and intensive conventional farming have caused degradation (Bogunovic *et al.*, 2022) of soils already recognized as highly prone to compaction and erosion (Mordhorst *et al.*, 2021). Agriculture can be sustainable if proper management is given with wide crop rotations, strip cropping, organic farming, cover cropping,

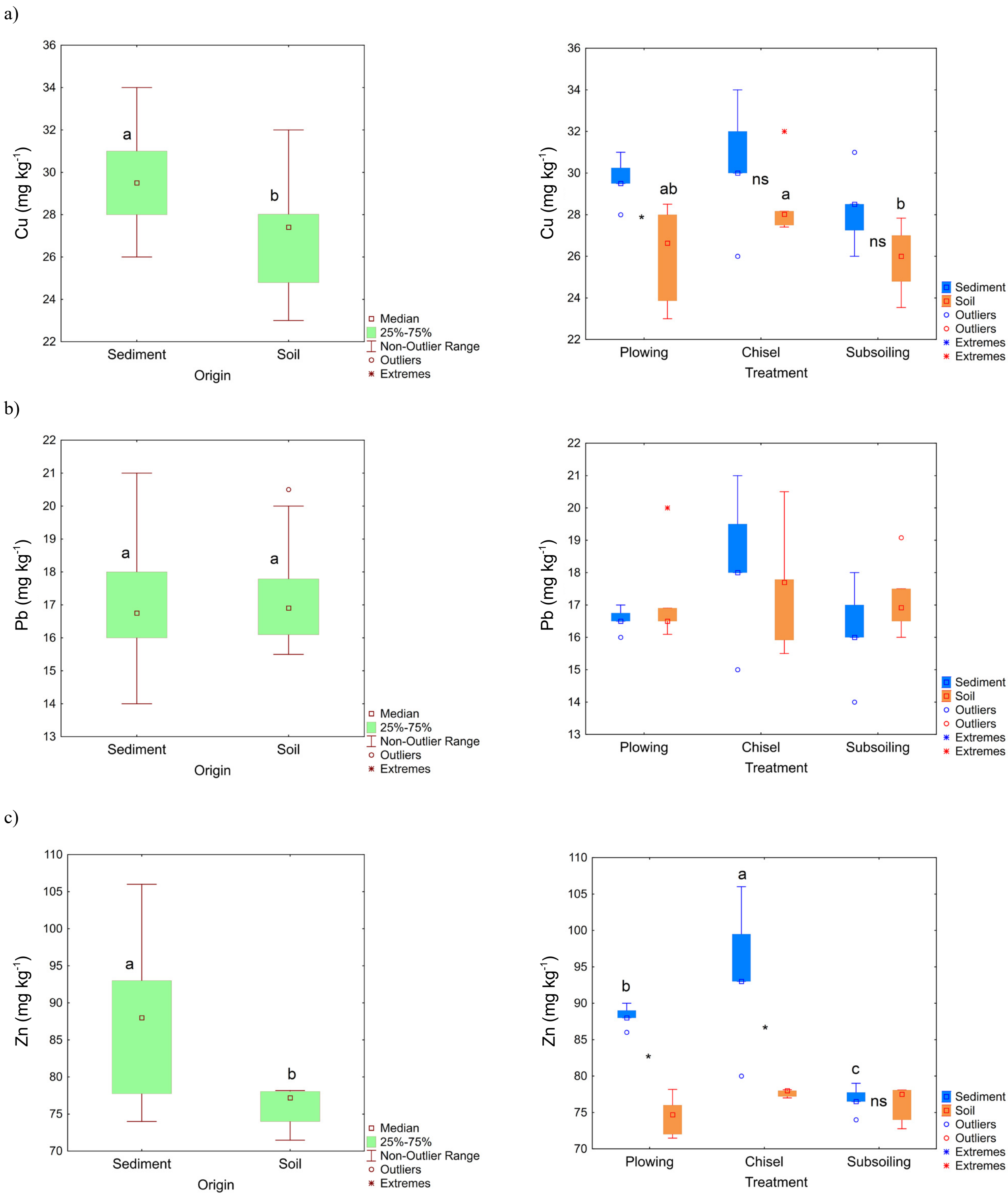

Fig. 7. Soil and sediment box plots of: a) Cu, b) Pb, and c) Zn during the studied period. Different letters between same-coloured boxplots indicate significant differences at a $p<0.05$. Symbol * indicates significant differences between soil and sediments in each treatment; ns indicates not significant.

Table 7. Yearly losses of chemical elements for the three replicate plots for the plowing, chisel, and subsoiling management treatments

Property		Mean	Sum	Minimum	Maximum	Std. dev.	CV	SE
C loss								
	Plowing	225.61	3384.09	81.99	561.09	129.10	57.22	33.33
	Chisel	45.51	682.69	3.26	125.33	48.32	106.16	12.48
	Subsoiling	5.91	88.61	0.38	25.80	6.28	106.25	1.62
N loss								
	Plowing	18.56	278.35	8.25	39.42	8.89	47.88	2.29
	Chisel	4.55	68.30	0.32	12.70	4.90	107.54	1.26
	Subsoiling	0.61	9.16	0.04	2.77	0.68	110.81	0.17
P loss								
	Plowing	11.6	174.6	5.5	22.7	5.1	44.0	1.3
	Chisel	3.4	50.6	0.3	9.3	3.6	106.6	0.9
	Subsoiling	0.4	6.0	0.0	1.7	0.4	100.8	0.1
K loss								
	Plowing	305.85	4587.79	144.10	600.84	136.81	44.73	35.32
	Chisel	83.96	1259.45	6.23	230.31	88.65	105.58	22.89
	Subsoiling	11.58	173.63	0.81	45.67	11.05	95.49	2.85
Cu loss								
	Plowing	0.47	7.00	0.21	0.94	0.22	47.35	0.06
	Chisel	0.13	1.99	0.01	0.38	0.14	108.65	0.04
	Subsoiling	0.02	0.27	0.00	0.06	0.02	89.69	0.00
Zn loss								
	Plowing	1.37	20.61	0.64	2.73	0.63	45.91	0.16
	Chisel	0.41	6.19	0.03	1.17	0.45	108.86	0.12
	Subsoiling	0.05	0.74	0.00	0.19	0.05	95.25	0.01
Pb loss								
	Plowing	0.26	3.88	0.12	0.52	0.12	46.30	0.03
	Chisel	0.08	1.22	0.01	0.23	0.09	109.72	0.02
	Subsoiling	0.01	0.16	0.00	0.04	0.01	100.15	0.00

CV – coefficient of variability, SE – standard error. Data in kg ha^{-1}.

mulching, or soil conditioning by organic additions as a regular practice. On the other hand, simple solutions, like continuous no-till, contour farming, or conservation tillage, profoundly impact soil properties, runoff generation, sediment loss, and erosion risk. Conservation practices on Stagnosols have been proven to improve soil properties, such as carbon accumulation (Telak *et al.*, 2021), soil structure (Sutri *et al.*, 2022), and water retention (Wilczewski *et al.*, 2023) and mitigate soil and water losses (Kisic *et al.*, 2017). This study focuses on hillslope cultivation and degradation patterns of Stagnosols, demonstrating that carefully chosen conservation tillage management can improve the soil physical system, reduce erosion, and preserve soil fertility, whereas plowing contributes to significant soil degradation.

4.1. Soil properties

Bulk density was significantly lower in the subsoiling than chisel and plowing treatments, indicating that deep loosening effectively reduces compaction and promotes better root growth and water infiltration. The significantly higher BD in plowed plots suggests that conventional tillage contributes to soil compaction over time, consistent with previous research (Jug *et al.*, 2024; Zhang *et al.*, 2024). The penetration resistance results confirmed higher soil compaction under plowing. In the spring, chisel plowing exhibited the highest PR at 10-30 cm depth, while in the fall, plowing had significantly higher PR than chisel and subsoiling. The increase in PR under plowing suggests that plowing creates artificial crumbs with lower temporal resistance to slaking (Weidhuner *et al.*, 2021) and that repeated interventions in wet soils lead to the formation of a plow pan, restricting root penetration and water movement (Jeřábek *et al.*, 2017).

The soil management practices significantly influenced SWC and WHC. In the spring, plowing retained the highest SWC; in the fall, subsoiling demonstrated superior SWC than the other tillage managements, although the differences were not statistically significant ($p>0.05$), meaning that the soil disturbance caused by plowing remains high in the short term after the intervention, creating greater differential porosity and water infiltration capacity (Salem *et al.*, 2015; Telak *et al.*, 2020). However, as the season progresses, pore systems in subsoiling and chisel-plowed plots appear to have a greater capacity to infiltrate rainfall and retain moisture, suggesting a higher percentage of pores and a more developed pore network (Yang *et al.*, 2021). This observation is also supported by the WHC data (Table 2), which indicates the superiority of subsoiling and plowing.

Typically, when subsoiling is performed on dry soils, it creates an ideal pore network. It improves connectivity between the topsoil and subsoil, modifying crumb size, fraction distribution (Ning *et al.*, 2022), and the soil's water-holding capacity. It is already well-established that medium-sized pores (mesopores, 0.2-10 μm) retain water more effectively than small pores (micropores, <0.2 μm) in compacted soils (Usowicz *et al.*, 2024). A similar trend is partially confirmed when soil structural stability is evaluated. In the spring, chisel plowing resulted in significantly higher MWD than plowing. By the end of the season, the chisel-plowed soils had a similar crumb size to those under the subsoiling and plowing treatments. However, subsoiling increased WSA percentages in the fall, suggesting improved soil aggregation and stability compared to the initial condition. Although the differences were not statistically significant, this observed trend underlines the long-term benefits of subsoiling in restoring soil's physical and hydrological environment, as previously mentioned (Yang *et al.*, 2021). Nevertheless, further field observations over several years are needed to confirm these results.

The maize biomass yields were high in all the tillage treatments compared to the world average of 9.1 t ha^{-1} (FAOSTAT, 2024). Relatively good annual rainfall distribution with tillage seedbeds ensures higher maize biomass yields than other production systems like organic cultivation or no-tillage systems in Stagnosols (Bogunovic *et al.*, 2018, 2024). The subsoiling resulted in 11% and 19% higher maize biomass yields than the plowing and chisel treatments. Moreover, previous works reported that maize biomass yields increase under deep loosening compared to conventional plowing (Botta *et al.*, 2006; Cai *et al.*, 2014; Abidela Hussein *et al.*, 2019). Loosening management is recognized as a viable strategy for regulating crop shoot and root growth in heavy textured soils with poor structure (Hartmann *et al.*, 2008; Seehusen *et al.*, 2025).

On the other hand, although the absolute differences in the biomass yields between the treatments reached several tons per hectare, these differences were not statistically significant due to within-treatment variability. This is in alignment with other tillage studies which have shown that similar yields can be reached in conservation tillage and conventional tillage systems (Temesgen *et al.*, 2009; Pittelkow *et al.*, 2015; Büchi *et al.*, 2017; Jug *et al.*, 2019). Secondly, such results are promising, considering a "ubiquitous farmers' fear" of decreasing the yield and income in the case of implementing conservation tillage management. Finally, despite numerical differences in biomass yields, the overlapping error bars indicate substantial within-treatment variability, preventing statistical significance. This indicates that although subsoiling tended to lead to higher biomass yields, the observed differences can be attributed to natural variations rather than a definitive effect of tillage. Further investigation of soil properties and environmental factors could help to clarify these trends.

4.2. Erosion monitoring

Soil erosion, a major factor in land degradation, is widely recognized as an accelerated process driven by human activities. This issue is particularly pronounced in Europe, where more than 196 853 km^2 are estimated to be at risk of severe erosion (European Commission, 2024), with croplands and natural grassland comprising > 80% of all areas affected by moderate to severe water erosion (Eurostat, 2020). Addressing this challenge has become a priority within the European Union, especially with the implementation of the Green Deal and the Soil Mission Board's objectives to ensure that 75% of European soils are healthy or improved by 2030 (European Commission, 2021). Beyond Europe, severe erosion rates are also reported in many other regions globally, underscoring the urgent need for widespread adoption of sustainable land management practices. Yadav *et al.* (2024) found that maize-cultivated croplands in the Himalayan region of India reach 21.0 t ha^{-1} y^{-1} when measured using a fixed plot manner. Many parts of Africa also show high erosion rates, such as Tamene and Le (2015), measured with the RUSLE model in sub-Saharan Africa, where an average soil erosion rate of 35 t ha^{-1} y^{-1} and 75 was measured in the White Volta and Nile basin, respectively. Klik and Rosner (2020) reported that mean long-term annual erosion rates for conventional tillage ranged between 8.6 and 33.2 t ha^{-1} in the croplands on silt loam soils of Austria. They confirmed the acceleration of soil erosion rates found by Basic *et al.* (2004) and Kisic *et al.* (2017) when they claimed that the use of conventional plowing on Stagnosols under maize cultivation after 20 years induces soil losses of 31.7 t ha^{-1} y^{-1}. Most of the rainfed croplands under wide-row spring crops of the world show non-sustainable soil losses. However, exacerbated erosion rates are dominantly reported under conventional plowing in Hungary (Madarász *et al.*, 2021), Nepal

(Chalise *et al.*, 2020), the USA (Thaler *et al.*, 2022), Italy (Preiti *et al.*, 2017), Mali (Traore and Zemadim, 2019), Brazil (Thomaz *et al.*, 2022), India (Sharma *et al.*, 2017), Rwanda (Kagabo *et al.*, 2013), and Croatia (Bogunovic *et al.*, 2018). On the other hand, literature research shows a decrease in surface runoff under conservation tillage management in semiarid (Kurothe *et al.*, 2014), semi-humid (Klik and Rosner, 2020; Madarász *et al.*, 2021), and humid (Traore and Zemadim, 2019; Chalise *et al.*, 2020) environments. The superior effectiveness of conservation tillage as a soil erosion control measure was evident, as chisel plowing and subsoiling significantly reduced soil loss compared to plowing. Specifically, chisel decreased sediment loss by 3.8 times, while subsoiling achieved an exceptional reduction of 25 times. Regarding runoff, subsoiling reduced total runoff by 77.9%, making it approximately 4.5 times lower than at plowing, while chisel plowing reduced it by 44.8%, or about 2.2 times less. The positive effect of subsoiling on Stagnosols is attributed to the significant reduction in compaction, enhanced porosity, and improved pore network connectivity between the topsoil and subsoil. These changes promote higher infiltration rates, reduce surface runoff, and consequently lower flow velocity, effectively minimizing soil erosion (Yang *et al.*, 2021). Similar results were reported by Kisic *et al.* (2017) on the same soil type. Soil compaction did not show a statistical difference between plowing and chiseling, yet chisel plowing reduces overland flow substantially. Reichert *et al.* (2017) also investigated the impact of chisel and plowing tillage management on soil physical properties and found no significant differences in BD. However, chisel effectively reduces the degradation level of Stagnosols in Croatia, which may be attributed to the higher percentage of residues. Non-invertive tillage management is proven to leave more residues on topsoil, while conventional plowing increases the turnover of the organic component in subsoil (Zheng *et al.*, 2014).

Sediment concentration also appears to be influenced by soil management practices. Across most runoff events, the sediment concentration was lower in the subsoiling treatment than under conventional plowing. This finding aligns with previous research (Araya *et al.*, 2011; Vaezi *et al.*, 2017; Carretta *et al.*, 2021), demonstrating that runoff reductions diminish the overland flow's transport capacity. While long-term effects on soil structure require further investigation, our results suggest that subsoiling can reduce sediment mobilization within a single year of treatment, likely due to its impact on water infiltration and runoff dynamics. In all the treatments, the sediment contained significantly higher parameters of monitored chemical properties. The eroded sediments, characterized by average and treatment, showed higher pH than the soil (Fig. 5), which can be explained by several key processes. Firstly, the transportation of soil particles by surface runoff preferentially removes clay and silt, which typically have higher cation exchange capacity (Wang and Shi, 2015) and retain basic cations, leading to a slightly higher pH in the transported sediments compared to the bulk soil (De Santis *et al.*, 2010). Secondly, an increase in sediment pH can be due to the loss of acidic components, like organic matter and iron/aluminum oxides. As is seen from Figs 6-7 and Table 7, a significant loss of these acidic components is a very likely reason for having a higher sediment pH than the original soil. Similarly, sediment soils contain higher concentrations of nutrients and heavy metals than bulk soils. In most properties, differences between sediments and bulk soil concentrations are significant. This enrichment is primarily due to the affinity of fine-grained particles for adsorbing these substances. For instance, research by Vdović *et al.* (2021) indicates that metal concentrations can be up to seven times higher in fine sediment fractions than in bulk samples, especially in river environments with substantial sand content. Similarly, investigations into sloping croplands have found that organic matter and nutrients are more enriched in finer sediment grains, with positive correlations among element concentrations and organic matter in sediments with total losses via runoff and soil nutrient contents (Du *et al.*, 2021). Moreover, eroded fine-grained sediments act as reservoirs for heavy metals due to their high surface area and reactivity, resulting in a greater accumulation of contaminants than in bulk soil (Jung, 2017).

The analysis of element concentrations in sediments and bulk soil revealed a significant influence of tillage treatments on their distribution. Plowed sediments exhibited consistently higher concentrations of most elements than bulk soil under plowing, suggesting that conventional tillage accelerates soil erosion and preferentially transports finer particles rich in organic matter and nutrients. This pattern aligns with previous studies demonstrating that hydrological processes selectively remove clay and silt fractions rich in elements (Wang and Shi, 2015; De Santis *et al.*, 2010). On the other hand, subsoiling did not result in significant differences in element concentrations between soil and sediments, reinforcing its role in reducing erosion rates. This observation corresponds with findings by Kisic *et al.* (2017), who reported that conservation tillage methods, including subsoiling, effectively reduce overland flow formation, sediment detachment, and nutrient loss. The primary cause of these contrasting trends is likely the variable erosion rates associated with each tillage practice. Plowing creates a poor and temporally unstable soil structure, increasing susceptibility to runoff and sediment transport, whereas subsoiling improves soil infiltration porosity, thereby reducing sediment movement (Vaezi *et al.*, 2017).

Element loss in runoff is usually controlled by runoff depth, element concentration, and soil element contents (Kleinman *et al.*, 2011). The results of total element losses indicate that soil management practices significantly influence nutrient and heavy metal losses through erosion processes. Plowing led to the highest nutrient losses across all studied elements, highlighting its role in accelerating topsoil degradation and the predominant negative cause of offsite pollution in the investigated area. The heavy metal losses were also tremendous under plowing, suggesting a strong association between sediment transport and trace element mobility. This finding was likely because the nutrient and heavy metal concentration and runoff in the plowed plots were higher than in the conservation treatments, confirming the previous findings (Uribe *et al.*, 2018; Klik and Rosner, 2020; Fang, 2021). Comparatively, the conservation tillage methods, such as subsoiling, resulted in significantly lower losses. The carbon loss was reduced by 97%, while the N, P, and K losses decreased by approximately 96, 97, and 99%, respectively, compared to plowing. Similarly, the heavy metal losses were significantly lower under subsoiling, with Cu, Pb, and Zn reduced by 96%, underscoring the role of erosion control in mitigating diffuse pollution. The reduced losses in the chisel and subsoiling plots also suggest a strong association between sediment transport and element mobility, which aligns with prior studies (Du *et al.*, 2021; Dugan *et al.*, 2022). The results of this study highlight the urgent need for sustainable soil management practices to prevent excessive nutrient depletion and heavy metal contamination in agricultural landscapes.

5. CONCLUSIONS

This study highlights the specific vulnerability of sloped Stagnosols to significant soil degradation. Although often perceived as stable due to their high water retention and flatland association, our results demonstrate that when Stagnosols occur on slopes, they are highly susceptible to runoff, compaction, and sediment transport. Subsoiling effectively mitigates these risks. In the monitored year, conventional plowing generated the highest sediment concentration and elemental losses, with plowed sediments consistently exhibiting greater C, N, P, K, Cu, Zn, and Pb concentrations than the bulk soil. This confirms that intensive tillage accelerates soil degradation by selectively removing fine, nutrient-rich particles, leading to offsite nutrient depletion and potential environmental contamination. In contrast, subsoiling significantly mitigated soil and nutrient losses, with no significant differences between sediment and bulk soil element concentrations. The reduced sediment transport under subsoiling is attributed to higher infiltration capacity and reduced runoff, limiting the mobilization of fine particles. Chisel tillage demonstrated an intermediate effect, reducing erosion compared to plowing but causing moderate nutrient losses. Beyond erosion control, subsoiling significantly improved soil physical properties by alleviating compaction and raising water holding capacity, which is crucial for improving drought resilience. The biomass yield did not vary statistically among the treatments; however, subsoiling recorded the highest maize biomass yield, while chisel had the lowest value. Conservation tillage enhances soil health and reduces degradation, but optimization of management strategies is necessary to balance erosion control and crop productivity. Subsoiling, in particular, emerges as an effective strategy for minimizing soil degradation and supporting sustainable agricultural production.

Conflict of interests: The authors do not declare any conflict of interest.

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