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Straw Mulch Application Enhanced Soil Properties and Reduced Diffuse Pollution at a Steep Vineyard in Istria (Croatia)

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Abstract: Straw mulching is a sustainable practice used to control soil erosion. However, different doses of mulch affect the efficiency of straw conservation. This study presents detailed research on how soil physicochemical properties and the hydrological response react to different types of vineyard soil management (Tilled, Grass, Low Straw, High Straw) and seasons (spring, summer, autumn) under conventional management on Anthrosols in Mediterranean conditions. To assess soil properties, core samples and disturbed samples were taken from the topsoil layer (0–10 cm). To evaluate erosion rates, a rainfall simulation experiment was conducted (58 mm h^{-1} for 30 min) with 10 replicates per treatment and season (120 in total). The results show higher water-stable aggregates (WSA) and soil organic matter (SOM) and lower bulk density (BD) in the mulch and grass treatment groups compared with the Tilled treatment group. High Straw treatment successfully mitigated runoff, while other treatments had significantly higher runoff that triggered sediment loss (SL) and translocation of P, K, Zn and Ni down the slope. There were 254% and 520% higher K losses with Tilled treatment in autumn compared with Low Straw and Grass treatments, respectively. Statistical analysis showed a strong association between element loss and SL, which indicates an ecological threat in degraded and endangered vineyards. Mulch application and grass cover reduce the vulnerability of vineyards, reduce evaporation, act as insulation against high temperatures, reduce erosion and suppress weed growth. The mulch dosage varies depending on the goals and conditions of the vineyard; thus, lower mulch dosage (2 t/ha) is appropriate when soil conditions are favourable and there is no significant need for moisture retention, while higher mulch dosage is necessary in dry regions to maintain soil moisture during high-temperature periods, as well as in sloped areas subjected to erosion.

Keywords: sustainable management; mulch application; element behaviour; soil erosion

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1. Introduction

The rising global population has certain demands (e.g., food, fuel and fibre), but at what cost? Agriculture is facing many changes. On one hand, there is a need to ensure sufficient quantities of food for the growing population, while on the other hand, this needs to be achieved sustainably, without endangering the soil and water [1,2]. Applying sustainable agricultural practices can be challenging, particularly bearing in mind that the environmental, social and economic impacts of agriculture are multifarious and interact with each other [3,4].

Soil and water conservation are necessary for mitigating and reversing land degradation. This can be achieved by incorporating conservation tillage management of highly jeopardized soils [5,6]. These soils are well represented in areas with intensive crop production such as croplands, fruit plantations and vineyards [7–9]. Vineyards are known for their high vulnerability in terms of soil and plant health. Soil health is widely affected by intensive management with tractor traffic, pesticide and fertilizer use, and frequent tillage [10–12]. All these activities have serious effects on soil degradation; they can disturb the soil pore system, increase bulk density, decrease soil organic matter and water-stable aggregates and increase diffuse pollution in steep areas [13–17]. To mitigate these consequences, soil conservation methods such as conservation tillage, permanent grass cover, mulching and the use of cover crops are needed [18–20]. Even though tillage has shown some positive effects, including reduced compaction and enhanced soil air-to-water ratio, these effects are short-lived, while in the long term, negative effects such as crust formation, reduced soil organic matter, deteriorated structure and increased soil compaction and erosion appear [21–24]. More sustainable practices are currently being implemented, particularly the use of mulch, which can take different forms such as harvest residues [25–29], sawmill byproducts [30–33], agricultural industry byproducts [34,35], pruning residues [36,37] and synthetic materials [38–40]. Mulching is one of the main features of conservation practice, along with reduced tillage. Conservation practice has certain advantages, including improving soil structure [31,41,42], reducing compaction [43,44], improving the air-to-water ratio [45,46], increasing soil micro and macro elements [47,48] and preventing further soil particle transport in sloped areas [49–51]. These measures are well-recognized and can be implemented in endangered agricultural areas such as vineyards. Croatia has recorded an increase in vineyards [52], and great concern has risen with regard to increasing soil erosion events, which often result in high rates of soil loss and diffuse pollution.

Diffuse pollution in vineyards can be very dangerous if the concentrations of elements exceed their normal rates. This is more pronounced in intensively managed vineyards with high pesticide use. In these vineyards, vines are exposed to phytotoxicity, and soil and water pollution often occurs, especially in lower-sloped areas. Additionally, higher amounts of trace elements affect yield quality, thus endangering human health [53,54]. This study presents a comprehensive evaluation of the impacts of soil management practices and seasonal variations on soil physicochemical properties, and the hydrological response and element transport in an intensively managed vineyard in Istria, Croatia.

By investigating the effects of different soil management techniques and seasonal variations on diffuse pollution and soil properties during simulated rainfall, we aimed to address the pressing concern of increasing soil erosion events and the associated soil loss and diffuse pollution in vineyards. This study contributes to the existing knowledge by providing valuable insights into the specific challenges faced by vineyards in terms of soil degradation and highlights the importance of implementing sustainable soil management practices to mitigate these issues in the context of the increasing number of vineyards in Croatia. The research was conducted to advance our knowledge of conservation management and land degradation in vineyards. The present research takes us a step forward by evaluating two dosages of mulch as well as bare and grass-covered soils and testing them in different seasons (under different soil conditions). The results presented in this work confirm the need for repeated experiments in different seasons to obtain a solid and accurate conclusion.

2. Materials and Methods

2.1. Study Area

The investigated vineyard is located in Grimalda (Central Istria, Croatia; Figure 1) and is situated on an average slope of 6.65° (3° min to 9° max) with NE–SW exposure at an average elevation of 285 m a.s.l. The vineyard is mostly surrounded by forest and olive orchards. The climate in the investigated area is classified as Cfb (temperate humid climate with warm summer) according to the Köppen climate classification [55]. The parent material is flysch, and the soil is classified as Anthrosols derived from Stagnosols by deep ploughing and ameliorative fertilisation [56]. The mean annual temperature (2021) is 12.7 °C and ranges from a minimum average of 3.9 °C in January to a maximum average of 23.7 °C in July. The mean annual precipitation is 829.9 mm, ranging from a minimum of 10.8 mm in October to a maximum of 113.7 mm in May (Figure 2).

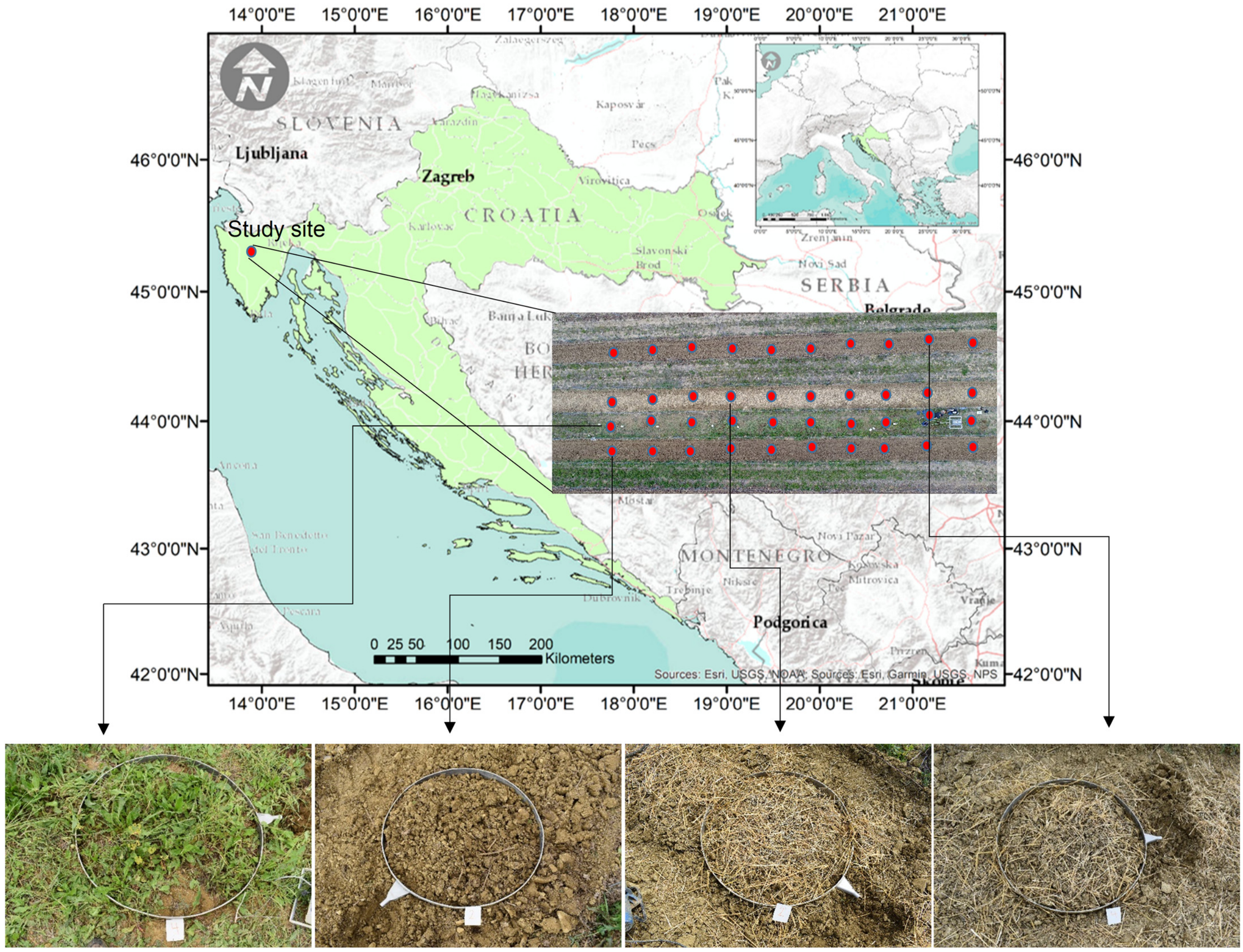

Figure 1. Study area and rainfall simulation experimental plots.

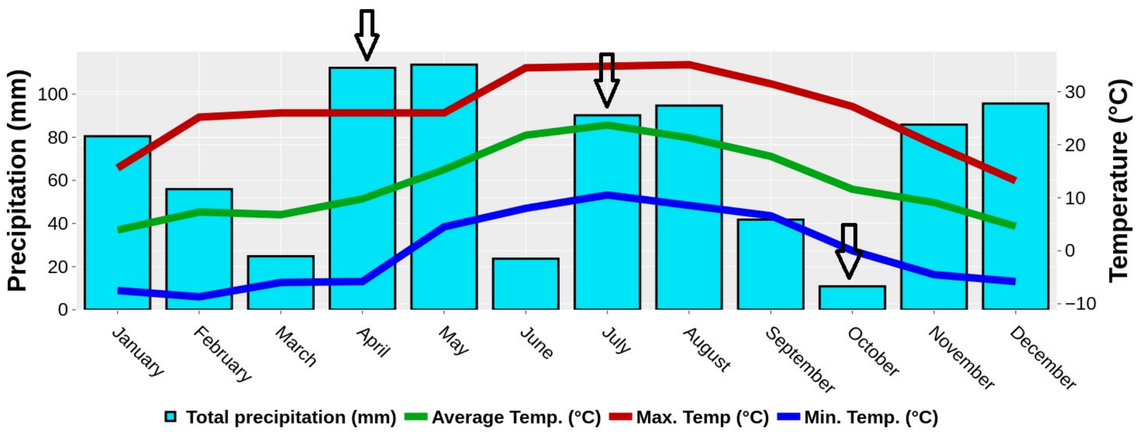

Figure 2. Monthly precipitation and temperature throughout the experimental period. Arrows indicate when measurements were taken.

2.2. Experimental Design

The experimental vineyard consisted of 4 treatment sections: grass-covered (Grass): grass mowed in June and right before the harvest; tillage (Tilled): conducted once a year (in spring); straw mulch: application of 2 t/ha (Low Straw) or a double dose of 4 t/ha (High Straw). Inter-row treatments were applied on the same soil type, slope, aspect and exposure using a paired-plot strategy (Figure 1). In each treatment, 10 plots were separated by 5 m. This is a 4-year-old vineyard where cv. Istrian Teran was planted on Kober 5BB (*Vitis berlandieri* × *Vitis riparia*) rootstock with 2 m between rows and 0.8 m between vines. Over the year, a tractor passed 25 times to apply pesticide and fertiliser, mow the grass, manage the canopy and conduct tillage. Pesticide and fertiliser were applied frequently (10–12 times during the growing period). Rainfall simulation experiments were conducted throughout the vegetation season to determine the impact of seasonal viticultural practices; 40 experiments were conducted per season (spring, summer and autumn 2021) for a total of 120 experiments. The simulations were conducted for 30 min with pressurized rainfall simulators (UGT Rainmaker, Müncheberg, Germany), with a rainfall intensity of 58 mm h^{-1}. The time and intensity of rainfall simulations were selected because 93% of annual soil loss was measured in a single rainstorm at that intensity [57]. Before the rainfall simulation experiments, the rainfall simulator was calibrated using a plastic vessel. The catchment area was enclosed by a metal ring with a small faucet (1 m diameter, 0.785 m^2) pressed 5–7 cm into the soil and extending 10 cm above the soil surface. The faucet on the ring was connected to a plastic canister to collect the total overland flow during the simulations. A Casio HS-6-1EF chronometer (Tokyo, Japan) was used during the rainfall experiment to determine the time to ponding (TP) and time to runoff (TR).

2.3. Laboratory Work

Undisturbed soil samples (4 treatments × 10 replicates × 3 seasons) and core samples (4 treatments × 10 replicates × 3 seasons) were taken from 0 to 10 cm depths close to the rainfall simulation plots and used to determine soil water content (SWC), bulk density (BD) and water-stable aggregates (WSA). SWC and BD were determined by wetting, weighing and drying soil core samples in an oven at 105 °C for 48 h, and all undisturbed samples were prepared by hand and broken down into aggregates [58] and left to dry for 1 week at room temperature (25 °C). The wet sieving method described in [59] was used to determine WSA. Eijkelkamp's wet sieving apparatus was utilized for the wet sieving of all samples that had previously undergone dry sieving. The percentage of WSA was obtained using the equation:

$$\mathrm{WSA} = \frac{Wds}{Wds + Wdw}, \tag{1}$$

where WSA is the percentage of water-stable aggregates, *Wds* is the weight of aggregates dispersed in dispersing solution (g) and *Wdw* is the weight of aggregates dispersed in distilled water (g). The rest of the undisturbed soil samples (aggregates not used for WSA determination) were milled and sieved through a 2 mm mesh, in preparation for further chemical analysis. Soil pH was measured using the electrometric method in a 1:5 (w/v) ratio using a Beckman Φ72 pH meter in H_2O. The digestion method by Walkley and Black [60] was used to measure the soil organic matter (SOM) content, utilizing the previously dried, milled and sieved samples.

Using the method described in [49], sediment concentration (SC) was calculated by dividing the sediment mass by the overland flow mass. Sediment yield was determined after air-drying at room temperature (25 °C) for 1 week to obtain the mass of the filter paper and sediment. Sediment loss (SL) was determined by calculating the mass of overland flow to obtain the runoff.

After drying, milling and sieving, the soil samples were placed in a plastic cylinder with a protective foil on the bottom and a plastic lid on the top. The cylinder was later placed in the workstation and set for pXRF analysis (Olympus, Waltham, MA, USA) after exposing the samples to X-ray beams for 2 min [61,62] to obtain the concentrations of elements (phosphorous (P), potassium (K), nickel (Ni), zinc (Zn) and lead (Pb)) in the soil and sediment. These elements were chosen due to their overall potentially harmful effects on agroecosystems.

2.4. Statistical Analysis

Before data analysis, the normality and homogeneity of variance were assessed using the Kolmogorov–Smirnov test. The data normality of variance was observed at $p > 0.05$. Many of the variables did not follow the Gaussian distribution and heteroscedasticity. Consequently, the dataset was normalized using natural logarithm and Box–Cox transformations. Two-way ANOVA and the Kruskal–Wallis test were performed to assess the impact of treatment and seasonality on soil properties, hydrological response and element transport (SOM, pH, TP, TR, runoff, SC, SL, P loss, K loss, Ni loss, Zn loss, Pb loss). When significant differences were observed at $p < 0.05$, Tukey's LSD test was applied post hoc. Using the Box–Cox transformed data, principal component analysis (PCA) was performed based on the correlation matrix to identify interrelations between variables. All data analyses were performed using Statistica 12.0 [63] and graphs were created using Plotly [64]. All the data in tables and graphs are presented in their original states.

3. Results

3.1. Soil Physical Properties

Statistical analysis showed a significant difference following Tilled treatment, with higher BD values observed in autumn (1.59 g cm^{-3}) compared with spring (1.34 g cm^{-3}) and summer (1.47 g cm^{-3}). Under the Low Straw treatment, lower BD values were recorded in spring (1.31 g cm^{-3}) while higher values were recorded in summer (1.47 g cm^{-3}) and autumn (1.52 g cm^{-3}). Significantly higher values were recorded following the High Straw treatment in autumn (1.48 g cm^{-3}) compared with spring (1.31 g cm^{-3}) and summer (1.27 g cm^{-3}). Grass treatment showed no significant differences between seasons. There were no significant differences between treatments in spring, while significantly lower values were observed in summer and autumn following the Grass treatment compared with the other treatments (Table 1). For SWC, statistical differences were noted only for treatments through seasons. For the Tilled treatment, SWC was significantly higher in spring (40.86%) than in summer (25.07%), while in autumn, the SWC of 30.93% was not statistically different compared with the spring or summer. For the Low Straw treatment, there were no significant differences in SWC between the seasons, with a minimum of 26.21% in autumn, 32.05% in summer and a maximum of 32.69% in spring. For the High Straw treatment, there were no significant differences in SWC through the seasons, with a minimum of 28.66% in autumn, 29.71% in summer and a maximum of 32.36% in autumn. For the Grass treatment, SWCF was significantly lower in summer (20.21%) than in spring (37.47%) and autumn (38.38%). Statistical analysis of WSA showed significant differences between treatments and seasons. For the Tilled treatment, WSA was significantly lower in summer (64.18%) and autumn (62.05%) than in spring (75.12%). For the Low Straw treatment, there were no significant differences through the seasons—values ranged from 73.26% in summer to 74.08% in autumn. For the High Straw treatment, significantly lower WSA values were recorded in spring (70.73%) compared with summer (81.11%) and autumn (80.77%). Grass treatment followed the same pattern as Low Straw treatment, with no significant differences through the seasons—values ranged from 82.33% in spring to 85.86% in summer. In spring, significantly higher WSA values were observed in the Grass treatment group than in the other treatment groups; the same pattern was observed in summer and autumn (Table 1).

Table 1. Results of two-way ANOVA based on soil properties. Different letters after mean values in columns represent significant differences at $p < 0.05$. Capital letters indicate statistical differences between treatments; lowercase letters indicate statistical differences between seasons. BD, bulk density; SWC, soil water content; WSA, water-stable aggregates.

Season	Treatment	BD (g cm^{-3})	SWC (%)	WSA (%)
Spring	Tilled	1.34 Ca	40.86 Aa	75.12 Ab
	Low Straw	1.31 Ba	32.69 Aa	73.80 Ab
	High Straw	1.31 Ba	29.71 Aa	70.73 Bb
	Grass	1.38 Aa	37.47 Aa	82.33 Aa
Summer	Tilled	1.47 Ba	25.07 Ba	64.18 Bd
	Low Straw	1.47 Ba	32.05 Aa	73. 26 Ac
	High Straw	1.27 Bb	28.66 Aa	81.11 Ab
	Grass	1.38 Aab	20.21 Ba	85.86 Aa
Autumn	Tilled	1.59 Aa	30.93 ABa	62.05 Bc
	Low Straw	1.52 Aab	26.21 Aa	74.08 Ab
	High Straw	1.48 Aab	32.36 Aa	80.77 Aab
	Grass	1.45 Ab	38.38 Aa	84.04 Aa

3.2. Soil Chemical Properties

Regarding the chemical properties, significant differences were noted for treatments and seasons. There were no significant differences in soil organic matter in the Tilled, Low Straw and Grass treatment groups through the seasons, with values ranging from a minimum of 1.38% for Tilled treatment in spring to a maximum of 2.51% for Grass treatment in autumn. For the High Straw treatment, there were significantly lower SOM values in spring (1.37%) compared with summer (1.56%) and autumn (1.73%). In every season, SOM values were significantly higher following Grass treatment (Table 2). There were no significant differences in soil pH based on treatments through the seasons. In spring, soil pH values were significantly higher (8.04) in the High Straw treatment group compared with the Tilled (7.54), Low Straw (7.93) and Grass (7.99) treatment groups. In summer, there were significantly lower pH values in the Tilled (7.52) and Low Straw (7.97) treatment groups compared with the Grass (8.16) treatment group, while pH values did not significantly differ between the High Straw (8.09) and the Low Straw and Grass treatment groups. The same pattern in soil pH values was observed in autumn, as presented in Table 2.

Soil P concentrations showed significant differences based on treatment and season. With Tilled treatment, there were no significant differences in soil P through the seasons, with a minimum of 390.66 kg ha^{-1} in summer, 425.29 kg ha^{-1} in spring and a maximum of 515.45 kg ha^{-1} in autumn. The same pattern was observed for p values in the High Straw treatment group (Table 2). For Low Straw treatment, p values were significantly lower in spring (380.58 kg ha^{-1}) than in summer (545.89 kg ha^{-1}) and autumn (533.79 kg ha^{-1}). For Grass treatment, there were significantly higher p values in spring (561.57 kg ha^{-1}) than in summer (377.2 kg ha^{-1}) and autumn (376.54 kg ha^{-1}). In spring, significantly higher P values were observed in the Grass treatment group compared with the other treatment groups, while in summer, significantly higher P values were recorded for the Low Straw treatment group compared with the other treatment groups, and in autumn, significantly lower values were recorded in the Tilled, Low Straw and High Straw treatment groups compared with the Grass treatment group (Table 2).

Table 2. Results of two-way ANOVA based on element concentrations. Different letters after mean values in columns represent significant differences at $p < 0.05$. Capital letters indicate statistical differences between treatments; lowercase letters indicate statistical differences between seasons. SOM, soil organic matter; pH; P, phosphorous; K, potassium; Ni, nickel; Zn, zinc; Pb; lead. Soil P, K, Ni, Zn and Pb data are given in kg ha^{-1}.

Season	Treatment	SOM (%)	pH	Soil P	Soil K	Soil Ni	Soil Zn	Soil Pb
Spring	Tilled	1.38 Ab	7.54 Ab	425.29 Aab	27,297.09 Ba	210.78 Ba	184.80 Ba	43.68 Aa
	Low Straw	1.40 Ab	7.93 Aab	380.58 Bb	26,282.59 Ba	206.08 ABa	180.54 ABa	34.72 Aa
	High Straw	1.37 Bb	8.04 Aa	418.21 Aab	26,460.90 Ba	200.48 Ba	184.58 Aa	40.32 Aa
	Grass	2.11 Aa	7.99 Aab	561.57 Aa	27,149.47 Aa	209.22 Aa	183.90 Aa	42.34 Aa
Summer	Tilled	1.52 Ab	7.52 Ac	390.66 Ab	31,471.10 Aa	249.76 Aa	219.97 Aa	41.44 Aa
	Low Straw	1.58 Aab	7.97 Ab	545.89 Aa	25,781.50 Bc	192.42 Bb	169.12 Bb	40.77 Aab
	High Straw	1.56 Ab	8.09 Aab	500.64 Aab	28,148.51 ABb	201.82 ABb	175.17 Ab	37.18 Ab
	Grass	2.29 Aa	8.16 Aa	377.22 Bb	27,588.51 Ab	211.23 Ab	174.72 Ab	32.26 Bb
Autumn	Tilled	1.59 Ab	7.50 Ac	515.45 Aab	28,293.22 Ba	218.40 Ba	193.06 Ba	44.38 Aa
	Low Straw	1.64 Aab	7.87 Ab	533.79 Aa	27,647.20 Aa	224.90 Aa	183.90 Aa	40.32 Aab
	High Straw	1.73 Aab	8.00 Aab	392.22 Ab	28,429.18 Aa	224.67 Aa	183.90 Aa	33.82 Ab
	Grass	2.51 Aa	8.13 Aa	376.54 Bb	27,327.78 Aa	219.30 Aa	180.32 Aa	34.50 Bb

Potassium values in the Tilled treatment group were significantly higher in summer (31,471.10 kg ha^{-1}) than in spring (27,297.09 kg ha^{-1}) and autumn (28,293.22 kg ha^{-1}). For the Low Straw treatment group, lower K values were recorded in spring (26,282.59 kg ha^{-1}) and summer (25,781.50 kg ha^{-1}) than in autumn (27,647.20 kg ha^{-1}). For the High Straw treatment group, significantly higher K values were observed in autumn (28,429.18 kg ha^{-1}) than in spring (26,460.90 kg ha^{-1}), while the value in summer (28,148.51 kg ha^{-1}) was not statistically different from those recorded in spring or autumn. For Grass treatment, there were no significant differences in soil K concentrations between seasons, with a minimum of 27,149.47 kg ha^{-1} in spring, 27,327.78 kg ha^{-1} in autumn and a maximum of 27,588.51 kg ha^{-1} in summer. There were no significant differences in soil K values between the treatments in spring and autumn, while in summer, the values were significantly lower for Low Straw, High Straw and Grass treatments compared with Tilled treatment (Table 2).

Soil Ni values differed significantly based on treatment and season. Significantly higher Ni values were recorded for the Tilled treatment in summer (249.76 kg ha^{-1}) compared with spring (210.78 kg ha^{-1}) and autumn (218.40 kg ha^{-1}). Significantly higher Ni values were observed for the Low Straw treatment in autumn (224.90 kg ha^{-1}) than in summer (192.42 kg ha^{-1}), but there were no significant differences between spring (206.08 kg ha^{-1}) and the other two seasons. Significantly lower Ni values were recorded for the High Straw treatment group in spring (200.48 kg ha^{-1}) than in autumn (224.67 kg ha^{-1}), but the value in summer (201.82 kg ha^{-1}) was not statistically different from those of the other seasons. There were no statistical differences in soil Ni values in the Grass treatment group in all seasons, with a minimum of 209.22 kg ha^{-1} in spring, 211.23 kg ha^{-1} in summer and a maximum of 219.30 kg ha^{-1} in autumn. Significantly higher Ni values were observed in the Tilled treatment group in summer, while no differences were observed in spring and autumn (Table 2).

Zinc values differed significantly based on treatment and season. Significantly lower Zn values were recorded for the Tilled treatment group in spring (184.80 kg ha^{-1}) and autumn (193.06 kg ha^{-1}) compared with summer (219.97 kg ha^{-1}). Significantly higher Zn values were recorded for the Low Straw treatment group in autumn (183.90 kg ha^{-1}) compared with summer (169.12 kg ha^{-1}), while the value did not differ statistically from other treatments in spring (180.54 kg ha^{-1}). There were no significant differences in Zn values in the High Straw treatment group across seasons, with a minimum of 175.17 kg ha^{-1} in summer, 183.90 kg ha^{-1} in autumn and a maximum of 184.58 kg ha^{-1} in spring. The same pattern was observed for Grass treatment, with lower values recorded in summer (174.72 kg ha^{-1}) and autumn (180.32 kg ha^{-1}) and higher Zn values recorded in spring (183.90 kg ha^{-1}).

Soil Pb values showed significant differences based on treatment and season. There were no significant differences in soil Pb in the Tilled treatment group through the seasons, with a minimum of 41.44 kg ha^{-1} in summer and a maximum of 43.68 kg ha^{-1} in spring and 44.38 kg ha^{-1} in autumn. The same pattern was observed in the Low Straw and High Straw treatment groups, as presented in Table 2. Significantly higher Pb values were recorded for Grass treatment in spring (42.34 kg ha^{-1}) compared with summer (32.26 kg ha^{-1}) and autumn (34.50 kg ha^{-1}). No significant differences between treatments were observed in spring. Significantly higher values were recorded in summer in the Tilled treatment group compared with the High Straw and Grass treatment groups, but the Pb value for the Low Straw treatment group was not significantly different from the Pb values for the other three treatment groups; the same pattern was observed in autumn (Table 2).

3.3. Hydrological Response

Statistical analysis of the hydrological response showed significant differences based on treatment and season (Table 3). Significantly higher values of time to ponding were recorded for Tilled treatment in spring (1326 s) compared with autumn (75.5 s), while the value recorded in summer (444 s) was not statistically different from the values recorded in the other two seasons. Significantly higher TP values were also recorded in the Low Straw treatment group in spring (1800 s) compared with autumn (96.5 s), while the value recorded in summer (1326 s) was not statistically different from the values recorded in spring and autumn. Significantly lower TP values were recorded in the High Straw treatment group in autumn (149 s) compared with spring (1800 s) and summer (1800 s). No significant differences were observed in the Grass treatment group across seasons, with a minimum of 49.5 s in spring and a maximum of 372 s in summer and 108.5 s in autumn. Regarding the differences between treatments by season, differences in TP were noted only in spring, with significantly lower values in the Grass treatment group compared with the other treatment groups. There were no significant differences in TP values between treatments in summer and autumn.

Time to runoff was significantly different in the Tilled treatment group, with higher values recorded in spring (1800 s) than in autumn (294 s), while the value recorded in summer (1164 s) was not significantly different from the values recorded in the other two seasons. Significantly lower TR values were recorded in the Low Straw treatment group in autumn (444 s) than in spring (1800 s) and summer (1800 s). No significant differences in TR were recorded between seasons in the High Straw treatment group since the value was the same in each season (1800 s). The same pattern was observed for Grass treatment, with TR values ranging from a minimum of 453 s and 460 s in autumn and spring to a maximum of 1416 s in summer. Significantly higher TR values were recorded for Tilled, Low Straw and High Straw treatments compared with Grass treatment in spring; there were no significant differences between treatments in summer, while significantly higher values were recorded for High Straw treatment compared with the other treatments in autumn (Table 3).

Regarding runoff, Tilled treatment resulted in significantly lower values in spring (0.00 m^3 ha^{-1}) than in summer (7.11 m^3 ha^{-1}), while the runoff value recorded in autumn (3.40 m^3 ha^{-1}) was not significantly different from the values recorded in spring and summer. Significantly higher runoff values were recorded for the Low Straw treatment in autumn (6.17 m^3 ha^{-1}) compared with spring (0.00 m^3 ha^{-1}) and summer (0.00 m^3 ha^{-1}). No significant differences in runoff were observed for High Straw treatment across seasons, with a value of 0.00 m^3 ha^{-1} for every season. Significantly lower runoff values were observed with Grass treatment in summer (1.20 m^3 ha^{-1}) compared with autumn (6.53 m^3 ha^{-1}), while the value in spring (4.48 m^3 ha^{-1}) was not statistically different from the values recorded in the other two seasons. Significantly lower values were recorded for Tilled, Low Straw and High Straw treatments compared with Grass treatment in spring. Significantly lower runoff values were recorded for Low Straw and High Straw treatments compared with Tilled treatment in summer, while the value recorded in the Grass treatment group was not statistically different from the values recorded in the other three treatment groups. Significantly lower runoff values were reported for High Straw treatment compared with Grass treatment in autumn, while there were no significant differences between Tilled and Low Straw treatments and High Straw and Grass treatments.

Table 3. Results of two-way ANOVA based on overland flow properties. Different letters after mean values in columns indicate significant differences at $p < 0.05$. Capital letters indicate statistical differences between treatments; lowercase letters indicate statistical differences between seasons. TP, time to ponding; TR, time to runoff; SC, sediment concentration; SL, sediment loss.

Season	Treatment	TP (s)	TR (s)	Runoff (m^3 ha^{-1})	SC (g kg^{-1})	SL (kg ha^{-1})
Spring	Tilled	1326 Aa	1800 Aa	0.00 Bb	0.00 Ba	0.00 Ba
	Low Straw	1800 Aa	1800 Aa	0.00 Bb	0.00 Ba	0.00 Ba
	High Straw	1800 Aa	1800 Aa	0.00 Ab	0.00 Aa	0.00 Aa
	Grass	49.5 Ab	460 Ab	4.48 ABa	1.31 Aa	6.15 Aa
Summer	Tilled	444 ABa	1164 ABa	7.11 Aa	18.19 Aa	138.34 Aa
	Low Straw	1326 ABa	1800 Aa	0.00 Bb	0.00 Bb	0.00 Bb
	High Straw	1800 Aa	1800 Aa	0.00 Ab	0.00 Ab	0.00 Ab
	Grass	372 Aa	1416 Aa	1.20 Bab	3.85 Aab	14.05 Ab
Autumn	Tilled	75.5 Ba	294 Bb	3.40 ABab	15.03 Aa	50.99 Aa
	Low Straw	96.5 Ba	444 Bb	6.17 Aab	6.59 Aa	41.49 Aab
	High Straw	149 Ba	1800 Aa	0.00 Ab	0.00 Ab	0.00 Ac
	Grass	108.5 Aa	453 Ab	6.53 Aa	3.94 Aa	25.91 Ab

Sediment concentrations showed significant differences between treatments and seasons. Significantly lower SC values were observed in the Tilled treatment group in spring (0.00 g kg^{-1}) compared with summer (18.19 g kg^{-1}) and autumn (15.03 g kg^{-1}). Similar observations were made for Low Straw treatment, with significantly higher values recorded in autumn (6.59 g kg^{-1}) than in spring (0.00 g kg^{-1}) and summer (0.00 g kg^{-1}). There were no significant differences between seasons in the High Straw treatment group, with an SC value of 0.00 g kg^{-1} in all seasons. Significantly higher SC values were recorded for Grass treatment in autumn (3.94 g kg^{-1}) than in spring (1.31 g kg^{-1}), while the value recorded in summer (3.85 g kg^{-1}) was not statistically different from the values recorded in the other treatment groups. Significantly higher SC values were recorded for Grass treatment than compared with the other treatments in spring, while significantly lower values were recorded for Low Straw and High Straw treatments compared with Tilled treatment; the value recorded in the Grass treatment group was not statistically different from the values recorded in the other treatments. Significantly lower SC values were observed in autumn in the High Straw treatment group compared with the other treatment groups (Table 3).

Sediment loss differed significantly between treatments and seasons. Significantly lower SL values were noted in Tilled treatment in spring (0.00 kg ha^{-1}) compared with summer (138.34 kg ha^{-1}) and autumn (50.99 kg ha^{-1}); the same pattern was observed in the Low Straw treatment group (Table 3). No SL was reported for High Straw treatment; thus, no significant differences were noted between seasons. There were also no significant differences in Grass treatment between seasons, with a minimum of 6.15 kg ha^{-1} in spring, 14.05 kg ha^{-1} in summer and a maximum of 25.91 kg ha^{-1} in autumn. There were no significant differences in SL between all treatments in spring, while SL values were significantly lower in Low Straw, High Straw and Grass treatment groups compared with the Tilled treatment group in summer. Finally, significantly higher SL values were recorded for Tilled treatment in autumn compared with High Straw and Grass treatments, while the SL value in the Low Straw treatment group was not significantly different from SL values in the Tilled and Grass treatment groups (Table 3).

3.4. Element Losses

Statistical analysis revealed noteworthy disparities in element losses across treatments and seasons (Table 4). A significant reduction in P losses was found for Tilled treatment during spring (0.00 g ha^{-1}) compared with substantial losses recorded in autumn (2353.07 g ha^{-1}). However, there was a statistically significant difference in P losses between treatments in summer (1127.66 g ha^{-1}). In contrast, significantly higher P losses were noted in the Low Straw treatment group in autumn (1041.62 g ha^{-1}) compared with negligible losses in spring and summer. Surprisingly, no P losses were observed in the High Straw treatment group throughout the seasons. Consistent P losses were noted in Grass treatment across all seasons, with no statistically significant differences. Notably, there were significantly higher P losses in Grass treatment compared with the other treatments in spring. There were significantly lower P losses in the Low Straw and High Straw treatment groups compared with the Tilled treatment group in summer, while the value recorded in the Grass treatment group did not differ significantly from the values recorded in the other three treatment groups. Moreover, Tilled treatment resulted in significantly higher P losses in autumn compared with High Straw treatment, while no significant differences were observed between Low Straw and Grass treatments and the other two treatments.

Table 4. Results of two-way ANOVA based on element losses. Different letters after mean values in columns indicate significant differences at $p < 0.05$. Capital letters indicate statistical differences between treatments; lowercase letters indicate statistical differences between seasons. P, phosphorous; K, potassium; Ni, nickel; Zn, zinc; Pb, lead. All data are given in g ha^{-1}.

Season	Treatment	P Loss	K Loss	Ni Loss	Zn Loss	Pb Loss
Spring	Tilled	0.00 Bb	0.00 Bb	0.00 Bb	0.00 Bb	0.00 Bb
	Low Straw	0.00 Bb	0.00 Bb	0.00 Bb	0.00 Bb	0.00 Bb
	High Straw	0.00 Ab	0.00 Ab	0.00 Ab	0.00 Ab	0.00 Ab
	Grass	397.27 Aa	19,999.94 Aa	150.64 Aa	234.37 Aa	23.47 Aa
Summer	Tilled	1127.66 ABa	55,044.90 ABa	394.76 ABa	452.67 ABa	64.00 ABa
	Low Straw	0.00 Bb	0.00 Bb	0.00 Bb	0.00 Bb	0.00 Bb
	High Straw	0.00 Ab	0.00 Ab	0.00 Ab	0.00 Ab	0.00 Ab
	Grass	180.89 Aab	9106.56 Aab	68.59 Aab	106.72 Aab	10.69 Aab
Autumn	Tilled	2353.07 Aa	115,627.66 Aa	888.93 Aa	1010.08 Aa	131.63 Aa
	Low Straw	1041.62 Aab	45,436.13 Aab	0.00 Ab	488.99 Aab	37.37 Aab
	High Straw	0.00 Ab	0.00 Ab	0.00 Ab	0.00 Ab	0.00 Ab
	Grass	465.50 Aab	22,227.22 Aab	170.33 Aab	264.71 Aab	25.59 Aab

Regarding K losses, a significant reduction in K was found in the Tilled treatment group in spring (0.00 g ha^{-1}) compared with substantial losses in autumn (115,627.66 g ha^{-1}) and no statistically significant difference in summer (55,044.90 g ha^{-1}). Surprisingly, significantly higher K losses were recorded in the Low Straw treatment group in autumn (45,436.13 g ha^{-1}) compared with negligible losses in spring and summer. Conversely, no significant variations in K losses were observed in the High Straw treatment group across seasons, as no losses were recorded. Notably, consistent K losses were found for Grass treatment across all seasons, with no statistically significant differences. However, significantly higher K losses were found for Grass treatment in spring compared with the other treatments. In summer, significantly lower K losses were recorded in the Low Straw and High Straw treatment groups compared with the Tilled treatment group, while the value recorded in the Grass treatment group did not differ significantly from the values recorded in the other three treatment groups. Additionally, in autumn, Tilled treatment resulted in significantly higher K losses compared with High Straw treatment, while no significant differences were found between Low Straw and Grass treatments and the other two treatments.

Analysis of Ni losses indicated significant differences between seasons for the Tilled treatment. Significantly lower Ni losses were recorded in the Tilled treatment group in spring (0.00 g ha^{-1}) compared with substantial losses in autumn (888.93 g ha^{-1}) and no statistically significant differences in summer (394.76 g ha^{-1}). Intriguingly, significantly higher Ni losses were observed in the Low Straw treatment group in autumn (408.56 g ha^{-1}) compared with negligible losses in spring and summer. Conversely, significant seasonal variations in Ni losses were not reported for High Straw treatment, as no losses were recorded. Notably, Grass treatment showed consistent Ni losses across all seasons, with no statistically significant differences. However, Grass had significantly higher Ni losses in spring compared with the other treatments. In summer, Low Straw and High Straw treatments showed significantly lower Ni losses compared with Tilled treatment, while Grass treatment did not show significantly different values compared with the other three treatments. Furthermore, Tilled treatment resulted in significantly higher Ni losses in autumn compared with High Straw treatment, while no significant differences were observed between Low Straw and Grass treatments and the other two treatments.

In terms of Zn losses, there was a significant reduction in the Tilled treatment group in spring (0.00 g ha^{-1}) compared with considerable losses in autumn (1010.08 g ha^{-1}) and no statistically significant differences in summer (452.67 g ha^{-1}). Surprisingly, significantly higher Zn losses were found in the Low Straw treatment group in autumn (488.99 g ha^{-1}) compared with negligible losses in spring and summer. Conversely, significant seasonal variations in Zn losses were not observed in the High Straw treatment group, as no losses were recorded. Notably, consistent Zn losses were observed for Grass treatment across all seasons, with no statistically significant differences. However, significantly higher Zn losses were observed for Grass treatment in spring compared with the other treatments. In summer, significantly lower Zn losses were recorded for Low Straw and High Straw treatments compared with Tilled treatment, while the value recorded for Grass treatment did not differ significantly from the values recorded for the other three treatments. Additionally, in autumn, Tilled treatment resulted in significantly higher Zn losses compared with High Straw treatment, while no significant differences were observed between Low Straw and Grass treatments and the other two treatments.

Regarding Pb losses, significantly lower losses were found for Tilled treatment in spring (0.00 g ha^{-1}) compared with autumn (131.63 g ha^{-1}), with no statistically significant difference in summer (64.00 g ha^{-1}). Significantly higher Pb losses were observed for Low Straw treatment in autumn (37.37 g ha^{-1}) compared with negligible losses in spring and summer. Conversely, no significant seasonal variations in Pb losses were noted in the High Straw treatment group, as no losses were recorded. Notably, consistent Pb losses were recorded in the Grass treatment group across all seasons, with no statistically significant differences. However, significantly higher Pb losses were recorded in the Grass treatment group in spring compared with the other treatment groups. In summer, significantly lower Pb losses were found in the Low Straw and High Straw treatment groups compared with the Tilled treatment group, while the value recorded in the Grass treatment group did not differ significantly from the values recorded in the other three treatment groups. Moreover, in autumn, Tilled treatment resulted in significantly higher Pb losses compared with High Straw treatment, while no significant differences were observed between Low Straw and Grass treatments and the other two treatments.

3.5. Principal Component Analysis

Principal component analysis identified four factors that explained at least one variable. Factor 1 explained 51.46%, factor 2 explained 14.47%, factor 3 explained 8.24% and factor 4 explained 6.00% of the total variance (80.18% in total). Factor 1 explained most of the variables and their correlations; TP and TR had a positive loading relationship with each other; while runoff, SC and SL had a strong positive impact on the loss of all elements (P, K, Ni, Zn, Pb). In factor 2, soil pH had a strong negative correlation with soil Zn and Pb concentrations, and a strong correlation was noted between WSA and SOM. Factor 3 revealed a negative correlation between soil P and Ni, and factor 4 revealed a negative correlation between BD and SWC. The correlation between factors 1 and 2 are presented in Figure 3A,B, while the correlations between seasons and treatments are presented in Figure 3C.

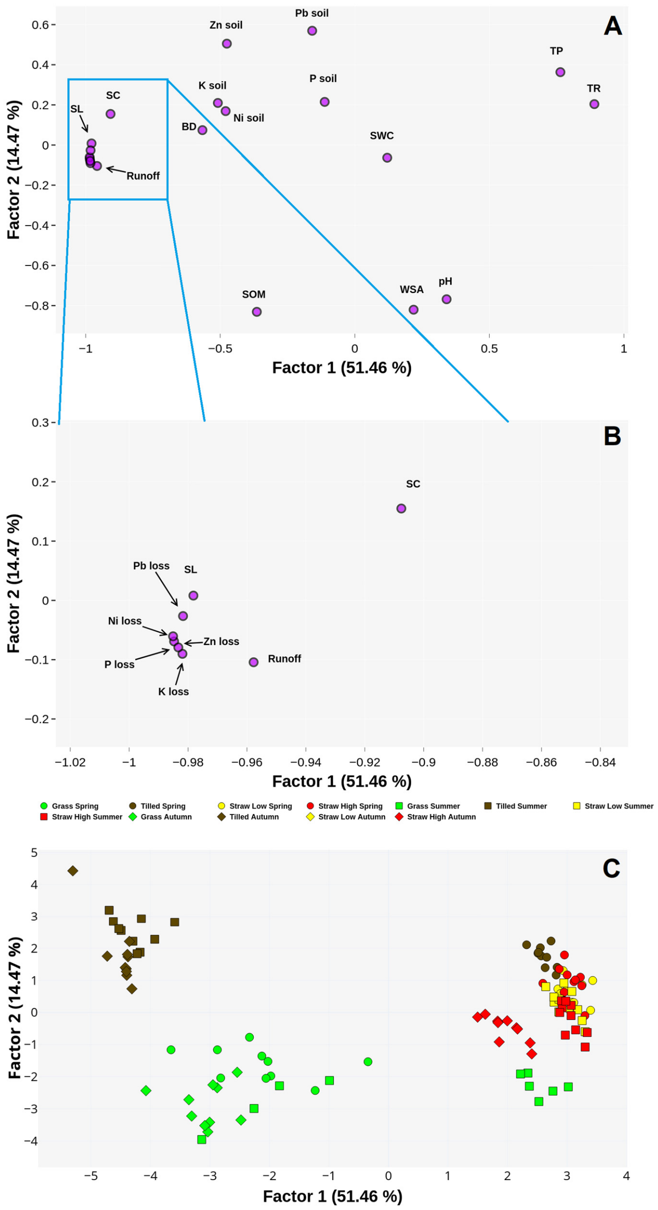

Figure 3. (**A**) Correlation between factors 1 and 2 (variables). BD, bulk density; SWC, soil water content; WSA, water-stable aggregates; SOM, soil organic matter; TP, time to ponding; TR, time to runoff; SC, sediment concentration; SL, sediment loss; P, phosphorous; K, potassium; Ni, nickel; Zn, zinc; Pb, lead. (**B**) Enlarged area, (**C**) Correlation between cases.

4. Discussion

Bulk density was higher in the Tilled, Low Straw and High Straw treatment groups in autumn compared with summer and spring, while the values in the Grass treatment group did not differ between seasons. Lower BD values in spring can be explained by (1) lower machinery traffic during that time of year, (2) freeze–thaw cycles that occurred in the previous winter [65] or (3) channels created by a growing and expanding grass root system, effectively loosening the soil and increasing pore spaces [66]. No differences were observed between treatments in spring. Higher values were noted with Tilled treatment in summer and autumn; this trend is expected since tillage is a well-known contributor to increased BD [67], and larger aboveground mass (such as in High Straw and Grass treatments) serves as a physical barrier between the soil surface and external forces, helping to disperse raindrop energy and reduce their impact on the soil, thus minimizing compaction [68].

Lower SWC values were recorded for Tilled and Grass treatments. Tillage instantly alters the soil air-to-water ratio and increases the soil's water infiltration capability [69], while grass favours soil structure via SOM accumulation, which directly improves the soil air-to-water ratio [70,71]. This is the main reason why WAS was significantly lower in all seasons in the Tilled treatment group, as noted in other studies [72,73]. Grass treatment had the highest WSA due to higher SOM content and grass mowing residue that is left on the soil surface to decompose [74]. This ensures aggregate stability during heavy rainfall [75].

Certain changes in SOM occurred between treatments and seasons. Higher amounts of SOM were found in the High Straw treatment group in autumn compared with spring and summer; this happened for two main reasons: (1) putting organic matter on the soil surface (twice as much as with Low Straw treatment) helped reduce the evaporation of water from the soil surface and increased soil temperature, thus creating favourable conditions for microbial activity and organic matter decomposition [76–78], and (2) reduced erosion left the soil intact, which allowed organic matter to accumulate and contribute to the soil's overall organic content [79,80]. Higher SOM was recorded in the Grass treatment group in all seasons; this was expected due to (1) the absence of annual soil disturbance [81], (2) the decomposition of larger amounts of mowed grass [82] and (3) the richness of organic compounds in grass root exudates [83].

The only differences in soil pH were noted between treatments based on season. In spring, the values were lower in Tilled and Low Straw treatment groups compared with the other treatment groups. The same pattern was observed in summer and autumn. This can be explained by (1) seasonal fluctuations and geomorphological characteristics of the investigated area [84,85] and (2) mineralization in the Tilled treatment, which causes faster decomposition and mineralization, releasing organic acids and other acidic compounds and causing soil acidification [86].

Soil P content did not differ between seasons in the Tilled and High Straw treatment groups; however, higher values were recorded in the Low Straw treatment group in summer and autumn and higher values were noted in the Grass treatment group in spring. Grass is well known for accumulating higher amounts of P on the soil surface and upper soil layer [87,88]. Higher P concentrations were recorded in the Low Straw treatment group in summer and autumn compared with the other treatment groups. This occurred due to (1) higher amounts of pesticide residues that collected on the ingrown grass under this treatment (which was mowed regularly), (2) organic fertilizer input and (3) decomposition of straw residue and ingrown grass, which released organic compounds (including P) in the soil [89,90]. Lower values in the Tilled treatment group were due to erosion events that occurred between seasons when P bound to soil particles and were then translocated to the lower parts, as noted in other studies [91,92].

There were no differences in soil K concentrations between treatment groups in spring and autumn; however, in summer, lower concentrations were noted in treatments with surface cover, very likely due to the uptake of potassium by vines, grass and weeds [93]. For treatments with surface cover (grass and mulch), no significant differences in soil Ni and Zn concentrations were recorded in the Tilled treatment group in spring and autumn; in summer, these values were significantly lower in the other treatment groups. This may be due to several reasons: (1) periodic vegetation consumption, (2) lower ability to incorporate previously applied fertilizers and (3) larger amounts of compounds absorbed from burning fossil fuel and residual oils from tractor traffic in the Tilled treatment group [94]. Further on, these changes occur because of sediment loss due to soil erosion, as reported in other studies. For example, Mirás-Avalos et al. [95] found that Zn losses were high, up to 30,000 g ha^{-1}, while Jiao et al. [96] recorded lower Ni losses, averaging 21.27 g ha^{-1}. Additionally, Dugan et al. [62] recorded Zn and Ni losses ranging from 360 and 200 g ha^{-1} in spring to 900 and 470 g ha^{-1} in autumn in the tilled treatment group. Finally, for treatments with the most surface cover (Grass and High Straw), significantly lower values of Pb were recorded in summer and autumn, while no differences were recorded between the treatments in summer. These values reflect constant tractor traffic and soil overuse [97,98].

Season and treatment had strong effects on overland flow properties, as presented in Table 3. In every season, time to ponding and TR were longer with High Straw treatment followed by Low Straw treatment. For Grass treatment, the shortest TP and TR were recorded in spring and summer; however, lower values were observed in the Tilled treatment group in autumn due to lower vegetation cover and higher BD in the later seasons. There were no differences between treatments in summer, while in spring, higher values were recorded for Tilled, Low Straw and High Straw treatments. This occurred due to straw application and surface roughness due to tillage intervention, which had a great effect on reducing BD, while surface cover served as a barrier between the impact of raindrops and the soil surface [99,100], thus postponing TP and TR. There were no differences in TP between treatments in autumn, but significantly higher TR values were found in the High Straw treatment group compared with the other treatment groups.

In the Tilled treatment group, runoff values were significantly lower in spring than in summer and autumn. While there were no differences in runoff between High Straw and Low Straw treatment groups in spring and summer, High Straw treatment completely mitigated runoff later in the season, meaning that applying less straw was not enough to successfully mitigate soil erosion. There was no runoff in the Tilled, High Straw and Low Straw treatment groups in spring due to (1) surface roughness on the freshly tilled ground and (2) application of straw mulch on previously tilled surfaces. There was higher runoff with Grass treatment in autumn than in spring, while the values did not statistically differ between summer and the other seasons. Lower runoff rates in summer can be explained by (1) higher vegetation cover [101], (2) soil cracking, which alters the overland flow [102], and (3) higher evaporation, enabling the soil to absorb more water, thus reducing the overland flow [103]. Low runoff rates in the straw mulch treatment groups are a consequence not only of surface cover but also of higher SOM content [104,105] and higher WSA [106]. Sediment concentrations and SL are strongly dependent on the previously mentioned soil properties [107,108]. For instance, recorded SC and SL values in the Tilled treatment group were higher in summer than in autumn, up to 121% and 271%. Due to the application of more straw, High Straw treatment successfully mitigated SL, as the straw improved the soil's physical properties, as confirmed by other studies [109–111], making the soil more resilient to raindrop-induced degradation [26]. Besides High Straw treatment, there are better conservation possibilities for Low Straw and Grass treatments than Tilled treatment. Cover on topsoil and enhanced SOM and physical status intercept raindrops, thus reducing SL and SC.

The loss of soil elements in our study was highly correlated with SL [112]. As stated before, there were higher element losses with Tilled treatment, proving that tillage has a negative impact on soil properties and the environment [113–115]. While there were element losses in the Grass treatment group only in spring, P losses in summer were 622% lower for Grass than for Tilled treatment. Higher element losses were recorded for Grass treatment in autumn than in spring and summer, which is a consequence of a lower percentage of surface vegetation cover [116,117] and higher BD [118] in that period. It is important to mention that higher losses in the Tilled treatment group were also associated with SOM loss [119] due to a strong connection between elements and SOM. Furthermore, the concentrations of elements such as P, Cu and Zn are higher on the soil surface, such as in grass treatment, where the elements decompose and bind to the surface cover as a result of repeated management [120].

Principal component analysis revealed that different soil management techniques alter soil physiochemical properties, hydrological response and element transport. Factor 1 showed a positive correlation between TP and TR. Additionally, strong correlations were found between runoff, SC and SL and P, K, Ni, Zn and Pb loss. Higher runoff increases sediment and element translocation since the elements are bound to soil particles and surface cover residues that can be easily transferred when they move into water flows. Similar findings were reported in [62,121–123]. The adsorption of certain elements, such as phosphorus, to clay-sized particles in surface runoff can contribute to eutrophication in the receiving water bodies [124]. Factor 2 showed a strong correlation between WSA and SOM, as stated in many previous studies [125–130]. Rain disrupts soil aggregates via (1) slaking, (2) differential swelling of clay, (3) mechanical dispersion and (4) physiochemical dispersion. SOM is assumed to stabilize soil aggregates by increasing the cohesion of aggregates through the binding of mineral particles by organic polymers but can also decrease the wettability of aggregates by slowing their wetting rate and thus the extent of slaking [131–133].

Strong negative correlations were observed between soil pH and soil Zn and Pb concentrations. Soil pH has a strong effect on Zn and Pb availability and solubility, hence acidic soils have higher Zn and Pb concentrations; On the other hand, under alkaline or basic conditions, Zn and Pb may become less soluble and available [134–136]. In factor 3, a negative correlation was observed between soil P and Ni; even though they have no direct effect on each other, higher P concentrations can affect soil pH due to the buffering capacity of phosphates [137], which increases soil pH, thus potentially affecting Ni behaviour by influencing its solubility and availability [136,138]. Finally, factor 4 showed a negative correlation between BD and SWC. High BD indicates compacted soil, which can negatively affect SWC since compacted soils have reduced pore space, thus limiting water infiltration and movement. This leads to decreased porosity and increased density, which restrict water retention and drainage [139]. It is also important to mention that the correlation between BD and SWC is not linear and can be influenced by many other factors, including SOM, clay content and soil structure.

Even though the research results are clear and precise, certain shortcomings should be highlighted. This research was carried out for only one year, which is not long enough to provide a full assessment of soil erosion rates. This was a short-term study, as the rainfall simulation experiments were conducted for 30 min, which may not fully capture long-term effects or seasonal variations. It is important to mention the lack of long-term implications because this study focused on the immediate effects and short-term implications of different soil management practices, thus it would be valuable to investigate the long-term effects of straw mulch application on soil erosion control, soil fertility and overall vineyard sustainability. Additionally, the rainfall simulator has limitations. For instance, the methods and equipment are not standardized. Furthermore, the plots were rather small, thus the data collected are not suitable for large-scale modelling. It is important to point out that straw mulch is a natural product that enhances soil functions in the long term and has an immediate effect on soil and water loss. Straw mulch also allows higher water availability for plants due to higher infiltration, as explained in [140]. Furthermore, straw is a natural byproduct of grain harvesting and as such is affordable and available for farmers, who can start employing sustainable management on their permanent plantations. An even more important advantage of straw mulch used in intensively managed vineyards is that pesticide residues do not land on the grass or bare soil surface, thus reducing the chances of potential phytotoxicity. Finally, in terms of soil erosion, straw mulch ensures the conservation of SOM and maintains all elements in their locations, preventing them from transferring to lower slope locations where they can increase mass water pollution.

5. Conclusions

The results presented in this research show that soil management has a significant impact on soil erosion and several soil properties in different seasons. For Tilled treatment, there were slight reductions in SOM and WSA but increased runoff, SC, SL and element transfer. Grass treatment significantly lowered BD, TP and TR but mitigated runoff and diffused pollution. Additionally, mulch treatments were a good substitute for grass-covered treatment, particularly the double dose of straw, as there was no runoff in all three investigated seasons. It successfully increased SOM and WSA but completely stopped soil loss and element transfer. Furthermore, there were considerable differences between seasons in all treatment groups, mainly in terms of overland flow; runoff, SC and SL were higher in autumn, while TP and TR were higher in spring. Conventional agricultural systems in intensively managed vineyards are detrimental and dangerous for the environment due to soil and water pollution and degradation. Straw application is a cost-effective and sustainable practice for minimizing the negative impact of conventional tillage.

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