sustainability

MDPI

Article

Tillage System as a Practice Affecting the Quality of Soils and Its Sustainable Management

Joanna Lemanowicz [1], Erika Balontayová [2], Bożena Dębska [1,*], Agata Bartkowiak [1] and Piotr Wasilewski [3]

[1] Department of Biogeochemistry, Soil Science and Irrigation and Drainage, Bydgoszcz University of Science and Technology in Bydgoszcz, 6/8 Bernardyńska Street, 85-029 Bydgoszcz, Poland; joanna.lemanowicz@pbs.edu.pl (J.L.); agata.bartkowiak@pbs.edu.pl (A.B.)
[2] Institute of Agronomic Sciences, Slovak University of Agriculture in Nitra, Tr. A. Hlinku 2 St., 949 76 Nitra, Slovakia
[3] Department of Agronomy and Food Processing, Bydgoszcz University of Science and Technology in Bydgoszcz, 7 Prof. S. Kaliskiego Street, 85-796 Bydgoszcz, Poland; piotr.wasilewski@pbs.edu.pl
* Correspondence: bozena.debska@pbs.edu.pl

Abstract: Sustainable soil management through the use of an appropriate tillage system can positively change the edaphic parameters. The aim of the present study was to compare the effects that reduced tillage (RT) and conventional tillage (CT) systems have on changes in selected physical and chemical properties and enzymatic activity in various soil types. The study included the following soil types: *Eutric Fluvisol*, *Mollic Fluvisol*, *Haplic Chernozem*, *Haplic Luvisol*, *Eutric Regosol*, *Eutric Gleysol*, and *Stagnic Planosol*. Soil samples were collected in the Danubian Lowland and Eastern Slovak Lowland. The following parameters were determined in the soil samples: soil texture, pH, hydrolytic acidity and the sum of basic exchangeable cations, the contents of carbon (TOC), nitrogen (TN), and dissolved organic carbon (DOC), and the activities of dehydrogenases (DEH), catalase (CAT), peroxidases (PER), alkaline phosphatase (AlP), acid phosphatase (AcP), proteases, and β-glucosidase (BG). The reaction of the analysed soils, in the RT and CT cultivations alike, ranged from acidic to neutral, and the sorption properties differed between individual soil types. The TOC ranged from 16.53 to 42.07 g kg^{-1} for conventional cultivation and from 15.51 to 38.90 g kg^{-1} for reduced tillage. The values of enzymatic soil quality indices values correlated with TOC, DOC, and TN, as well as with pH, the sum of exchangeable base cations, cation exchange capacity, and degree of base saturation of the sorption complex. The tillage system determined changes in the activity of the studied enzymes, but the intensity and direction of these changes depended on the soil type. Based on the enzyme activity results, soil quality indices such as GMea and TEI were calculated. TEI proved to be a more sensitive indicator than GMea. It was shown that, of all studied soil types and regardless of the cultivation system, *Eutric Gleyosols* had the most variable properties. For conventional tillage, Haplic *Luvisol* and *Eutric Regosol* were characterised by the greatest uniformity. In general, the edaphic properties of soils under conventional tillage differed from those of soils under simplified tillage.

Keywords: enzyme activity; organic matter; soil types; soil quality indicators; sorption properties

check for updates

Academic Editor: Eleftherios Evangelou

Received: 13 February 2025
Revised: 7 March 2025
Accepted: 18 March 2025
Published: 24 March 2025

Citation: Lemanowicz, J.; Balontayová, E.; Dębska, B.; Bartkowiak, A.; Wasilewski, P. Tillage System as a Practice Affecting the Quality of Soils and Its Sustainable Management. *Sustainability* **2025**, *17*, 2867. https://doi.org/10.3390/su17072867

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The production of food in sufficient quantities requires intensive agriculture. The cultivation practices used in intensive agriculture cause the deterioration of the physical,

chemical, and biological parameters of soils, thus increasing the rate of mineralisation of organic matter [1,2]. As follows from the main policy objectives of the European Union, the management of an agricultural production space should involve taking actions aimed at protecting soil organic matter and its biodiversity [3].

Agricultural practices can modify the soil environment and provide good conditions for the growth and development of crops. At the same time, they influence nutrient cycling and soil biological activity [4–6]. Therefore, there is a demand for agricultural systems that will not increase soil degradation, while still producing an adequate quantity of agricultural products [7]. A tillage system entails processes that change the edaphic parameters of soil [8,9]. Inappropriate agricultural practices degrade soil quality by, among other things, disturbing the circulation of elements, acidification, and reducing the level of biological activity, including enzymatic activity [10,11]. Excessive mineral fertilisation often brings about far-reaching changes in the soil sorption complex, which may have a negative impact on crop yields and quality [12]. Introducing various tillage systems may also bring about changes in soil pH. Agrotechnical treatments that help accelerate the mineralisation of organic matter and fertilisation with nitrogen fertilisers may decrease pH [13]. According to Aye et al. [14] and Debska et al. [15], long-term liming may lead to a reduction in the TOC content. However, the authors showed that TOC losses caused by liming can be compensated by introducing exogenous organic matter (EOM) into the soil. As reported by, among others, Mensik et al. [16], fertilisation with NPK alone causes a drop in the content and quality of OM (lower contents of TOC and humic substances, and dominance of FA over HA). Therefore, the goal of proper soil tillage is to develop optimal conditions for the growth and development of crops and, consequently, to increase yields.

In recent years, within the concept of sustainable agricultural development, "conservation tillage" has become more popular [17,18]. Conservation tillage excludes tillage operations that turn the soil and bury crop residues. It involves reducing the depth of tillage occasionally or constantly. It recommends using shallower tillage using other tools and/or reducing the intensity of seedbed preparation. Conservation tillage is a broad concept which includes operations such as no tillage, reduced tillage, minimum tillage, or mulching. Some researchers have emphasised that [19] leaving crop residues on the soil surface also reduces evaporation, improves infiltration, and inhibits weed growth. Debska et al. [15] drew attention to the beneficial effect of mulching on TOC content.

Depending on the method applied, tillage can positively or negatively affect soil properties, including soil organic matter [20]. Reduced tillage is probably the most researched agricultural practice [21]. A meta-analysis conducted by Allam et al. [22] has shown that a reduced tillage system using only organic fertilisation can increase the amount of legume grains. However, the combination of organic and inorganic fertilisation was shown to have a positive effect on increasing cereal crop yields. Abandoning plough tillage and introducing reduced tillage causes organic carbon and nutrients to accumulate in the topsoil [23]. According to Debska et al. [23], the use of ploughless tillage and strip-tilling significantly reduces the leaching of C and N from the surface layer to the 30–50-cm layer. As reported in other literature [24,25], reduced tillage has only a minor direct effect on carbon sequestration. Those authors drew attention to the impact of this tillage method by emphasising the need to select appropriate plants in a rotation and in the number of rotations. Han et al. [26], Yue et al. [27], and Armas-Herrera et al. [28] also emphasised the importance of organic fertilisation and post-harvest residues in shaping TOC resources in the soil. According to Balesdent et al. [11], the cessation of ploughing causes changes in soil functioning, i.e., in the availability of nutrients, biodiversity, or soil water-retention capacity. Those authors emphasised that modelling and forecasting TOC sources in soils

requires knowledge of the impact that various agricultural practices have in different soils and under different climatic conditions.

Szostek et al. [29] showed that simplifications in soil cultivation contribute to improving soil parameters and enzyme activity through the application of organic fertilisers and limiting the impact on the topsoil. Similarly, Blanco-Canqui and Ruis [30] found that improving soil structure and reducing soil compaction through less intense tillage prevent organic matter and essential macro- and microelements from being lost from a soil ecosystem. However, the reduction in cultivation intensity depends on both biotic and abiotic factors, such as soil type and texture, the tillage system used, and the hydro-thermal conditions [31]. According to Derpsch et al. [32], reducing or completely abandoning soil tillage is currently a popular approach to sustainable agriculture. As reported by Cenini et al. [33] and Rahmati et al. [34], extracellular enzymes produced by soil microorganisms catalyse chemical reactions associated with the decomposition of soil organic carbon. Therefore, an evaluation of soil enzymatic responses to tillage systems may suggest mechanisms for differences in carbon fraction characteristics.

According to Tobiašová et al. [35], each soil type has its own specific profile resulting from its genesis, the place where it is formed, and the method of soil management. Natural classifications divide soils according to genetic criteria, i.e., according to the way a given soil is formed and the soil-forming processes that create it. Soil type is the basic classification unit that categorises soils according to shared configurations of horizons through a soil profile. Soils of such types share similar physical, chemical, and biological properties, as well as a similar type of humus and degree of nutrient richness. According to the IUSS Working Group WRB, [36] soils of various groups differ not only in the structure of the soil profile but also in their properties. Many studies have shown that a soil's biological activity is determined primarily by its physicochemical properties [37]. It is important to understand how soils that differ in properties variously affect the soil parameters that are shaped by various tillage systems [35,38].

Based on the literature on the subject, it can be hypothesised that reduced tillage has a beneficial effect on endogenous soil parameters and increases carbon sequestration. The aim of our study was to assess how soil type determines the impact that two cultivation systems (reduced and conventional tillage) have on soil fertility by assessing:

- the contents of organic carbon, nitrogen, and soluble organic matter;
- sorption properties;
- the activities of selected enzymes involved in the biogeochemistry of C, N, and P in soil.

2. Materials and Methods

2.1. Materials

The localities included in the study are situated in the Danubian Lowland (Nové Zámky, Šaľa, Vráble, Piešťany) and Eastern Slovak Lowland (Trebišov, Michalovce, Sobrance). All fields represent real farms with their management systems, including tillage systems. The geological substrates of the lowlands are Neogene marine sediments clays, sands, and gravels, which are covered with loess and loess loam in some areas. Fluvial sediments are found along the Vah and Laborec rivers. The relief is monotonous, mostly wavy, and covered with loess and loess loam. In some places, Neogene rafts of clays, sands, or gravels are found above the surface [35]. The study areas are located in "slightly warm" to "warm" climatic regions. The average altitude is 100–160 m above sea level, with a range of average temperature of 9.0–10.5 °C and average annual rainfall of 565–610 mm [39].

The study included seven soil types, i.e., *Eutric Fluvisol*, *Mollic Fluvisol*, *Haplic Chernozem*, *Haplic Luvisol*, *Eutric Regosol*, *Eutric Gleysol*, and *Stagnic Planosol* [36], each in three repetitions (various crop rotations) of agricultural land in Slovakia. Soil samples were taken in spring 2023. Cereals were the main crops in all of the fields. The organic carbon balance, according to method Jurčová and Bielek [40] used for arable land in SR, fluctuated in a range of 7–16 t ha^{-1} for the last 8 years. Soil samples were collected from a depth of 0–30 cm under simplified tillage (only discing was used; RT) and conventional cultivation (CT). Detailed information on soil types is provided in Table 1

Table 1. Specifics of soil types in relation to their genesis and general properties.

EF *	Shallow humus horizon; huge heterogeneity of soil substrate; natural vegetation in flooded forests; higher underground water before water flow regulation; the composition of the microbial community is strongly influenced by anthropogenic cultivation; the initial process of organic carbon accumulation is dominant
MF	Deep humus horizon; specific hydromorphic regime; rich in a clay content and organic substances of high quality with dominance of humic acids; originally humus accumulation under hydrophilic vegetation with humification as a dominant process; high abundance and diversity of soil organisms
HC	Deep humus horizon with intensive humification; originally rich grass vegetation supported the creation and accumulation of humus substances of high quality; the presence of areas with a longer period of dryness results in the dominance of organisms that adapted to these conditions; ammonium can briefly release and nitrates can accumulate
HL	Shallow humus horizon mixed with genetic horizon in the arable land; strong risk of soil erosion; accumulation of clay in genetic illuvial luvic horizon with dominant process of illimerisation, which results in soil compaction and worse soil structure; biological activity is relatively high with dominance of bacteria
ER	Shallow humus horizon influenced by soil erosion; unsuitable textural composition, usually coarse soils; high aeration and dominance of non-capillary pores; small amount of organic sources for heterotrophic microbial community; high intensity of oxidation processes; risk of nutrient leaching
EG	Unsuitable textural composition with clay dominance; high level of underground water and poor aeration; reduction processes are dominant; accumulation of organic sources is high but with dominant production of low molecular substances and creation of fulvic acids; usually soils with a lower pH and unsuitable soil structure
SP	Soil of the areas with the accumulation of water with unsuitable hydromorphic regimes; frequent fluctuation of water level, changes in oxidation, and reduction conditions in the genetic horizon, mobilisation of Fe, Al, Mn; low diversity of microbial community; special hydrogenetic development of humus-forming process with FA dominance

* EF—Eutric Fluvisol; MF—Mollic Fluvisol; HC—Haplic Chernozem; HL—Haplic Luvisol; ER—Eutric Regosol; EG—Eutric Gleysol; SP—Stagnic Planosol.

2.2. Methods

2.2.1. Physicochemical Properties of Soil

The physical and chemical properties of the soil material were determined as follows:

- Soil texture was determined according to the pipette method [41]. Soil was treated to remove carbonates and organic matter. After dissolution of $CaCO_3$ with 2 M HCl dm^{-3} and oxidation of the organic carbon with 30% H_2O_2, there followed repeated washing, and, finally, the samples were dispersed using $Na(PO_3)_6$. Silt, sand, and clay fractions were determined. The fraction content is expressed in %.
- pH was determined in 1M KCl potentiometrically [42];
- Hydrolytic acidity (Hh) and total exchangeable base cations (TEB) were assessed by the Kappen method [43];

– Cation exchange capacity (CEC) was calculated based on TEB and Hh, and the degree of base saturation (BS) of the sorption complex was calculated from CEC and TEB.

2.2.2. Content of Organic Carbon, Total Nitrogen, and Dissolved Organic Matter

In the air-dried soil samples, the contents of total organic carbon (TOC) and total nitrogen (TN) were determined with a Vario Max CN analyser provided by Elementar (Langenselbold, Germany). In the soil samples, dissolved organic carbon (DOC) and dissolved nitrogen (DTN) were assayed in extracts of 0.004 M $CaCl_2$ (dissolved organic matter, DOM) using a Multi N/C 3100 analyser (Analytik Jena, Jena, Germany). The detailed DOM extraction method was described in a previous work Debska et al. [23].

2.2.3. Activity of Enzymes

The activities of oxidoreductive enzymes (dehydrogenases, catalase, and peroxidases) and hydrolytic enzymes (alkaline and acid phosphatase, β-glucosidase, and proteases) were measured on fresh-sieved (<2 mm) soils.

– The activity of dehydrogenases (DEH) was determined by the Thalmann [44] method after incubating the sample with 2,3,5-triphenyltetrazolium chloride and measuring the absorbance of triphenylformazan (TPF) at 546 nm; results are expressed in mg TPF kg^{-1} 24 h^{-1}.
– Catalase (CAT) was determined by the method of Johnson and Temple [45] using 0.3% hydrogen peroxide solution as the substrate. The remaining H_2O_2 was determined by titration with 0.02 M $KMnO_4$ under acidic conditions.
– The activity of peroxidases (PER) was determined by the method of Barth and Bordeleau [46] by measuring the amount of purpurogallin (PPG) formed by the oxidation of pyrogallol in the presence of H_2O_2.
– The activities of alkaline phosphatase (AlP) and acid phosphatase (AcP) were determined based on the detection of p-nitrophenol (pNP) released after incubation (37 °C, 1 h) at pH ~6.5 for acid phosphatase and pH ~11.0 for alkaline [47].
– β-glucosidase (BG) was measured by the method of Eivazi and Tabatabai [48], using p-nitrophenyl-β-D-glucopyranoside as a substrate. Concentrations of p-Nitrophenol were determined by direct reading of the sample at 400 nm after alkalisation with Tris/NaOH buffer (pH 10.0) and $CaCl_2$.
– The activity of proteases was determined using the method of Ladd and Butler [49], where the concentration of the amino acid tyrosine (Tyr) was determined in soil samples after incubation with sodium caseinate. Absorbance was measured with a spectrophotometer at λ = 680.

Based on the obtained enzyme activity results, enzymatic soil quality indices were calculated as follows:

– the geometric mean of enzyme activities (GMea) [50]:

$$GMea = \sqrt[7]{DEH \times CAT \times PER \times AlP \times AcP \times BG \times PRO} \quad (1)$$

– total enzyme activity index (TEI) [51]:

$$TEI = \sum \frac{Xi}{\overline{Xi}} \quad (2)$$

2.3. Statistical Analyses

The research results were statistically analysed in the Statistica software. The normality of distributions of observed features was verified using the Shapiro–Wilk normality test [52] and expressed as the arithmetic mean ±standard deviation (SD). The obtained data

were analysed using one-way ANOVA with the tillage system (reduced and conventional tillage) as the factor. Prior to the analysis of variance, in the distribution of each variable assuming hypothesis H0, the variables showing a normal distribution were investigated. The evaluation was made using the Shapiro–Wilk test. This test is based on the so-called studentised range, which makes it possible to group means and allows for comparisons of all possible pairs of groups in a way that controls the risk of making a type I error (falsely rejecting the null hypothesis). In the case that the tillage system was shown to have a statistically significant effect on the intensity of the study parameters, the mean values for tillage system were compared using the Tukey HSD test for $p = 0.05$ and, on this basis, homogeneous groups were designated and marked with the same letters in the tables below.

The paper also presents correlation coefficients between granulometric composition, pH, selected sorption properties, TOC and TN content, DOC and DTN content, and enzyme activity (DEH, CAT, PER, AlP, AcP, BG and PRO), which were calculated using the PAST 4.13 program [53]. A multivariate statistical data analysis also involved cluster analysis (CA). This analysis can include groups that share similar characteristics to one another and, at the same time, possess different from the elements from those in other groups. In a given group, the smaller the Euclidean distance, the more similar the objects. Data clustering was performed with the Ward method [54]. The analysis was performed after data standardisation.

3. Results and Discussion

3.1. Selected Physico-Chemical Properties

Granulometric composition analysis showed that all soil samples shared a similar granulometric composition. Among all soil fractions, the silt fraction dominated (Table 2). The reaction of the analysed soils under RT and CT tillage alike ranged from acidic to neutral (Table 2). The pH values of soils are mainly related to their mineralogical composition (the acidic or alkaline nature of parent rocks), transformations and content of organic matter, and climatic conditions that determine the leaching of components. However, based on studies [55], it was found that the method of cultivation significantly influences the physical and chemical condition of the soil environment. Among the many scientific studies devoted to changes in soil chemical properties affected by tillage, one may find results that indicate both increases and decreases in pH as a result of the introduction of various cultivation systems. However, it is most often assumed that soils in RT systems become slightly acidic [13,56,57]. In our own studies, a decrease in pH was observed only in some soils and only under the RT system.

Table 2. Texture and pH soil.

Soil Types	Sand%		Silt%		Clay%		pH KCl	
	Tillage Systems							
	RT	CT	RT	CT	RT	CT	RT	CT
EF	2.33 ± 0.07	7.33 ± 0.07	64.27 ± 1.41	62.04 ± 0.47	33.4 ± 0.41	30.66 ± 0.06	4.6 ± 0.14	6.29 ± 0.12
MF	19.70 ± 0.37	14.90 ± 0.33	52.44 ± 0.04	45.74 ± 0.86	27.86 ± 0.76	39.36 ± 0.10	7.16 ± 0.21	6.99 ± 0.12
HC	14.54 ± 0.16	13.77 ± 0.15	61.26 ± 0.01	59.29 ± 0.19	24.20 ± 0.70	26.94 ± 0.05	5.57 ± 0.18	6.24 ± 0.05
HL	27.07 ± 0.34	9.75 ± 0.30	51.47 ± 0.05	66.07 ± 0.46	21.46 ± 0.41	24.18 ± 0.10	6.91 ± 0.10	5.27 ± 0.10
ER	10.48 ± 0.76	9.43 ± 0.67	65.40 ± 0.1	61.92 ± 0.69	24.12 ± 0.55	28.65 ± 0.12	7.02 ± 0.19	5.57 ± 0.14
EG	7.17 ± 0.08	16.58 ± 0.08	58.05 ± 0.02	45.30 ± 0.29	4.78 ± 0.23	38.12 ± 0.07	5.55 ± 0.06	5.70 ± 0.10
SP	19.04 ± 0.21	10.45 ± 1.09	64.96 ± 0.11	63.20 ± 0.25	16.00 ± 0.69	26.35 ± 0.46	4.67 ± 0.08	6.05 ± 0.09

EF—*Eutric Fluvisol*; MF—*Mollic Fluvisol*; HC—*Haplic Chernozem*; HL—*Haplic Luvisol*; ER—*Eutric Regosol*; EG—*Eutric* Gleysol; SP—*Stagnic Planosol*; RT—reduced tillage; CT—conventional tillage; ± Standard Deviation.

The sorption properties of the tested soils varied between soil types (Table 3). The hydrolytic acidity of the tested soils ranged from 1.3 to 3.9 cmol(+) kg^{-1} for RT and from 0.37 to 2.25 cmol(+) kg^{-1} for CT. Statistical analysis showed significantly higher values of the discussed parameter in soils of types EF, MF, HC, EG, and SP under RT. The degree of saturation of the sorption complex with basic cations ranged from 1.6 to 5.4 cmol(+) kg^{-1} in soils where RT was used and from 2.50 to 4.80 cmol(+) kg^{-1} in CT soils. The value of this parameter was highest in *Molic Fluvisol* under both RT and CT. *Molic Fluvisol* also showed the highest CEC (5.70 cmol(+) kg^{-1}) and BS (93.59%) values for RT. Statistical analysis showed that the Hh, TEB, and CEC results for *Eutric Fluvisol* and *Mollic Fluvisol* were significantly higher under reduced tillage than under conventional tillage. The sorption capacity of the soil, which includes all the parameters discussed, is considered to be one of the most important factors influencing soil fertility. This soil characteristic is related to the structure of the sorption complex. The quantity and quality of humic compounds in combination with mineral colloids determines the sorption capacity and the composition of adsorbed exchangeable cations [58–60]. A correlation analysis showed highly significant relationships between total organic carbon and TEB (r = 0.780), CEC (r = 0.580), and BS (r = 0.500) (Figure 1). As pH increases, the amount of variable negative charge in organic soil increases and CEC also increases [60,61]. In addition to organic matter content, soil pH also influences cation exchange capacity. In general, acidic soils (low pH) reduce cation exchange capacity, while alkaline soils (high pH) can increase cation exchange capacity. The correlation analysis confirmed this relationship (Figure 1). The literature shows that in arable soils, the soil sorption capacity can also be changed by different soil management practices [62–64]. In our own research, statistical analysis showed that in most of the analysed soils, reduced tillage significantly increased the values of hydrolytic acidity and cation exchange capacity.

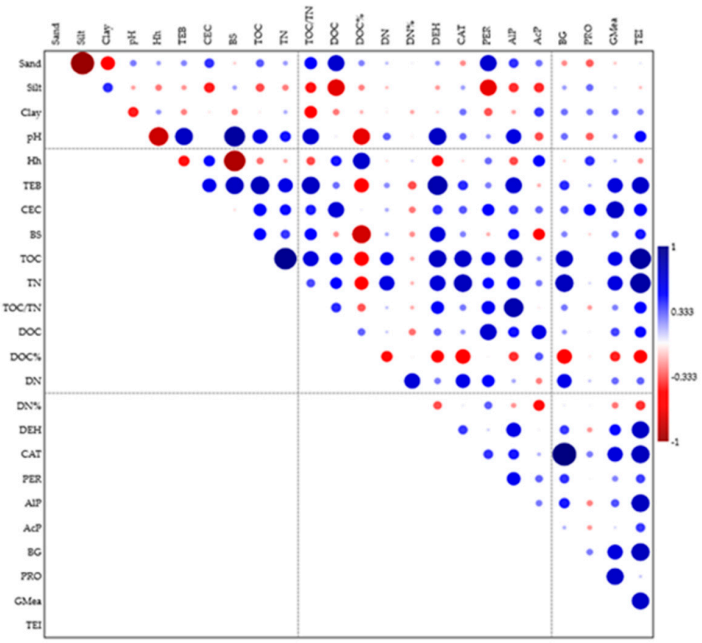


Figure 1. Correlogram of the physicochemical parameters and the activity of enzymes in soil for reduced tillage (RT) and conventional tillage CT. Abbreviations: Hh—hydrolytic acidity; TEB—total exchangeable bases; CEC—cation exchange capacity; BS—base saturation; TOC—total organic carbon, TN—total nitrogen, DOC—dissolved organic carbon; DEH—dehydrogenases, CAT—catalase, PER—peroxidases; AlP—alkaline phosphatase, AcP—acid phosphatase, BG—β-glucosidase; PRO—protease, GMea—the geometric mean of enzyme activities; TEI—total enzyme activity index.

Table 3. Sorption properties of soils.

Soil * Types	Hh (cmol(+) kg^{-1})		TEB (cmol(+) kg^{-1})		CEC (cmol(+) kg^{-1})		BS (%)	
	Tillage Systems							
	RT	CT	RT	CT	RT	CT	RT	CT
EF	3.90 a ± 0.8	0.75 b ± 0.3	3.30 a ± 0.6	2.50 b ± 1.4	7.20 a ± 2.2	3.25 b ± 0.8	45.83 b ± 2.3	76.92 a ± 3.2
MF	1.30 a ± 0.2	0.37 b ± 0.1	5.40 a ± 0.5	4.80 b ± 2.2	6.70 a ± 1.1	5.17 b ± 1.1	80.60 b ± 3.1	92.84 a ± 3.0
HC	2.92 a ± 0.8	0.90 b ± 0.2	2.40 b ± 1.3	3.40 a ± 1.3	5.32 a ± 2.1	4.30 b ± 1.0	45.11 b ± 1.8	79.07 a ± 2.4
HL	1.45 b ± 0.1	2.25 a ± 0.8	4.30 a ± 4.1	2.90 b ± 1.1	5.75 a ± 2.2	5.15 a ± 1.2	74.78 a ± 2.6	56.31 b ± 2.0
ER	1.37 b ± 0.0	1.87 a ± 0.4	3.60 a ± 2.5	3.30 a ± 0.8	4.97 b ± 1.4	5.17 a ± 1.1	72.43 a ± 3.4	63.83 b ± 1.5
EG	1.87 a ± 0.5	1.87 a ± 0.4	1.90 b ± 1.5	2.90 a ± 15.1	3.77 b ± 1.1	4.67 a ± 1.3	50.40 b ± 2.8	59.96 a ± 4.1
SP	2.85 a ± 0.5	0.98 b ± 0.1	1.60 b ± 0.15	3.20 a ± 0.3	4.45 a ± 1.1	4.18 a ± 1.1	35.96 b ± 1.5	76.56 a ± 1.4

Hh—hydrolityc acidity; TEB—total exchangeable bases; CEC—cation exchange capacity; BS—basic saturation; EF—*Eutric Fluvisol*; MF—*Mollic Fluvisol*; HC—*Haplic Chernozem*; HL—*Haplic Luvisol*; ER—*Eutric Regosol;* EG—*Eutric* Gleysol; SP—*Stagnic Planosol*; RT—reduced tillage; CT—conventional tillage; small letters (a, b) indicate a differences on between the soil tillage systems at $p = 0.05$; ± Standard Deviation.

3.2. Content of Organic Carbon, Total Nitrogen and Dissolved Organic Matter

The TOC content (Table 4) in soil samples collected from fields where conventional tillage was used ranged from 16.53 (HL) to 42.07 g kg^{-1} (MF). For soil samples from reduced tillage, the TOC content ranged from 15.51 (SP) to 38.90 g kg^{-1} (HF). For EF, HC, HL, and ER, the TOC content was higher in samples from reduced tillage than from conventional tillage; the inverse relationship was noted for MF, EG, and SP. The difference in TOC content in favour of reduced tillage was highest for *Haplic Luvisols* (92% increase) and lowest for *Eutric Fluvisols* (34% increase). In reduced tillage soils with lower TOC content, the differences in carbon content between cultivation methods were 7.5% (MF), 26.04% (SP), and 36.5% (EG). According to the results of Francaviglia et al. [18], the use of reduced tillage significantly promotes carbon sequestration. Studies conducted by Friedrich et al. [17], Busari et al. [20], Laufer et al. [65], and Powlson et al. [66], among others, showed that reduced tillage systems can lead to carbon sequestration, but it should be remembered that the degree of change in TOC content may vary by soil type (soil properties), crop rotation, and the amount of post-harvest residues left. Kumar et al. [67] believe that, compared to intensive systems, no-till cultivation preserves post-harvest residues on the field surface, thereby increasing or maintaining soil organic carbon resources at a certain level. The relationships obtained in the cited work allow us to conclude that the determinants of the effects of RT may include the physicochemical parameters of the soil.

Table 4. Content of total organic carbon and total nitrogen.

Soil * Types	TOC (g·kg^{-1})		TN (g·kg^{-1});		TOC/TN	
	Tillage Systems					
	RT *	CT	RT	CT	RT	CT
EF *	25.06 a ± 0.35	18.73 b ± 0.22	2.49 a ± 0.05	1.86 b ± 0.04	10.13 a	10.10 a
MF	38.90 b ± 0.50	42.07 a ± 0.55	2.86 b ± 0.06	3.73 a ± 0.08	13.64 a	11.30 b
HC	27.63 a± 0.22	18.13 b ± 0.30	2.87 a ± 0.03	1.81 b ± 0.02	9.63 a	10.02 a
HL	31.67 a ± 0.32	16.53 b ± 0.20	2.51 a ± 0.03	1.57 b ± 0.04	12.71 a	10.53 b
ER	24.20 a ± 0.25	17.75 b ± 0.35	2.12 a ± 0.04	1.91 a ± 0.03	11.41 a	9.32 b
EG	18.63 b ± 0.35	29.36 a ± 0.35	1.84 b ± 0.03	2.89 a ± 0.04	10.13 a	10.17 a
SP	15.51 b ± 0.20	20.97 a ± 0.30	1.49 b ± 0.03	1.92 a ± 0.03	10.41 a	10.95 a

TOC—total organic carbon; TN—total nitrogen; *—see Table 1; a, b—see Table 3.

The TN content for soils ranged from 1.57 (HL) to 3.73 g kg^{-1} (MF) under conventional tillage and, for reduced tillage, from 1.49 to 2.86 (MF) and 2.87 g kg^{-1} (HC). For MF, EG, and SP soils, the nitrogen content was higher under conventional cultivation. The MF,

EG, and SP soils under reduced tillage were characterised by, respectively, 23.4, 36.22, and 22.19% lower TN content compared to conventional tillage (Table 4). In EF, HC, and HL soils, the TN content was, respectively, 34.0, 58.6, and 59.6% higher compared to conventional cultivation. The values of TOC and TN contents in the soil were used to calculate the TOC/TN ratio values (Table 4). The values of this ratio under conventional tillage ranged from 9.32 (ER) to 11.30 (MF), and under simplified tillage ranged from 9.63 (HC) to 13.64 (MF). Only for MF, HL, and ER was a significant difference noted between conventional and reduced tillage, with lower values of this ratio being recorded.

One of the components of organic matter that is very sensitive to agrotechnical treatments is dissolved organic matter (DOM) [68]. DOM content is determined on the basis of dissolved organic carbon content (DOC)—and sometimes on the basis of dissolved nitrogen content (DTN). The DOC content in soils ranged from 141.9 (EF) to 275.1 mg kg^{-1} (EG) under conventional tillage and from 141.2 (EG) to 294.9 mg kg^{-1} (HC) under reduced tillage. In general, soils under reduced tillage (except EG and SP) were characterised by higher DOC contents (Table 5). It should be emphasised that soils under reduced tillage were also characterised by a higher share of DOC (except for HL and EG) in comparison to soils under conventional tillage. The share of DOC ranged from 0.42 (MF) to 1.03% (SP) for conventional tillage and 0.72 (MF) to 1.41% (SP) for reduced tillage. Similarly, Wright et al. [69] and Liu et al. [70] obtained higher DOM contents in soils under reduced tillage compared to conventional tillage. Leinweber et al. [71], however, indicated that ploughing may stimulate the microbiological decomposition of post-harvest residues, which may lead to increased DOM.

Table 5. Content of dissolved organic carbon and dissolved nitrogen.

Soil * Types	DOC (mg kg^{-1})		DOC (%)		DTN (mg kg^{-1})		DTN(%)	
	Tillage Systems							
	RT *	CT	RT	CT	RT	CT	RT	CT
EF *	271.3 a ± 10.5	141.9 b ± 5.5	1.08 a ± 0.05	0.76 b ± 0.03	54.4 a ± 3.0	47.2 b ± 2.5	2.19 a ± 0.05	2.54 a ± 0.07
MF	278.4 a ± 9.3	177.9 b ± 8.5	0.72 a ± 0.03	0.42 b ± 0.01	43.7 b ± 2.1	85.5 a ± 8.8	1.53 b ± 0.03	2.30 a ± 0.09
HC	294.9 a ± 8.5	150.6 b ± 5.8	1.07 a ± 0.06	0.83 b ± 0.05	66.7 a ± 3.3	43.7 b ± 2.5	2.32 a ± 0.03	2.41 a ± 0.11
HL	280.1 a ± 10.2	172.5 b ± 8.5	0.88 b ± 0.05	1.04 a ± 0.07	45.2 a ± 1.6	22.7 b ± 1.8	1.80 a ± 0.05	1.45 a ± 0.08
ER	232.6 a ± 5.5	169.7 b ± 8.5	0.96 a ± 0.05	0.96 a ± 0.08	59.5 a ± 3.8	24.2 b ± 2.0	2.81 a ± 0.08	1.27 b ± 0.05
EG	141.2 b ± 7.5	275.1 a ± 11.0	0.76 b ± 0.04	0.94 a ± 0.08	54.0 a ± 3.0	32.7 b ± 2.2	2.93 a ± 0.10	1.13 b ± 0.04
SP	218.0 a ± 10.8	215.1 a ± 8.9	1.41 a ± 0.09	1.03 b ± 0.07	41.3 a ± 2.5	19.9 b ± 1.9	2.77 a ± 0.09	1.04 b ± 0.05

DOC—dissolved organic carbon; DTN—dissolved nitrogen; *—see Table 1; a, b—see Table 3.

The content and share of DNT was significantly higher in soils under reduced tillage (except MF) compared to conventional tillage. DTN ranged from 1.04 (SP) to 2.54% (EF) under conventional tillage and from 1.53 (MF) to 2.93% (EG) under reduced tillage.

3.3. The Activity of Enzymes in Soil

In order to determine how tillage systems in different soil types might affect levels of enzymatic activity, the activity of selected redox enzymes, i.e., dehydrogenases (DEH), catalase (CAT), and peroxidase (PER) (Table 6), and hydrolytic enzymes, i.e., alkaline (AlP) and acidphosphatase (AcP), β-glucosidase (BG), and proteases (PR), was determined (Table 7). DEH activity was significantly higher under reduced tillage in EF soils (3.42 mg TPF kg^{-1} 24 h^{-1}), HL soils (7.23 mg TPF kg^{-1} 24 h^{-1}), and ER soils (9.73 mg TPF kg^{-1} 24 h^{-1}) as compared to conventional tillage CT (Table 5). DEH activity was 2%, 33%, and 17% higher, respectively. The highest activity of the tested oxidoreductive enzymes (excluding PER under CT) was obtained in MF. *Mollic Fluvisols* are a soil composed of fluvial mud and are characterised by high content and quality of organic matter [72]. According to

Furtak et al. [73], *Fluvisols* are among the most fertile soils. There were no statistically significant differences in DEH between MF and HC, nor in CAT among MF, HL, ER, EG, and SP. Significantly, the highest CAT activity in the RT system was obtained in EF (1.76 mg H_2O_2 $kg^{-1}h^{-1}$) and in HC (1.48 mg H_2O_2 $kg^{-1}h^{-1}$). Soils with high biomass show high CAT activity. The tillage system was the greatest determinant of variation in PER activity. Statistically significant higher PER activity was found in RT soils, with the exception of EG.

Table 6. Activity of oxidoreductive enzymes.

Soil * Types	DEH (mg TPF kg^{-1} 24 h^{-1})		CAT (mg H_2O_2 kg^{-1} h^{-1})		PER (mM PPG kg^{-1} h^{-1})	
	Tillage Systems					
	RT *	CT	RT	CT	RT	CT
EF *	3.42 a ± 0.009	2.36 b ± 0.008	1.76 a ± 0.002	1.52 b ± 0.009	2.08 a ± 0.002	1.86 b ± 0.004
MF	10.85 a ± 0.021	11.28 a ± 0.01	1.93 a ± 0.009	1.89 a ± 0.011	2.20 a ± 0.002	1.92 b ± 0.002
HC	6.54 a ± 0.042	6.12 a ± 0.053	1.48 a ± 0.005	0.96 b ± 0.005	2.11 a ± 0.005	1.81 b ± 0.002
HL	7.23 a ± 0.056	4.87 b ± 0.006	0.89 a ± 0.003	0.81 a ± 0.004	2.16 a ± 0.003	1.72 b ± 0.003
ER	9.73 a ± 0.012	8.09 b ± 0.072	1.06 a ± 0.009	0.86 a ± 0.002	1.95 a ± 0.001	1.62 b ± 0.002
EG	2.63 b ± 0.005	7.23 a ± 0.068	1.72 a ± 0.009	1.69 a ± 0.0011	1.98 a ± 0.002	1.94 a ± 0.004
SP	2.05 b ± 0.004	6.32 a ± 0.009	0.72 a ± 0.004	0.69 a ± 0.008	2.01 a ± 0.004	1.75 b ± 0.001

DEH—dehydrogenases; CAT—catalase; PER—peroxidase; *—see Table 1; a, b—see Table 3.

The analysis of the results obtained for most of the soils showed statistically significant differences in the activity of selected hydrolytic enzymes between tillage systems (Table 7). AlP activity under RT was significantly higher in MF (3.90 mM pNP kg^{-1} kg^{-1}), HL (2.14 mM pNP kg^{-1} kg^{-1}), and ER (1.70 mM pNP kg^{-1} kg^{-1}) soils. Meanwhile, in EG, AlP activity (2.15 mM pNP kg^{-1} kg^{-1}) was significantly highest under CT. No significant differences in AlP were found between the two tillage systems in EF, HC, and SP. A study by Spiegel et al. [74] showed that alkaline phosphatase activity was significantly higher in soils under minimum tillage conditions compared to conventional tillage. According to Nannipieri et al. [75], no-till systems usually have higher enzyme activity in surface soils than in tilled soils due to the increased organic matter content. BG activity was significantly affected by tillage system in all soils except HL. The activity of this enzyme under RT was higher in EF (2.80 mM pNP $kg^{-1}h^{-1}$), HC (2.55 mM pNP $kg^{-1}h^{-1}$), ER (2.24 mM pNP $kg^{-1}h^{-1}$), and EG (2.84 mM pNP $kg^{-1}h^{-1}$). In MF and SP, BG activity was significantly higher under CT (2.23 mM pNP $kg^{-1}h^{-1}$) (Table 6) and tended to be higher under reduced tillage compared to no-till or conventional tillage. Research by Panettieri et al. [76] indicated that reduced tillage had a positive effect on BG activity compared to conventional tillage. Studies by Fernandez-Ortega et al. [77] showed that dehydrogenase activity was higher in the no-tillage system compared to conventional tillage. Also, significant differences found in β-glucosidase activity were attributed to, among other things, the cultivation system. The no-tillage system caused a 53% increase in β-glucosidase activity. PRO activity under CT was significantly higher in HC, HL, ER, EG, and SP soils compared to EF. An absence of differences between RT and CT was found only in MF. Mirzavand et al. [78] showed that replacing conventional tillage with conservation tillage (especially reduced tillage) can increase soil enzyme activity in the short term. The highest acid phosphatase enzyme was obtained in reduced tillage in wheat and maize rotation. However, alkaline phosphatase and urease activity was the highest in no-till soil. Phosphatases catalyse the conversion of organic phosphorus compounds into inorganic phosphates [79]. Research conducted by Piazza et al. [80] showed that minimum tillage together with N fertilisation increased the activity of enzymes (*β*-cellobiohydrolases, N-acetyl-*β*-glucosaminidase, *β*-glucosidase, *α*-glucosidase, *β*-xylosidase, acid phosphatase,

arylsulphatase, and leucine aminopeptidase). A comprehensive meta-analysis by Wen et al. [81] showed that conservation tillage has a positive effect on soil enzymatic activity. However, the results depend on the type of enzyme and other conservation practices (e.g., no till, straw return). The results of a meta-analysis by Zhu et al. [82] showed that conservation tillage significantly increased SOC and the activities of enzymes related to carbon (C), nitrogen (N), phosphorus (P), and sulphur (S). A meta-analysis conducted by Li et al. [83] showed a significant increase in the activity of enzymes related to C and N cycling and oxidative enzymes under the influence of no-till. The inclusion of legumes in the cultivation significantly increased only enzymes related to P cycling in the soil. However, Woźniak [84] found higher activity of dehydrogenases and phosphatases in soil under CT compared to under RT. The activity of proteases and ureases was higher in soils under RT.

Table 7. The activity of hydrolytic enzymes.

Soil * Types	AlP (mM pNP $kg^{-1}h^{-1}$)		AcP (mM pNP $kg^{-1}h^{-1}$)		BG (mM pNP $kg^{-1}h^{-1}$)		PRO (mg TYR $kg^{-1}h^{-1}$)	
	Tillage Systems							
	RT *	CT	RT	CT	RT	CT	RT	CT
EF *	1.05 a ± 0.002	1.31 a ± 0.001	3.40 a ± 0.014	1.93 b ± 0.085	2.80 a ± 0.014	2.30 b ± 0.021	38.26 a ± 0.081	22.79 b ± 0.065
MF	3.90 a ± 0.008	2.14 b ± 0.005	4.65 a ± 0.055	2.21 b ± 0.091	2.99 b ± 0.021	3.37 a ± 0.008	18.06 a ± 0.058	19.87 a ± 0.041
HC	1.10 a ± 0.001	1.12 a ± 0.031	5.18 a ± 0.061	2.26 b ± 0.047	2.55 a ± 0.009	1.57 b ± 0.009	15.04 b ± 0.035	19.96 a ± 0.022
HL	2.14 a ± 0.002	0.58 b ± 0.008	3.07 a ± 0.034	3.50 a ± 0.009	1.94 a ± 0.008	1.87 a ± 0.006	17.42 b ± 0.009	20.88 a ± 0.012
ER	1.70 a ± 0.001	1.17 b ± 0.012	1.85 b ± 0.019	3.58 a ± 0.014	2.24 a ± 0.012	1.98 b ± 0.011	18.64 b ± 0.017	20.76 a ± 0.061
EG	1.23 b ± 0.001	2.15 a ± 0.038	3.36 b ± 0.022	5.91 a ± 0.052	2.84 a ± 0.008	2.50 b ± 0.025	17.51 b ± 0.012	18.35 a ± 0.016
SP	1.55 a ± 0.002	1.42 a ± 0.018	3.81 a ± 0.020	3.17 a ± 0.017	1.58 b ± 0.006	2.23 a ± 0.019	13.57 b ± 0.008	15.79 a ± 0.014

AlP—alkaline phosphatase (mM pNP $kg^{-1}h^{-1}$); AcP—acid phosphatase (mM pNP $kg^{-1}h^{-1}$); BG—β-glucosidase (mM pNP $kg^{-1}h^{-1}$); PRO—proteases (mg TYR $kg^{-1}h^{-1}$); *—see Table 1; a, b—see Table 3.

Based on the enzyme activity results, enzymatic soil quality indices such as GMea and TEI were calculated (Figure 2). Soil enzyme activity indices TEI and GMea were used to analyse different soil types under two different tillage systems. GMea can directly show the variability of total enzyme activity, whereas TEI values can be used to make easy comparisons of total enzyme activity and soil quality between samples. As compared to GMea, the TEI index showed more varied soil quality results under both tillage systems in the different soil types. Significant differences in GMea were found between tillage systems only in EF, EG, and SP. Under CT, a significantly higher GMea value was obtained in EG and SP soils. The TEI value was similar in these two soils. In the remaining soils, except for ER, the TEI value was significantly higher under RT. Similarly, studies by Tan et al. [44] and Jaskulska et al. [10] showed that TEI was a more sensitive enzymatic indicator of soil quality compared to GMea.

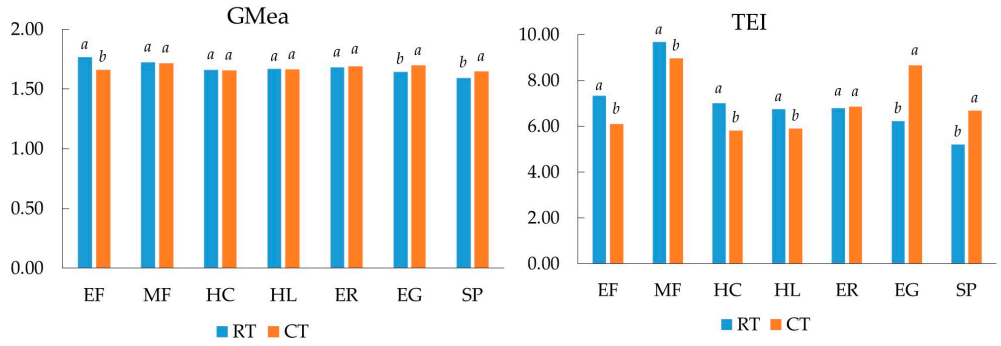


Figure 2. Index of soil enzymes: GMea and TEI (EF—*Eutric Fluvisol*; MF—*Mollic Fluvisol*; HC—*Haplic Chernozem*; HL—*Haplic Luvisol*; ER—*Eutric Regosol*; EG—*Eutric Gleysol*; SP—*Stagnic Planosol*; RT—reduced tillage; CT—conventional tillage).

A correlation analysis showed a significant positive correlation between pH and DEH (r = 0.74) and AlP (r = 0.63) activity (Figure 1). Phosphatases are the enzymes most sensitive to changes in soil pH [79], which also controls phosphorus availability in the soil. A positive significant correlation was also obtained between Hh and AcP (r = 0.48). Soil reaction is a factor that stimulates the activity of most soil enzymes, which is related to the appropriate/related state of ionisation of the active site of protein enzymes. In some soils, pH is masked by the content of organic matter, which affects enzyme activity [85]. Soil enzymes mediate soil biochemical processes and are closely involved in decomposing organic matter, nutrient cycling and environmental quality [86].

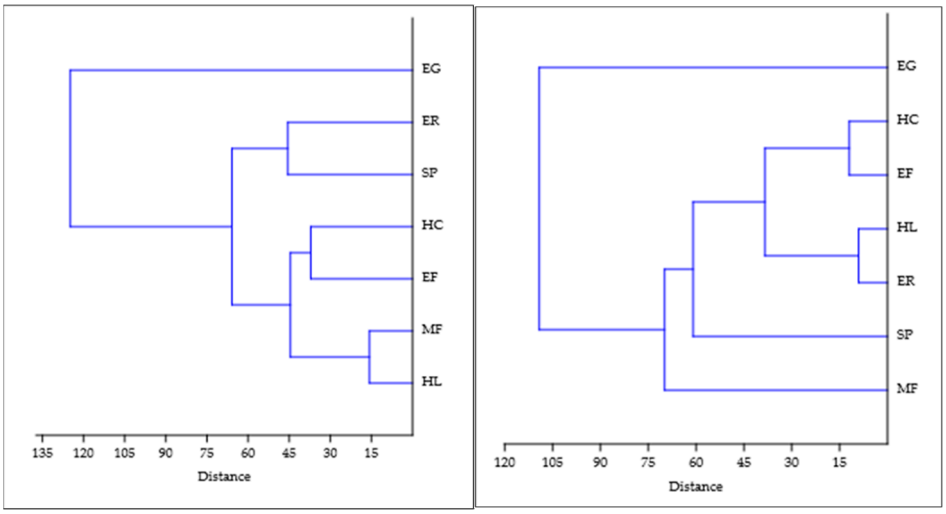
The strongest correlation coefficients were found to be between enzyme activity and TOC content (r = 0.74 with DEH; r = 0.72 with CAT; r = 0.57 with PER; r = 0.75 with AlP and r = 0.72 with BG). The coefficient of determination (R^2) showed that as much as 54.7% of the variability of DEH, 51.8% of CAT, 32.5% of PER, 56.3% of AlP, and 51.8% was related to the TOC content in soil. Dehydrogenases are enzymes that play an important role in the biological oxidation of soil organic matter by transferring protons and electrons from substrates to acceptors [87]. Normally, organic matter stabilises and protects extracellular enzymes in the soil, slowing their degradation [88]. The process of OM degradation is related to the activity of BG, as it involves an enzyme catalysing the hydrolysis of cellulose to glucose as a source of energy for soil microorganisms [89]. De Almeida et al. [90] showed that soils enriched with OM with a high C/N ratio are characterised by lower BG activity and slow OM decomposition. Higher soil moisture levels with the no-tillage system, which reduces soil disturbance, led to increased dehydrogenase and β-glucosidase activity. This contributed to greater stabilisation of soil organic carbon [91]. Significant correlations were observed between the activity of PER, AlP, and AcP and the content of DOC, whose fraction contains carbon compounds that are soluble in aqueous solutions and, thus, is the most available in the soil system. Extracellular oxidative and hydrolytic enzymes are responsible for converting organic matter in DOC from high- to low-molecular-weight compounds [92]. Typically, an increased DOC content stimulates the production of a substrate for microbial metabolism and enzyme synthesis. Similarly to Shao et al. [86], no significant correlation was found herein between BG activity and DOC content. BG catalyses the hydrolysis of oligosaccharides to glucose, which can be rapidly utilised by microorganisms. This led to a decrease in DOC content in the soil [86]. Enzymes have their own specific substrates and abilities to catalyse specific biochemical reactions [93]. Differences in substrate availability sources and composition may lead to altered enzyme activity behaviour. Furthermore, soil enzyme activity was significantly and positively correlated with TN content (r = 0.66 with DEH; r = 0.0.76 with CAT; r = 0.55 with AlP; and r = 0.76 with BG). According to Uwituze et al. [94], soil pH was positively correlated with glycosidase activity, which increased

with TOC content. Increased N content in the soil caused an increase in the number of microorganisms associated with the C cycle, which affects the production of glucosidases. However, no significant correlations were found between TN and PRO activity. This was confirmed by the meta-analysis conducted by Chen et al. [95]. However, the opposite results were also obtained by Chen et al. [96]. Proteases are enzymes that catalyse the hydrolysis of proteins by catalysing the cleavage of peptide bonds to produce peptides and/or amino acids [97].

Also noteworthy were the high correlations of TEI with TOC values (r = 0.89), DOC (r = 0.47), TN (r = 0.86), pH (r = 0.47), TEB (r = 0.72), CEC (r = 0.52), and BS (r = 0.47). Similarly, studies by Mierzwa-Hersztek et al. [98] and Jaskulska et al. [10] found that TEI is usually positively correlated with TOC and TN content. It was also found that GMea was significantly positively correlated with TEB (r = 0.64), CEC (r = 0.74), TOC (r = 0.60), and TN (r = 0.63) (Figure 1).

4. Summary and Conclusions

The dendograms presented in Figure 3a,b are based on the discussed edaphic parameters of the tested soils. Figure 3a shows the dendogram obtained for soils under reduced tillage and Figure 3b for those under conventional tillage. For reduced tillage, two groups were distinguished, one containing ER and SP, the other HC, HL, and EF. MF and EG lay outside these groups. As the relationships presented in Figure 3a,b show, *Eutric Gleyosols* were the most divergent in properties—regardless of tillage system. Under conventional tillage, ER and HL soils were the two most similar to one another. In general, Euclidean distances were slightly smaller between the studied soil parameters from conventional tillage compared to reduced tillage.



(**a**) Reduced tillage RT (**b**) Conventional tillage CT

Figure 3. Cluster analysis based on soil parameters for reduced tillage (**a**) and conventional tillage (**b**). The distance described on the x-axis represents the Euclidean distance; (EF—*Eutric Fluvisol*; MF—*Mollic Fluvisol*; HC—*Haplic Chernozem*; HL—*Haplic Luvisol*; ER—*Eutric Regosol*; EG—*Eutric Gleysol*; SP—*Stagnic Planosol*).

The identified relationships confirm, among other things, the relationships obtained by Banach-Szott et al. [99], i.e., that organic matter characteristics are a distinctive feature of a given soil type, but that these can nonetheless be modified by the tillage method. Jaskulska et al. [10] clearly demonstrated that the properties of soil under conventional tillage differ from those under reduced tillage and strip-till. The tillage system determined changes in the activity of the studied enzymes, but the intensity and direction of these

changes depended on the soil type. Soil type should thus be the key factor in selecting a tillage system.

As can be seen from the data presented in the paper, the intensity and direction of changes in soil quality parameters depend on its type. The TOC decreased in the following order:

For RT: MF > HL > HC > EF = ER > EG > SP; for CT: MF > EG > SP > EF = HC > ER > HR.

The CEC parameter decreased in the following order:

For RT: EF > MF > HL = HC > ER > SP > EG; for CT: MF > ER = HL > EG > HC > SP > EF.

On the basis of the TEI parameter—the enzymatic activity index—the tested soils can be ranked as follows:

For RT: MF > EF + HC > ER + HL > EG > SP for CT: MF = EG > ER > SP > EF > HL = HC.

The total enzyme activity index proved to be a more sensitive enzymatic indicator of soil quality than the geometric mean of enzyme activity indices. However, the diverse properties of soils prevented the precise selection of an enzyme or enzymes for use as soil quality indicators. Therefore, further research is necessary in a direction that will take into account the processes resulting from changes in the use of different types of soil.

Author Contributions: Conceptualisation, E.B. and J.L.; methodology, E.B., J.L., B.D. and A.B.; validation, J.L. and P.W.; formal analysis, E.B., J.L., B.D. and A.B.; investigation, E.B., J.L., B.D. and A.B.; resources, E.B.; writing—original draft preparation, J.L., B.D., A.B. and E.B. writing—review and editing, J.L. and P.W.; visualisation, J.L.; supervision, J.L., B.D. and A.B.; project administration, E.B. All authors have read and agreed to the published version of the manuscript.

Funding: The research was part of the project KEGA 005SPU-4/2022: "Incorporation of contemporary environmental topics into the teaching of soil-related subjects". Bydgoszcz University of Science and Technology under Grant BN-WRiB-1/2022 and BN-WRiB-2/2022.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hartmann, M.; Frey, B.; Mayer, J.; Mäder, P.; Widmer, F. Distinct soil microbial diversity under long-term organic and conventional farming. *ISME J.* **2015**, *9*, 1177–1194. [CrossRef]
2. Wiesmeier, M.; Urbanski, L.; Hobley, E.; Lang, B.; von Lutzow, B.; Marin-Spiotta, E.; van Wesemael, B.; Rabot, E.; Ließ, M.; Garcia-Franco, N.; et al. Soil organic carbon storage as a key function of soils—A review of drivers and indicators at various scales. *Geoderma* **2019**, *333*, 149–162. [CrossRef]
3. European Commision. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions—The European Green Deal, Brussels. 2019. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0016.02/DOC_1&format=PDF (accessed on 11 December 2019).
4. Vittori Antisari, L.; Trenti, W.; De Feudis, M.; Bianchini, G.; Falsone, G. Soil quality and organic matter pools in a temperate climate (Northern Italy) under different land uses. *Agronomy* **2021**, *11*, 1815. [CrossRef]
5. Simon, L.M.; Augustine, K.O.; Holman, J.D.; Roozeboom, K.L. Long-term cover crop management effects on soil properties in dryland cropping systems. *Agric. Ecosyst. Environ.* **2022**, *328*, 107852. [CrossRef]
6. Karaca, A.; Cetin, S.C.; Turgay, O.C.; Kizilkaya, R. Soil enzymes as indication of soil quality. In *Soil Enzymology*; Shukla, G., Varma, A., Eds.; Springer: Berlin/Heidelberg, Germany, 2010; Volume 22. [CrossRef]

7. Lori, M.; Symnaczik, S.; Mäder, P.; De Deyn, G.; Gattinger, A. Organic farming enhances soil microbial abundance and activity—A meta-analysis and meta-regression. *PLoS ONE* **2017**, *12*, e0180442. [CrossRef]
8. Jaskulska, I.; Romaneckas, K.; Jaskulski, D.; Gałęzewski, L.; Breza-Boruta, B.; Dębska, B.; Lemanowicz, J. Soil properties after eight years of the use of strip-till one-pass technology. *Agronomy* **2020**, *10*, 1596. [CrossRef]
9. Jaskulska, I.; Jaskulski, D. Strip-till one-pass technology in central and Eastern Europe: A MZURI Pro-Till hybrid machine case study. *Agronomy* **2020**, *10*, 925. [CrossRef]
10. Jaskulska, I.; Lemanowicz, J.; Dębska, B.; Jaskulski, D.; Breza-Boruta, B. Changes in soil organic matter and biological parameters as a result of long-term strip-till cultivation. *Agriculture* **2023**, *13*, 2188. [CrossRef]
11. Balesdent, J.; Chenu, C.; Balabane, M. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil Tillage Res.* **2000**, *53*, 215–230. [CrossRef]
12. Jaskulska, I.; Jaskulski, D. Influence of many years' fertilization on the dynamics of soil properties. *Adv. Agric. Sci.* **2003**, *4*, 21–35.
13. Blecharczyk, A.; Małecka, I.; Sierpowski, J. Long-term effect of tillage systems on physico-chemical soil properties. *Fragm. Agron.* **2007**, *1*, 7–13.
14. Aye, N.S.; Sale, P.W.G.; Tan, C. The impact of long-term liming on soil organic carbon and aggregate stability in low-input acid soils. *Biol. Fertil. Soils.* **2016**, *52*, 697–709. [CrossRef]
15. Debska, B.; Kotwica, K.; Banach-Szott, M.; Spychaj-Fabisiak, E.; Tobiašová, E. Soil fertility improvement and carbon sequestration through exogenous organic matter and biostimulant application. *Agriculture* **2022**, *12*, 1478. [CrossRef]
16. Menšík, L.; Hlisnikovský, L.; Pospíšilová, L.; Kunzová, E. The effect of application of organic manures and mineral fertilizers on the state of soil organic matter and nutrients in the long-term field experiment. *J. Soils Sediments* **2018**, *18*, 2813–2822. [CrossRef]
17. Friedrich, T.; Derpsch, R.; Kassam, A.H. Global overview of the spread of conservation agriculture. *J. Agric. Sci. Technol.* **2015**, *6*, 1–7.
18. Francaviglia, R.; Almagro, M.; Vicente-Vicente, J.L. Conservation agriculture and soil organic carbon: Principles, processes, practices and policy options. *Soil Syst.* **2023**, *7*, 17. [CrossRef]
19. Stavi, I.; Bel, G.; Zaady, E. Soil functions and ecosystem services in conventional, conservation, and integrated agricultural systems. A review. *Agron. Sustain. Dev.* **2016**, *36*, 32.
20. Busari, A.M.; Kukal, S.S.; Kaur, A.; Bhatt, R.; Dulazi, A.A. Conservation tillage impacts on soil, crop and the environment. *Int. Soil Water Conserv. Res.* **2015**, *3*, 119–129. [CrossRef]
21. Horowitz, J.; Ebel, R.; Ueda, K. *Economic Information Bulletin No. 70: "No-Till" Farming Is a Growing Practice*; Economic Research Service, U.S. Department of Agriculture: Washington, DC, USA, 2010.
22. Allam, M.; Radicetti, E.; Petroselli, V.; Mancinelli, R. Meta-analysis approach to assess the effects of soil tillage and fertilization source under different cropping systems. *Agriculture* **2021**, *11*, 823. [CrossRef]
23. Debska, B.; Jaskulska, I.; Jaskulski, D. Method of tillage with the factor determining the quality of organic matter. *Agronomy* **2020**, *10*, 1250. [CrossRef]
24. Virto, I.; Barre, P.; Burlot, A.; Chenu, C. Carbon input differences as the main factor explaining the variability in soil organic C storage in notilled compared to inversion tilled agrosystems. *Biogeochemistry* **2012**, *108*, 17–26. [CrossRef]
25. Dimassi, B.; Mary, B.; Wylleman, R.; Labreuche, J.; Couture, D.; Piraux, F.; Cohan, J.P. Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. *Agric. Ecosyst. Environ.* **2014**, *188*, 134–146. [CrossRef]
26. Han, P.; Zhang, W.; Wang, G.; Sun, W.; Huang, Y. Changes in soil organic carbon in croplands subjected to fertilizer management: A global metaanalysis. *Nat. Sci. Rep.* **2016**, *6*, 27199. [CrossRef]
27. Yue, K.; Peng, Y.; Peng, C.; Yang, W.; Peng, X.; Wu, F. Stimulation of terrestrial ecosystem carbon storage by nitrogen addition: A metaanalysis. *Sci. Rep.* **2016**, *6*, 19895. [CrossRef]
28. Armas-Herrera, C.M.; Dignac, M.-F.; Rumpel, C.; Arbelo, C.D.; Chabbi, A. Management effects on composition and dynamics of cutin and suberin in topsoil under agricultural use. *Eur. J. Soil Sci.* **2016**, *67*, 360–373. [CrossRef]
29. Szostek, M.; Szpunar-Krok, E.; Pawlak, R.; Stanek-Tarkowska, J.; Ilek, A. Effect of different tillage systems on soil organic carbon and enzymatic activity. *Agronomy* **2022**, *12*, 208. [CrossRef]
30. Blanco-Canqui, H.; Ruis, S.J. No-tillage and soil physical environment. *Geoderma* **2018**, *326*, 164–200. [CrossRef]
31. Chenu, C.; Angers, D.A.; Barré, P.; Derrien, D.; Arrouays, D.; Balesdent, J. Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. *Soil Tillage Res.* **2019**, *188*, 41–52. [CrossRef]
32. Derpsch, R.; Friedrich, T.; Kassam, A.; Li, H. Current status of adoption of no-till farming in the world and some of its main benefits. *Int. J. Agric. Biol. Eng.* **2010**, *3*, 1–25. [CrossRef]
33. Cenini, V.L.; Fornara, D.A.; McMullan, G.; Ternan, N.; Carolan, R.; Crawley, M.J.; Clément, J.-C.; Lavorel, S. Linkages between extracellular enzyme activities and the carbon and nitrogen content of grassland soils. *Soil Biol. Biochem.* **2016**, *96*, 198–206. [CrossRef]

34. Rahmati, M.; Eskandari, I.; Kouselou, M.; Feiziasl, V.; Mahdavinia, G.R.; Aliasgharzad, N.; McKenzie, B.M. Changes in soil organic carbon fractions and residence time five years after implementing conventional and conservation tillage practices. *Soil Tillage Res.* **2020**, *200*, 104632. [CrossRef]
35. Tobiašová, E.; Lemanowicz, J.; Dębska, B.; Kunkelová, M.; Sakáč, J. The Effect of reduced and conventional tillage systems on soil aggregates and organic carbon parameters of different soil types. *Agriculture* **2023**, *13*, 818. [CrossRef]
36. IUSS Working Group WRB. World Reference Base for Soil Resources. In *International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*, 4th ed.; International Union of Soil Sciences (IUSS): Vienna, Austria, 2022.
37. Haddad, S.A.; Lemanowicz, J.; Abd El-Azeim, M.M. Cellulose decomposition in clay and sandy soils contaminated with heavy metals. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 3275–3290. [CrossRef]
38. Tobiašová, E.; Lemanowicz, J.; Dębska, B.; Kunkelová, M.; Sakáč, J. Suitability of various parameters for the determination of the condition of soil structure with dependence to the quantity and quality of soil organic matter. *Sustainability* **2023**, *15*, 11047. [CrossRef]
39. Korec, P.; Lauko, V.; Tolmáči, L.; Zubrický, G.; Mičietová, E. *Region and Districts of Slovakia. A New Administrative Structure*; Q111: Bratislava, Slovakia, 1997; 391p.
40. Jurčová, O.; Bielek, P. *Method of Soil Organic Method Balance and the Determination of Necessity of Organic Fertilization*; VÚPÚ: Bratislava, Slovakia, 1997; 154p.
41. van Reeuwijk, L.P. *Procedures for Soil Analysis*; International Soil Reference and Information Centre: Wageningen, The Netherlands, 2002; 120p.
42. *PN-ISO 10390*; Chemical and Agricultural Analysis: Determining Soil pH. Polish Standards Committee: Warszawa, Poland, 1997.
43. Skjemstad, J.O.; Gillman, G.P.; Massis, A.; Spouncer, L.R.; Leonie, R. Measurement of the exchange capacity of the cationic fraction of organic matter from soils using the modified compulsive exchange method. *Soil Sci. Soc. Am. J.* **2008**, *39*, 926–937. [CrossRef]
44. Thalmann, A. Zur methodic derestimung der dehydrogenaseaktivität und boden mittels triphenyltetrazoliumchlorid (TTC). *Landwirtsch. Forsch.* **1968**, *21*, 249–258.
45. Johnson, J.I.; Temple, K.L. Some variables affecting the measurements of catalase activity in soil. *Soil Sci. Soc. Am.* **1964**, *28*, 207–209. [CrossRef]
46. Bartha, R.; Bordeleau, L. Cell-free peroxidases in soil. *Soil Biol. Biochem.* **1969**, *1*, 139–143. [CrossRef]
47. Tabatabai, M.A.; Bremner, J.M. Use of p–nitrophenol phosphate for assay of soil phosphatase activity. *Soil Biol. Biochem.* **1969**, *1*, 301–307. [CrossRef]
48. Eivazi, F.; Tabatabai, M.A. Glucosidases and galactosidases in soils. *Soil Biol. Biochem.* **1988**, *20*, 601–606. [CrossRef]
49. Ladd, J.N.; Jackson, R.B. Biochemistry of ammonification. In *Nitrogen in Agricultural Soil*; American Society of Agronomy, Inc. Crop Science Society of America, Inc. Soil Science Society of America Inc.: Madison, WI, USA, 1982. [CrossRef]
50. Hinojosa, M.B.; Garcia-Ruiz, R.; Viñegla, B.; Carreira, J.A. Microbiological rates and enzyme activities as indicators of functionality in soils affected by the Aznalcóllar toxic spill. *Soil Biol. Biochem.* **2004**, *36*, 1637–1644. [CrossRef]
51. Tan, X.; Xie, B.; Wang, J.; He, W.; Wang, X.; Wei, G. County-scale spatial distribution of soil enzyme activities and enzyme activity indices in agricultural land: Implications for soil quality assessment. *Sci. World J.* **2014**, *2014*, 535768. [CrossRef]
52. Shapiro, S.S.; Wilk, M.B. An analysis of variance test for normality (complete samples). *Biometrika* **1965**, *52*, 591–611. [CrossRef]
53. Hammer, Ø.; Harper, D.A.; Ryan, P.D. Past: Paleontological statistics software package for education and data anlysis. *Palaeontol. Electron.* **2001**, *4*, 9.
54. Ward, J.H. Hierarchical grouping to optimize an objective function. *J. Am. Stat. Ass.* **1963**, *58*, 236–244. [CrossRef]
55. Ahmad, N.; Virk, A.L.; Hafeez, M.B.; Ercisli, S.; Golokhvast, K.S.; Qi, Y.; Guo, X.; Zhang, Y.; Wang, R.; Wang, X.; et al. Effects of different tillage and residue management systems on soil organic carbon stock and grain yield of rice–wheat double cropping system. *Ecol. Indic.* **2024**, *158*, 111452. [CrossRef]
56. Yuan, J.; Yan, l.; Li, G.; Sadiq, M.; Rahim, N.; Wu, J.; Ma, W.; Xu, G.; Du, M. Effects of conservation tillage strategies on soil physicochemical indicators and N2O emission under spring wheat monocropping system conditions. *Sci. Rep.* **2022**, *12*, 7066. [CrossRef]
57. Mosley, L.M.; Rengasamy, P.; Fitzpatrick, R. Soil pH: Techniques, challenges and insights from a global dataset. *Eur. J. Soil Sci.* **2024**, *75*, 70021. [CrossRef]
58. He, G.; Zhang, Z.; Wu, X.; Cui, M.; Zhang, J.; Huang, X. Adsorption of heavy metals on soil collected from Lixisol of typical karst areas in the presence of $CaCO_3$ and soil clay and their competition behavior. *Sustainability* **2020**, *12*, 7315. [CrossRef]
59. Stawn, D. Sorption Mechanisms of chemicals in soils. *Soil Syst.* **2021**, *5*, 13. [CrossRef]
60. Bi, X.; Chu, H.; Fu, M.; Xu, D.; Zhao, W.; Zhong, Y.; Wang, M.; Li, K.; Zhang, Y. Distribution characteristics of organic carbon (nitrogen) content, cation exchange capacity, and specific surface area in different soil particle sizes. *Sci. Rep.* **2023**, *13*, 12242. [CrossRef]
61. Vasudevan, D.; Bruland, G.L.; Torrance, B.S.; Upchurch, W.G.; MacKay, A.A. pH-dependent ciprofloxacin sorption to soils: Interaction mechanisms and soil factors influencing sorption. *Geoderma* **2009**, *151*, 68–76. [CrossRef]

62. Lorandi, R. Evaluation of cation exchange capacity (CEC) in tropical soils using four different analytical methods. *J. Agric. Sci.* **2012**, *4*, 278–289. [CrossRef]
63. Šimansky, V.; Pollakova, N. Soil organic matter and sorption capacity under different soil management practices in a productive vineyard. *Arch. Agron. Soil Sci.* **2014**, *60*, 1145–1154. [CrossRef]
64. Tian, K.; Zhao, Y.; Xu, X.; Hai, N.; Huang, B.; Deng, W. Effects of long-term fertilization and residue management on soil organic carbon changes in paddy soils of China: A meta-analysis. *Agric. Ecosyst. Environ.* **2015**, *204*, 40–50. [CrossRef]
65. Laufer, D.; Loibl, B.; Marlander, B.; Koch, H.J. Soil erosion and surface run-of under strip tillage for sugar beet (*Beta vulgaris* L.) in Centraf Europe. *Soil Tillage Res.* **2016**, *162*, 1–7. [CrossRef]
66. Powlson, D.S.; Bhogal, A.; Chambers, B.J.; Coleman, K.; Macdonald, A.J.; Goulding, K.W.T.; Whitmore, A.P. The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: A case study. *Agric. Ecosyst. Environ.* **2012**, *146*, 23–33. [CrossRef]
67. Kumar, S.; Kadono, A.; Lal, R.; Dick, W. Long-term no-till impacts on organic carbon and properties of two contrasting soils and corn yields in Ohio. *Soil Sci. Soc. Am. J.* **2012**, *76*, 1798–1809. [CrossRef]
68. Bolan, N.S.; Adriano, D.C.; Kunhikrishnan, A.; James, T.; McDowell, R.; Senesi, N. Dissolved organic matter: Biogeochemistry, dynamics, and environmental significance in soils. *Adv. Agron.* **2011**, *110*, 1–75. [CrossRef]
69. Wright, A.; Dou, F.; Hons, M.F. Soil organic C and N distribution for wheat cropping systems after 20 years of conservation tillage in central Texas. *Agric. Ecosyst. Environ.* **2007**, *121*, 376–382. [CrossRef]
70. Liu, E.; Teclemariam, S.G.; Yan, C.; Yu, J.; Gu, R.; Liu, S.; He, W.; Liu, Q. Long-term efects no-tillage management practice on soil organic carbon and its fractions in the northern China. *Geodema* **2014**, *213*, 379–384. [CrossRef]
71. Leinweber, P.; Schulten, H.R.; Körschens, M. Hot water extracted organic matter: Chemical composition and temporal variations in a long-term field experiment. *Biol. Fertil. Soils* **1995**, *20*, 17–23. [CrossRef]
72. Shaheen, S.M.; Rinklebe, J. Geochemical fractions of chromium, copper, and zinc and their vertical distribution in floodplain soil profiles along the Central Elbe River, Germany. *Geoderma* **2014**, *228*, 142–159. [CrossRef]
73. Furtak, K.; Grządziel, J.; Gałązka, A.; Niedźwiecki, J. Analysis of soil properties, bacterial community composition, and metabolic diversity in fluvisols of a floodplain area. *Sustainability* **2019**, *11*, 3929. [CrossRef]
74. Spiegel, H.; Sandén, T.; Sandén, H.; Götzinger, S.; Miloczki, J.; Kandeler, E. Changes in biological and chemical soil properties in an Austrian long-term tillage experiment. *Eur. J. Soil Sci.* **2025**, *76*, e70037. [CrossRef]
75. Nannipieri, P.; Giagnoni, L.; Landi, L.; Renella, G. Role of phosphatase enzymes in soil. In *Phosphorus in Action*; Bünemann, E., Oberson, A., Frossard, E., Eds.; Soil Biology Series; Springer: Berlin/Heidelberg, Germany, 2011; Volume 26. [CrossRef]
76. Panettieri, M.; de Sosa, L.L.; Domínguez, M.T.; Madejón, E. Long-term impacts of conservation tillage on Mediterranean agricultural soils: Shifts in microbial communities despite limited effects on chemical properties. *Agric. Ecosyst. Environ.* **2020**, *304*, 107144. [CrossRef]
77. Fernández-Ortega, J.; Álvaro-Fuentes, J.; Delgado, A.; García-López, A.M.; Cantero-Martínez, C. Assessing management strategies for carbon storage in Mediterranean soils: Double-cropping, no-tillage, and nitrogen fertilization reduction. *Soil Tillage Res.* **2025**, *249*, 106496. [CrossRef]
78. Mirzavand, J.; Asadi-Rahmani, H.; Moradi-Talebbeigi, R. Biological indicators of soil quality under conventional, reduced, and no-tillage systems. *Arch. Agron. Soil Sci.* **2022**, *68*, 311–324. [CrossRef]
79. Dick, W.A.; Cheng, L.; Wang, P. Soil acid and alkaline phosphatase activity as pH adjustment indicators. *Soil Biol. Biochem.* **2000**, *32*, 1915–1919. [CrossRef]
80. Piazza, G.; Pellegrino, E.; Moscatelli, M.C.; Ercoli, L. Long-term conservation tillage and nitrogen fertilization effects on soil aggregate distribution, nutrient stocks and enzymatic activities in bulk soil and occluded microaggregates. *Soil Tillage Res.* **2020**, *196*, 104482. [CrossRef]
81. Wen, L.; Peng, Y.; Zhou, Y.; Cai, G.; Lin, Y.; Li, B. Effects of conservation tillage on soil enzyme activities of global cultivated land: A meta-analysis. *J. Environ. Manag.* **2023**, *345*, 118904. [CrossRef]
82. Zhu, Y.; Zhang, H.; Wang, Q.; Zhu, W.; Kang, Y. Soil extracellular enzyme activity linkage with soil organic carbon under conservation tillage: A global meta-analysis. *Eur. J. Agron.* **2024**, *155*, 127135. [CrossRef]
83. Li, T.; Li, G.; Lu, Z.; Zhao, D.; Li, Y.; Wang, Z.; Wen, X.; Liao, Y. Crop diversification increases soil extracellular enzyme activities under no tillage: A global meta-analysis. *Soil Tillage Res.* **2024**, *235*, 105870. [CrossRef]
84. Woźniak, A. Chemical properties and enzyme activity of soil as affected by tillage system and previous crop. *Agriculture* **2019**, *9*, 262. [CrossRef]
85. Lasota, J.; Błońska, E.; Piaszczyk, W. State of soil enzymatic activity in relationship to some chemical properties of Brunic Arenosols. *Soil Sci. Ann.* **2021**, *72*, 140641. [CrossRef]
86. Shao, X.; Yang, W.; Wu, M. Seasonal dynamics of soil labile organic carbon and enzyme activities in relation to vegetation types in Hangzhou Bay Tidal Flat Wetland. *PLoS ONE* **2015**, *11*, e0142677. [CrossRef]

87. Daunoras, J.; Kačergius, A.; Gudiukaitė, R. Role of soil microbiota enzymes in soil health and activity changes depending on climate change and the type of soil ecosystem. *Biology* **2024**, *13*, 85. [CrossRef]
88. Geisseler, D.; Horwath, W.R. Relationship between carbon and nitrogen availability and extracellular enzyme activities in soil. *Pedobiologia* **2009**, *53*, 87–98. [CrossRef]
89. Chaves, V.B.S.; Guimarães, T.M.; Bezerra, A.C.T.P.; da Costa, C.H.M.; Cruz, S.C.S. Enzymatic activity in different crop succession systems in the Cerrado Region. *Agronomy* **2024**, *14*, 810. [CrossRef]
90. de Almeida, R.F.; Naves, E.R.; da Mota, R.P. Soil quality: Enzymatic activity of soil β-glucosidase. *Glob. J. Agric. Res. Rev.* **2015**, *3*, 146–450.
91. Fernández-Ortega, J.; Álvaro-Fuentes, J.; Talukder, R.; Lampurlanés, J.; Cantero-Martínez, C. The use of double-cropping in combination with no-tillage and optimized nitrogen fertilization improve crop yield and water use efficiency under irrigated conditions. *Field Crops Res.* **2023**, *301*, 109017. [CrossRef]
92. Tian, L.; Dell, E.; Shi, W. Chemical composition of dissolved organic matter in agroecosystems: Correlations with soil enzyme activity and carbon and nitrogen mineralization. *Appl. Soil Ecol.* **2010**, *46*, 426–435. [CrossRef]
93. Song, Y.; Song, C.; Yang, G.; Miao, Y.; Wang, J.; Guo, Y. Changes in labile organic carbon fractions and soil enzyme activities after marshland reclamation and restoration in the Sanjiang Plain in Northeast China. *Environ. Manag.* **2012**, *50*, 418–426. [CrossRef]
94. Uwituze, Y.; Nyiraneza, J.; Fraser, T.D.; Dessureaut-Rompré, J.; Ziadi, N.; Lafond, J. Carbon, nitrogen, phosphorus, and extracellular soil enzyme responses to different land use. *Front. Soil Sci.* **2022**, *2*, 814554. [CrossRef]
95. Chen, H.; Li, D.; Zhao, J.; Xiao, K.; Wang, K. Effects of nitrogen addition on activities of soil nitrogen acquisition enzymes:A meta-analysis. *Agric. Ecosyst. Environ.* **2018**, *252*, 126–131. [CrossRef]
96. Chen, T.; Cheng, R.; Xiao, W.; Shen, Y.; Wang, L.; Sun, P.; Zhang, M.; Li, J. Nitrogen addition enhances soil nitrogen mineralization through an increase in mineralizable organic nitrogen and the abundance of functional genes. *J. Soil Sci. Plant Nutr.* **2024**, *24*, 975–987. [CrossRef]
97. Landi, L.; Renella, G.; Giagnoni, L.; Nannipieri, P. Activities of proteolytic enzymes. *Methods Soil Enzymol.* **2011**, *9*, 247–260. [CrossRef]
98. Mierzwa-Hersztek, M.; Gondek, K.; Klimkowicz-Pawlas, A.; Chmiel, M.J.; Dziedzic, K.; Taras, H. Assessment of soil quality after biochar application based on enzymatic activity and microbial composition. *Int. Agrophys.* **2019**, *33*, 331–336. [CrossRef]
99. Banach-Szott, M.; Debska, B.; Tobiasova, E. Properties of humic acids depending on the land use in different parts of Slovakia. *Environ. Sci. Pollut. Res.* **2021**, *28*, 58068–58080. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.