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# Chemical and Physical Aspects of Soil Health Resulting from Long-Term No-Till Management

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**Abstract:** The aim of this study was to compare the long-term effects of conventional tillage (CT) and no-till (NT) systems on the main soil properties that determine soil health. The research was conducted in a field experiment established in 1975 in Chylice, central Poland, at the WULS-SGGW Experimental Station Skierniewice. Soil samples collected from 0–10 and 10–20 cm of the mollic horizon of the Phaeozem were analysed for total organic carbon (TOC) content, fractional composition of SOM and spectroscopic properties of humin, soil structural stability, soil water retention characteristics and soil water repellency (SWR). The results showed that NT practice almost doubled the TOC in the 0–10 cm layer. However, optical parameters of humin indicated that NT management promoted the formation of humin with a lower molecular weight and lower degree of condensation of aromatic structures. In the NT 0–10 cm layer, a significant increase in the number of water-resistant macroaggregates was found. In the 0–10 cm layer, the water capacity increased by 9%, 18%, 22% and 26% compared to CT at (certain soil suction) pF values of 0.0, 2.0, 3.0 and 4.2, respectively. SWR occurs regardless of the cultivation method at a soil moisture equivalent to pF 4.2, and the greatest range of SWR was found in the NT 0–10 cm layer.

**Keywords:** soil organic carbon; humin; soil structure; soil water retention; soil water repellency; spectroscopic properties; fluorescence properties

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## 1. Introduction

Soil is a key component of the terrestrial biosphere, not only for its production of food and fibre, but also for its role in maintaining environmental quality. For this reason, the provision of high-quality soil is a major concern for many researchers, not just soil scientists. The metaphor of "soil health", which refers to the ability of a soil to provide ecosystem services, was widely adopted by the scientific community in the 1990s [1]. However, the concept of applying this metaphor to soil is much older. The earliest mention of "soil health" comes from a 1910 thesis at Iowa State University by H.A. Wallace, who wrote about the importance of humus in maintaining soil health [2]. This first concept of soil health was based on the physical and chemical properties of the soil and its fertility, and over time has been complemented by the biological properties of the soil.

Today, "soil health" is defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" [3], while its longer version is "the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health" [4]. A soil is considered healthy if it provides comparable or better ecosystem services than undisturbed reference soils of a similar type in the same region [5]. The sustainable management of agricultural soils fits into the current European research needs on the health of agricultural soils and soil resilience to climate change [6,7]. However, soil health is neither a readily quantifiable nor measurable object, so there are no simple indicators for it [8].

In addition to soil properties being limited by the parent rock type, soil organic matter (SOM) content and quality, moisture regime, and chemical and biological properties, they are influenced by anthropogenic activities [9]. This includes preferred cropping practices and intensive land use management, which can have positive or negative effects on soil health. No-tillage (NT) is considered an effective way to improve soil health in both the short and long term, with the magnitude of benefits depending on specific practices and environmental conditions [10–12].

NT practices have been observed to improve soil's physical, chemical and biological properties. The longer the duration of NT, the better the effect. Improvements include increased soil organic carbon (SOC) content, especially in surface layers [13,14], but little is known about changes in the soil's organic matter characteristics, including those of humic substances. In particular, the humin fraction is the least known component of the SOM, although this fraction may represent an important part of the pool responsible for carbon sequestration [15–18]. Changes in the directions of SOM transformation, including the humin fraction, can be accurately determined using advanced techniques such as UV–Vis supported by fluorescence [19–21].

Long-term NT significantly increases soil aggregation and aggregate stability, especially in the surface layers [10–12], which improves soil structure and reduces erosion [10,13]. Conventional tillage (CT), in contrast to NT, contributes to an increase in soil bulk density, particularly in the upper soil layers, which can lead to soil compaction problems [10]. NT has also been shown to increase soil infiltration and water storage, improving soil moisture retention [10,13,22,23]. In Tahad's et al. [24] review of agricultural practices, NT reduced the amount of irrigation water applied by 1/8 to 1/4 compared to CT. Thus, NT increases water use efficiency and, consequently, overall net returns. The NT system also increased the soil water repellency (SWR), contributing to soil degradation by changing some soil processes (e.g., carbon sequestration and soil erosion). Soil structure had a direct influence on SWR [25–27], and was a result of the interactions between the pore structure and hydrophobic substances [26]. Further studies into the mechanisms controlling SWR require more than a quantification of TOC [27].

The aim of this study was to assess the effects of almost 50 years of NT vs. CT treatments on soil's physical and chemical properties, including changes in the molecular structure of the rarely studied humin fraction of SOM, with particular attention to differences between the 0–10 cm and 10–20 cm layers.

## 2. Materials and Methods

### 2.1. Long-Term Tillage Experiment

The 47-year field experiment in Chylice (central Poland, 52.098° N, 20.548° E) was established in 1975 at the WULS-SGGW Experimental Station in Skierniewice. The experiment is the longest-running soil cultivation type of experiment in Poland and one of the oldest in Europe. The area has an average annual temperature of 9.3 °C and an average annual rainfall of 600 mm, classifying its climate as warm temperate (Cfb) [28]. In the decade 2011–2020, the average annual precipitation was 604.1 mm (min 476 mm in 2019, and max 725 mm in 2016) and the average annual temperature was 9.4 °C (min 8.8° in 2012, and max 10.5° in 2019), respectively. The groundwater level ranges from 70 cm in April to 170–200 cm in the summer months.

The experiment was carried out on Phaeozem derived from sandy loam (sand 70%, silt 17%, clay 13%) on 20 $m^2$ plots. A randomised block design was used with two contrasting tillage systems, i.e., traditional full inversion tillage with mouldboard plough (CT), and NT with direct drilling. Both tillage systems used the same crop rotation and mineral fertiliser regime. Crop rotation was dominated by cereals, but from 2020 onwards, a monoculture of maize was grown. The average fertilisation level over many years was 100–170 kg N adapted to the needs of crops (in legumes 20 kg), 30.6 kg P and 87.2 kg K per hectare. Cereals dominated crop rotation. In 2022 in CT and NT systems, the same crop (winter wheat in 2021), corn variety (Gallery), sowing date, fertilisation and level of chemical plant protection were used. On 28 April 2022, NPK mineral fertilisers were applied in the following doses: 21 kg of N in ammonium and 92 kg in amide forms, 30.6 kg of P and 87.2 kg of K in potassium chloride per hectare. Mineral fertilisers in the CT were mixed with the soil using a cultivator. On 29 April 2022, corn was sown in 88 thousand seeds per hectare with simultaneous under-sowing NP mineral fertilisers: 21 kg of N in ammonium form and 30,6 kg of P per hectare. A mixture of nicosulfuron, sulcotrione and terbuthylazine was sprayed after the emergence of maize plants. Three plots of each tillage system were selected (Figure 1) and in mid-season 2022, soil samples were collected from 0–10 cm and 10–20 cm soil layers at 10 points in each block plot and averaged by gently mixing.

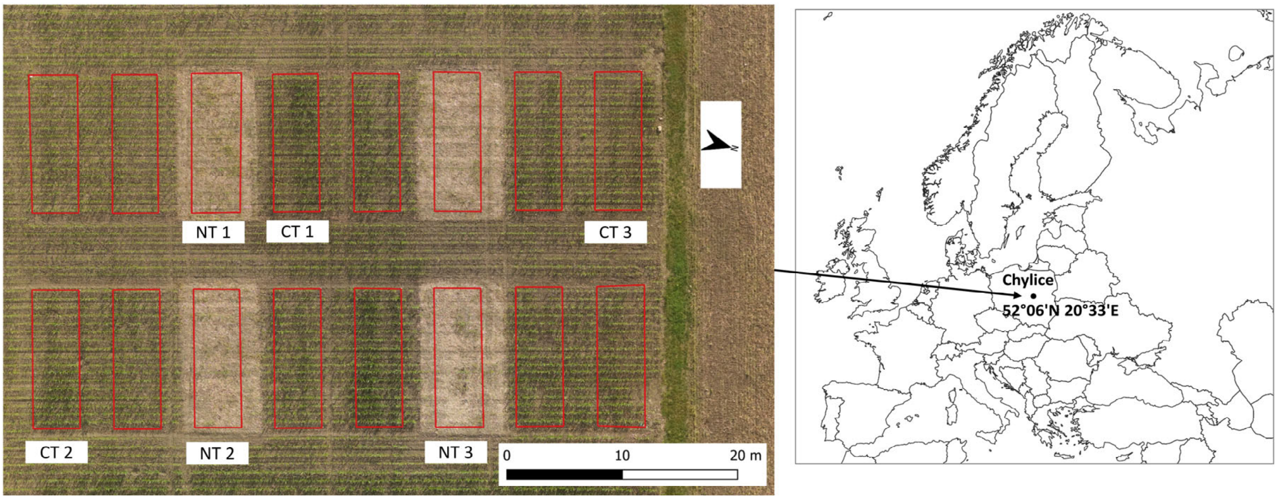


**Figure 1.** Localisation and the scheme of the long-term tillage experiment.

### *2.2. Basic Chemical Properties*

Soil pH was measured potentiometrically in a 1:2.5 suspension of soil and 1 M KCl. Total organic carbon (TOC) and total nitrogen (TN) were determined using the Enviro TOC+N analyser (Elementar; Langenselbold, Germany). Cation exchange capacity (CEC) was calculated as the sum of H+ ions determined in 1 M KCl, and exchangeable base cations extracted with 1 M NH4Ac, and measured by atomic emission spectroscopy (K+, Na+ and $Ca^{2+}$) and atomic absorption spectroscopy ($Mg^{2+}$). Plant available nutrients (P, K, Mg) were determined by the Mehlich 3 method [29].

### *2.3. The Fractional Composition of SOM*

The fractional composition of SOM was determined using the modified method of Swift [30]. $H_2SO_4$ was used to decalcify the soil, which allowed us to obtain a low-molecular-weight fraction called fulvic fraction (FF). The C content of the supernatant (FF) was determined using the Enviro TOC+N analyser (Elementar; Langenselbold, Germany). An exhaustive alkaline extraction with 0.1 M NaOH was then performed until the supernatant was light-coloured, in which the C content was determined as total extractable carbon (TEC). This fraction contained humic acids (HAs) and fulvic acids (FAs). In the next step, the alkaline supernatant was acidified to pH = 2, which caused HA precipitation. The HA was separated from the FA by centrifugation. Finally, hot 0.02 M NaOH was used to dissolve the precipitate and the C concentration in the whole volume was determined as HA. The content of the FA fraction was calculated as the balance between the TEC and HA fractions (FA = TEC − HA). The content of the humin fraction was calculated according to the formula HUM = TOC − (TEC + FF).

*2.4. Spectroscopic Analysis*

The spectroscopic properties of the humin isolated from the 0–10 cm layers were determined by means of UV–Vis spectroscopy and fluorescence analysis. The UV–Vis spectra were recorded in the wavelength range of 200–700 nm using a Jasco UV-VIS-NIR 770 spectrometer (Jasco-Global, Tokyo, Japan).

Fluorescence spectra were recorded using a Hitachi F 7000 spectrofluorometer (Hitachi, Tokyo, Japan). Emission spectra were recorded at several fixed excitation wavelengths ex. Synchronous scan spectra were measured in the range of 220–620 nm, keeping the scan difference constant, $\Delta\lambda = \lambda em - \lambda ex = 20$ nm. The monochromators of the excitation and emission slits were 5 nm and 10 nm, respectively, and the scan speed was a 240 nm $min^{-1}$.

Humin was dissolved in a mixture of DMSO and 98% $H_2SO_4$ (94% and 6% $v/v$, respectively) to obtain a carbon concentration of 10 mg $dm^{-3}$. Prior to optical analysis, the samples were filtered through a syringe filter with a pore size of 0.45 µm.

*2.5. Bulk Density and Structural Stability*

Soil bulk density was determined by the gravimetric method in undisturbed samples in three replications for each plot and layer. Structural stability was determined in 30 g samples of dry soil aggregates placed on top of a set of sieves in cylindrical containers filled with distilled water in Baksheev′s apparatus [31].

Mean weight diameter of water-resistant aggregates (*MWDw*) was calculated based on the share of weighted mean diameters of aggregates of all size-fraction classes in the soil according to the formula described by Elliott [32]:

$$MWDw = \sum_{n=1}^{n} \overline{x}iwi \quad (1)$$

where $MWD$ = mean weight diameter (mm) = mean diameter of each size faction,
$wi$ = proportion of total sample weight,
$n$ = number of size fractions.

*2.6. Soil Water Retention Characteristic*

The undisturbed, standard soil samples (100 $cm^3$) were collected in three replicates from each block plot design in the two layers (36 samples in total) for the determination of soil water retention characteristics (SWRCs). Retention curves were measured in the laboratory using reference methods [33]. Moisture content values in the range of pF = 0 to pF = 2 were determined on a sand table, while the amounts of water at the pF: 2.3, 2.7, 3.0 and 4.2 were measured in pressure chambers. The plant available water capacity (AWC) was calculated as the difference between the field capacity pF = 2.0 and the permanent wilting point (pF = 4.2), the easily available water (EAW) was calculated as the difference between pF = 2.0 and 3.0 and the difficultly available water (DAW) for the plant was calculated as the difference between pF = 3.0 and pF = 4.2.

*2.7. Soil Water Repellency Assessment*

SWR was assessed by the most widespread method, the water drop penetration time (WDPT) test [34]. The WDPT test was performed at different moisture contents that had been adjusted by equilibrating the undisturbed soil samples at characteristic pF values in triplicate, for each block plot and layer. A detailed description has been presented in previous work by Hewelke [35]. The classification of SWR proposed by Dekker and Jungerius [36] was used to evaluate the test results.

*2.8. Statistical Analysis*

Statistical analysis was performed using analysis of variance and the Fisher procedure of multiple comparisons, $\alpha = 0.05$. The Kruskal–Wallis test was used for WDPT test values that did not follow a normal distribution. Principal component analysis (PCA) was used to investigate the multivariate relationships between the examined soil variables studied and the tillage systems. All analyses were carried out using the data analysis programme Statistica version 13 [37].

## 3. Results and Discussion

### 3.1. Basic Chemical Properties

Compared to CT, NT can have a positive effect on most soil parameters, with changes usually limited to the top 10 cm [12]. The basic chemical properties of the soils studied are shown in Table 1. A global meta-analysis of soil pH responses to NT by Zhao et al. [38] suggested that changes in organic matter decomposition under undisturbed soil could lead to higher H+ concentration, thereby lowering soil pH. Our research indicated that long-term NT can reduce the pH of a surface layer of soil from 6.19 to 5.33. No such effect was observed in the 10–20 cm layer.

**Table 1.** Basic chemical properties.

| Variant | pH (KCl) | TOC | TN | TOC/TN | CEC | P | K | Mg |
|---|---|---|---|---|---|---|---|---|
| | | g kg$^{-1}$ | | | cmol (+) kg$^{-1}$ | mg kg$^{-1}$ | | |
| 0–10 cm layer | | | | | | | | |
| CT | 6.19 b | 9.87 a | 1.00 a | 10.50 a | 8.21 a | 128.33 a | 125.33 a | 107.67 a |
| NT | 5.33 a | 17.60 b | 1.63 b | 10.83 a | 9.31 a | 196.67 b | 218.00 b | 114.67 a |
| 10–20 cm layer | | | | | | | | |
| CT | 5.38 a | 12.13 a | 1.07 a | 11.30 a | 7.56 a | 121.33 a | 121.67 a | 100.67 a |
| NT | 5.54 a | 11.43 a | 1.20 a | 9.73 a | 10.61 a | 121.67 a | 109.00 a | 120.00 a |

NT resulted in a significant increase in TOC and TN, but only in the top layer of the soil, indicating the beneficial effect of NT on SOM content [39–41]. Increased soil C levels under NT compared to CT are a result of a 1.5 times slower C turnover, leading to a stabilisation of C within microaggregates [42]. Our results showed that compared to CT (9.87 g kg$^{-1}$), almost 50 years of continuous use of NT increased TOC by 78%, indicating that this type of practice maintains soil health [43] and minimises the risk of soil degradation [44].

Despite an increase in TOC content of almost 80% in the surface soil layer, no effect of NT on CEC was observed in either the surface or deeper soil layers. However, there was a significant increase in the content of plant-available forms of potassium and phosphorus, in the upper 0–10 cm layer.

### 3.2. The Fractional Composition of SOM

Several studies have demonstrated the positive effects of NT on soil organic carbon stocks, but little is known about the effects of this soil management on the characteristics of accumulated SOM. CT generally reduces the aggregation and content of particulate organic matter (POM). Six et al. [42] found that C concentrations in fine intra-aggregate POM were on average 51% lower under CT than under NT. Results obtained by Aduhene-Chinbuah et al. [45] in a 19-year field experiment showed an increase in carbon, nitrogen and phosphorus in POM fractions at 0–7.5 cm depth in the NT system, leading the authors to suggest that this system must be highly effective in improving soil fertility.

There is a lack of comprehensive research on the effect of NT on changes in the fractional composition of humic substances. Our results showed that this type of soil management had a significant effect on the FF fraction in the 0–10 cm soil layer (Table 2). The content of this highly mobile fraction, consisting mainly of low molecular weight organic matter, was significantly lower in the NT system (8.77% of TOC) than in the CT (11.65% of TOC). Szajdak et al. [46] found a 42 to 59% higher concentration of HA in NT soils, whereas the concentration of FA was 54% higher in conventionally cultivated soils. In contrast, Wulanningtyas et al. [47] showed negative effects of NT in combination with fallow, hairy vetch and rye on the ratio of humic acids to fulvic acids. Our research did not show a clear effect of NT on the humification process. A higher, but not statistically significant, proportion of HA (51.55% of TOC for CT vs. 46.25% of TOC for NT) and a higher HA/FA ratio (3.46 for CT vs. 2.50 for NT) were found in both the 0–10 cm and 10–20 cm layers. This may suggest that CT favours the humification process and the formation of organic matter with highly reactive organic fractions to a greater extent than NT practice. However, this hypothesis requires more in-depth research on a larger number of samples.

**Table 2.** Fractional composition of SOM.

| Variant | TOC g $kg^{-1}$ | FF | HA | FA | HUM | HUMg $kg^{-1}$ | HA/FA |
|---|---|---|---|---|---|---|---|
| | | % of TOC | | | | | |
| | | | 0–10 cm layer | | | | |
| CT | 9.87 a | 11.65 b | 51.66 a | 15.65 a | 21.05 a | 2.08 a | 3.46 a |
| NT | 17.60 b | 8.77 a | 46.25 a | 18.64 a | 26.34 a | 4.63 b | 2.50 a |
| | | | 10–20 cm layer | | | | |
| CT | 12.13 a | 10.04 ab | 48.84 a | 15.65 a | 25.47 a | 3.09 a | 3.28 a |
| NT | 11.45 a | 11.22 b | 41.98 a | 21.10 a | 25.70 a | 2.92 a | 2.03 a |

TOC—total organic carbon, FF—low molecular fraction, HA—humic acids, FA—fulvic acids, HUM—humin; HA and FA% of TOC and HA/FA value were calculated based on values from individual replications and, because of that, are not exactly equal to ratio calculated based on the means of HA and FA% of TOC and HA and FA values.

Also noteworthy is the quantitatively significant increase in the content of the humin fraction in the NT system (from 2.08 g $kg^{-1}$ to 4.63 g $kg^{-1}$ for CT and NT, respectively, in the 0–10 cm layer). This is of environmental importance, as the increase in this fraction, considered the most resistant to decomposition, has a significant effect on the increase in carbon sequestration. However, it should be noted that this is the effect of the increase in TOC content.

### *3.3. Spectroscopic Properties of Humin*

In the study of various organic substances, including SOM, their optical properties are increasingly used. Thanks to the high sensitivity of fluorescence methods, they allow the identification of even small differences in their structure, which may indicate the directions of incipient changes in their transformation. Sometimes they are not advanced enough to be detected by other methods.

#### 3.3.1. UV–Vis Analysis

The UV–Vis spectra of the investigated humin showed a specific profile with a prominent double maximum in the short wavelength range, at 260 nm and 280 nm (Figure 2). In this range, humin isolated from objects with CT showed a much higher absorption capacity. Light absorption by organic matter in this wavelength range increases with increasing degree of condensation of aromatic rings, a higher ratio of carbon in the aromatic core of the molecule to carbon in aliphatic chains and higher molecular weight [48]. On the other hand, at higher wavelength values, corresponding to the Vis range, the absorption efficiency is due to acceptor–donor complexes formed as a result of internal and external molecular aggregation [48,49]. In this range, the analysed humin did not show significant differences.

Differences in soil management and their influence on the transformation of fresh organic matter are also reflected in the absorption coefficient values often used in the literature (Table 3). They are calculated for the absorption values at individual wavelengths. Lower $E_{260}$:$E_{280}$ and $E_{465}$:$E_{665}$ values for humin from CT indicated their larger size and molecular weight [50] and increased highly complex aromatic structures and alkyl substitution [51], indicating a more advanced stage of the transformation [52]. Changes in the values of the $E_{280}$:$E_{365}$ and $E_{280}$:$E_{470}$ coefficients of the discussed humin samples also indicated different dynamics of the transformation processes of SOM, as well as the influx of fresh mass [53,54]. Higher values of these indices for humin from CT indicated its higher degree of humification.

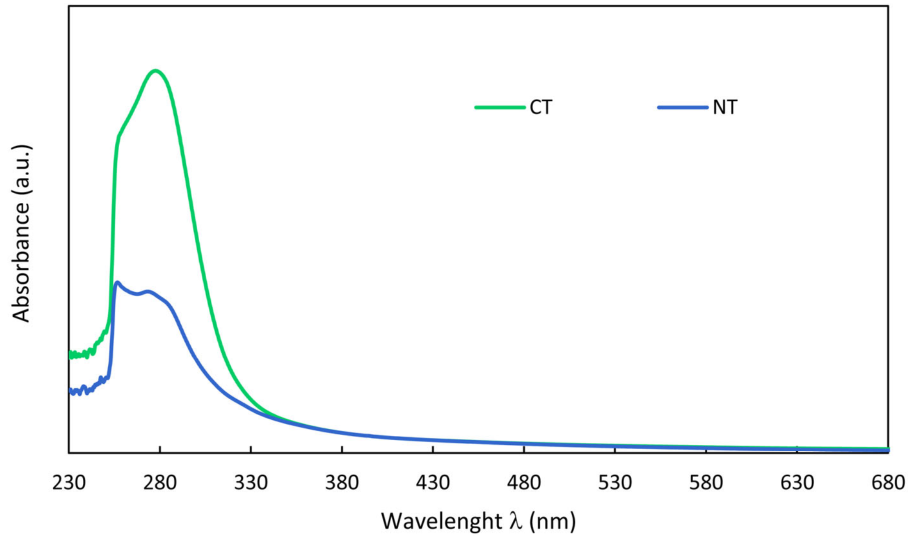


**Figure 2.** UV–Vis spectra of investigated humin (0–10 cm layer).

**Table 3.** UV–Vis and fluorescence spectroscopic analysis and correspondent indices.

| Variant | UV–Vis Spectroscopy | | | | Fluorescence Spectroscopy | | | |
|---|---|---|---|---|---|---|---|---|
| | $E_{260}$:$E_{280}$ | $E_{465}$:$E_{665}$ | $E_{280}$:$E_{365}$ | $E_{280}$:$E_{470}$ | $IFl_{330}$:$IFl_{390}$ | $IFl_{330}$:$IFl_{470}$ | HIX | $A_{440}$ |
| CT | 0.77 | 2.37 | 12.90 | 35.48 | 1.88 | 5.48 | 1.76 | 30.04 |
| NT | 1.04 | 3.40 | 6.61 | 14.79 | 2.67 | 7.69 | 1.39 | 25.24 |

3.3.2. Fluorescence

Differences in SOM transformation processes in NT and CT soils were also visible in the synchronous scan fluorescence spectra (Figure 3), mainly in the shortwave region (280–340 nm). Humin from NT showed a greater ability to emit fluorescence. This band is attributed to the presence of fluorophores of lower molecular complexity. In particular, the band at 280–300 nm is due to the presence of aromatic amino acids, such as tryptophan, and other substances with strongly coupled aliphatic structures [55,56]. According to Duarte et al. [57], in the synchronous scan fluorescence spectra, the band at about 280 nm can be attributed to structural fragments derived from lignin. Its intensity increases towards smaller sizes and lower molecular complexity.

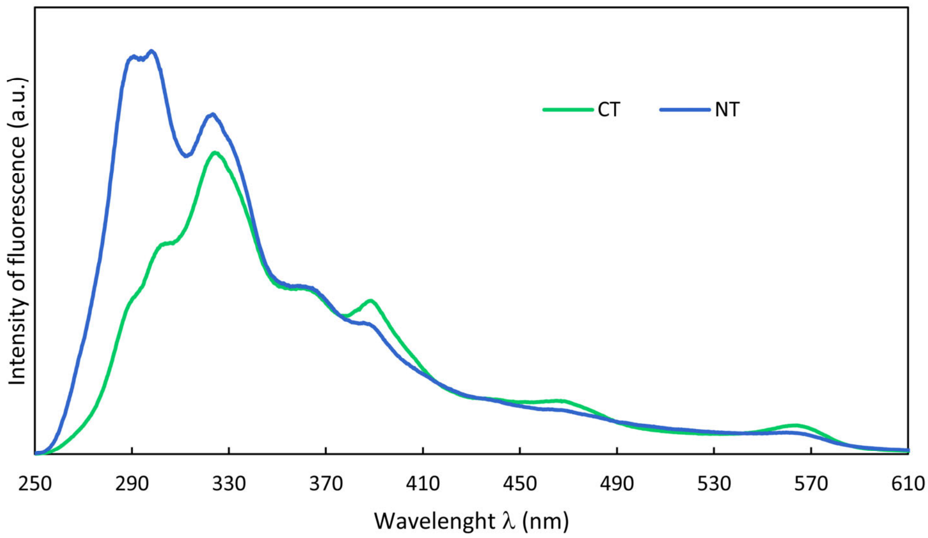


**Figure 3.** Synchronous scan fluorescence spectra.

The humin fractions tested showed very weak fluorescence in the 340–600 nm range, with CT humin showing slightly higher fluorescence. Peaks in the 420–600 nm range indicate the presence of high molecular weight polycyclic aromatic compounds, while increased fluorescence in the 340–420 nm range indicates the presence of large amounts of simple, dissociated phenolic and quinone groups [18,56,58,59]. It is assumed that the increase in humification leads to a higher fluorescence intensity in the longer wavelength range. This is related to the increase in the number of highly substituted aromatic rings and/or highly conjugated unsaturated systems [54,60]. The observed low fluorescence in the long wavelength part of the tested humin may indicate the degradation of high molecular weight components and the formation of smaller fractions.

The calculated fluorescence coefficients (Table 3) are related to the degree of humification and to the degree of condensation of the aromatic group in humin. They indicate a similar effect of the cultivation method on the humin properties as the UV–Vis data. Higher values of $IFl_{330}$:$IFl_{390}$ and $IFl_{330}$:$IFl_{470}$ for NT indicate a lower degree of humification of these samples. This reflects the relationship between relatively simple fluorophores and the number of strongly coupled and condensed aromatic nuclei [54,61]. Similarly, lower HIX and $A_{440}$ values for NT confirm a lower degree of internal transformation of the humin molecule, thus indicating a lower "packing" of this humin. According to Fuentes et al. [62], higher HIX values may be associated with a lower share of oxygen-containing functional groups.

### *3.4. Bulk Density and Structural Stability*

In our investigation, NT caused a significant reduction in bulk density for the 0–10 cm layer, with values of 1.56 g $cm^{-3}$ for NT and 1.65 g $m^{-3}$ for CT, respectively. There were no differences in the 10–20 cm layer. Similar results were reported by Blanco-Canqui and Ruis [12], although they noted in their review that NT can have different effects on bulk density, depending on soil texture.

The 0–10 cm layer showed significantly more large water-resistant macroaggregates with fraction sizes of 10–7, 7–5, 5–3 and 3–1 mm in NT compared to CT (Figure 4a,b). Their proportion was 204, 302 and 244% higher in NT, respectively. In contrast, there were significantly more water-stable macroaggregates of smaller diameters (1–0.5 mm and 0.5–0.25 mm) and microaggregates (<0.25 mm) in CT (by 39.5, 42.6 and 45.3%). This varied share of water-resistant fractions of different sizes significantly influenced *MWDw*—the average diameter of the water-resistant aggregate in NT was almost twice that in CT (Figure 4c). The obtained results clearly indicate that the soil structure of CT was unstable and easily disrupted in the water environment into smaller macroaggregates and microaggregates compared to NT. Zheng et al. [63] also reported the enhancement of soil macroaggregate stability in the 0–10 cm surface soil layer under long-term NT conditions. The improvement of the surface soil structure in NT was also confirmed in different regions and soils [64–66]. The use of NT was associated with the cessation of periodic mechanical destruction of soil aggregates and the accumulation soil organic matter, which increases the dominance of stabilisation processes over destabilisation processes and enhances the process of the cementation of soil particles into stable structures by organic binding agents [67,68].

### *3.5. Soil Water Retention Characteristic*

SWRCs were significantly affected by the tillage treatments, especially in the 0–10 cm layer for all soil water pressures (Figure 5a–d). The NT treatment in 0–10 cm significantly increased the SWRCs at all soil water pressures compared to the CT. In the 0–10 cm layer, under the influence of 47 years of NT, the water capacity increased by 9%, 18%, 22% and 26% compared to CT at pF values of 0.0 (Figure 5a), 2.0 (Figure 5b), 3.0 (Figure 5c) and 4.2 (Figure 5d), respectively. It is noteworthy that differences were obtained at pressures corresponding to the permanent wilting point in the 0–10 cm layer, compared to the 10–20 cm layers, where no significant differences were found. Layer 0–10 cm can retain 50% more water in the NT system compared to CT and 25% more compared to the 10–20 cm layer in both treatments. Similar observations were made by De Vita et al. [69], who concluded that NT performed better with limited rainfall during the durum wheat growing season. Higher moisture contents obtained for NT under certain conditions indicate the water-saving effect due to low soil structure disturbance, as documented for Scandinavia [70], the North American drylands [71] as well as for Germany [72].

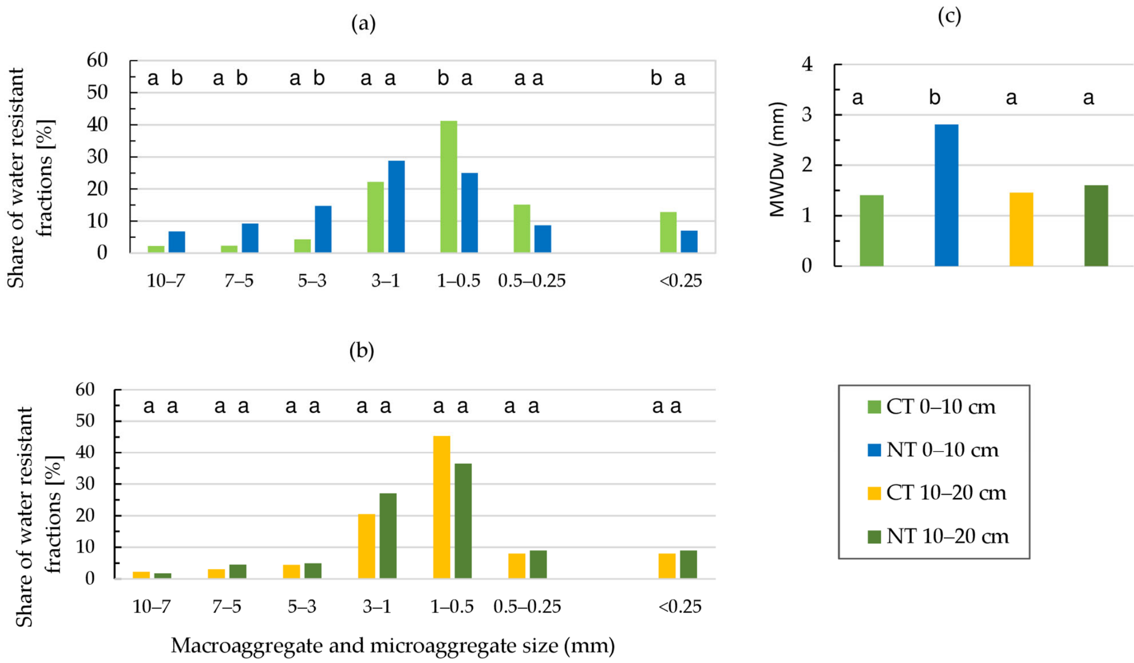


**Figure 4.** Water-stable soil macroaggregate and microaggregate size distribution for CT and NT treatment in 0–10 cm (**a**) and 10–20 cm (**b**) layers. Mean weight diameter of the water-stable macroaggregates (*MWDw*) (**c**). Different letters indicate significant differences (according to analysis of variance and Fisher's procedure, $p < 0.05$).

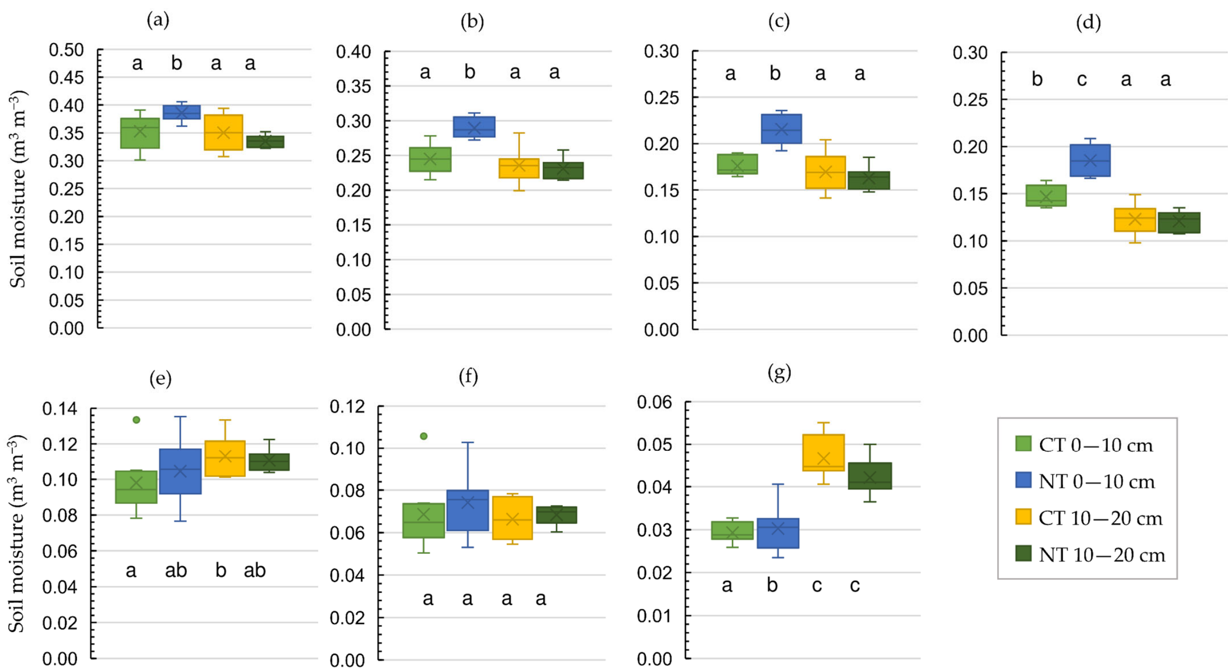


**Figure 5.** Soil water retention (box plots) measured at pF 0.0 (**a**), pF 2.0 (**b**), pF 3.0 (**c**) and pF 4.2 (**d**). Water available (boxplots and outliers) to the plant (**e**), including easily available (**f**) and difficultly available (**g**). Mean value $n = 9$; different letters indicate significant differences (according to analysis of variance and Fisher's procedure, $p < 0.05$) for the analysed CT and NT, and for the layers 0–10 and 10–20 cm.

Research conducted by Jabro and Stevens [73] during a four-year tillage study showed that soils under NT management had significantly higher plant AWC than soils under CT practices. This long-term study provided critical information on the effect of NT and CT on the range of water that is difficult for plants to access (Figure 5g), which may not effect plant development (Figure 5e,f), but may affect SOM transformation processes.

### *3.6. Soil Water Repellency*

The results indicated by the WDPT test medians for dry soil, i.e., potential SWR and actual SWR obtained at different soil moisture levels, assess it as the hydrophilic, wettable class of SWR [32]. Hydrophobicity was obtained at a single soil moisture content of pF 4.2 (Figure 6) for different system managements and layers, allowing it to be classified as SWR class 2, i.e., strongly repellent. As drought becomes more common, SWR is expected to become more common [74]. Bianco-Canqui [75] found an increase in SWR of 1.5 to 40 times in NT compared to CT management. Fifteen years of NT practice increased the water repellency index compared to the CT, as a consequence of the interactions between the hydrophobic substance and pore structure [26]. In our case, the significant difference and the lowest value of SWR were found for 10–20 cm of the NT system, which is beneficial for water infiltration. However, the widest range of values was found for NT 0–10 cm, from wettable to highly hydrophobic, suggesting that hydrophobic components accumulate in the unmixed 0–10 cm layer. The importance of the wetting history, i.e., the strength and duration of soil drying and wetting [76,77], is suggested to be the key for the effectiveness of SOM stabilisation by SWR. Bianco-Canqui and Ruis [12] and Behrends Kraemer et al. [78] proposed SWR as a driver to maintaining or improving the structural quality of the soil. Zhang et al. [79] stressed the SWR protection of aggregates is mainly related to the reduction in the initial wetting rate, which diminishes the build-up of air pressure in soil pores and reduces the slaking stress. The environmental implications of SWR occurrence are negatively perceived, i.e., slow water infiltration, increased runoff, reduced water storage and thus plant growth [80–82]. Increased SWR may cause significant restrictions and conditions for agricultural production, land use and environmental protection [83].

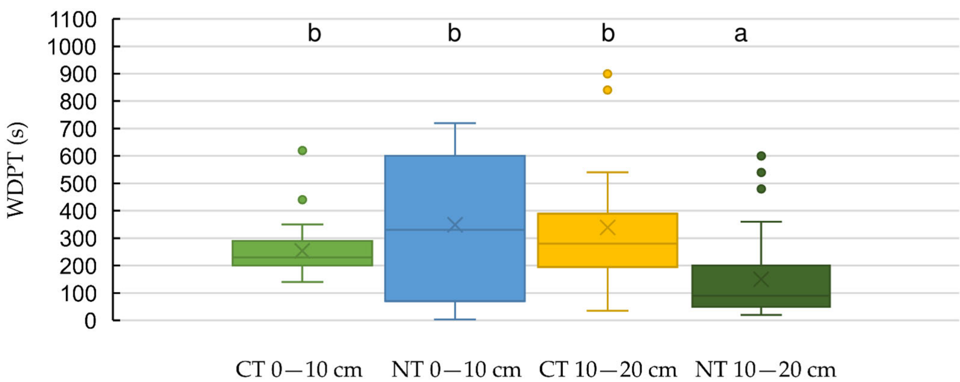


**Figure 6.** Soil water repellency, indicated by Water Drop Penetration Time (WDPT) test (boxplots and outliers) at pF = 4.2 for different system managements and layers. Median value $n$ = 45, different letters indicate significant differences determined with the Kruskal–Wallis test ($\alpha < 0.05$).

### *3.7. Soil Health Assessment*

The results of the PCA are presented in Figure 7. The first two principal components (PC1 and PC2) explain about 81% of the total variability of the data set of soil properties, which was used for the analysis. This means that most of the variability is explained by these two PCs. Both treatments (NT and CT) for the soil layer 10–20 cm were very similar according to all the soil properties used for the PCA. These two treatments, NT (10–20) and CT (10–20), have high DAW, BD and AWC, while simultaneously having a low $p$ = F0, pF = 4.2, SWR and sand content. For the 0–10 cm layer, very large differences were observed between NT and CT. CT (0–10) was characterised by high HA (C% in TOC), pH (KCl), parts < 0.25 and low HUM (C% in TOC).

NT (0–10) was characterised by high HUM (g kg$^{-1}$), TOC, TN, parts 10–7, 3–7, pF = 0, PF = 4.2 and SWR and simultaneously by low BD and FF (C% in TOC).

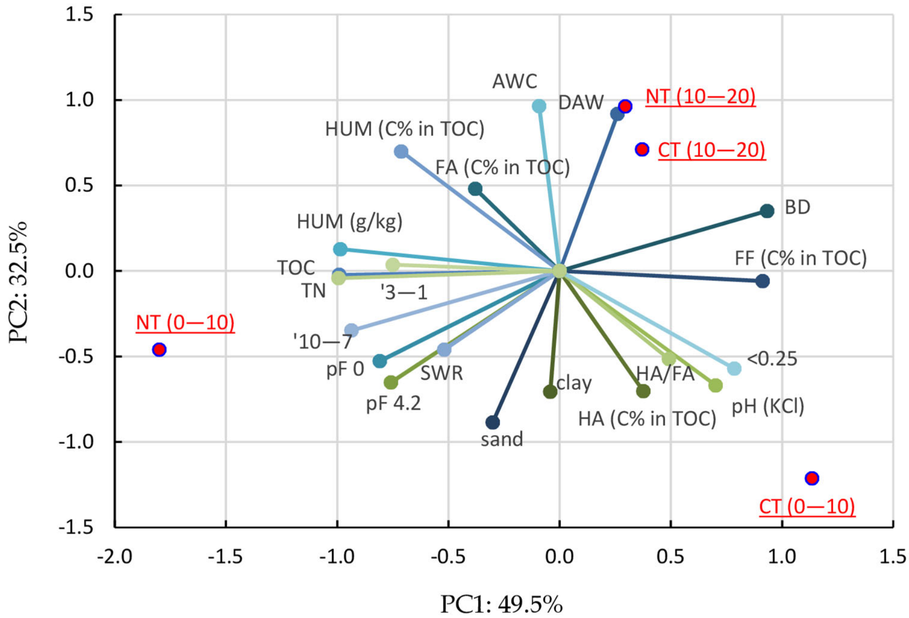


**Figure 7.** Biplot based on the results of PCA showing multivariate differences between treatments (NT 0–10—no tillage, CT—conventional tillage) and soil layers (and 10–20 cm) based on the data-characterised soil properties.

## 4. Conclusions

Our long-term study showed that a 47-year application of NT, compared to CT, resulted in a doubling of the TOC content and an improvement in the soil structure and water regime. The fractional composition of humic substances, considered as a percentage of TOC, did not change significantly, indicating that, despite a significantly slowed mineralisation of SOM, the directions of its transformation were similar in both treatments. As a result, the humin content, quantified in g kg$^{-1}$, doubled under NT. This is ecologically important because the increase in this fraction, which is considered to be the most resistant to decomposition, has a significant effect on carbon sequestration.

The UV–Vis and fluorescence properties of the humin studied showed the different dynamics of the SOM transformation processes occurring under the cultivation methods discussed. The spectroscopic properties of the humin fraction formed under NT conditions indicated its smaller size and lower molecular weight, suggesting a lower degree of humification of these substances formed under NT cultivation conditions.

NT also induced changes in physical properties, but these were confined to the 0–10 cm layer only. There was a significant improvement in soil structure and water holding capacity. A particularly positive effect on water retention was observed at pF values of 3.0 and 4.2, where soil water retention increased by 22% and 26%, respectively. However, it should be stressed that SWR occurs at low soil moisture levels, regardless of the cultivation method. The identified wide range of its values in 0–10 cm NT may lead to unfavourable phenomena related to the irregular wetting front after dry periods. Increasing the SOM content and water retention of the soils under NT conditions may be a good way to contribute to climate change mitigation and ensure food security. An integrated sustainable approach linked to soil health is needed for a long-term strategy and recognition of resilience to climate change.

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## References

1. Powlson, D.S. Soil Health—Useful Terminology for Communication or Meaningless Concept? Or Both? *Front. Agric. Sci. Eng.* **2020**, *7*, 246. [CrossRef]
2. Brevik, E.C. *A Brief History of the Soil Health Concept*; Soil Science Society of America: Madison, WI, USA, 2019.
3. USDA-NRCS Soil Health. *Soil Health*; Natural Resources Conservation Service, U.S. Department of Agriculture: Washington, DC, USA, 2019. Available online: https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/ (accessed on 25 September 2024).
4. Doran, J.W.; Zeiss, M.R. Soil Health and Sustainability: Managing the Biotic Component of Soil Quality. *Appl. Soil Ecol.* **2000**, *15*, 3–11. [CrossRef]
5. Guo, M. Soil Health Assessment and Management: Recent Development in Science and Practices. *Soil Syst.* **2021**, *5*, 61. [CrossRef]
6. EJP Soil. 2020. Available online: https://ejpsoil.eu/ (accessed on 25 September 2024).
7. Smreczak, B.; Hewelke, E.; Kowalik, M.; Ukalska-Jaruga, A.; Weber, J. Rational Management of Agricultural Soils under Climate Change. *Soil Sci. Annu.* **2024**, *75*, 193074.
8. Harris, J.A.; Evans, D.L.; Mooney, S.J. A New Theory for Soil Health. *Eur. J. Soil Sci.* **2022**, *73*, e13292. [CrossRef]
9. Purakayastha, T.J.; Trivedi, A.; Biswas, S.; Kumar, D. Soil Health and Climate Change. In *Climate Change Impacts on Soil-Plant-Atmosphere Continuum*; Advances in Global Change Research; Pathak, H., Chatterjee, D., Saha, S., Das, B., Eds.; Springer Nature: Singapore, 2024; Volume 78, pp. 107–137. ISBN 978-981-9979-34-9.
10. Mitchell, J.P.; Shrestha, A.; Mathesius, K.; Scow, K.M.; Southard, R.J.; Haney, R.L.; Schmidt, R.; Munk, D.S.; Horwath, W.R. Cover Cropping and No-Tillage Improve Soil Health in an Arid Irrigated Cropping System in California's San Joaquin Valley, USA. *Soil Tillage Res.* **2017**, *165*, 325–335. [CrossRef]
11. Page, K.L.; Dang, Y.P.; Dalal, R.C.; Reeves, S.; Thomas, G.; Wang, W.; Thompson, J.P. Changes in Soil Water Storage with No-Tillage and Crop Residue Retention on a Vertisol: Impact on Productivity and Profitability over a 50 Year Period. *Soil Tillage Res.* **2019**, *194*, 104319. [CrossRef]
12. Blanco-Canqui, H.; Ruis, S.J. No-Tillage and Soil Physical Environment. *Geoderma* **2018**, *326*, 164–200. [CrossRef]
13. Toth, M.; Stumpp, C.; Klik, A.; Strauss, P.; Mehdi-Schulz, B.; Liebhard, G.; Strohmeier, S. Long-Term Effects of Tillage Systems on Soil Health of a Silt Loam in Lower Austria. *Soil Tillage Res.* **2024**, *241*, 106120. [CrossRef]
14. Sangotayo, A.O.; Chellappa, J.; Sekaran, U.; Bansal, S.; Angmo, P.; Jasa, P.; Kumar, S.; Iqbal, J. Long-term Conservation and Conventional Tillage Systems Impact Physical and Biochemical Soil Health Indicators in a Corn–Soybean Rotation. *Soil Sci. Soc. Am. J.* **2023**, *87*, 1056–1071. [CrossRef]
15. Ćwieląg-Piasecka, I. Soil Organic Matter Composition and pH as Factors Affecting Retention of Carbaryl, Carbofuran and Metolachlor in Soil. *Molecules* **2023**, *28*, 5552. [CrossRef] [PubMed]
16. Hayes, M.H.B.; Mylotte, R.; Swift, R.S. Humin. In *Advances in Agronomy*; Elsevier: Amsterdam, The Netherlands, 2017; Volume 143, pp. 47–138. ISBN 978-0-12-812421-5.
17. Hayes, M.H.B.; Swift, R.S. Vindication of Humic Substances as a Key Component of Organic Matter in Soil and Water. In *Advances in Agronomy*; Elsevier: Amsterdam, The Netherlands, 2020; Volume 163, pp. 1–37. ISBN 978-0-12-820769-7.
18. Weber, J.; Jerzykiewicz, M.; Ukalska-Jaruga, A.; Ćwieląg-Piasecka, I.; Jamroz, E.; Kocowicz, A.; Debicka, M.; Bekier, J.; Mielnik, L.; Bejger, R.; et al. Properties of Humin Isolated from Polish Arable Soils: The Most Recalcitrant Fraction of Soil Organic Matter That Prevent Soil Degradation. *Land Degrad. Dev.* **2024**, *35*, 2425–2436. [CrossRef]
19. Debska, B.; Spychaj-Fabisiak, E.; Szulc, W.; Gaj, R.; Banach-Szott, M. EPR Spectroscopy as a Tool to Characterize the Maturity Degree of Humic Acids. *Materials* **2021**, *14*, 3410. [CrossRef]
20. Jiménez-González, M.A.; Álvarez, A.M.; Carral, P.; Almendros, G. Influence of Soil Forming Factors on the Molecular Structure of Soil Organic Matter and Carbon Levels. *Catena* **2020**, *189*, 104501. [CrossRef]
21. Machado, W.; Franchini, J.C.; De Fátima Guimarães, M.; Filho, J.T. Spectroscopic Characterization of Humic and Fulvic Acids in Soil Aggregates, Brazil. *Heliyon* **2020**, *6*, e04078. [CrossRef] [PubMed]
22. Reynolds, W.D.; Drury, C.F.; Yang, X.M.; Fox, C.A.; Tan, C.S.; Zhang, T.Q. Land Management Effects on the Near-Surface Physical Quality of a Clay Loam Soil. *Soil Tillage Res.* **2007**, *96*, 316–330. [CrossRef]
23. Fernández, F.G.; Sorensen, B.A.; Villamil, M.B. A Comparison of Soil Properties after Five Years of No-Till and Strip-Till. *Agron. J.* **2015**, *107*, 1339–1346. [CrossRef]
24. Tahat, M.M.; Alananbeh, K.M.; Othman, Y.A.; Leskovar, D.I. Soil Health and Sustainable Agriculture. *Sustainability* **2020**, *12*, 4859. [CrossRef]

25. Li, S.; Liu, X.; Wu, X.; Lu, J.; Abdelrhman, A.A.; Liang, G. Factors Governing Soil Hydrological Function under Long-term Tillage Practices: Insight into Soil Water Repellency. *Soil Sci. Soc. Am. J.* **2023**, *87*, 781–796. [CrossRef]
26. Li, S.; Lu, J.; Liang, G.; Wu, X.; Zhang, M.; Plougonven, E.; Wang, Y.; Gao, L.; Abdelrhman, A.A.; Song, X.; et al. Factors Governing Soil Water Repellency under Tillage Management: The Role of Pore Structure and Hydrophobic Substances. *Land Degrad. Dev.* **2021**, *32*, 1046–1059. [CrossRef]
27. Urbanek, E.; Hallett, P.; Feeney, D.; Horn, R. Water Repellency and Distribution of Hydrophilic and Hydrophobic Compounds in Soil Aggregates from Different Tillage Systems. *Geoderma* **2007**, *140*, 147–155. [CrossRef]
28. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World Map of the Köppen-Geiger Climate Classification Updated. *Meteorol. Z.* **2006**, *15*, 259–263. [CrossRef] [PubMed]
29. Mehlich, A. Mehlich 3 Soil Test Extractant: A Modification of Mehlich 2 Extractant. *Commun. Soil Sci. Plant Anal.* **1984**, *15*, 1409–1416. [CrossRef]
30. Swift, R.S. *Methods of Soil Analysis. Part 3. Chemical Methods*; Soil Science Society of America: Madison, WI, USA, 1996.
31. Suwara, I.; Pawlak-Zaręba, K.; Gozdowski, D.; Perzanowska, A. Physical Properties of Soil after 54 Years of Long-Term Fertilization and Crop Rotation. *Plant Soil Environ.* **2016**, *62*, 389–394. [CrossRef]
32. Elliott, E.T. Aggregate Structure and Carbon, Nitrogen, and Phosphorus in Native and Cultivated Soils. *Soil Sci. Soc. Am. J.* **1986**, *50*, 627–633. [CrossRef]
33. Klute, A. Water Retention: Laboratory Methods. In *SSSA Book Series*; Klute, A., Ed.; Soil Science Society of America, American Society of Agronomy: Madison, WI, USA, 2018; pp. 635–662. ISBN 978-0-89118-864-3.
34. Doerr, S.H.; Shakesby, R.A.; Walsh, R.P.D. Soil Water Repellency: Its Causes, Characteristics and Hydro-Geomorphological Significance. *Earth-Sci. Rev.* **2000**, *51*, 33–65. [CrossRef]
35. Hewelke, E. Influence of Abandoning Agricultural Land Use on Hydrophysical Properties of Sandy Soil. *Water* **2019**, *11*, 525. [CrossRef]
36. Dekker, L.W.; Jungerius, P.D. Water Repellency in the Dunes with Special Reference to the Netherlands. *Catena* **1990**, *18*, 173–183.
37. TIBCO Statistica (Data Analysis Software System). Version 13; TIBCO Software Inc.: Santa Clara, CA, USA, 2017.
38. Zhao, X.; He, C.; Liu, W.; Liu, W.; Liu, Q.; Bai, W.; Li, L.; Lal, R.; Zhang, H. Responses of Soil pH to No-till and the Factors Affecting It: A Global Meta-analysis. *Glob. Change Biol.* **2022**, *28*, 154–166. [CrossRef]
39. Arshad, M.A.; Schnitzer, M.; Angers, D.A.; Ripmeester, J.A. Effects of till vs No-till on the Quality of Soil Organic Matter. *Soil Biol. Biochem.* **1990**, *22*, 595–599. [CrossRef]
40. Jayaraman, S.; Naorem, A.; Dalal, R.C.; Sinha, N.K.; Srinivasa Rao, C.; Lal, R.; Kundu, S.; Prasad, J.V.N.S.; Singh, A.K. No-till Farming and Climate Change Mitigation: Lessons Learnt from Long-Term No-till Experiments and Future Perspectives. In *Advances in Agronomy*; Elsevier: Amsterdam, The Netherlands, 2024; Volume 187, pp. 21–107. ISBN 978-0-443-29530-0.
41. Mondal, S.; Chakraborty, D.; Paul, R.K.; Mondal, A.; Ladha, J. No-till is More of Sustaining the Soil than a Climate Change Mitigation Option. *Agric. Ecosyst. Environ.* **2023**, *352*, 108498. [CrossRef]
42. Six, J.; Elliott, E.T.; Paustian, K. Aggregate and Soil Organic Matter Dynamics under Conventional and No-Tillage Systems. *Soil Sci. Soc. Am. J.* **1999**, *63*, 1350–1358. [CrossRef]
43. Nunes, M.R.; Van Es, H.M.; Schindelbeck, R.; Ristow, A.J.; Ryan, M. No-till and Cropping System Diversification Improve Soil Health and Crop Yield. *Geoderma* **2018**, *328*, 30–43. [CrossRef]
44. Hussain, S.; Sharma, V.; Arya, V.M.; Sharma, K.R.; Rao, C.S. Total Organic and Inorganic Carbon in Soils under Different Land Use/Land Cover Systems in the Foothill Himalayas. *Catena* **2019**, *182*, 104104. [CrossRef]
45. Aduhene-Chinbuah, J.; Sugihara, S.; Komatsuzaki, M.; Nishizawa, T.; Tanaka, H. No Tillage Increases SOM in Labile Fraction but Not Stable Fraction of Andosols from a Long-Term Experiment in Japan. *Agronomy* **2022**, *12*, 479. [CrossRef]
46. Szajdak, L.; Jezierski, A.; Cabrera, M.L. Impact of Conventional and No-Tillage Management on Soil Amino Acids, Stable and Transient Radicals and Properties of Humic and Fulvic Acids. *Org. Geochem.* **2003**, *34*, 693–700. [CrossRef]
47. Wulanningtyas, H.S.; Gong, Y.; Li, P.; Sakagami, N.; Nishiwaki, J.; Komatsuzaki, M. A Cover Crop and No-Tillage System for Enhancing Soil Health by Increasing Soil Organic Matter in Soybean Cultivation. *Soil Tillage Res.* **2021**, *205*, 104749. [CrossRef]
48. Enev, V.; Doskočil, L.; Kubíková, L.; Klučáková, M. The Medium-Term Effect of Natural Compost on the Spectroscopic Properties of Humic Acids of Czech Soils. *J. Agric. Sci.* **2018**, *156*, 877–887. [CrossRef]
49. Ukalska-Jaruga, A.; Bejger, R.; Smreczak, B.; Podlasiński, M. Sorption of Organic Contaminants by Stable Organic Matter Fraction in Soil. *Molecules* **2023**, *28*, 429. [CrossRef]
50. Chen, Y.; Senesi, N.; Schnitzer, M. Information Provided on Humic Substances by E4/E6 Ratios. *Soil Sci. Soc. Am. J.* **1977**, *41*, 352–358. [CrossRef]
51. Bensa, A.; Miloš, B.; Jurković Balog, N.; Torić, I. Spectroscopic Characterization of Humic Substances of Anthropogenic Soils Derived from Terra Rossa. *Agrofor* **2016**, *1*, 5–11. [CrossRef]
52. Fuentes, M.; Baigorri, R.; Garcia-Mina, J.M. Maturation in Composting Process, an Incipient Humification-like Step as Multivariate Statistical Analysis of Spectroscopic Data Shows. *Environ. Res.* **2020**, *189*, 109981. [CrossRef] [PubMed]
53. Mielnik, L.; Hewelke, E.; Weber, J.; Oktaba, L.; Jonczak, J.; Podlasiński, M. Changes in the Soil Hydrophobicity and Structure of Humic Substances in Sandy Soil Taken out of Cultivation. *Agric. Ecosyst. Environ.* **2021**, *319*, 107554. [CrossRef]
54. Nieweś, D.; Marecka, K.; Huculak-Mączka, M. Application of Alkaline Deep Eutectic Solvents as a Green Alternative to the Traditional Extractants for the Isolation of Humic Substances. *ACS Omega* **2024**, *9*, 25265–25276. [CrossRef] [PubMed]

55. Coble, P.G. Characterization of Marine and Terrestrial DOM in Seawater Using Excitation-Emission Matrix Spectroscopy. *Mar. Chem.* **1996**, *51*, 325–346. [CrossRef]
56. Peuravuori, J.; Koivikko, R.; Pihlaja, K. Characterization, Differentiation and Classification of Aquatic Humic Matter Separated with Different Sorbents: Synchronous Scanning Fluorescence Spectroscopy. *Water Res.* **2002**, *36*, 4552–4562. [CrossRef]
57. Duarte, R.M.B.O.; Santos, E.B.H.; Duarte, A.C. Spectroscopic Characteristics of Ultrafiltration Fractions of Fulvic and Humic Acids Isolated from an Eucalyptus Bleached Kraft Pulp Mill Effluent. *Water Res.* **2003**, *37*, 4073–4080. [CrossRef]
58. Rodríguez, F.J.; Schlenger, P.; García-Valverde, M.A. Comprehensive structural evaluation of humic substances using several fluorescence techniques before and after ozonation. Part I: Structural characterization of humic substances. *Sci. Total Environ.* **2014**, *476–477*, 718–730. [CrossRef]
59. Chen, J.; LeBoeuf, E.J.; Dai, S.; Gu, B. Fluorescence Spectroscopic Studies of Natural Organic Matter Fractions. *Chemosphere* **2003**, *50*, 639–647. [CrossRef]
60. Kalbitz, K.; Geyer, W.; Geyer, S. Spectroscopic Properties of Dissolved Humic Substances? A Reflection of Land Use History in a Fen Area. *Biogeochemistry* **1999**, *47*, 219–238. [CrossRef]
61. Weber, J.; Mielnik, L.; Leinweber, P.; Hewelke, E.; Kocowicz, A.; Jamroz, E.; Podlasiński, M. The Influence of Different, Long-Term Fertilizations on the Chemical and Spectroscopic Properties of Soil Organic Matter. *Agronomy* **2024**, *14*, 837. [CrossRef]
62. Fuentes, M.; González-Gaitano, G.; García-Mina, J.M. The Usefulness of UV–Visible and Fluorescence Spectroscopies to Study the Chemical Nature of Humic Substances from Soils and Composts. *Org. Geochem.* **2006**, *37*, 1949–1959. [CrossRef]
63. Zheng, H.; Liu, W.; Zheng, J.; Luo, Y.; Li, R.; Wang, H.; Qi, H. Effect of Long-Term Tillage on Soil Aggregates and Aggregate-Associated Carbon in Black Soil of Northeast China. *PLoS ONE* **2018**, *13*, e0199523. [CrossRef] [PubMed]
64. Blanco-Canqui, H. Enhancing Soil Aggregation in No-Till Farming Systems. In *No-Till Farming Systems for Sustainable Agriculture*; Dang, Y.P., Dalal, R.C., Menzies, N.W., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 233–249. ISBN 978-3-030-46408-0.
65. Li, P.; Ying, D.; Li, J.; Deng, J.; Li, C.; Tian, S.; Zhao, G.; Wu, C.; Jiao, J.; Jiang, M.; et al. Global-Scale No-Tillage Impacts on Soil Aggregates and Associated Carbon and Nitrogen Concentrations in Croplands: A Meta-Analysis. *Sci. Total Environ.* **2023**, *881*, 163570. [CrossRef]
66. Sithole, N.J.; Magwaza, L.S.; Thibaud, G.R. Long-Term Impact of No-till Conservation Agriculture and N-Fertilizer on Soil Aggregate Stability, Infiltration and Distribution of C in Different Size Fractions. *Soil Tillage Res.* **2019**, *190*, 147–156. [CrossRef]
67. Six, J.; Elliott, E.T.; Paustian, K. Soil Macroaggregate Turnover and Microaggregate Formation: A Mechanism for C Sequestration under No-Tillage Agriculture. *Soil Biol. Biochem.* **2000**, *32*, 2099–2103. [CrossRef]
68. Oades, J.M. The Role of Biology in the Formation, Stabilization and Degradation of Soil Structure. *Geoderma* **1993**, *56*, 377–400. [CrossRef]
69. Devita, P.; Dipaolo, E.; Fecondo, G.; Difonzo, N.; Pisante, M. No-Tillage and Conventional Tillage Effects on Durum Wheat Yield, Grain Quality and Soil Moisture Content in Southern Italy. *Soil Tillage Res.* **2007**, *92*, 69–78. [CrossRef]
70. Rasmussen, K.J. Impact of Ploughless Soil Tillage on Yield and Soil Quality: A Scandinavian Review. *Soil Tillage Res.* **1999**, *53*, 3–14. [CrossRef]
71. Fuentes, J.P.; Flury, M.; Huggins, D.R.; Bezdicek, D.F. Soil Water and Nitrogen Dynamics in Dryland Cropping Systems of Washington State, USA. *Soil Tillage Res.* **2003**, *71*, 33–47. [CrossRef]
72. Gruber, S.; Möhring, J.; Claupein, W. On the Way towards Conservation Tillage-Soil Moisture and Mineral Nitrogen in a Long-Term Field Experiment in Germany. *Soil Tillage Res.* **2011**, *115–116*, 80–87. [CrossRef]
73. Jabro, J.D.; Stevens, W.B. Soil-Water Characteristic Curves and Their Estimated Hydraulic Parameters in No-Tilled and Conventionally Tilled Soils. *Soil Tillage Res.* **2022**, *219*, 105342. [CrossRef]
74. Davis, P.; Park, D.M. Food Security in a Changing Climate Starts with Managing Soil Water Repellency. *Geoderma* **2024**, *447*, 116922. [CrossRef]
75. Blanco-Canqui, H. Does No-till Farming Induce Water Repellency to Soils? *Soil Use Manag.* **2011**, *27*, 2–9. [CrossRef]
76. Lamparter, A.; Bachmann, J.; Goebel, M.-O.; Woche, S.K. Carbon Mineralization in Soil: Impact of Wetting–Drying, Aggregation and Water Repellency. *Geoderma* **2009**, *150*, 324–333. [CrossRef]
77. Goebel, M.-O.; Bachmann, J.; Reichstein, M.; Janssens, I.A.; Guggenberger, G. Soil Water Repellency and Its Implications for Organic Matter Decomposition—Is There a Link to Extreme Climatic Events?: Extreme Events and Soil Water Repellency. *Glob. Change Biol.* **2011**, *17*, 2640–2656. [CrossRef]
78. Behrends Kraemer, F.; Hallett, P.D.; Morrás, H.; Garibaldi, L.; Cosentino, D.; Duval, M.; Galantini, J. Soil Stabilisation by Water Repellency under No-till Management for Soils with Contrasting Mineralogy and Carbon Quality. *Geoderma* **2019**, *355*, 113902. [CrossRef]
79. Zhang, B.; Yao, S.-H.; Hu, F. Microbial Biomass Dynamics and Soil Wettability as Affected by the Intensity and Frequency of Wetting and Drying during Straw Decomposition. *Eur. J. Soil Sci.* **2007**, *58*, 1482–1492. [CrossRef]
80. Coelho, C.O.A.; Laouina, A.; Regaya, K.; Ferreira, A.J.D.; Carvalho, T.M.M.; Chaker, M.; Naafa, R.; Naciri, R.; Boulet, A.K.; Keizer, J.J. The Impact of Soil Water Repellency on Soil Hydrological and Erosional Processes under Eucalyptus and Evergreen Quercus Forests in the Western Mediterranean. *Soil Res.* **2005**, *43*, 309. [CrossRef]
81. Lichner, L.; Hallett, P.D.; Feeney, D.S.; Ďugová, O.; Šír, M.; Tesař, M. Field Measurement of Soil Water Repellency and Its Impact on Water Flow under Different Vegetation. *Biologia* **2007**, *62*, 537–541. [CrossRef]

82. Hewelke, E.; Szatylowicz, J.; Gnatowski, T.; Oleszczyk, R. Spatial Variability in Soil Moisture Content under Preferential Flow in Hydrophobic Organic Soil. *Rocz. Ochr. Sr.* **2014**, *16*, 580–607.
83. Keesstra, S.; Nunes, J.P.; Saco, P.; Parsons, T.; Poeppl, R.; Masselink, R.; Cerdà, A. The Way Forward: Can Connectivity Be Useful to Design Better Measuring and Modelling Schemes for Water and Sediment Dynamics? *Sci. Total Environ.* **2018**, *644*, 1557–1572. [CrossRef] [PubMed]