agronomy

MDPI

Article

# The Effect of Organic and Conventional Farming Systems with Different Tillage on Soil Properties and Enzymatic Activity

**Mirosław Kobierski *, Joanna Lemanowicz, Piotr Wojewódzki and Krystyna Kondratowicz-Maciejewska**

Department of Biogeochemistry and Soil Science, UTP University of Science and Technology in Bydgoszcz, Bernardynska 6/8 Street, 85-029 Bydgoszcz, Poland; jl09@interia.pl (J.L.); piotr.wojewodzki@utp.edu.pl (P.W.); kondratowicz@utp.edu.pl (K.K.-M.)

* Correspondence: kobierski@utp.edu.pl; Tel.: +48-52-374-9551

Received: 1 October 2020; Accepted: 14 November 2020; Published: 17 November 2020

check for updates

**Abstract:** The chemical properties and enzymatic activity of the surface soil horizon were compared between an organic farm (OF) (crop rotation with legume plants, fertilisation with manure) and a conventional farm (CF) (simplified crop rotation, mineral fertilisation, chemical crop protection products). In the years 2001-2017 on the OF (near the village of Juchowo, northern Poland), a reduced tillage system (ploughless) was used, while plough cultivation was used on a CF located in its immediate vicinity. The parameters used to assess the properties of soils were: particle size composition, pH, total organic carbon (TOC) and total nitrogen (TN), dissolved organic carbon (DOC) and dissolved organic nitrogen (DON). The activity of dehydrogenases (DEH), catalase (CAT), alkaline phosphatase (AlP) and acid phosphatase (AcP) and the content of easily extractable glomalin-related soil protein (EEGRSP) were also determined. Sixteen years of soil use in accordance with ecological principles significantly increased the average content of TOC, NT, DOC and DON. Soil samples rich in TOC and DOC showed significantly higher DEH and AcP activity, and EEGRSP content. Statistical analysis showed that the activity of DEH, AlP and CAT in the soil was significantly higher for the OF than for the conventional cultivation system. Limiting soil cultivation procedures on the OF improved the balance of soil organic matter (SOM) and pH value, and significantly increased the content of EEGRSP as compared to the cultivation system used on the CF.

**Keywords:** farming system; quality of soil; enzymatic activity; glomalin

## 1. Introduction

The primary goal of both conventional and organic farming is plant production. However, in organic farming, all cultivation procedures aim to protect the environment while also maintaining high crop quality, whereas in conventional agriculture the ultimate end is high yield, i.e., maximum economic efficiency. In order to achieve the intended goal in conventional agriculture, repeated high doses of artificial fertilisers and chemical crop protection materials are often used [1,2]. These may then degrade the soil environment, contaminate the groundwater and negatively affect microorganisms. Hence, an alternative to the intensification of conventional agriculture is organic farming, including biodynamic farming [3,4]. European Union legislation [5] defines organic farming as a system of sustainable management of plant and animal production within a farm, based on technologically unprocessed biological and mineral substances.

Modern agriculture is increasingly departing from the traditional, plough-based, soil tillage system, and no-tillage and non-inversion tillage are described as pro-ecological activities. Tillage systems refer to the tillage practices carried out between the harvests and describe cultivation operation with the main two groups: ploughed and ploughless soil tillage. Conventional tillage defines soil management practices with mouldboard ploughing, followed by the secondary cultivation to create a seedbed. Conservation tillage and strip-till cultivation systems are increasingly being opted for. The description of these soil cultivation systems and the simplifications they apply requires that not only their production-related aspects but also those related to environmental effects be considered. Deen and Kataki [6] report that reducing tillage treatments and performing them more shallowly slows the rate of SOM mineralisation and increases $CO_2$ sequestration in soil. Conservation tillage also prevents nutrient leaching and leaving plant residues on the soil surface reduces water loss from the soil and prevents erosion [7]. The reduced tillage practices, also referred to as conservation tillage, are one of the best alternatives to conventional tillage and they have increased globally over the last two decades [8–10]. Conservation tillage is considered an agroecological practice for a sustainable agriculture [11]. The non-plough-based cultivation practices, due to a reduction in soil disturbance, have many benefits including the enhance water retention and reduce soil erosion by maintaining a minimum of 30% of the soil surface covered by plant residues [12].

Organic farming promotes plant biodiversity management practices, conservation tillage with permanent plant cover, more extensive use of crop rotation, associated crops or intercropping, weed management and establishment of refuge areas for natural enemies of pests. The transition from conventional to organic farming, with extensive use of organic practices, may lead to increase of pest populations [13]. The decreasing pesticide application and stable environment in organic management could improve the diversity of species suppressing pest populations [14]. The agroecological approach implemented in organic management underlines the relevance of maintaining permanent plant cover on the ground and enhancing biological control by providing favorable habitats to the natural species of predators [14]. Weed management in organic farming system relies on the integrated cropping-system with a balance between crop plants and weed reproduction cycles [15]. Crop rotation, cover cropping, mulching, and conservation tillage methods, play an important role in organic farming system. These practices can suppress weeds, reduce weed populations in the subsequent crops and reduce the contribution of weed seeds to the soil seedbank. It also benefits soil fertility, disease, and pest management. Chemical control in conventional agriculture may be employed in a short period of time, but in organic farming effective weed management requires more time [16].

Soil productivity determinants that are very often decreased by tillage erosion include loss of SOM, deterioration of soil structure, and lowered water-holding capacity. Agricultural management practices significantly affect SOM amount and quality. Dissolved organic matter is defined as the part of SOM that is decomposed by soil microbes relatively easily and at quite a high rate [17,18]. The turnover of DOC and DON are described as major pathways of element cycling in arable soils [19].

Arable soil is a very diverse environment in which microorganisms play a key role in the biogeochemistry and circulation of elements, and in the decomposition of organic matter [2,20]. Enzymes in the soil environment affect the rate of release and availability of minerals to plants and catalyse reactions involved in the decomposition of SOM [21–23]. Enzymatic activity is increasingly being studied to assess the properties of soils being exploited in various ways, because it reflects the current state of the soil environment [4,24]. According to some scientists [25–27], the factors significantly affecting the content of soil organic matter in agricultural soils are fertilisation, crop rotation and tillage treatments. Over recent years, as part of sustainable agriculture, the concept of a conservation tillage system has been increasing in popularity [28]. This system is designed to leave harvest residues on the soil surface. This produces conditions favourable to the increased activity of soil microorganisms and arbuscular mycorrhizal fungi (AMF). AMFs are obligatory biotrophic organisms that live in symbiosis with the roots of plants (80% of vascular plant species), and this ensures better water and nutrient uptake. Glomalin is a kind of glycoprotein produced by AMF [29]. Furthermore, the quantity of glomalin-related soil protein (GRSP) in soil is linked with land use. It is reported that cropping systems and land management practices significantly influence the appearance of GRSP in soil. For example, the transition from plow tillage to a no-tillage system resulted in increasing GRSP concentration and stability of soil aggregates [30]. Generally, intensive crop management exerts a negative impact on GRSP content [31]. The more treatments mix the soil, the lower the concentration of GRSP. In comparison to crop rotation systems, GRSP was determined in higher quantities in undisturbed soil under perennial crops, especially grasslands [32,33]. It was found that GRSP accounts for 25% and 52% of the total carbon in mineral soils and organic soil, respectively [34]. The amount of GRSP is also affected by fertilisation. It was found that crop residues and natural fertilisers are more favourable to GRSP increase than mineral fertilisation [35–37].

Two systems of cultivation were compared on soils with similar physical properties and similar habitat conditions. On the OF, for 16 years, reduced tillage was used and manure or compost and biodynamic preparations were applied. Meanwhile, on the CF, conventional tillage by ploughing was used along with simplified crop rotation, and mineral fertilisation and synthetic crop protection products were applied. The farming system with plougless tillage on the OF and ploughed tillage on the CF have been compared. In addition, the differences also include the crop rotation, soil fertility management with on-farm organic manure production and crop protection with bio-control of pests and diseases used on the OF. Manure-based fertilization is an alternative to mineral fertilizer to improve the soil environment and soil quality. Adding the legumes into the crop rotation allows fixing atmospheric nitrogen and provides the source of easily absorbable nitrogen for subsequent crops. The research objective was to assess the chemical properties and enzymatic activity of ecologically and conventionally used soils.

## 2. Materials and Methods

### 2.1. Site Description and Soil Sampling

The study was carried out in fields of an OF (based on biodynamic agriculture) in Juchowo (53°40′17.40″ N 16°29′24.00″ E, Northern Poland) and CF fields in the immediate vicinity. Soils samples represent the area being tested and the fields which are of the same soil type and appearance. The soil type was classified as Luvisols according to WRB [38]. The fields of both farms have similar relief features and the morphology of soil. This is an example of the transition from conventional tillage to reduced tillage and the soils on the CF can be considered as control area for the soils of OF, which allows assessing the soil properties and enzymatic activity after 16 years of organic soil management. Twenty-four samples were taken from the arable horizon (0–20 cm) of both farms. The soil samples were collected after the wheat harvest in the summer of 2017 prior to tillage operations on both of farms. Soils on the OF before 2001 were actively farmed using conventional practices with ploughed tillage method, with chemical fertilizers, without manure application and with cereals domination in crop rotation. Until 2017, similar tillage practices were used on the CF. The soil sampling (24 soil samples) was made up of 24 ha from the fields of both farms after at least 100 days after the last mineral fertilization in spring; however, as for manure fertilization on the OF—after at least year. One composite (average) sample represents an area of up to 1 ha and consists of 20 sub-samples collected in a zig-zag pattern to represent the area as best as possible. The sub-samples were mixed together thoroughly to obtain the composite soil sample which was submitted for analysis. To collect sub-samples at the proper depth, an eject soil probe was used. A reduced tillage system was applied in the OF continuously from 2001 onwards (Table 1). Mineral fertilisation of soils on the CF did not exceed 140 kg NPK/ha/year (no liming). The mineral fertilisation of the OF soils involved fertilisers permitted for ecological crops in doses of about 12 kg P and 20 kg K per hectare, while manure was applied at a dose of 15–20 tonnes per hectare in a 3–4-year cycle.

**Table 1.** Cultivation system.

| OF—Reduced Tillage | CF—Conventional Tillage |
|---|---|
| Post-harvest cultivation: stubble cultivator to a depth of 6–8 cm and harrow | Post-harvest cultivation: disk harrow to a depth of 8–10 cm and fertilization |
| Basic preparation: cultivator to a depth of 15–20 cm | Basic preparation: ploughing to a depth of 30 cm |
| Pre-plant tillage: cultivating and sowing aggregate | Pre-plant tillage: cultivator followed by harrowing |

### 2.2. *Soil Sample Treatment and Methods of Analysis*

The collected soil samples were dried and sieved through a 2-mm mesh. In the soil samples (tree replication) the following were determined: particle size composition; pH in 1 M KCl; content of TOC, TN, DOC, and DON. The particle size distribution was determined using a Mastersizer 2000 laser diffraction particle size analyser (Malvern Instrument, Malvern, UK). Values of pH were measured potentiometrically in 1 M KCl solution (soil:solution ratio of 1:2.5 *w*/*v*) using a pH-meter. The contents of total organic carbon (TOC) and total nitrogen (TN) were assayed with a Vario Max CN analyser from Elementar (Langenselbold, Germany). The content of dissolved organic carbon (DOC) was assayed in soil solutions from extracting the soil of 0.004 mol $dm^{-3}$ $CaCl_2$. The content of DOC was determined with a Multi N/C 3100 Analityk Jena (Jena, Germany) analyser.

### 2.3. *The Activity of Enzymes*

Enzyme activity studies were performed on fresh soils that had been stored at 4 °C for no more than two weeks. The activity of selected enzymes: the activity of dehydrogenases (DEH) [E.C.1.1.1] in soil was assayed with the Thalmann [39] method, the activity of catalase (CAT) [E.C.1.11.1.6] with the Johnson and Temple [40] method, and the activity of alkaline (AlP) [E.C.3.1.3.1] and acid (AcP) [E.C.3.1.3.2] phosphatase with the Tabatabai and Bremner [41] method, which facilitated the calculation of enzymatic pH indicator defining the right soil reaction [42]:

$$\mathrm{AlP/AcP} \tag{1}$$

Based on the enzymatic activities of the samples, the biological index of fertility (BIF) was calculated according to Stefanic et al. [43]:

$$\mathrm{BIF} = \frac{1.5\mathrm{DEH} + 100\mathrm{kCAT}}{2}, \tag{2}$$

where: k is the factor proportionality equal to 0.01.

The indices of biochemical soil activity (BA12 and BA13) [44] were proposed based on the activities of soil enzymes, the content of clay and the content of organic carbon:

$$\mathrm{BA12} = \log_{10}\mathrm{TOC}\sqrt{\mathrm{DEH} + \mathrm{CAT} + \mathrm{AlP} + \mathrm{AcP}}, \tag{3}$$

$$\mathrm{BA13} = \log_{10}\mathrm{Clay}\sqrt{\mathrm{DEH} + \mathrm{CAT} + \mathrm{AlP} + \mathrm{AcP}}. \tag{4}$$

Based on the enzymatic activities of the samples, the geometric mean of enzyme activities (GMea) was calculated using a method [45] as follows:

$$\mathrm{GMea} = \sqrt[4]{(\mathrm{CAT} * \mathrm{DEH} * \mathrm{AlP} * \mathrm{AcP})}. \tag{5}$$

### 2.4. *EEGRSP Extraction and Determination*

Because of the different methods of extraction and determination, the term "glomalin" is reserved for purified protein [46], while the glycoprotein obtained using pressure extraction in sodium citrate solution is described as GRSP. Additionally, according to the number of extraction cycles it is specified as EEGRSP: easily extractable GRSP (one cycle of extraction) or TGRSP: total extractable GRSP (several extraction cycles) [47,48]. EEGRSP in soil samples was extracted following Wright and Upadhyaya's pressure method [47]. Determination of EEGRSP content was realised by the Bradford assay [49]. The absorbance of extracts was measured by UV-VIS Smartspec spectrophotometer (Bio-Rad 170-2525).

### *2.5. Statistical Analyses*

Soil properties were treated with standard statistics and statistical tests (ANOVA). The statistical analyses were performed using Statistica 10.0 (StatSoft Inc, Tulsa, OK, USA). Data was checked for normal distribution. The significance of the differences between means was evaluated drawing on Tukey's test for uneven number. The relationship between the parameters was determined with the Pearson correlation coefficient. The coefficient of variation (CV) was also calculated for the parameters analysed for the entire study area. As for the values, 0–15%, 16–35%, and >36% indicate low, moderate or high variation, respectively.

## **3. Results**

### *3.1. Basic Properties of Soil and Content of EEGRSP*

The studied soils were Luvisols with characteristic luvic and argic subsurface genetic horizons (field observation). The OF surface horizon soil comprised 1.08–68.80% sand fraction, 28.41–89.42% silt fraction, and 2.59–9.50% clay fraction. The percentage share of individual fractions in the CF soil was similar, at 20.33–72.45% sand fraction, 23.9–71.82% silt fraction, and 2.65–7.85% clay fraction (Tables 1 and 2). The soil texture classes on the OF were: sandy loam (14 samples), silty loam (9 samples) and silt (sample) and was similar to that on the CF, where 17 samples were sandy loam in texture and 7 were silty loam. The mean soil pH value at the OF was 6.04, which was significantly higher than the soil cultivated in the conventional system (pH 4.82) (Tables 2 and 3).

**Table 2.** Basic parameters of soil and enzymatic activity.

| Parameters | Organic Farming | | | | | Conventional Farming | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Min. | Max. | Med. | SD | CV | Min. | Max. | Med. | SD | CV |
| Sand | 1.08 | 68.80 | 50.91 | 16.34 | 34.8 | 20.33 | 72.45 | 55.80 | 11.83 | 22.7 |
| Silt | 28.41 | 89.42 | 44.55 | 14.64 | 30.4 | 23.90 | 71.82 | 39.59 | 10.66 | 24.7 |
| Clay | 2.59 | 9.50 | 4.46 | 1.84 | 37.5 | 2.65 | 7.85 | 4.79 | 1.32 | 27.4 |
| pH (1 M KCl) | 4.52 | 6.82 | 6.06 | 0.53 | 8.80 | 2.65 | 7.85 | 4.79 | 1.32 | 27.4 |
| TOC | 8.80 | 36.2 | 11.4 | 6.92 | 48.7 | 6.50 | 24.0 | 9.70 | 3.73 | 36.2 |
| TN | 0.80 | 3.90 | 1.10 | 0.71 | 50.7 | 0.70 | 2.4 | 1.00 | 0.38 | 34.5 |
| DEH | 0.25 | 0.66 | 0.41 | 0.12 | 28.6 | 0.21 | 0.48 | 0.29 | 0.07 | 22.6 |
| CAT | 0.05 | 0.16 | 0.08 | 0.03 | 33.3 | 0.03 | 0.11 | 0.08 | 0.02 | 28.6 |
| AlP | 0.63 | 2.21 | 1.01 | 0.41 | 36.6 | 0.41 | 1.48 | 0.71 | 0.29 | 37.2 |
| AcP | 1.08 | 3.46 | 1.90 | 0.59 | 29.9 | 0.79 | 3.22 | 1.62 | 0.52 | 30.8 |
| EEGRSP | 0.41 | 2.12 | 1.05 | 0.341 | 33.1 | 0.42 | 1.17 | 0.87 | 0.247 | 31.3 |
| DOC | 70.3 | 138 | 93.1 | 18.46 | 19.0 | 89.9 | 251 | 118 | 42.64 | 31.3 |
| DON | 19.9 | 47.1 | 30.3 | 7.82 | 25.1 | 17.7 | 46.9 | 22.0 | 7.93 | 30.5 |

Sand, Silt, Clay [%]; TOC—total organic carbon [g kg$^{-1}$]; TN—total nitrogen [g kg$^{-1}$]; EEGRSP—easily extractable glomalin-related soil protein [g kg$^{-1}$]; DOC—dissolved organic carbon [g kg$^{-1}$]; DON—dissolved organic nitrogen [g kg$^{-1}$]; DHA—dehydrogenases [mg TPF kg$^{-1}$ 24 h$^{-1}$]; CAT—catalase [mg $H_2O_2$ g$^{-1}$ min$^{-1}$]; AlP—alkaline phosphatase and AcP—acid phosphatase [mM pNP kg$^{-1}$ h$^{-1}$]; Med.—median; SD—standard deviation; CV—coefficient of variation.

Sixteen years of soil use in accordance with biodynamic principles had a significant influence, increasing not only the pH value, but also the average contents of TOC and TN, which were 14.2 g kg$^{-1}$ and 1.42 g kg$^{-1}$, respectively. The CV values for the above-mentioned properties were higher in the OF soil, indicating their high variability. The content of DOC, DON and EEGRSP was significantly lower in the soil cultivated on the CF than in the OF soil. Specifically, in the CF soil, the average contents were: DOC 97.1 g $kg^{-1}$ DON 26.0 g $kg^{-1}$ and EEGRSP 0.79 g $kg^{-1}$, while in the OF soil the contents were significantly higher, at DOC 136 g $kg^{-1}$, DON 31.2 g $kg^{-1}$ and EEGRSP 1.03 g $kg^{-1}$. The CV values for these properties indicated moderate variability and were similar for both farming systems.

**Table 3.** Results of statistical analysis (Anova, Tukey's test).

| Parameters * | Organic Farming Mean (N = 24) | Conventional Farming Mean (N = 24) | Significant ($p$) |
|---|---|---|---|
| pH (1 M KCl) | 6.04 | 4.82 | 0.0002 |
| sand | 46.92 | 52.04 | 0.21 |
| silt | 48.17 | 43.14 | 0.18 |
| Clay | 4.91 | 4.82 | 0.84 |
| TOC | 14.2 | 10.3 | 0.019 |
| TN | 1.42 | 1.10 | 0.043 |
| DHA | 0.42 | 0.31 | 0.0005 |
| CAT | 0.09 | 0.07 | 0.048 |
| AlP | 1.12 | 0.78 | 0.002 |
| AcP | 1.97 | 1.69 | 0.094 |
| EEGRSP | 1.03 | 0.79 | 0.007 |
| DOC | 136 | 97.1 | 0.007 |
| DON | 31.2 | 26.0 | 0.026 |

* explanations as in Table 2.

The content of TOC in both OF and CF soils, was found to significantly positively correlate with TN, DOC and DON (Table 4). Significant correlation was designated, in both farming systems, for EEGRSP and TOC—positive relationship, and between EEGRSP and clay content—negative relationship (Table 4). The obtained results also indicate significant positive correlation between content of soil carbon (TOC, DOC) and DEH and AcP activity in OF as well as CF (Table 4).

**Table 4.** Significant correlation coefficients at $p < 0.05$.

| Parameters * | Organic Farming (N = 24) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Clay | TOC | TN | DOC | DEH | AlP | AcP | EEGRSP |
| pH | | | | | | | −0.55 | |
| TN | | 0.99 | | | 0.53 | | 0.64 | 0.80 |
| DOC | | 0.95 | | | 0.44 | | 0.62 | 0.75 |
| DON | | 0.69 | 0.69 | 0.78 | | | | 0.60 |
| DEH | 0.58 | 0.54 | | | | | | |
| AcP | | 0.65 | | | 0.65 | | | |
| EEGRSP | −0.60 | 0.78 | | | | | | |
| **Parameters *** | **Conventional Farming (N = 24)** | | | | | | | |
| | **Clay** | **TOC** | **TN** | **DOC** | **DEH** | **AlP** | **AcP** | **EEGRSP** |
| TN | | 0.97 | | | 0.58 | 0.76 | 0.79 | 0.58 |
| DOC | | 0.84 | | | 0.42 | 0.73 | 0.79 | 0.69 |
| DON | | 0.80 | 0.87 | 0.82 | 0.48 | 0.57 | 0.63 | |
| DEH | | 0.54 | | | | | | |
| AlP | | 0.81 | | | | | | |
| AcP | | 0.81 | | | 0.51 | 0.73 | | |
| EEGRSP | −0.47 | 0.65 | | | | 0.81 | 0.59 | |

* explanations as in Table 2.

### 3.2. The Activity of Enzymes in Soil

The DEH activity of OF soil ranged from 0.25 to 0.66 mg TPF $kg^{-1}$ 24 $h^{-1}$ (mean 0.42 mg TPF $kg^{-1}$ 24 $h^{-1}$), CAT from 0.03 to 0.11 mg $H_2O_2$ $g^{-1}$ $min^{-1}$ (mean 0.07 mg $H_2O_2$ $g^{-1}$ $min^{-1}$), AlP from 0.42 to 1.48 mM pNP $kg^{-1}$ $h^{-1}$ (mean 0.78 mM pNP $kg^{-1}$ $h^{-1}$) and AcP from 0.79 to 3.22 mM pNP $kg^{-1}$ $h^{-1}$ (mean 1.69 mM pNP $kg^{-1}$ $h^{-1}$) (Tables 2 and 3). Statistical analysis revealed that the activity of DEH, CAT and AlP was significantly higher in soil from OF than from CF—35%, 29% and 45% higher, respectively. The activity of AcP was higher, though not statistically significantly ($p = 0.094$) (Table 2). The CV values for the tested enzymes ranged from 22.6 to 37.2% for CF soils and from 28.6 to 36.6% for OF soils, indicating moderate variability. However, distribution analysis showed that most results are below average, as indicated by the median being less than the mean. Correlation analysis showed significant positive relationships between the activities of: AlP and AcP (r = 0.73, $p < 0.05$) and AcP and DEH (r = 0.51, $p < 0.05$) in *CF* soil; and AcP and DEH (r = 0.65) in OF soil. The activity of DEH was also determined to have significant positive correlations with contents of: TOC (r = 0.54, $p < 0.05$), DOC (r = 0.42, $p < 0.05$), TN (r = 0.58, $p < 0.05$) and DON (r = 0.48, $p < 0.05$). The soil glomalin content correlated significantly with the activity of AlP (r = 0.81, $p < 0.05$) and AcP (r = 0.59, $p < 0.05$). Significant positive correlations were determined between the activity of soil phosphatases and the content of TOC, DOC, TN and DON in the CF soils. In the OF soils, there was a significant positive correlation between DEH activity and clay fraction (r = 0.58, $p < 0.05$) and a significant negative correlation between pH and AcP (r = −0.55, $p < 0.05$) (Table 4).

The enzyme activity results were used to calculate values for multiparametric biochemical indices of the state of the soil environment (AlP/AcP, BIF, BA12, BA13 and GMea) (Figure 1), which in turn were used to assess the influence of the cultivation system. The value of the AlP/AcP enzymatic index of soil pH [42] was 0.60 in the OF soils, and 0.46 for CF (Figure 1). The value of the biological index of soil fertility (BIF), calculated based on DEH and CAT activity [43] was 35% higher in the OF soil compared to CF soil. The indices BA12, BA13 and GMea were also higher in the OF soil (1.8, 1.86 and 0.526 respectively) than in the CF soil (1.73, 1.17 and 0.369 respectively).

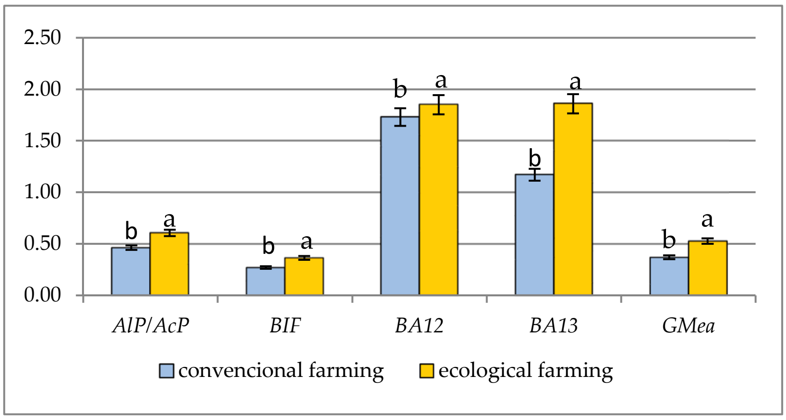


**Figure 1.** Values of enzymatic indices: pH value (AlP/AcP), soil fertility (BIF), soil activity (B12 and B13) and geometric mean of enzyme activities (GMea), standard deviation bar is presented in each column. (Different small letters indicate significant difference between two farming systems).

## 4. Discussion

The arable soils of the two farms were located in close proximity to one another and so had similar physical properties. The particle size composition of the two soils was so similar as to represent no effective qualitative difference, as indicated by the lack of significant differences between the content of individual granulometric fractions. Managing soil organic matter in organic crop rotation involved introducing crop residue from crops with different nutrient needs, using cover plants and adding organic soil additives. Legume crops were used in plant rotations to meet the needs of nitrogen-demanding crops. Finally, cattle manure could supplement nutrients at specific times during a rotation. The comparison of the described data may only refer to the considered agricultural system, i.e., conventional and organic farming, as there is no evidence of a clear influence on the tillage system on soil properties and enzymatic activity, due to different organic and mineral fertilization and different crop rotation applied on both farms.

The sixteen years of soil use in accordance with ecological (biodynamic) principles significantly increased the average TOC and NT contents in their surface horizon as compared to the soil of the CF. Significantly lower means of DOC and DON were noted in the soil samples from the CF. As reported by Leinweber et al. [50], the plough is a factor that can stimulate the microbiological composition of post-harvest residue, thus increasing the DOC content. A high rate of SOM mineralisation due to intensive treatments can intensify release of DOC [51]. Sosulski et al. [52] found that the content of DOC in the surface horizon depends on the type of fertilisation, especially the application of manure. Labile carbon compounds, in contrast to the total SOC pool, are more measurably affected by tillage and residue management. Halpern et al. [53] stated that the labile carbon fractions are physically protected in aggregates under a no-tillage system and suggested that the measurements of labile fractions may be the best indicators of management-induced changes in the total SOC content. Moreno et al. [54] found that long-term conservation tillage increased TOC content and the quality and stability of SOM. The labile fractions of organic carbon are more sensitive to changes in soil management practices [55]. Both tillage treatments and the application of cattle manure as well as the addition of legumes in crop rotation have increased SOC, enzymatic activity and improved soil fertility on the OF. The addition of cattle manure to soils on the OF increased the activity of a variety of soil enzymes. Applying solid manure to soils has beneficial effects on nutrient cycling and soil microbial activity [56]. Schoenau and Davis [57] indicate that manure should be regarded as a beneficial soil conditioner and applying solid cattle manure improves soil pH towards neutral in acidic [58].

The obtained results indicate the positive influence that OF with reduced tillage and manure application has on the content of EEGRSP, which was significantly higher in comparison to CF. Other authors [34,59] have also observed a similar dependence that confirms the adverse effect of intensive soil-mixing treatments on the AMF community and GRSP concentration in soil. Another factor that influenced EEGRSP content was fertilisation. Gosh et al. [36] observed that the application of manure in addition to mineral fertilisation is associated with an increase in the content of glomalin. The increased EEGRSP content in soil was related to a similar phenomenon concerning soil carbon and nitrogen. A significant positive correlation was designated between TOC, DOC, TN and EEGRSP (Table 4). The same relationship is confirmed by results presented by Borie et al. [33], Wojewódzki and Cieścińska [60] and Kobierski et al. [24]. Correlation analysis also revealed a significant positive relationship between EEGRSP and soil phosphatases (AlP, AcP) in the system of CF and a negative one between EEGRSP and clay content (Table 4) in CF as well as in OF. This result is consistent with examination of soils under trees in urban parks (AlP-EEGRSP: $r = 0.846$, AcP-EEGRSP: $r = 0.734$, EEGRSP-clay: $r = -0.815$) [23] and soils from stands of common dandelion (clay-EEGRSP $r = -0.54$) [20].

The research confirmed the positive effect that using a simplified tillage treatments for sixteen years on the OF had on the enzymatic activity of the soil and on the indices calculated based on them, as compared to the cultivation system used on the CF. The higher enzymatic activity of OF soils can be attributed to the higher availability of nutrients from natural and organic fertilisers [61]. Manure and harvest residues are a source of organic carbon, which stimulates the development of soil microflora and the secretion of extracellular enzymes [62]. These are responsible for converting nutrients into forms available to plants. This is confirmed by previous studies on enzyme activity conducted by Furtak and Gajda [63] and Sheoran et al. [64]. The CV analysis for the two soil-use systems ranked the enzymes as follows: for CF soils: AlP > AcP > CAT > DEH; and for OF soils: AlP > CAT > AcP > DEH, showing that alkaline phosphatase was the most sensitive to the cultivation treatments used. Research by Gałązka et al. [65], Qiau et al. [66], and Lemanowicz et al. [23] showed soil enzymes to have a significant effect on the production of glomalins, and thus on the transformation of nutrients. Soil enzymes are involved in all biochemical processes in the soil environment. They are closely involved in the decomposition of organic matter, energy transfer, and the circulation of nutrients [67]. Dehydrogenases act via the biological oxidation of organic matter in the soil, which is why they are considered indicators of overall soil microbial activity [68]. Phosphatases play an important role in the biochemical mineralisation of organic phosphorus, and so can be a good indicator of phosphorus circulation in soil [22,69]. Statistical analysis showed that the basic soil properties (pH, TOC, DOC, TN, DON) determined the activity of enzymes in OF and CF soils alike. According to Tian et al. [70] extracellular hydrolytic and oxidative enzymes are responsible for converting organic matter from high-molecular-weight compounds to the low-molecular-weight compounds present in DOC. The positive correlations between the activity of soil enzymes that were obtained indicate that the activity of one enzyme in the soil may reflect the activity of another [70].

The practical need to use indices to determine soil quality has been emphasised in previous studies [71,72]. They make it possible to assess the effects of soil use and human impact. According to Dick et al. [42] and Piotrowska-Długosz et al. [73], when the value of the enzymatic soil pH indicator (AlP/AcP) is above 0.5, soil pH should be taken as alkaline or neutral. For an AlP/AcP ratio of approximately 0.5, soil pH can be considered optimal for plant growth and development. Soil phosphatases are enzymes sensitive to changes in soil pH [42], and the optimal pH for acid phosphatase activity is around pH 6.0. As the pH rises, this enzyme's activity falls [68]. García-Ruiz et al. [74] consider the geometric mean of enzyme activities (GMea) to be another index depicting changes in soil fertility. According to Wyszkowska et al. [44], in combination with TOC and clay fraction, enzymatic activity reflects the fertility and intensity of soil processes. Notably higher values of the presented indices were observed in OF soil, where reduced tillage was used, manure or compost was applied, and biodynamic preparations stimulating enzymatic activity were utilised. This warrants the conclusion that soil enzymatic activity reflects qualitative and quantitative changes in soil that depend on the system of soil farming. Limiting cultivation procedures, including refraining from deep ploughing, significantly increased the SOM content in OF soil. Saviozzi et al. [75] and Lemanowicz et al. [76] conclude that the activity of enzymes is mainly determined by organic matter content, whose composition and transformation both depend on the tillage system.

## 5. Conclusions

It is difficult to clearly define whether the current properties of soils in OF have been significantly influenced by tillage methods or whether all agricultural practices. Therefore the entire farming system used in OF and CF was compared. Sixteen years of soil cultivation in accordance with ecological (biodynamic) principles significantly improved the soil reaction and average TOC, NT, DOC, DON and EEGRSP contents in the surface horizon, as compared to a conventional cultivation system. The study concluded that the soils under an organic farming system were found to be superior in terms of the activity of enzymes than those under a conventional farming system. The input of readily available organic material in OF resulted in an increase in soil enzymatic activity. The amount of EEGRSP, DEH and AcP activity were significantly positively correlated with DOC in both analysed farming systems. To sum up, the use of the reduced tillage method, legumes in crop rotation and the application of manure improved the soil quality for OF management, as compared with the conventional tillage method, cereals domination in crop rotation and the lack of manure in soil fertilization on the CF.

**Author Contributions:** Conceptualisation. M.K. and J.L.; methodology. M.K., J.L. and P.W.; software. M.K.; validation. J.L., P.W. and K.K.-M.; formal analysis. M.K., J.L., P.W. and K.K.-M.; investigation. M.K., J.L., P.W. and K.K.-M.; resources. M.K., J.L., P.W. and K.K.-M.; data curation. M.K., J.L., P.W. and K.K.-M.; writing—original draft preparation. M.K., J.L., and P.W.; writing—review and editing. M.K., J.L. and P.W.; visualisation. M.K. and J.L.; supervision. M.K. and J.L.; project administration. M.K.; funding acquisition. M.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was partly funded by Karlowski Foundation [Fundacja im. Stanisława Karłowskiego] Spółka Rolnicza Juchowo Sp. z o.o. Nr KRS 0000051026.

**Acknowledgments:** This research was supported by UTP, University of Science and Technology in Bydgoszcz, Poland. We acknowledge the administrative support given by Renata Żelazna—Member of the Karlowski Foundation Board. We thank Anna Szumełda and Krzysztof Ostrowicki from Spółka Rolnicza Juchowo for providing insight that greatly assisted the research.

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

## References

1. Domagała-Świątkiewicz, I.; Gąstoł, M. Soil chemical properties under organic and conventional crop management systems in south Poland. *Biol. Agric. Hortic.* **2013**, *29*, 12–28. [CrossRef]
2. Fess, T.L.; Benedito, V.A. Organic versus conventional cropping sustainability: A comparative system analysis. *Sustainability* **2018**, *10*, 272. [CrossRef]
3. Medan, D.; Torretta, J.P.; Hodara, K.; de la Fuente, E.B.; Montaldo, N.H. Effects of agriculture expansion and intensification on the vertebrate and invertebrate diversity in the Pampas of Argentina. *Biodivers Conserv.* **2011**, *20*, 3077–3100. [CrossRef]
4. Bobulská, L.; Fazekašová, D.; Angelovičová, L.; Kotorová, D. Impact of ecological and conventional farming systems on chemical and biological soil quality indices in a cold mountain climate in Slovakia. *Biol. Agric. Hortic.* **2015**, *26*, 2–17. [CrossRef]
5. Council of the European Union. Council Regulation (EEC) No 2092/91 of 24 June 1991 on Organic Production of Agricultural Products and Indications Referring Thereto on Agricultural Products and Foodstuffs. EUR-Lex Home Page. Available online: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A31991R2092 (accessed on 17 November 2020).
6. Deen, W.; Kataki, P.K. Carbon sequestration in a long-term conventional versus conservation tillage experiment. *Soil Tillage Res.* **2003**, *74*, 143–150. [CrossRef]
7. Skaalsveen, K.; Ingram, J.; Clarke, L.E. The effect of no-till farming on the soil functions of water purification and retention in north-western Europe: A literature review. *Soil Tillage Res.* **2019**, *189*, 98–109. [CrossRef]
8. Holland, J.M. The environmental consequences of adopting conservation tillage in Europe: Reviewing the evidence. *Agric. Ecosyst. Environ.* **2004**, *103*, 1–25. [CrossRef]
9. Mäder, P.; Berner, A. Development of reduced tillage systems in organic farming in Europe. *Renew. Agric. Food Syst.* **2012**, *27*, 7–11. [CrossRef]
10. Hofmeijer, M.A.J.; Krauss, M.; Berner, A.; Peigné, J.; Mäder, P.; Armengot, L. Effects of reduced tillage on weed pressure, nitrogen availability and winter wheat yields under organic management. *Agronomy* **2019**, *9*, 180. [CrossRef]
11. Wezel, A.; Casagrande, M.; Celette, F.; Vian, J.-F.; Ferrer, A.; Peigné, J. Agroecological practices for sustainable agriculture. A review. *Agron. Sustain. Dev.* **2014**, *34*, 1–20. [CrossRef]
12. Peigné, J.; Ball, B.C.; Roger-Estrade, J.; David, C. Is conservation tillage suitable for organic farming? A review. *Soil Use Manag.* **2007**, *23*, 129–144. [CrossRef]
13. Bianchi, F.J.J.A.; Ives, A.R.; Schellhorn, N.A. Interactions between conventional and organic farming for biocontrol services across the landscape. *Ecol. Appl.* **2013**, *23*, 1531–1543. [CrossRef] [PubMed]
14. Deguine, J.P.; Penvern, S. Agroecological crop protection in organic farming: Relevance and limits. In *Organic Farming, Prototype for Sustainable Agricultures*; Bellon, S., Penvern, S., Eds.; Springer: Dordrecht, The Netherlands, 2014; pp. 107–130. [CrossRef]
15. Lundkvist, A.; Verwijst, T. Weed biology and weed management in organic farming. *Res. Org. Farming* **2011**, 157–186. [CrossRef]
16. Bastiaans, L.; Paolini, R.; Baumann, D.T. Focus on ecological weed management: What is hindering adoption? *Weed Res.* **2008**, *48*, 481–491. [CrossRef]
17. McLachlan, K.K.; Hobbie, S.E. Comparison of soil organic matter fractionation technique. *Soil Sci. Soc. Am. J.* **2004**, *68*, 1616–1625. [CrossRef]
18. Garbuio, F.J.; Jones, D.L.; Allioni, L.R.F.; Murphy, D.V.; Caires, E.F. Carbon and nitrogen dynamics in an Axisol as affected by liming and crop residue under no-till. *Soil Sci. Soc. Am. J.* **2011**, *75*, 1723–1730. [CrossRef]
19. Kalbitz, K.; Solinger, S.; Park, J.-H.; Michalzik, B.; Matzner, E. Controls on the dynamics of organic matter in soils: A review. *Soil Sci.* **2000**, *165*, 277–304. [CrossRef]

20. Nielsen, S.; Minchin, T.; Kimber, S.; Zwieten, L.; Gilbert, J.; Munroe, P.; Joseph, S.; Thomas, T. Comparative analysis of the microbial communities in agricultural soil amended with enhanced biochars or traditional fertilizers. *Agric. Ecosyst. Environ.* **2014**, *191*, 73–82. [CrossRef]
21. Gianfreda, L.; Ruggiero, P. Enzyme Activities in Soil. In *Nucleic Acids and Proteins in Soil*; Soil Biology; Nannipieri, P., Smalla, K., Eds.; Springer: Berlin/Heidelberg, Germany, 2006; Volume 8.
22. Piotrowska-Długosz, A. Significance of enzymes and their application in agriculture. In *Biocatalysis*; Husain, Q., Ullah, M., Eds.; Springer: Cham, Switzerland, 2019.
23. Lemanowicz, J.; Haddad, S.A.; Bartkowiak, A.; Lamparski, R.; Wojewódzki, P. The role of an urban park's tree stand in shaping the enzymatic activity, glomalin content and physicochemical properties of soil. *Sci. Total Environ.* **2020**, *741*, 140446. [CrossRef]
24. Kobierski, M.; Kondratowicz-Maciejewska, K.; Banach-Szott, M.; Penas Castejon, J.M. Humic substances and aggregate stability in rhizospheric and non-rhizospheric soil. *J. Soils Sediments* **2018**, *18*, 2777–2789. [CrossRef]
25. Chantigny, M.H. Dissolved and water-extractable organic matter in soils: A review on the influence of land use and management practice. *Geoderma* **2003**, *113*, 357–380. [CrossRef]
26. Balík, J.; Černý, J.; Kulhánek, M.; Sedlář, O. Soil carbon transformation in long-term field experiments with different fertilization treatments. *Plant Soil Environ.* **2018**, *64*, 578–586. [CrossRef]
27. Si, P.; Liu, E.; He, W.; Sun, Z.; Dong, W.; Yan, C.; Zhang, Y. Effect of no-tillage with straw mulch and conventional tillage on soil organic carbon pools in Northern China. *Arch. Agron. Soil Sci.* **2018**, *64*, 398–408. [CrossRef]
28. Busari, A.M.; Kukal, S.S.; Kaur, A.; Bhatt, R.; Dulazi, A.A. Conservation tillage impacts on soil, crop and the environment. *J. Soil Water Conserv.* **2015**, *3*, 119–129. [CrossRef]
29. Gonzalez-Chavez, M.C.; Carrillo-Gonzalez, R.; Wright, S.F.; Nichols, K.A. The role of glomalin, a protein produced by arbuscular mycorrhizal fungi, in sequestering potentially toxic elements. *Environ. Pollut.* **2004**, *130*, 317–323. [CrossRef] [PubMed]
30. Wright, S.F.; Starr, J.L.; Paltineanu, I.C. Changes in aggregate stability and concentration of glomalin during tillage management transition. *Soil Sci. Soc. Am. J.* **1999**, *63*, 1825–1829. [CrossRef]
31. Avio, L.; Castaldini, M.; Fabiani, A.; Bedini, S.; Sbrana, C.; Turrini, A.; Giovannetti, M. Impact of nitrogen fertilization and soil tillage on arbuscular mycorrhizal fungal communities in a Mediterranean agroecosystem. *Soil Biol. Biochem.* **2013**, *67*, 285–294. [CrossRef]
32. Wright, S.F.; Anderson, R.L. Aggregate stability and glomalin in alternative crop rotations for the central Great Plains. *Biol. Fertil. Soils.* **2000**, *31*, 249–253. [CrossRef]
33. Borie, F.; Rubio, R.; Rouanet, J.L.; Morales, A.; Borie, G.; Rojas, C. Effects of tillage systems on soil characteristics, glomalin and mycorrhizal propagules in a Chilean Ultisol. *Soil Tillage Res.* **2006**, *88*, 253–261. [CrossRef]
34. Schindler, F.V.; Mercer, E.J.; Rice, J.A. Chemical characteristics of glomalin-related soil protein (GRSP) extracted from soils of varying organic matter content. *Soil Biol. Biochem.* **2007**, *39*, 320–329. [CrossRef]
35. Wright, S.F.; Green, V.S.; Cavigelli, M.A. Glomalin in aggregate size classes from three different farming systems. *Soil Tillage Res.* **2007**, *94*, 546–549. [CrossRef]
36. Ghosh, A.; Bhattacharyya, R.; Meena, M.C.; Dwivedi, B.S.; Singh, G.; Agnihotri, R.; Sharma, C. Long-term fertilization effects on soil organic carbon sequestration in an Inceptisol. *Soil Tillage Res.* **2018**, *177*, 134–144. [CrossRef]
37. Singh, G.; Bhattacharyya, R.; Das, T.K.; Sharma, A.R.; Ghosh, A.; Das, S.; Jha, P. Crop rotation and residue management effects on soil enzyme activities, glomalin and aggregate stability under zero tillage in the Indo-Gangetic Plains. *Soil Tillage Res.* **2018**, *184*, 291–300. [CrossRef]
38. IUSS Working Group WRB. *World Reference Base for Soil Resources 2014, Update 2015. International for Soil Classification System for Naming Soil and Creating Legends for Soil Maps*; World Soil Resources Reports No 106; FAO: Rome, Italy, 2015.
39. Thalmann, A. Zur methodic derestimung der Dehydrogenaseaktivität und Boden mittels Triphenyltetrazoliumchlorid (TTC). *Landwirtsch. Forsch.* **1968**, *21*, 249–258.
40. Johnson, J.I.; Temple, K.I. Some variables affecting the measurements of catalase activity in soil. *Soil Sci. Soci. Am.* **1964**, *28*, 207–209. [CrossRef]

41. 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]
42. Dick, W.A.; Cheng, L.; Wang, P. Soil acid alkaline phosphatase activity as pH adjustment indicators. *Soil Biol. Biochem.* **2000**, *32*, 1915–1919. [CrossRef]
43. Stefanic, F.; Ellade, G.; Chirnageanu, J. Researches concerning a biological index of soil fertility. In *Proceeding of the Fifth Symposium of Soil Biology*; Nemes, M.P., Kiss, S., Papacostea, P., Stefanic, C., Rusan, M., Eds.; Romanian National Society of Soil Science: Bucharest, Romania, 1984; pp. 35–45.
44. Wyszkowska, J.; Borowik, A.; Kucharski, M.; Kucharski, J. Applicability of biochemical indices to quality assessment of soil polluted with heavy metals. *J. Elemen.* **2013**, *18*, 733–756. [CrossRef]
45. 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]
46. Gillespie, A.W.; Farrell, R.E.; Walley, F.L.; Ross, A.R.S.; Leinweber, P.; Eckhardt, K.U.; Regier, T.Z.; Blyth, R.I.R. Glomalin-related soil protein contains non-mycorrhizal-related heat-stable proteins, lipids and humic materials. *Soil Biol. Biochem.* **2011**, *43*, 766–777. [CrossRef]
47. Wright, S.F.; Upadhyaya, A. Extraction of an abundant and unusual protein from soil and comparison with hyphal protein of arbuscular mycorrhizal fungi. *Soil Sci.* **1996**, *161*, 575–586. [CrossRef]
48. Rillig, M.C. Arbuscular mycorrhizae, glomalin, and soil aggregation. *Can. J. Soil Sci.* **2004**, *84*, 355–363. [CrossRef]
49. Bradford, M.M. A rapid and sensitive metod for the quantitation of microgram quantities of protein utilizing the principle of proteine dye-binding. *Anal. Biochem.* **1976**, *72*, 248–254. [CrossRef]
50. Leinweber, P.; Schulten, H.R.; Kalbitz, K.; Meisner, R.; Jancke, H. Fulvic acid composition in degraded fenlands. *J. Plant Nutr. Soil Sci.* **2001**, *164*, 371–379. [CrossRef]
51. Andruschkewitsch, R.; Geisseler, D.; Koch, H.J.; Ludwig, B. Effects of tillage on contents of organic carbon, nitrogen, water-stable aggregates and light fraction four different long-term trials. *Geoderma* **2013**, *192*, 368–377. [CrossRef]
52. Sosulski, T.; Szara, E.; Korc, M.; Stepień, W. Dissolved organic carbon in Luvisol under different fertilization and crop rotation. *Soil Sci. Ann.* **2013**, *64*, 114–118. [CrossRef]
53. Halpern, M.T.; Whalen, J.K.; Madramootoo, C.A. Long-term tillage and residue management influences soil C and N dynamics. *Soil Sci. Soc. Am. J.* **2010**, *74*, 1211–1217. [CrossRef]
54. Moreno, F.; Murillo, J.M.; Pelegrin, F.; Giron, I.F. Long-term impact of conservation tillage on stratification ratio of soil organic carbon and loss of total and active $CaCO_3$. *Soil Tillage Res.* **2006**, *85*, 86–93. [CrossRef]
55. Rosa, E.; Dębska, B. Seasonal changes in the content of dissolved organic matter in arable soils. *J. Soil Sediments* **2018**, *18*, 2703–2714. [CrossRef]
56. Lalande, R.; Gagnon, B.; Simard, R.R.; Coté, D. Soil microbial biomass and enzyme activity following liquid hog manure application in a long-term field trial. *Can. J. Soil Sci.* **2000**, *80*, 263–269. [CrossRef]
57. Schoenau, J.J.; Davis, J.G. Optimizing soil and plant responses to land applied manure nutrients in the Great Plains of North America. *Can. J. Soil. Sci.* **2006**, *86*, 587–595. [CrossRef]
58. Benke, M.B.; Hao, X.; O'Donovan, J.T.; Clayton, G.W.; Lupwayi, N.Z.; Caffyn, P.; Hall, M. Livestock manure improves acid soil productivity under a cold northern Alberta climate. *Can. J. Soil Sci.* **2009**, *90*, 685–697. [CrossRef]
59. Preger, A.C.; Rillig, M.C.; Johns, A.R.; Du Preez, C.C.; Lobe, I.; Amelung, W. Losses of glomalin-related soil protein under prolonged arable cropping: A chronosequence study in sandy soils of the South African Highveld. *Soil Biol. Biochem.* **2007**, *39*, 445–453. [CrossRef]
60. Wojewódzki, P.; Cieścińska, B. Effect of crop rotation and long term fertilization on the carbon and glomalin content in the soil. *J. Cent. Eur. Agric.* **2012**, *13*, 814–821. [CrossRef]
61. Tamilselvi, S.M.; Chinnadurai, C.; Hamuruga, K.; Arulmozhiselvan, K.; Balachandran, D. Effect of long-term nutrient management on biological and biochemical properties of semi-arid tropical Alfisol during maize crop development stages. *Ecol. Indic.* **2015**, *48*, 76–87. [CrossRef]
62. Piotrowska-Długosz, A.; Wilczewski, E. Soil phosphatase activity and phosphorus content as influenced by catch crops cultivated as green manure. *Pol. J. Environ. Stud.* **2014**, *23*, 157–165.
63. Furtak, K.; Gajda, A.M. Activity of dehydrogenases as an indicator of soil environment quality. *Pol. J. Soil Sci.* **2017**, *50*, 33–40. [CrossRef]

64. Sheoran, H.S.; Phogat, V.K.; Dahiya, R.; Gera, R. Long-term effect of organic and conventional farming practices on microbial biomass carbon. enzyme activities and microbial populations in different textured soils of haryana state (India). *Appl. Ecol. Env. Res.* **2018**, *16*, 3669–3689. [CrossRef]
65. Gałązka, A.; Gawryjołek, K.; Grządziel, J.; Księżak, J. Effect of different agricultural management practices on soil biological parameters including glomalin fraction. *Plant Soil Environ.* **2017**, *63*. [CrossRef]
66. Qiao, L.; Li, Y.; Song, Y.; Zhai, J.; Wu, Y.; Chen, W.; Liu, G.; Xue, S. Effects of vegetation restoration on the distribution of nutrients, glomalin-related soil protein, and enzyme activity in soil aggregates on the loess plateau, China. *Forests* **2019**, *10*, 796. [CrossRef]
67. Yao, X.H.; Min, H.; Lü, Z.H.; Yuan, H.P. Influence of acetamiprid on soil enzymatic activities and respiration. *Eur. J. Soil Biol.* **2006**, *42*, 120–126. [CrossRef]
68. Curyło, K.; Telesiński, A. Use of phosphatase and dehydrogenase activities in the assessment of calcium peroxide and citric acid effects in soil contaminated with petrol. *Open Life Sci.* **2020**, *15*, 12–20. [CrossRef]
69. Nannipieri, P.; Giagnoni, L.; Landi, L.; Renella, G. Role of phosphatase enzymes in soil. In *Phosphorus in Action*; Soil Biology; Bünemann, E.K., Oberson, A., Frossard, E., Eds.; Springer: Berlin/Heidelberg, Germany, 2011; Volume 26, pp. 215–243. [CrossRef]
70. 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]
71. Lemanowicz, J. Activity of selected enzymes as markers of ecotoxicity in technogenic salinization soils. *Environ. Sci. Pollut. Res.* **2019**, *26*. [CrossRef] [PubMed]
72. Bastida, F.; Zsolnay, A.; Hernández, T.; García, C. Past, present and future of soil quality indices: A biological perspective. *Geoderma* **2008**, *147*, 159–171. [CrossRef]
73. Piotrowska-Długosz, A.; Lemanowicz, J.; Długosz, J. The spatial pattern and seasonal changes in the soil phosphorus content in relation to the phosphatase activity: A case study of Luvisols. *Arch. Agron. Soil Sci.* **2020**, *66*, 1583–1597. [CrossRef]
74. García-Ruiz, R.; Ochoa, V.; Hinojosa, M.B.; Carreira, J.A. Suitability of enzyme activities for the monitoring of soil quality improvement in organic agricultural systems. *Soil Biol. Biochem.* **2008**, *40*, 2137–2145. [CrossRef]
75. Saviozzi, A.; Levi-Minzi, R.; Cardelli, R.; Riffaldi, R. A comparison of soil quality in adjacent cultivated, forest and native grassland soils. *Plant Soil* **2001**, *233*, 251–259. [CrossRef]
76. Lemanowicz, J.; Bartkowiak, A.; Lamparski, R.; Wojewódzki, P.; Pobereżny, J.; Wszelaczyńska, E.; Szczepanek, M. Physicochemical and enzymatic soil properties influenced by cropping of primary wheat under organic and conventional farming systems. *Agronomy* **2020**, *10*, 1652. [CrossRef]


**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.