Soil Properties after Eight Years of the Use of Strip-Till One-Pass Technology

Iwona Jaskulska 1,*, Kestutis Romaneckas 2, Dariusz Jaskulski 1, Lech Galżewski 1, Barbara Breza-Boruta 3, Bożena Dębska 4 and Joanna Lemanowicz 4

1 Department of Agronomy, Faculty of Agriculture and Biotechnology, UTP University of Science and Technology, 7 Prof. S. Kaliskiego St., 85-796 Bydgoszcz, Poland; darekjas@utp.edu.pl (D.J.); lechgalzewski@op.pl (L.G.)

2 Institute of Agroecosystems and Soil Sciences, Vytautas Magnus University, Agriculture Academy, K. Donelaiciu Str. 58, 44248 Kaunas, Lithuania; kestutis.romaneckas@vdu.lt

3 Department of Microbiology and Food Technology, Faculty of Agriculture and Biotechnology, UTP University of Science and Technology, 6 Bernardyńska Street, 85-029 Bydgoszcz, Poland; breza@utp.edu.pl

4 Department of Biogeochemistry and Soil Science, UTP University of Science and Technology, Bernardyńska 6/8 Street, 85-029 Bydgoszcz, Poland; debska@utp.edu.pl (B.D.); jl09@interia.pl (J.L.)

* Correspondence: jaskulska@utp.edu.pl

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Abstract: Tillage is an agrotechnical practice that strongly affects the soil environment. Its effect on soil properties depends on the system and, more specifically, on the degree of soil inversion and loosening. Strip-till is a non-inversive method that loosens only narrow soil strips. In strip-till one-pass (ST-OP) technology, tillage is combined with a simultaneous application of fertilizers and seed sowing. In a static multi-year field experiment, the soil properties after application of ST-OP for 8 years were compared to those of soil under conventional tillage with the use of a moldboard plough to a depth of 20 cm (CT), and equally deep loosened and mixed reduced tillage (RT). A field experiment of these three treatments was performed since 2012 in sandy loam soil, Luvisol. A total of 44 features were examined that described the physical, chemical, biological, and biochemical soil properties in the 0–20 cm layer, and penetration resistance (PR), bulk density (BD), and soil moisture (SM) in the 25–30 cm layer. The influence of the ST-OP technology on the yield of crops was also determined. Multivariate analysis shows that the ST-OP method, in terms of affecting the soil properties, differs considerably from RT and CT treatments. The soil after the ST-OP method contained two- to four-fold more earthworms (En), with a mass (Em) 2- to 5-fold higher, than those in the soil following RT and CT, respectively. In the ST-OP soil the content of available phosphorus (Pa) and available potassium (Ka); the total count of bacteria (Bt), cellulolytic microorganisms (Bc), and fungi (Ff); and the activity of phosphatases (AlP, AcP) were significantly higher. Compared with CT, the content of total organic carbon (Ct) and its content in the fractions of organic matter were also higher, with the exception of humins (CH). The yields of winter rapeseed and winter wheat using the ST-OP technology were marginally higher compared with those using the CT and RT technology.

Keywords: multi-year experiment; soil environment; tillage system; zonal tillage

1. Introduction

Intensive agricultural activity is one cause of degradation of the environment, including soil [1,2]. Deep inversion tillage and numerous treatments affecting the seedbed show an especially unfavorable effect on soil properties. The effects of this tillage include reducing the content of organic matter, a degradation of structure, a decrease in the stability of aggregates, soil crusting, surface runoff
and erosion, reduced biodiversity, and a decrease in biological activity [3]. Conventional tillage consumes energy, fuel, and labor while also emitting greenhouse gases to the atmosphere [4]. Soil inversion, multiple loosening, and mixing, as part of conventional tillage, cause water losses [5]. The conventional system with the moldboard plough is, however, the most common approach used globally, and particularly in Europe [6,7]. Due to economic, ecological, and social reasons, the acreage of soils under ploughless tillage has successively increased. Systems of reduced tillage and direct drilling, as elements of conservation agriculture, are increasingly common [8,9]. Many studies, including field experiments, focus on a comparison of the effect of various tillage systems on soil properties and crop yields [10–12]. In recent decades, strip-till, particularly the one-pass method, has attracted significant interest [13]. This approach allows for a single pass of a specialized machine to not only till the soil but also to apply fertilizers, sow seeds, and even perform additional agrotechnical tasks. The benefits of strip-till are due to a combination of deep tillage without soil inversion in the immediate plant growth zone and the rows, and without soil loosening between the rows [14]. Because of the short history of this tillage method, which is frequently limited to growing crops in a wide row spacing [15], few scientific studies have presented the effect of the strip-till one-pass approach on soil. Changes in many soil properties due to tillage occur relatively slowly and in interaction with other agrotechnical practices. Some of these changes can be observed after a few years, while the effects of others are only visible after many years [16,17]. Thus, long-term agricultural experiments are particularly valuable [18,19]. These long-term experiments facilitate determining and comparing physical, chemical, and biological changes in soil [20,21] due to various tillage systems. Such experiments have shown that ploughless reduced tillage, compared with conventional tillage, facilitates a more effective use of water in field plant production, particularly in semi-drought regions [22]. The tillage method, especially when combined with mulching, protects not only water but also the soil structure, and enhances the stability of aggregates [10,23]. The method also affects bulk density and soil penetration resistance [24]. A limited soil loosening and aeration enhances the sequestration of organic carbon. Without soil inversion, the content of organic matter and some nutrients, e.g., phosphorus, especially in the upper layer, increases [25,26]. A high content of organic matter, in addition to stable air and water conditions, are favorable to microorganisms. Under ploughless tillage and after direct drilling, high counts of bacteria and fungi are present in the soil, although their diversity and activity depend on the depth [27–29]. Reduced tillage also enhances the occurrence of earthworms [30]. However, few studies exist which compare the strip-till one-pass method with other tillage and plant growing systems [31,32], especially in terms of multi-year experiments. The results of the few existing experiments show that the effect of the strip-till one-pass method on soil is more similar to that of reduced tillage than that of conventional tillage [33].

A multi-year field experiment to compare three tillage systems and related plant cultivation technologies has facilitated the evaluation of the effect of the strip-till one-pass method on soil properties after 8 years of ST-OP application. The main aim of the research was to compare the physical, chemical, biological, and biochemical properties of soil tilled conventionally using the moldboard plough and ploughless approaches, and, specifically, strip tillage.

2. Materials and Methods

2.1. Experiment Location

The research site was a farm at Śmielin (53°09′04.0″ N; 17°29′10.7″ E; 93.8 m above sea level), in the Kujawsko-Pomorskie province, Poland (Figure 1) cooperating with the Department of Agronomy of the UTP University of Science and Technology in Bydgoszcz, Poland. In 2012, a multi-year experiment was established in sandy loam soil, Luvisol [34], with three soil tillage systems, basic fertilization, and sowing. The properties of the soil prior to the experiment for the 0–20 cm layer are presented in Table 1. The research site according to the Köppen classification is located in a moist continental climate zone [35]. The weather conditions in the study area, compared with the mean values of precipitation
and air temperature during a multi-year period, are provided in Table 2. On average during the research period, the annual total precipitation was 522 mm, and in three years it was lower than the multi-year mean. The monthly air temperature was 9.2 °C, and only the first two years were colder than the multi-year mean.

Table 1. Soil properties before commencing the field experiment at Śmielin in 2012.

| Property                  | Tillage Treatment          |
|---------------------------|----------------------------|
|                            | Strip-Till One-Pass (ST-OP)| Reduced (RT)  | Conventional (CT) |
| Texture (%)                |                           |               |                   |
| sand (2–0.05 mm)           | 49.0                      | 47.8          | 48.5              |
| silt (0.05–0.002 mm)       | 45.6                      | 47.0          | 46.3              |
| clay (<0.002 mm)           | 5.4                       | 5.2           | 5.2               |
| pH                        | 5.9                       | 6.0           | 6.0               |
| Organic carbon (g C kg⁻¹ soil) | 10.8                   | 10.6          | 10.7              |
| Total nitrogen (g N kg⁻¹ soil) | 0.98                    | 1.01          | 0.97              |
| Available nutrients:       |                           |               |                   |
| phosphorus (mg P kg⁻¹ soil) | 96.3                     | 94.5          | 98.0              |
| potassium (mg K kg⁻¹ soil)  | 280.5                     | 276.4         | 281.3             |
| magnesium (mg Mg kg⁻¹ soil) | 93.1                      | 95.0          | 94.4              |

Figure 1. Site of research at Śmielin, Kuyavian-Pomeranian province, Poland [36].
Table 2. Meteorological conditions during the study period at Śmielin.

| Month | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 1981–2010 |
|-------|------|------|------|------|------|------|------|------|------|------------|
| Air temperature (°C) |      |      |      |      |      |      |      |      |      |            |
| January | -3.5 | -3.2 | 1.1  | -3.3 | -2.6 | 0.8  | -0.7 | 2.6  | -1.8 |            |
| February | -0.9 | 2.0  | 0.1  | 2.5  | -0.5 | -3.2 | 2.6  | 3.6  | -0.9 |            |
| March | -3.0 | 5.6  | 4.1  | 33.0 | 5.4  | -0.2 | 5.4  | 3.9  | 2.5  |            |
| April | 7.0  | 9.9  | 7.6  | 8.3  | 6.8  | 12.0 | 9.3  | 8.2  | 7.9  |            |
| May | 14.2 | 13.3 | 12.4 | 14.7 | 13.4 | 16.9 | 12.1 | 11.2 | 13.3 |            |
| June | 17.4 | 16.0 | 15.6 | 17.7 | 16.8 | 18.4 | 21.9 | 17.9 | 16.1 |            |
| July | 18.9 | 21.5 | 18.5 | 18.3 | 17.7 | 20.5 | 18.6 | 18.3 | 18.6 |            |
| August | 17.6 | 18.1 | 17.2 | 21.0 | 16.4 | 17.7 | 19.9 | 19.7 | 17.9 |            |
| September | 13.3 | 10.7 | 14.4 | 13.8 | 14.3 | 13.0 | 15.6 | 13.5 | 13.1 |            |
| October | 7.4  | 8.2  | 9.6  | 6.4  | 6.3  | 10.1 | 9.8  | 9.8  | 8.2  |            |
| November | 4.5  | 4.9  | 4.3  | 4.8  | 2.5  | 4.5  | 4.5  | 5.5  | 2.9  |            |
| December | -2.5 | 1.8  | 0.5  | 3.7  | 1.4  | 2.0  | 2.0  | 2.7  | -0.6 |            |
| Average | 7.8  | 9.3  | 9.1  | 11.0 | 8.7  | 9.8  | 10.0 | -8.1 |      |            |
| Precipitation (mm) |      |      |      |      |      |      |      |      |      |            |
| January | 44.0 | 23.5 | 33.2 | 20.3 | 14.5 | 46.3 | 32.6 | 37.7 | 26.8 |            |
| February | 31.3 | 18.0 | 8.9  | 19.0 | 30.3 | 5.8  | 18.1 | 36.0 | 20.7 |            |
| March | 14.7 | 49.7 | 35.7 | 23.2 | 27.5 | 16.4 | 28.8 | 26.1 | 31.9 |            |
| April | 13.6 | 40.7 | 15.6 | 28.7 | 40.8 | 40.4 | 1.5  | 0.7  | 27.0 |            |
| May | 91.7 | 65.7 | 21.6 | 51.4 | 56.3 | 14.2 | 89.2 | 34.2 | 49.3 |            |
| June | 49.3 | 44.9 | 33.0 | 98.1 | 54.3 | 26.4 | 17.7 | 142.0 | 52.8 |            |
| July | 79.0 | 55.5 | 50.4 | 133.8 | 118.9 | 86.0 | 22.4 | 67.2 | 69.8 |            |
| August | 51.8 | 56.6 | 57.3 | 20.3 | 55.3 | 126.1 | 23.7 | 37.7 | -62.6 |            |
| September | 25.1 | 64.1 | 25.9 | 52.4 | 19.4 | 78.4 | 17.0 | 98.5 | -46.0 |            |
| October | 40.3 | 18.6 | 18.0 | 20.9 | 116.3 | 106.8 | 34.1 | 35.9 | -31.5 |            |
| November | 53.7 | 28.5 | 24.5 | 37.0 | 41.7 | 30.5 | 7.2  | 69.6 | -32.4 |            |
| December | 27.2 | 19.1 | 69.3 | 24.4 | 42.7 | 38.8 | 50.3 | 21.1 | -34.0 |            |
| Total | 510.5 | 492.9 | 353.4 | 649.9 | 723.2 | 367.8 | 473.1 | -484.8 |      |            |

2.2. Design and Performance of the Experiment

The field experiment is a one-factor experiment in a randomized block design. Three treatments in four replicates were compared, including three tillage systems and the accompanying agrotechnical practices of plant cultivation technology, basic fertilization, and sowing as follows:

i. conventional tillage (CT)—shallow tillage after the previous crop harvest (5–6 cm), 20 cm deep plough, pre-sowing basic mineral fertilization all across the soil surface, seedbed preparation, sowing;

ii. reduced tillage (RT)—tillage with the cultivator (5–6 cm deep) after the harvest of the previous crop, deep soil loosening without plough (20 cm), pre-sowing basic mineral fertilization all across the soil surface, seedbed preparation, sowing;

iii. strip-till one-pass (ST-OP)—loosening the soil strips 12 cm wide by 20 cm deep, the application of mineral fertilisers on the strip of loosened soil, sowing the seeds in one pass of the machine.

The size of experimental units (plots) was 250 m long × 12 m wide. The plants were grown in the winter rapeseed/wheat rotation. Agrotechnical practices were performed using commercially available machinery and agricultural tools. Post-harvest tillage and basic deep tillage following CT technology were performed using a Joker 3 CT disc harrow, a Maschio Gaspardo s4 plough, and RT with a Horsch Tiger 6 AS cultivator, respectively. For the purposes of fertilization and sowing for both technologies, Amazone ZG-TS 8200 and Horsch Pronto 4DC were used, respectively. As for ST-OP technology, tillage, fertilization and sowing were performed in a single pass with the Mzuri-Pro Til hybrid machine. The
dates of successive agrotechnical practices, the sowing density, the type and fertilizer rates, and plant protection treatments were the same for all experimental treatments. The annual mean NPK fertilizer rate was 275 kg ha\(^{-1}\). Prior to the experiment, calcium and magnesium carbonate (MgO + CaO 45%) were applied across the field at a rate of 1.5 t ha\(^{-1}\). To protect wheat against agrophages, the following active ingredients were used: herbicides (diflufenican, isoproturon, metribuzin, flufenacet, fenoxaprop-P-ethyl), fungicides (proteonazol, bixafen, spiroxamine, tebuconazole), insecticides (deltamethrin, dimethoate), and growth regulators (meipiquat chloride, calcium prohexadione, chlormequat chloride). To protect winter rapeseed, the following were applied: herbicides (dimetachlor, napropamide, clomazone, metazachlor, fluazifop-P-butyl), fungicides (dimoxystrobin, boscalid, flutriafol, tebuconazole), insecticides (deltamethrin, thiacloprid, chlorpyrifos), and growth regulators (meipiquat chloride, chlormequat chloride). The winter wheat and rapeseed yields were determined from the entire surface of the experimental plots. Plant yields were expressed by the standard content of water, 15%/8%, respectively.

### 2.3. Soil Samples and Measurements

In the 2019/2020 season, 8 years after the start of the experiment, a number of physical, chemical, biological, and biochemical soil properties were determined. Physical properties were evaluated immediately after the winter wheat harvest in the tilled layer (depths of 0–5 cm, 15–20 cm) and below the tilled layer (25–30 cm). Soil penetration resistance (PR) was assayed in 20 places in each plot along the plant rows and inter-rows with the use of penetrologger, the Eijkelkamp electronic penetrometer. In those places, soil was sampled into Eijkelkamp cylinders (100 cm\(^3\)) to evaluate bulk density (BD). Soil moisture (SM) was determined with a FieldScout TDR 350 m. To evaluate physical properties, the soil was sampled from the depth of 0–20 cm for chemical and biological studies. In 10 places in each plot, soil monoliths 15 × 15 × 20 cm were sampled to find the number (En) and mass (Em) of earthworms. Earthworms were counted and weighed at the experimental plots, without species identification, and then placed back in the soil. In the soil sampled directly from the plots, microorganisms (the total count of bacteria—Bt, cellullolytic microorganisms—Bc, Actinobacteria—Ac, filamentous fungi—Ff) and the activity of enzymes (dehydrogenase—DEH, alkaline phosphatase—AlP, acid phosphatase—AcP, catalase—CAT) were assayed. Organic carbon (Ct) and total nitrogen (Nt) content, extractable carbon (Ce) and nitrogen (Ne), as well as the content of carbon and nitrogen in the fractions of organic matter: after decalcifying—Cd, Nd; humic acids—CHAs, NHAs; fluvic acids—CFAs, NFAs and humins—CH, NH were assayed in the soil samples after drying, crushing and sieving through the sieve 2 mm in mesh.. In the samples of air-dried soil, the contents of the available forms of phosphorus (Pa), potassium (Ka), and magnesium (Mga) were assayed in 1M KCl (pH).

Bulk density (BD) was determined with the following formula:

\[
BD = \frac{D - (B + C)}{100}[g/cm^3]
\]

where

- **B**—weight of the dish under the Eijkelkamp cylinder;
- **C**—Eijkelkamp cylinder weight;
- **D**—weight of the cylinder with soil and the dish after drying.

The microorganisms were evaluated in the laboratory, where Ringer’s solution was added to soil samples and shaken for 30 min. Afterwards, a series of decimal dilutions (10\(^{-1}\) to 10\(^{-7}\)) was performed. From the soil solutions, the following inoculations were made into the culture media:

- YPS with soil extract (incubation for 5 days at 26 °C) added to evaluate the total bacteria count;
- Pochon medium with 100 µg mL\(^{-1}\) of nystatin added (incubation for 10 days at 27 °C) to evaluate Actinobacteria;
- Martin medium with 30 µg mL⁻¹ streptomycin added (incubation for 5 days at 25 °C) to evaluate filamentous fungi;
- Congo selective medium, Red Agar with CMC-Na (0.1% carboxymethylcellulose sodium salt) to evaluate cellulolytic microorganisms.

The number of colony-forming units (CFUs) was converted per 1 g of soil (CFU g⁻¹ of soil).

The activity of dehydrogenase in soil was evaluated following the Thalmann method [37]. The soil was incubated with 2,3,5-triphenyl tetrazolium chloride (TTC), and then colorimetric absorbance with triphenyl formazan (TPF) was measured at 546 nm. The activity of dehydrogenase was expressed in mg TPF kg⁻¹ 24 h⁻¹. The activity of phosphatase in soil was assayed with the method developed by Tabatabai and Bremner [38]. The soil was incubated with MUB solutions at pH 11 (for alkaline phosphatase) and pH 6.5 (for acid phosphatase) and with p-nitrophenylphosphate substrate at 37 °C for one hour. Phosphatase catalyzes the hydrolysis of p-nitrophenylphosphate to p-nitrophenol. The compound was calorimetrically assayed at the wavelength of 420 nm. The activity of catalase was determined with the Johnson and Temple method [39]. The remaining hydrogen peroxide in the soil sample after a 20 min incubation was titrated potassium permanganate in an acidic environment (in the presence of sulphuric acid).

Organic carbon and total nitrogen content were assayed with a Vario Max CN analyzer by Elementar. In brief, the procedure follows combustion with oxygen dosing, clearing the interfering gases, separating into adsorption columns, and assaying with a thermal conductivity detector. The content of Ct and Nt was expressed in g kg⁻¹ d.w. of soil. Extractable organic carbon and extractable total nitrogen were assayed after soil extraction with 0.004 M CaCl₂ at a soil:extractant ratio of 1:10. Assaying involved use of a Multi N/C 3100 analyzer Analityk Jena. The content of Ce and Ne was expressed in mg kg⁻¹ d.w. of soil. The fractional composition of humus was assayed based on the fractions determined in the extracts using a Multi N/C 3100 Analityk Jena (Germany) with the following procedure: carbon and nitrogen in solutions after decalcification—decalcification (24 h) with 0.05 M HCl (1:10 w/v); total carbon (C_HAs + FAs) and nitrogen (N_HAs + FAs) of humic and fulvic acids—extraction (24 h) of the remaining solid with 0.5 M NaOH (1:10 w/v) with occasional mixing, followed by centrifugation; carbon of fulvic acids in solutions after precipitation (24 h) of humic acids from the resulting alkaline extract with 2M HCl to pH = 2 and centrifugation. The carbon (nitrogen) in humic acids (C(N)_HAs) and carbon (nitrogen) in humins (C(N)_H) were calculated as:

C(N)_HAs = C(N)_HAs + FAs - C(N)_FAs
C(N)_H = Ct(Nt) - C(N)_HAs + FAs - C(N)_d

The fractional composition was expressed in mg kg⁻¹ of dry weight of soil.

pH was assayed with the potentiometric method after extraction in 1M KCl (pH meter CPC−551). The content of available phosphorus and available potassium was determined following the Egner-Riehm method after extracting soil with a solution of calcium lactate buffered to pH 3.6. In the extract, phosphorus was assayed colorimetrically after it was dyed with phosphoromolybdenum blue. Potassium was assayed with the flow photometer after calcium was precipitated with oxalic acid and filtered.

2.4. Data Analysis

The results were mathematically and statistically verified. The soil properties were determined after 8 years of applying various technologies and compared to the values of those features obtained prior to the start of field experiments; results are presented in graphical form. All physical, chemical, biological, and biochemical soil features were analyzed by ANOVA. The significance of the effect of the tillage systems on the properties of soil was verified with Fisher’s test. The significance of the differences between the mean values of respective features was evaluated with the Tukey post-hoc test at p < 0.05. The yields of winter wheat and winter rapeseed were statistically analyzed in the same way. Mean values are shown graphically. The results of soil pH measurements were not tested by analysis of variance due to the logarithmic scale of that feature. Multivariate analysis was also undertaken.
Taking into account the 44 features measured, the similarity of tillage systems was represented with a dendrogram, based on the impact on soil properties. The analysis was performed for standardized data. The results were verified with the Statistica.PL 12 software package [40].

### 3. Results

The soil tillage systems and related plant cultivation technologies affected the physical, chemical, biological, and biochemical soil properties. After 8 years, the CT decreased the content of organic carbon and available forms of phosphorus, potassium, and magnesium in the 0–20 cm soil layer (Figure 2A,D–F). After that period, the soil contained significantly more organic carbon, total nitrogen, and available macronutrients, determined following the ST-OP technology, and its pH value was higher compared to that of soil under CT (Figure 2A–F). The ST-OP technology, as compared with RT technology, also increased the content of total nitrogen, available phosphorus, and potassium. It increased the soil pH by 0.1 (Figure 2B–E).

![Figure 2](image-url)

#### Figure 2.
Soil chemical properties (A—content of organic carbon, B—content of total nitrogen, C—pH value, D—content of available phosphorus, E—content of available potassium, F—content of available magnesium) as a result of 8 years of different tillage systems—black columns; strip-till one-pass (ST-OP), reduced (RT), conventional (CT) and before starting a field experiment—blue columns. A—homogeneous group of results in 2012; a, b, c—letters indicate significant differences in 2020 at $p < 0.05$, $n = 4$.

The quality of organic matter, namely the content of carbon and nitrogen in its various fractions, was similar in the soil tilled for 8 years with the ST-OP and RT technology. The content of the respective

|          | ST-OP | RT   | CT   | 2012 | 2020 |
|----------|-------|------|------|------|------|
| Organic Carbon (g kg\(^{-1}\)) |       |      |      |      |
| 2012     | 10.8  | 10.6 | 10.7 | 10.6 |
| 2020     | 11.6  | 11.3 | 10.6 | 10.6 |

| Total Nitrogen (g kg\(^{-1}\)) |       |      |      |      |
| 2012     | 1.10  | 1.04 | 1.02 | 1.02 |
| 2020     | 1.11  | 1.04 | 1.04 | 1.02 |

| pH      |       |      |      |      |      |      |
| 2012    | 5.9   | 6.0  | 6.0  | 6.0  |      |
| 2020    | 6.4   | 6.3  | 6.2  |      |      |

| Available Phosphorus (mg kg\(^{-1}\)) |       |      |      |      |
| 2012     | 282.6 | 276.4| 281.3| 255.9|
| 2020     | 280.5 | 275.6| 260.4| 255.9|

| Available Potassium (mg kg\(^{-1}\)) |       |      |      |      |
| 2012     | 93.1  | 95.0 | 94.4 | 93.5 |
| 2020     | 93.1  | 95.0 | 94.4 | 93.5 |
organic carbon fractions under those systems did not differ significantly, and it was, except for the carbon of humins, higher than in the soil under conventional tillage (Table 3). The content of nitrogen in the fractions of organic matter in the ST-OP system was higher than in RT and CT. Only the content of nitrogen of fulvic acids in the soil following the ST-OP system was similar as that in RT, and the nitrogen of humins was significantly lower than that in the soil tilled with RT and CT.

Table 3. Quality of soil organic matter (in 2020, n = 4) as a result of different tillage systems; strip-till one-pass (ST-OP), reduced (RT), and conventional (CT).

| Components of Organic Matter | Unit  | Strip-Till One-Pass (ST-OP) | Reduced (RT) | Conventional (CT) |
|-----------------------------|-------|-----------------------------|--------------|-------------------|
| Dissolved organic carbon (DOC) | g kg⁻¹ | 129.9 a | 132.0 a | 93.4 b |
| Carbon after decalcification (C₄d) | mg kg⁻¹ | 329.2 a | 317.5 a | 278.0 b |
| Carbon of humic acids (C₄Ha) | mg kg⁻¹ | 3339.3 a | 3276.3 a | 2408.4 b |
| Carbon of fulvic acids (C₄Fa) | mg kg⁻¹ | 3022.5 a | 2932.2 a | 2279.4 b |
| Carbon in humins (C₄h) | mg kg⁻¹ | 5496.1 a | 5448.9 a | 5211.0 a |
| Dissolved nitrogen (DN₄) | mg kg⁻¹ | 36.5 a | 34.6 b | 28.6 c |
| Nitrogen after decalcification (N₄d) | mg kg⁻¹ | 57.3 a | 44.7 b | 31.8 c |
| Nitrogen of humic acids (N₄Ha) | mg kg⁻¹ | 177.1 a | 156.7 b | 117.9 c |
| Nitrogen of fulvic acids (N₄Fa) | mg kg⁻¹ | 171.5 a | 169.0 a | 137.9 b |
| Nitrogen in humins (N₄h) | mg kg⁻¹ | 720.8 b | 784.0 a | 785.5 a |

a, b, c—letters in rows indicate significant differences at p < 0.05.

Analysis of spatial variation in the physical properties of the surface 5 cm soil layer shows that penetration resistance, bulk density, and moisture in the inter-rows in the ST-OP system were significantly higher than in the row zone as well as in the rows and inter-rows in the RT and CT systems (Table 4). Similarly, in the deeper layer (15–20 cm), the highest bulk density, penetration resistance, and moisture were found in the zone of inter-rows following ST-OP, although soil moisture in rows and inter-rows with this tillage system did not differ significantly. Conventional tillage with ploughing (CT) made the soil penetration resistance on the tillage depth border lower than that in the RT and ST-OP systems. However, ST-OP regularly performed for 8 years resulted in a significant decrease in soil penetration resistance below the tilled layer, namely 25–30 cm, as compared with RT and CT, as well as in a lower bulk density compared to that of the soil following CT.

Table 4. Physical properties of soil in the rows (R) and inter-rows (I-R) in 2020, n = 4, as a result of different tillage systems; strip-till one-pass (ST-OP), reduced (RT), and conventional (CT).

| Property               | Strip-Till One-Pass (ST-OP) | Reduced (RT) | Conventional (CT) |
|------------------------|----------------------------|--------------|-------------------|
|                        | R  | I-R | R  | I-R | R  | I-R |
| 0–5 cm                 |    |     |    |     |    |     |
| Penetration resistance—PR (MPa) | 0.43 b | 0.64 a | 0.38 c | 0.38 c | 0.40 bc | 0.39 c |
| Moisture—SM (% vol.)  | 12.1 b | 14.5 a | 11.6 b | 11.8 b | 11.4 b | 11.6 b |
| Bulk density—BD (g cm⁻³) | 1.27 b | 1.46 a | 1.25 b | 1.26 b | 1.23 b | 1.21 b |
| 15–20 cm               |    |     |    |     |    |     |
| Penetration resistance—PR (MPa) | 2.38 b | 2.73 a | 2.35 b | 2.26 bc | 2.14 c | 2.06 c |
| Moisture—SM (% vol.)  | 16.2 ab | 17.0 a | 15.0 b | 15.4 b | 15.2 b | 14.9 b |
| Bulk density—BD (g cm⁻³) | 1.46 b | 1.58 a | 1.45 b | 1.43 b | 1.41 b | 1.39 b |
| 25–30 cm               |    |     |    |     |    |     |
| Penetration resistance—PR (MPa) | 2.51 c | 2.48 c | 2.70 b | 2.70 b | 3.03 a | 2.98 a |
| Moisture—SM (% vol.)  | 18.4 a | 18.2 a | 17.9 a | 18.0 a | 18.3 a | 18.0 a |
| Bulk density—BD (g cm⁻³) | 1.62 b | 1.63 b | 1.67 ab | 1.68 ab | 1.77 a | 179 a |

a, b, c—letters in rows indicate significant differences at p < 0.05.
The tillage systems strongly differentiated biological and biochemical soil properties (Table 5). After 8 years of zonal tillage (ST-OP), the count of Actinobacteria was significantly higher than that in soil after CT, and there were more earthworms, bacteria, cellulolytic microorganisms, and fungi as compared with the soil in the RT and CT systems. ST-OP also increased the activity of alkaline phosphatase and acid phosphatase, as compared to RT and CT, as well as dehydrogenase and catalase, as compared to RT.

Table 5. Earthworms, microorganisms, and activity of soil enzymes (in 2020, \( n = 4 \)) as a result of different tillage systems; strip-till one-pass (ST-OP), reduced (RT), and conventional (CT).

| Property                  | Unit               | Strip-Till One-Pass (ST-OP) | Reduced (RT) | Conventional (CT) |
|---------------------------|--------------------|----------------------------|--------------|-------------------|
| Earthworms                | no m\(^{-2}\)      | 86.3 a                     | 48.5 b       | 20.3 c            |
| Earthworms                | g m\(^{-2}\)       | 111.9 a                    | 52.3 b       | 23.2 c            |
| Bacteria                  | \(10^6\) cfu g\(^{-1}\) | 44.6 a                  | 36.7 b       | 31.3 c            |
| Cellulolytic microorganisms | \(10^6\) cfu g\(^{-1}\) | 25.5 a               | 22.4 b       | 17.9 c            |
| Actinobacteria            | \(10^5\) cfu g\(^{-1}\) | 63.6 a               | 64.1 a       | 43.0 b            |
| Filamentous fungi         | \(10^4\) cfu g\(^{-1}\) | 62.8 a               | 55.7 b       | 38.4 c            |
| Dehydrogenase             | mg TPF kg\(^{-1}\) 24 h\(^{-1}\) | 1.086 a           | 0.903 b      | 1.004 a           |
| Alkaline phosphatase (AlP)| mM pNP kg\(^{-1}\) h\(^{-1}\) | 1.106 a           | 0.985 b      | 0.899 c           |
| Acid phosphatase (AcP)   | mM pNP kg\(^{-1}\) h\(^{-1}\) | 2.231 a           | 2.075 b      | 1.921 b           |
| Catalase (CAT)            | mg H\(_2\)O\(_2\) kg\(^{-1}\) h\(^{-1}\) | 0.467 a           | 0.411 b      | 0.452 a           |

a, b, c—letters in rows indicate significant differences at \( p < 0.05 \).

The ST-OP system, when considering its effect on the 44 soil properties, differed considerably from the tillage inversion system or loosening the entire soil surface (Figure 3). In the dendrogram, a separate cluster for RT and CT is presented next to the ST-OP system.
The yield of winter wheat grain using ST-OP technology during the research period was, on average, comparable to the yield using conventional technology and was significantly higher, by 0.65 t ha\(^{-1}\), than that using RT technology (Figure 4). On the other hand, the yield of winter rapeseed grown using ST-OP technology was significantly higher than that using both CT and RT technology, by 0.27 ha\(^{-1}\) and 0.34 t ha\(^{-1}\), respectively.

![Graph showing winter wheat and winter rapeseed yields](image)

**Figure 4.** Winter wheat and winter rapeseed yields (average in 2012–2020) depending on the soil tillage treatments: strip-till one-pass (ST-OP), reduced (RT), and conventional (CT). a, b—letters indicate significant differences for crops.

### 4. Discussion

Zonal tillage, especially strip-till, is an important element in conservation tillage and conservation agriculture [41]. For that reason, over the last decades, tillage systems have become more and more important in global and European agriculture. Strip-till has been used as an agrotechnical practice for crops with a wide row spacing (e.g., maize, sunflower) but also, as reported by authors, for growing rapeseed and cereals in a narrow row spacing [42–44]. Strip-till combines the advantages of loosening deep soil, no-tillage, and direct drilling methods. Pöhlitz et al. [45], following traditional physical measurements and applying computer tomography, concluded that soil properties in the strip rows (strip-till) and after tillage with mulching on the surface were similar. Properties of non-loosened soil in inter-rows in the strip-till and no-till systems were also similar. Strip-till thus creates heterogenic hydrothermal effects and conditions air in the soil space. In tilled zones the soil shows low compaction, bulk density, and penetration resistance; it absorbs water faster and is heated, thus creating favorable conditions for plant root growth. In unloosened inter-rows, the soil is more compacted, moist, and has mulch on the surface [46]. Tabatabaeekoloor [47] reports, drawing on field experiments, that soil in the row zones is strongly loosened and crushed, demonstrating a low value of bulk density and penetration resistance. Plant residue is set aside and remains on the surface of inter-rows, which lowers the soil temperature and limits water losses. As reported by Shen et al. [48], the temperature of untilled soil with plant residue can be 1.5 °C lower than that after plough tillage. For that reason, the content of water down to 15 cm in the inter-row zone was about 18% higher than that in rows. In our own study, when comparing soil moisture in the rows and inter-rows in various tillage systems at the depth of 15–20 cm, the highest moisture was identified in ST-OP inter-rows. Soil moisture in that zone was about 2% (relatively 13%) higher than that in the rows and inter-rows in CT and RT systems. The difference in the soil moisture in the surface layer was even greater under the ST-OP system.

At the
same time, the soil in ST-OP inter-rows was not mechanically loosened, and including plant residue of the catch crop the highest bulk density and penetration resistance were recorded. The physical properties of soil following ST-OP, especially in the inter-rows, must be related to the high amount of plant residue on the soil surface acting as mulch. Plant material on the soil surface affects water conditions and other soil properties, and it is an important element in conservation tillage. According to Mulumba and Lal [49], multi-year mulching enhanced the physical properties of soil. After 11 years of annually placing 2–16 t ha\(^{-1}\) of mulch on the soil surface, the available water capacity increased by 18–35%, total porosity by 35–46%, and soil moisture retention at low suctions increased from 29 to 70%.

So far, few results have been reported regarding the effects of strip-till on the properties of soil in long-term, multi-year field experiments. The few experiments performed usually point to favorable changes after many years [50]. Fernandez et al. [51] presented that after 5 years of strip-till, as compared with no-till, the content of organic matter in soil increased relatively by 8.6%, the bulk density of soil decreased by 4%, and the penetration resistance decreased by 18% of the recorded value. Fernandez and Schaefer [52] and Fernandez and White [53] also related the greater effectiveness of nutrients and higher plant yield to improved physical properties of soil, including water conditions, as a result of strip-till. In our present research, after 8 years of strip-till one-pass application, there was a relative increase in the content of organic carbon in soil of 9.4% and 2.7% as compared to CT and RT, respectively. A higher amount of organic carbon was also found in the extractable fraction of humic and fulvic acids. Additionally, the content of available nutrients in soil increased: phosphorus by 17.4% and 12.0%, potassium by 10.4% and 8.5%, magnesium by 10.8% and 3.3%, respectively. Yuan et al. [54] stress that strip-tilling with a deep strip application of fertilizers, technology similar to that applied in our research, increases the use and effectiveness of nutrients, decreases losses, and limits the risk of environmental pollution.

The lack of ploughing for eight years and replacing the soil inversion with soil loosening resulted in an increase in biomass and activity of soil organisms. Krauss et al. [55] demonstrated that after 15 years of reduced tillage, as compared with conventional tillage, the content of organic carbon in the soil surface layer (0–10 cm) increased by 25%, the content of microorganism biomass increased by 32%, and the activity of dehydrogenase increased by 34%. The mass of organisms and their activity were higher also in the 10–20 cm soil layer, respectively by 15% and 9%. The results confirm the changes in biological and biochemical soil properties in this experiment. After 8 years of RT, as compared with CT, the authors recorded 17.3% higher count of bacteria and 45.1% more fungi in the 0–20 cm soil layer. The activities of alkaline and acid phosphatases were also, respectively, 9.6% and 8.0% higher. Ploughless tillage and RT especially enhanced the occurrence of earthworms in soil; their number and mass were more than double that recorded in the soil under conventional tillage. Such a favorable effect of no-plough and no-soil-inversion methods on the occurrence of earthworms has been recorded by many authors [56,57]. In the present research, it must be stressed that the values of the qualities describing the biological and biochemical properties of soil tilled for 8 years following ST-OP technology were significantly higher, except for the count of Actinobacteria, than those following RT. The relative difference ranged from 7.5% (activity of acid phosphatase) to 21.5% (count of total bacteria), and as for the number and mass of earthworms, they accounted for increases of 77.9% and 114%, respectively.

The scientific literature provides few direct comparisons of the effect of strip-till, simplified tillage, and other tillage systems on soil properties, including RT and CT, as was done in the present research. Some studies were performed a few decades ago [58], while others refer to different environmental and/or agrotechnical conditions [59,60]. With that in mind, further in-depth studies on strip-till are required, especially strip tillage technology accompanied by other treatments such as fertilization and sowing. Particularly valuable are wide, multi-point meta-analyses. Such studies refer to a high number of experiments and to the effect of tillage on physical properties, including soil structure indicators such as wet aggregate stability, bulk density, and soil penetration resistance (295 study sites) [61], or biological properties such as fungal and bacterial biomass (60 studies) [62]. These studies, however,
did not address the strip-till system or tillage and crop growing with ST-OP technology. The fertility and productivity of soils do not result from single soil properties but from the interaction of a high number of features. For that reason, multivariate analyses are especially valuable. Such analyses facilitate a comparison of various tillage systems or crops considering many features, including bulk density, penetration resistance, water aggregate stability, soil reaction (pH), and the contents of soil organic matter, total nitrogen, and available micronutrients [63]. Multivariate analyses also facilitate grouping similar treatments based on many features, as reported by Niewiadomska et al. [64]. The authors investigated soil microorganisms (bacteria, fungi, Actinobacteria) and the activity of soil enzymes (dehydrogenase, phosphatase, and catalase) affected by various tillage methods and growing cover crops. However, of the five treatments compared, strip-till was not studied. In our research, soil evaluation included 44 physical, chemical, biological, and biochemical features. Multivariate cluster analysis with a graphic representation of results in the form of a dendrogram indicates that after 8 years of tillage at the same depth (20 cm), the properties of soil inverted (CT) and intensively loosened (RT) are similar. Soil properties under the influence of ST-OP were significantly different. These favorable changes in soil properties potentially led to slightly higher reported crop yields compared to that of other tillage treatments. The yields of winter wheat and winter rapeseed were slightly higher than those recorded in CT, and significantly higher than those yields recorded in RT, ploughless tillage. The relative difference in yields of 9.5% to 10.1% improvement was comparable to that of other authors [65,66]. Additionally, our previous studies, although conducted in different soil (Cambisol) and agrotechnical conditions (Central and Eastern European countries), show that use of ST-OP technology leads to higher yields than those in other reduced tillage systems. This is the result of both the favorable soil properties and the plant population on the field scale from the emergence phase [32,42–44].

5. Conclusions

A change in ploughing, soil inversion, and tillage to equal the depth of soil loosening enhanced the soil properties. After 8 years of loosening tillage (RT), the soil contained significantly more organic carbon and available forms of phosphorus and magnesium in the layer tilled than that following CT. The values of penetration resistance and bulk density of soil in the layer below the tillage depth decreased. In RT-tilled soil more microorganisms from various groups were found, and the number and mass of earthworms as well as the activity of alkaline phosphatase were higher. Even more enhancing to soil properties was the multi-year crop growth following use of ST-OP technology. As a result, the soil after 8 years contained more organic carbon, total nitrogen, and available macronutrients. Use of ST-OP technology, as compared with CT, resulted in a significant increase not only in the amount of total organic carbon but also in its content in the fractions of organic matter, except for humins. In the soil tilled with ST-OP technology about two- to four-fold more earthworms were found, and their mass was two- to five-fold higher than that in the soil compared to RT and CT, respectively. The ST-OP technology also recorded higher contents of available phosphorus and potassium, higher bacteria, cellulolytic microorganisms, and fungi counts, and increased activity of phosphatases. Beneficial agronomic properties of the soil were measured with 44 physical, chemical, biological, and biochemical features, and after 8 years of using the ST-OP technology they were significantly different from the properties of the soil tilled with CT and RT methods. Favorable changes in soil properties lead to increases in productivity. This provided greater yields of winter wheat compared to that of the ploughless tillage system, and greater yields of winter rapeseed compared to that of conventional and reduced tillage.

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