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Optimizing Tillage and Fertilization Patterns to Improve Soil Physical Properties, NUE and Economic Benefits of Wheat-Maize Crop Rotation Systems

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Abstract: Winter wheat and summer maize rotation is the main cropping pattern in the North China Plain (NCP). There are still problems with farmers' production modes, including shallow tillage layers, single application of chemical fertilizer causing plow bottom layer thickening and soil pH decrease. A two-factor location experiment was conducted to investigate the effects of different tillage and fertilization patterns on the soil physical properties, soil organic carbon (SOC), nitrogen-use efficiency, and crop yield of wheat–maize rotation systems during the years 2018–2020. The different treatments were deep tillage + organic fertilizer (DTF), shallow tillage + organic fertilizer (STF), no tillage + organic fertilizer (NTF), deep tillage + nitrogen fertilizer (DT), shallow tillage + nitrogen fertilizer (ST), and no tillage + nitrogen fertilizer (NT). The results showed that STF treatment could effectively improve the physical properties of soil and, SOC content, and increase both the crop yield and revenue of farmers. In the STF treatment, soil water content was highest in the 0–20 cm layer (2018), which was 4.89–11.31% higher than that of the other treatments; additional organic fertilizer application reduced soil bulk and increased the proportion of <0.25 mm aggregates; SOC and soil total nitrogen (TN) content were highest in the 20–40 cm layer, (15.82–32.63% and 28.57–42.86%, respectively). The total yield of wheat–maize rotation for both years was the highest under STF treatment. The annual economic benefits under this treatment were 42,182.26 and 42,254.54 CNY ha^{-1}, which were 1.02–12.94% and 2.29–9.87% higher than those of the other treatments. Therefore, the suggested planting method in the NCP is tillage of over 20 cm and additional organic fertilizer.

Keywords: tillage; organic fertilizer; soil physical properties; soil organic carbon; fertilizer use efficiency; economic benefits

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1. Introduction

Agricultural soils are an important resource for food security and the environment and play important roles in water storage, nutrient cycling, and crop production [1]. Currently, mechanized agricultural production has been extensively employed across China, not only to conserve water and improve land utilization but also to reduce the physical labor required of farmers and decrease production costs [2]. However, shallow mechanical tillage, inappropriate irrigation, and the excessive application of fertilizers have resulted in deeper plow bottoms [3,4], high soil bulk density and compaction, and low porosity and oxygen concentrations in plow bottoms [5]. There are issues with shallow tillage that can cause a significant reduction in the effective soil in the tillage layer and a tendency towards the deterioration of the physical properties of the tilled soil [6]. While nitrogen fertilizer is essential for crop growth, farmers often apply it excessively to increase yields. However, increased nitrogen fertilization can lead to large amounts of reactive nitrogen being lost to the environment, which can cause water pollution that poses serious threats to human and ecosystem health [7–9]. Accordingly, the optimization of nitrogen fertilization has great potential benefits for agricultural production in China [10].

Reasonable tillage in coordination with the prudent application of water and fertilizer activates soil nutrients, which optimizes the physical and chemical properties of the soil, establishing a more suitable soil structure for crop growth and development needs [11,12]. In cases where the soil water content is more influenced by tillage treatments, shallow tilling or not tilling at all can effectively reduce soil water evaporation and increase its capacity to retain water and moisture by reducing structural disturbances [13,14]. Many other studies have indicated that soil aggregates are also critical for the retention and effectiveness of fertilizers [15,16]. Furthermore, several critical structural properties such as total soil porosity, bulk density, and infiltration resistance can impact the soil water content and soil organic carbon [17,18]. The partial replacement of chemical fertilizers by organic fertilizers exploits both the available nutrients and total nutrients, and also benefits the optimization of soil physical and chemical properties [19]. Meanwhile, the decrease in chemical fertilizer use and increase in organic and inorganic fertilizer application are important measures for sustainable agricultural development [20]. Non-harmful organic fertilizer contains organic matter, humus, and beneficial microorganisms [21]. It can promote the formation of macro-aggregates, enhance the physical protection of organic matter [22,23], and increase the total contents of soil nutrients, such as total organic carbon, nitrogen, and phosphorus and available nitrogen (nitrate and ammonium nitrogen, and available phosphorus and potassium), in the soil [19]. Numerous investigations have revealed that a combination of inorganic and organic fertilizers is the most effective way to increase the yield of crops such as wheat and maize [24–26]. Research has also indicated that the regular application of organic fertilizers is effective at enhancing crop yields, primarily through directly increasing soil fertility and enhancing the effectiveness of nitrogen [27]. Replacing mineral fertilizers with organic fertilizers has excellent potential for improving the economic and environmental sustainability of agricultural production [28]. Therefore, it is beneficial for reasonable farm management measures to enhance the capacity of soil nitrogen supplies while increasing nitrogen use efficiencies and crop yields [29].

Consequently, there is no conclusive answer as to what tillage and fertilizer application patterns might optimize the use of straw and fertilizers to maximize economic benefits. While the winter wheat–summer maize rotation is an important cropping pattern in the NCP, many issues remain in the terms of sustaining abundant and stable crop production in the region. These include tillage patterns that are still dominated by plowing, excessive use of chemical fertilizers, and low organic fertilizer inputs, which concurrently decrease soil fertility and pH, negatively affect crop growth, and limit resource utilization [30,31]. Furthermore, although current crop production in China has the capacity to fully meet the domestic demand for food, there remains a lack of research on ensuring crop quality while enhancing the economic efficacy of farmland and providing higher economic returns for farmers. Currently, most research remains focused on a single tillage or fertilization mode; thus, there is not much research into the enhancement of soil physical properties, nitrogen supplies, and the beneficial farm economics of tillage and fertilization intercropping under straw return conditions. Therefore, there is an urgent need to develop a reasonable tillage and fertilization pattern strategy under straw return conditions. This has emerged as one of the most critical issues for crop production in the NCP. This has importance for the achievement of sustainable agricultural development, high and stable yields, and agricultural profitability.

2. Materials and Methods

2.1. Experimental Site and Design

The experiment was located at the crop high-yield experimental station in Xuchang City (started in 2010, 34°03′ N, 114°25′ E), Henan Province, China, with a winter wheat and summer maize rotation system. The area has a continental monsoon climate and four distinct seasons. As shown in Figure 1, the annual mean temperature and annual mean precipitation in wheat season were 11.8 °C and 356.8 mm, respectively (October 2018 to June 2019, and October 2019 to June 2020), and the annual mean temperature and annual mean precipitation in maize season were 25.2 °C and 308.2 mm, respectively (July to September 2019, and July to September 2020).

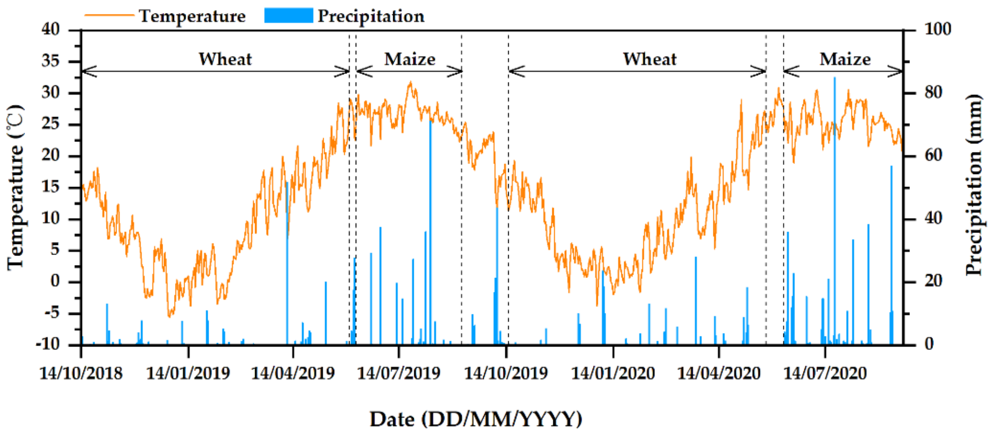

Figure 1. Changes in rainfall and temperature during crop growth.

The long-term conservation experiment was based on a two-factor block design from 2010 to the present. The experiment consisted of six treatments with three replications and each district area was 280 m^2. Three tillage methods are combined with nitrogen or organic fertilization. The treatments were as follow: (1) deep tillage with organic fertilizer (DTF); (2) shallow tillage with organic fertilizer (STF); (3) no tillage with organic fertilizer (NTF); (4) deep tillage with nitrogen (DT); (5) shallow tillage with nitrogen (ST); (6) no tillage with nitrogen (NT). Deep tillage (30–40 cm), shallow tillage (15–25 cm) and no tillage (no tillage treatment and only a surface rake) before wheat season sowing. Fertilizer application in wheat season was 168.75 kg ha^{-1} of N fertilizer alone and 168.75 kg ha^{-1} of N fertilizer + 950 kg ha^{-1} of organic fertilizer (equivalent to 55.1 kg ha^{-1} of pure N, 0 kg ha^{-1} of P_2O_5 and 9.5 kg ha^{-1} of K_2O). In the maize season, only the surface was raked, and 210 kg ha^{-1} of nitrogen fertilizer were applied before sowing. Wheat cultivar Zhengmai 618 was used in this experiment, two years sowing dates were 14 October 2018 and 16 October 2019, harvest dates were 1 June 2019 and 24 May 2020; the maize cultivar Denghai 605 was sowed on 7 June 2019 and 8 June 2020, and harvested on 26 September 2019 and 19 September 2020. The soil type is medium loam soil. Samples from 0–20 cm soil layer were collected and analyzed before wheat sowing in 2018 and 2019, respectively, and the soil physical and chemical properties are shown in Table 1.

Table 1. The basic physical and chemical properties of soil before sowing.

Year	Treatment	Soil pH	Organic Matter (g kg^{-1})	Total Nitrogen (g kg^{-1})	Total Phosphorus (g kg^{-1})	Unit Weight (g cm^{-3})	Water Content (%)
2018	DTF	8.68	29.65	1.09	0.76	1.51	21.21
	STF	8.77	32.35	1.17	0.78	1.49	22.93
	NTF	8.30	34.67	1.33	0.81	1.58	20.98
	DT	8.78	27.97	1.12	0.68	1.61	21.86
	ST	8.19	29.20	1.25	0.81	1.50	21.09
	NT	8.52	28.58	1.18	0.74	1.66	20.60
2019	DTF	8.71	29.76	1.11	0.74	1.41	12.79
	STF	8.78	31.32	1.17	0.85	1.43	21.66
	NTF	8.45	29.88	1.16	0.81	1.46	16.30
	DT	8.77	28.23	1.19	0.72	1.51	11.71
	ST	8.35	29.45	1.28	0.72	1.54	21.73
	NT	8.49	28.97	1.25	0.71	1.58	11.56

2.2. Sampling Method and Measurement

2.2.1. Soil Water Content, Bulk Density and Porosity

Soil samples of 0–20, 20–40 and 40–60 cm soil layers were collected with a ring knife during the overwintering period of wheat and the maturity period of maize and replicated three times for the measurement of soil water content, bulk density and porosity.

2.2.2. Soil Aggregate

The undisturbed soil in the 0–20, 20–40 and 40–60 cm soil layers was collected with a ring knife and air-dried naturally. The removed part of the soil was squeezed and deformed by the sampling equipment, and then the soil sample was brought back to the greenhouse to air dry for use. Dry screening method was used to classify soil aggregates. The soil aggregates with different particle size ratios were calculated as:

$$W_i = M_i / M \times 100$$

where W_i is the weight percent of a certain grade of dry sieved soil aggregates (%); M_i is the air-dried mass of soil aggregates at this level (g); M is the mass of the air-dried soil sample (g).

2.2.3. Soil Organic Carbon

Soil was taken at the maturity stage of maize every year, and the TOC analyzer was used for the measurement of soil organic carbon [32]. Since the tested soil samples did not contain calcium carbonate (measured by the potassium dichromate volumetric method and TOC analyzer, the results were basically the same), the measured total carbon content was the organic carbon content.

2.2.4. Soil Nitrogen

Total nitrogen was digested with $CuSO_4$-K_2SO_4 H_2SO_4 and measured with AA3 continuous flow analyzer (SEAL, Norderstedt, Germany). Nitrate nitrogen (NO_3-N) was measured by dual wavelength colorimetry [33]. Ammonium nitrogen (NH_4-N) was determined by the indophenol blue colorimetric method [34].

2.2.5. N Use Efficiency

Nitrogen partial factor productivity (*PFP*) was used to evaluate NUE:

$$PFP = Y / N_{rate}$$

where *PFP* is the partial productivity of fertilizer, kg kg^{-1} N; Y represents crop yield (kg ha^{-1}); N_{rate} is the amount of fertilizer (kg N ha^{-1}) applied to the crop [35].

2.2.6. Yield Measurement and Annual Economic Value Calculation

During the wheat harvest period, 1 m^2 of plants were randomly taken from each plot, replicated three times, dried naturally, threshed and weighed to calculate yield. During the maize harvest period, each plot was removed from the side rows and one plant at each end of each row, and then 2 rows of maize were harvested, dried naturally and calculated the yield.

The service value of agricultural products is calculated using the market value method as:

$$V = S \times Y \times P - C$$

where V is the service value of agricultural products (CNY ha^{-1}); S is the planting area (ha); Y is the yield (kg ha^{-1}); P is the market price of wheat and maize (CNY kg^{-1}), respectively 2.2 and 1.8 CNY kg^{-1}; C is the production cost (CNY); The prices of wheat and maize seeds are 5 and 6 CNY kg^{-1}, respectively. From 2018 to 2019, the compound fertilizers for wheat and maize were 2.6 and 2.2 CNY kg^{-1}, respectively, and the organic fertilizer was

2 CNY kg^{-1}. In 2019–2020, the compound fertilizers for wheat and maize were 2.6 and 2 CNY kg^{-1}, respectively, and the organic fertilizer was 1.1 CNY kg^{-1}.

2.3. Statistical Analysis

The experimental data were processed and analyzed by Excel 2010 software, used Origin 2021 for graphing, and SPSS 21.0 for significance analysis (Duncan method, $p < 0.05$) and stepwise regression analysis.

3. Results

3.1. Soil Physical Properties

3.1.1. Soil Water Content

The soil water content varied from 8.31 to 22.93%, which was influenced by interannual rainfall (Figure 2) caused by greater precipitation during the 2018–2019 wheat season and an overall higher soil water content in this year than in 2019–2020. The soil water content in the 0–20 cm soil layer was highest under the STF treatment (2018) at 22.93%, which was 4.89–11.31% higher than under the other treatments. For the 20–40 cm and 40–60 cm soil layers, the soil water content was higher under the NT and NTF treatment at 14.90% and 14.36%, respectively, with the highest levels occurring in 2019–2020, which were 0.54–17.88% and 0.63–15.81% higher than under the other treatments, respectively. An analysis of the soil water content during maize maturity revealed that it was generally higher during 2020 than in 2019 due to precipitation. The highest water contents were found in all three soils layers under DT treatment in 2020 at 22.02%, 20.58%, and 18.08%, respectively, which were 2.8–19.8%, 5.48–37.94%, and 1.40–39.94% higher than under the other treatments.

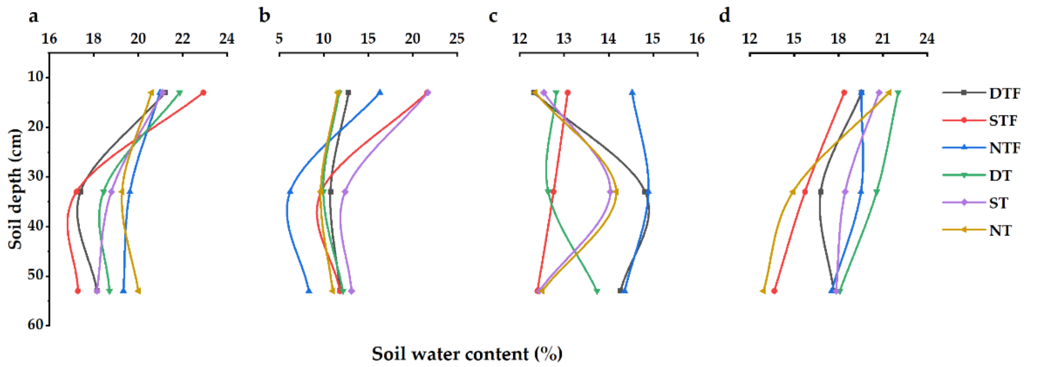

Figure 2. The soil water content was measured from soil samples of the 0–20 cm, 20–40 cm, and 40–60 cm soil layers after two years of wheat and maize crop rotation. Soil water content during the overwintering period of wheat in 2018 (**a**), maize maturity in 2019 (**b**), overwintering period of wheat in 2019 (**c**), and maize maturity in 2020 (**d**).

3.1.2. Soil Bulk Density and Porosity

The soil bulk density and porosity for 2018–2020 are shown in Figure 3. Overall, the soil bulk density exhibited a tendency to increase and then decrease with deeper soil layers, while the opposite was true for soil porosity. Under the same tillage mode, the increased application of organic fertilizer reduced the bulk density and enhanced the porosity of the soil. Comparing the different tillage treatments, the soil bulk density was higher and the porosity was lower under the no-till treatment. During the wheat production season in 2018–2019, the soil bulk density was 1.37–1.52 g cm^{-3} in the 0–20 cm soil layer and was significantly lower under the STF treatment in contrast to the other treatments ($p < 0.05$). Further, the soil porosity was highest in the 0–20 cm soil layer at 42.73–48.41%, which was 10.58–29.42% and 7.15–23.25% higher than in the 20–40 cm and 40–60 cm soil layers, respectively.

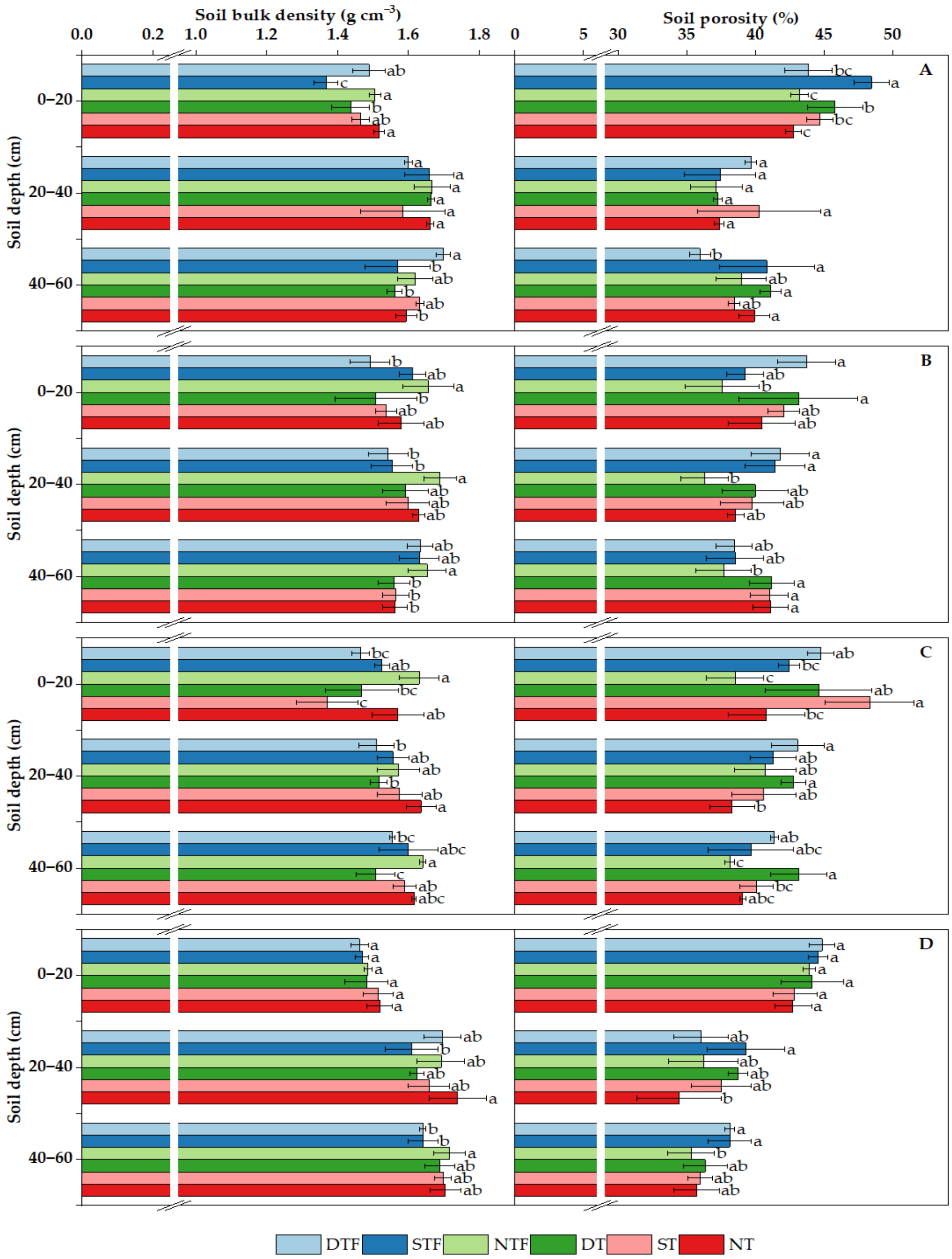

Figure 3. Soil bulk density and porosity of wheat and maize rotations, 2018–2020. Soil bulk density and porosity during the overwintering period of wheat in 2018–2019 (**A**), maize maturity period in 2019 (**B**), overwintering period of wheat in 2019–2020 (**C**) and maize maturity period in 2020 (**D**). Different letters indicate significant differences in soil bulk density and porosity between treatments ($p < 0.05$).

Similarly, during the maize season, the soil bulk density was lower in the 0–20 cm soil layer. The different tillage treatments showed the pattern of deep tillage < shallow tillage < no tillage. In 2020, the soil bulk density under the STF treatment was significantly lower than that under the NT treatment in the 20–40 cm soil layer ($p < 0.05$), while the soil porosity exhibited the opposite trend. The bulk density of STF in the 40–60 cm soil layer was significantly lower than that of NTF ($p < 0.05$) and the highest soil porosity was 38.1%, with the soil porosity appearing in the following order: STF > DTF > DT > ST > NT > NTF.

3.1.3. Soil Aggregates

The soil aggregate status for 2018–2020 is depicted in Figure 4 with the same trend being observed for the wheat season, while the maize season showed a different trend. Overall, the proportion of >5 mm aggregates was the largest and the proportion of 0.25–0.5 mm aggregates was the smallest among all levels of soil aggregates during the 2018–2020 wheat and maize seasons.

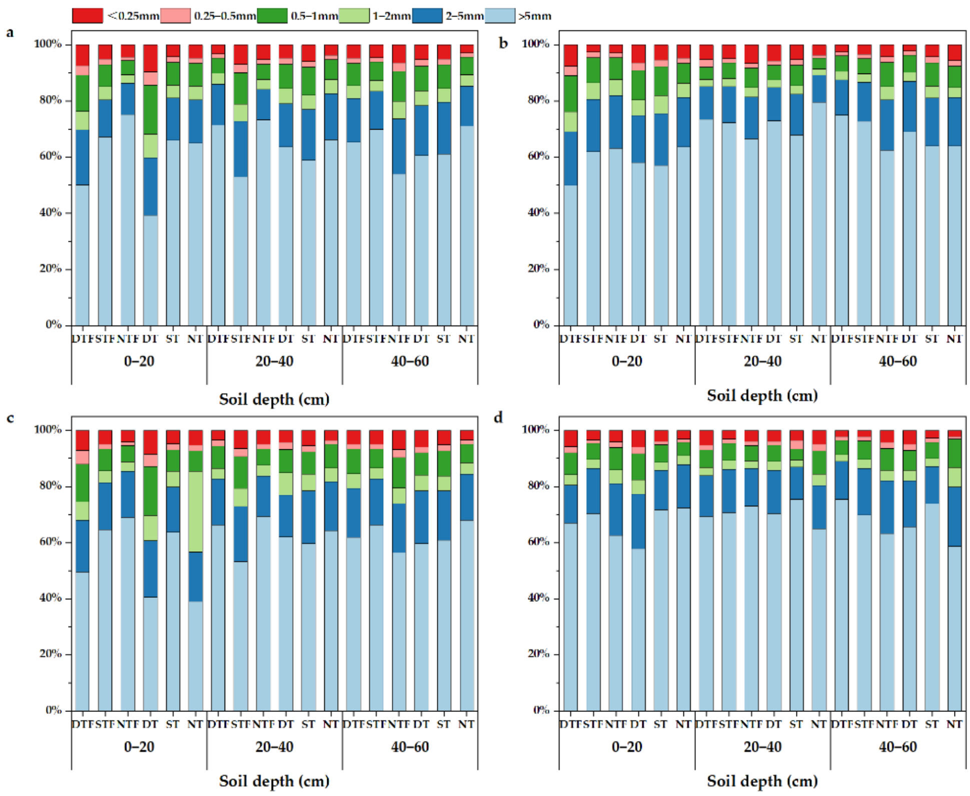

Figure 4. Soil aggregates for overwintering wheat in 2018–2019 (**a**), the maturity period of maize in 2019 (**b**), overwintering wheat in 2019–2020 (**c**), and the maturity period of maize in 2020 (**d**).

Comparing the different tillage treatments in the 0–20 cm soil layer during the wheat season, the proportion of >0.25 mm aggregates was higher under the no tillage treatment. Furthermore, in 2020 the <0.25 mm aggregates in the 20–40 cm soil layer accounted for 3.36–6.39% of the total, and organic fertilizer treatment increased the number of mboxtextless0.25 mm aggregates. The >0.25 mm soil aggregates accounted for more than 90% of the total during the maize season, with the proportion being lower than for the wheat season. In the 0–20 cm soil layer, comparing the different tillage treatments, the results were the same as in the wheat season. In 2019, the proportion of <0.25 mm aggregates in the 20–40 cm soil layer under the STF treatment was low at 4.83%. In 2020, the lowest numbers of <0.25 mm aggregates under the STF were observed in the 20–40 cm and 40–60 cm soil layers at 3.00% and 2.25%, respectively.

3.2. Soil Organic Carbon

As is shown in Table 2, the soil organic carbon content showed an overall decreasing trend with deeper soil layers from 2018 to 2020. Comparing different tillage treatments, during the 2019 maize season the soil organic carbon content ranged from 16.74 to 19.38 g kg^{-1} in the 0–20 cm soil layer, which showed shallow tillage < deep tillage < no tillage. In the 20–40 cm soil layer, the STF exhibited the highest level of soil organic carbon content at 11.42 g kg^{-1}, which was 15.82–32.63% higher than the other treatments ($p < 0.05$). In the 40–60 cm soil layer, STF was significantly lower than DTF and ST, at 8.32 g kg^{-1} ($p < 0.05$).

In 2020, the soil organic carbon content ranged from 16.68 to 17.84 g kg^{-1} in the 0–20 cm soil layer at maize maturity, and was significantly higher under the STF treatment (17.84 g kg^{-1}) than under the DTF and DT treatments. The soil organic carbon content was reduced under STF treatment in the 20–40 cm and 40–60 cm soil layers compared to the previous year.

Table 2. Changes in soil organic carbon content of each soil layer under different treatments from 2018 to 2020.

Year	Treatment	Soil Organic Carbon (g kg^{-1})		
		0–20 cm	20–40 cm	40–60 cm
2019	DTF	17.52 b	8.61 d	8.78 a
	STF	17.48 b	11.42 a	8.32 b
	NTF	19.38 a	9.41 c	8.49 ab
	DT	17.44 b	9.70 bc	7.17 c
	ST	16.74 b	8.70 d	8.78 a
	NT	17.57 b	9.86 b	8.51 ab
2020	DTF	16.69 b	12.89 a	8.23 c
	STF	17.84 a	9.08 d	8.30 c
	NTF	17.24 ab	10.36 c	9.70 b
	DT	16.68 b	9.49 d	10.69 a
	ST	17.48 a	9.56 d	8.34 c
	NT	17.65 a	11.77 b	9.67 b

Different lowercase letters in each column indicate significant differences in soil organic carbon between treatments ($p < 0.05$).

3.3. Total and Inorganic Nitrogen Content

Table 3 shows the soil TN, NH_4-N, and NO_3-N contents for each soil layers from 2018 to 2020. The contents of TN, NH_4-N, and NO_3-N exhibited a decreasing trend at deeper soil layers. The shallow tillage treatment resulted in a higher TN content than the other tillage methods in 2019 at 1.17 g kg^{-1} and 1.28 g kg^{-1}, respectively, under the same fertilization method in the 0–20 cm soil layer, while the opposite was true in 2020 at 1.11 g kg^{-1} and 1.04 g kg^{-1}, respectively. In the 20–40 cm layer, the TN content of soil under STF treatment (28.57–42.86%) was significantly higher than under other treatments ($p < 0.05$).

Table 3. Soil TN, NO_3-N, and NH_4-N in each soil layer from 2018 to 2020.

Year	Treatment	TN (g kg^{-1})			NO_3-N (mg kg^{-1})			NH_4-N (mg kg^{-1})		
		0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm
2019	DTF	1.11 e	0.63 b	0.62 ab	8.68 a	4.21 ab	2.51 ab	29.18 a	23.12 b	17.82 a
	STF	1.17 d	0.90 a	0.62 ab	9.13 a	4.45 ab	1.95 ab	30.02 a	26.14 a	15.88 b
	NTF	1.16 d	0.67 b	0.59 c	9.29 a	4.93 a	1.78 b	30.07 a	23.36 b	15.70 b
	DT	1.19 c	0.70 b	0.60 bc	8.73 a	4.39 ab	2.58 a	30.42 a	21.25 c	18.05 a
	ST	1.28 a	0.66 b	0.64 a	8.89 a	4.04 b	2.30 ab	30.35 a	22.36 bc	18.01 a
	NT	1.25 b	0.67 b	0.58 c	8.01 a	4.01 b	1.91 ab	24.19 b	22.49 bc	16.59 b
2020	DTF	1.17 a	0.78 a	0.61 a	8.23 ab	4.50 b	2.01 b	28.11 a	24.08 a	17.28 a
	STF	1.11 b	0.75 ab	0.60 a	9.17 a	4.44 b	2.21 b	29.11 a	24.96 a	17.70 a
	NTF	1.19 a	0.69 ab	0.58 a	8.29 ab	5.34 ab	3.62 ab	27.69 a	23.33 ab	17.91 a
	DT	1.07 bc	0.67 b	0.57 a	7.13 b	5.89 ab	4.48 a	28.03 a	22.94 ab	18.36 a
	ST	1.04 c	0.73 ab	0.60 a	7.58 ab	6.32 a	3.28 ab	28.15 a	22.94 ab	17.49 a
	NT	1.05 c	0.72 ab	0.60 a	6.92 b	4.98 ab	3.84 ab	27.57 a	20.77 b	15.86 a

Different lowercase letters mean significant differences in soil TN, NO_3-N, and NH_4-N between treatments ($p < 0.05$).

In the 0–20 cm soil layer there was an overall higher inorganic N content in 2019 than in 2020. The soil NO_3-N content in 2019 ranged from 8.01 to 9.29 mg kg^{-1}, with non-significant differences between treatments. In the 20–40 cm layer, the soil NO_3-N content was higher under the application of organic fertilizer in 2019, with the highest level under the NTF treatment being 10.79–22.94% higher than those of the other treatments ($p < 0.05$). The soil NH_4-N contents of the STF treatment were significantly higher than those of the other treatments at 26.14 mg kg^{-1} ($p < 0.05$). In 2020, the NH_4-N content was highest under the STF treatment and was significantly different from that of NT ($p < 0.05$).

3.4. Nitrogen Use Efficiency

As can be seen in Figure 5, the partial productivity of fertilizer (PFP) of wheat and maize followed the same trend from 2018 to 2020. During this period, the shallow tillage resulted in a higher PFP under the treatment with additional organic fertilizer. The PFP from 2018 to 2019 was 46.36–51.16 kg kg^{-1} N, whereas that of the STF treatment was significantly higher than that of the NTF at 48.87 kg kg^{-1} N ($p < 0.05$). Under the STF treatment, it was relatively higher with the additional application of organic fertilizer in 2019–2020 at 49.39 kg kg^{-1} N, which was 2.92–4.93% higher than the DTF and NTF.

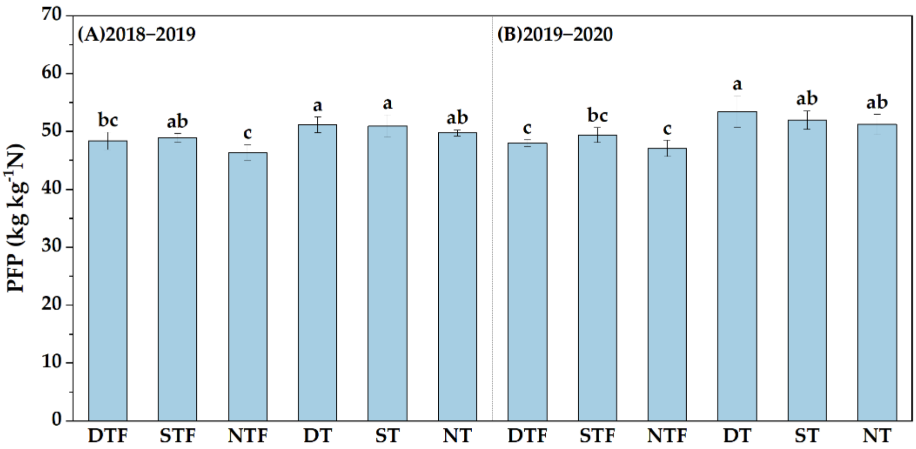

Figure 5. PFP of wheat and maize from 2018 to 2020. PFP from 2018 to 2020 (**A**) and from 2019 to 2020 (**B**). Different lowercase letters indicate significant differences in PFP between treatments ($p < 0.05$). Note: PFP is the partial productivity of fertilizer.

3.5. Crop Yields and Economic Returns

Table 4 shows the total annual yield and economic benefits of wheat–maize under different treatments, and we found that the additional organic fertilizer was better than the N fertilizer treatment. From 2018 to 2020, the annual total yield of wheat and maize was highest under the STF treatment at 21,200.57 kg ha^{-1} and 21,252.23 kg ha^{-1}, respectively. Yields under the STF treatment were significantly higher (by 5.41–12.55%; $p < 0.05$) than those under the NTF, DT, ST, and NT treatments from 2018 to 2019. The yield under the STF treatment was significantly higher than those under the ST and NT treatments from 2019 to 2020 (by 7.94–9.59%; $p < 0.05$). In 2018–2019, the economic value under the STF treatment was significantly higher than under the NTF, DT, ST, and NT treatments at 42,182.26 CNY ha^{-1} (1.02–12.94% higher; $p < 0.05$). In 2019–2020, the economic value under the STF treatment was significantly higher than those under the ST and NT treatments at 42,254.54 CNY ha^{-1} (2.29–9.87% higher; $p < 0.05$). Different tillage and fertilizer applications led to changes in input costs between treatments, thereby translating to differences in annual net crop returns. Overall, the organic fertilizer application treatment was better than the nitrogen fertilizer treatment. The annual net returns from crops ranged from 25,946.80 to 28,389.76 and 26,930.96 and 28,612.04 CNY ha^{-1} in 2018–2019 and 2019–2020, with the returns under STF being the highest, which were 2.62–9.42% and 3.22–6.24% higher than the other treatments, respectively.

Table 4. The annual economic benefit of wheat–maize under different tillage and fertilization treatments.

Year	Treatment	Yield (kg ha^{-1})	Economic Value (CNY ha^{-1})	Mechanical Input (CNY ha^{-1})	Field Management (CNY ha^{-1})	Other Inputs (CNY ha^{-1})			Income Net (CNY ha^{-1})
						Seed	Pesticides	Fertilizer	
2018–2019	DTF	20,991.80 ^{ab}	41,756.95 ^{ab}	2100.00	5250.00	1612.50	30.00	5100.00	27,664.45 ^{ab}
	STF	21,200.57 ^{a}	42,182.26 ^{a}	1800.00	5250.00	1612.50	30.00	5100.00	28,389.76 ^{a}
	NTF	20,112.22 ^{bc}	40,043.28 ^{bc}	900.00	5250.00	1612.50	30.00	5100.00	27,150.78 ^{ab}
	DT	19,376.23 ^{cd}	38,539.30 ^{cd}	2100.00	5250.00	1612.50	30.00	3600.00	25,946.80 ^{b}
	ST	19,294.02 ^{cd}	38,408.84 ^{cd}	1800.00	5250.00	1612.50	30.00	3600.00	26,116.34 ^{b}
	NT	18,837.30 ^{d}	37,347.88 ^{d}	900.00	5250.00	1612.50	30.00	3600.00	25,955.38 ^{b}
2019–2020	DTF	20,821.40 ^{ab}	41,306.68 ^{ab}	2100.00	5250.00	1612.50	30.00	4275.00	28,039.18 ^{a}
	STF	21,252.23 ^{a}	42,254.54 ^{a}	1800.00	5250.00	1612.50	30.00	4275.00	29,287.04 ^{a}
	NTF	20,420.49 ^{ab}	40,462.88 ^{ab}	900.00	5250.00	1612.50	30.00	4275.00	28,395.38 ^{a}
	DT	20,230.30 ^{ab}	40,133.62 ^{ab}	2100.00	5250.00	1612.50	30.00	3450.00	27,691.12 ^{a}
	ST	19,689.36 ^{b}	39,073.46 ^{b}	1800.00	5250.00	1612.50	30.00	3450.00	26,930.96 ^{a}
	NT	19,392.39 ^{b}	38,458.93 ^{b}	900.00	5250.00	1612.50	30.00	3450.00	27,216.43 ^{a}

Different lowercase letters mean significant differences in yield and net returns between treatments ($p < 0.05$).

3.6. Correlation Analysis

Soil physical properties, soil organic carbon and nitrogen and yield were analyzed by stepwise regression analysis. Soil water content (x_1), bulk density (x_2), porosity (x_3), <0.25 mm aggregates content (x_4), soil organic carbon (x_5), soil TN (x_6), NO_3-N (x_7) and NH_4-N (x_8) were used as independent variables and yield (y) as dependent variable. The two stepwise regression equations are as follows:

$$y_{2018-2019} = 43534.058 - 22961.642 \times x_6 + 19395.104 \times x_1 \left(R^2 = 0.753\right)$$

$$y_{2019-2020} = 37491.472 + 393.934 \times x_7 - 14175.129 \times x_2 \left(R^2 = 0.573\right)$$

Correlation analysis showed that total wheat and maize yield in 2018–2019 was significantly negatively correlated with soil TN and significantly positively correlated with soil water content ($p < 0.01$), with soil total nitrogen and soil water content explaining 75.3% of the yield variation. Total wheat and maize yield in 2019–2020 were significantly positively correlated with soil NO_3-N and negatively correlated with bulk density ($p < 0.05$), with both explaining 57.3% of the yield variation.

4. Discussion

4.1. Effects of Tillage and Fertilization on the Physical Properties of Soil

The combination of soil management and continuous application of organic fertilizers are important for optimizing soil physical properties [36]. Tillage practices have significant impacts on the soil water content, bulk density, infiltration resistance, and crop yields through changes in soil porosity, aggregate structures, particle–water–air ratios, and soil hydrothermal properties [11,12]; thus, they represent an important method of regulating soil ecologies [37]. Tillage practices can also change the physicochemical properties of the soil, thus reducing or eliminating the negative impacts of over-application of a single inorganic fertilizer to the soil [19].

This study revealed that the soil water content was higher during the wheat season under no-till treatment when using the winter wheat–summer maize double cropping system in the NCP, which is consistent with the results of Yang et al. [38]. In contrast, the soil water content was higher during the maize season in 2020 under the deep tillage treatment. As not tilling reduces soil disturbance and evaporation, the water content is higher, which simultaneously increases the soil bulk density and reduces its porosity as well as the downward movement of water. Conversely, deep tillage treatment enhances soil porosity, which is conducive to increasing the water content of the deep soil layer [39]. The highest soil water content was found in the 0–20 cm layer under the STF treatment during the wheat season from 2018 to 2019. Research has indicated that the combination of organic and inorganic fertilizers can reduce evaporation and increase soil water content [40]. This research revealed that the soil water content was greatly influenced by the annual precipitation with little difference in the water content between treatments during wet years, and more significant differences between tillage and fertilization treatments when the precipitation was low. Changes in the bulk density and porosity of the soil can reflect the improvement of its physical properties through tillage and fertilization. This research revealed that no-till soils had a higher bulk density and lower porosity compared to deep and shallow-tilled soils, which is in agreement with Amami et al. [41]. This is likely because not tilling the soil imparted negligible disturbances to the soil. Not tilling long term enables soil particles to move down due to their own sedimentation, thereby reducing soil porosity, which increases the soil bulk, whereas long-term deep tillage often loosens the soil. In this study, the additional organic fertilizer application was effective at reducing the soil bulk density and increasing the porosity. This is beneficial for crop roots to grow deeper, while the root death increases soil porosity. Chen's research also showed that continuous application of organic fertilizers can loosen the soil, decrease the bulk density, and increase the porosity [42]. The formation of large aggregates plays a major role in soil nutrient transformation. Several studies have revealed that continuous tillage destroys the structure of aggregates, whereas the absence of tilling promotes the formation of large aggregates. The influence of tillage on the percentage of aggregates in the 0–20 cm layer was more significant in this experiment, and the overall percentage of >0.25 mm aggregates under no-till conditions was higher than those of deep and shallow tilling conditions, which was consistent with previous studies [43]. The fertilizer application year and fertilizer application type had a significant effect on aggregate content at different grain levels [44]. The addition of organic fertilizer in this study increased the content of <0.25 mm aggregates, which is consistent with the findings of earlier studies [45]. Higher levels of organic fertilizer loosen the soil, increase the porosity, enhance the contact area with air, improve microbial activities, and accelerate the mineralization of organic matter, which leads to the decreased stability of aggregates.

4.2. Effects of Tillage and Fertilization on Soil Organic Carbon

The soil organic carbon content, as a major indicator of soil quality, is closely related to agro-ecosystem sustainability [46,47]. It is essential to adopt appropriate on-farm management practices to optimize the conservation of organic carbon and establish the sustainability of agro-ecosystems [48]. There is evidence that organic carbon on farmland is regulated by agricultural practices such as tillage, irrigation and fertilization [49,50]. The results of this experiment are consistent with the results of previous studies in that they indicated that soil organic carbon had an overall decreasing trend with increasing soil depth [51]. The soil organic carbon content was the highest in 2019 at 20–40 cm and in 2020 at 0–20 cm. The reason for this may have been that deep ploughing excessively disturbed the surface soil and destabilized soil aggregates, reducing the physical protection of soil organic carbon, accelerating its mineralization and decomposition, and hindering the accumulation of the soil surface layer [52].

4.3. Effects of Tillage and Fertilizer Application on Soil Nitrogen Availability and Nitrogen Fertilizer Use Efficiency

While soil nitrogen is one of the key elements that ensures crop growth, reasonable farm management patterns can effectively enhance soil nitrogen supply capacities and increase crop yields [53]. Gai X et al., revealed through an experimental study that increased organic fertilizer could increase the soil TN content [54]. This study's results suggest that the TN content was significantly elevated under increased levels of organic fertilizer, which was significantly higher under the STF treatments in contrast to the others in the 20–40 cm layer, in line with the results of previous studies. The addition of organic fertilizer boosts microbial activities, which enhances nitrogen fixation and enhances the soil nitrogen pool [55]. In deeper soil layers, the TN content is gradually reduced, with large differences between treatments in each soil layer. Several studies have revealed that shallow tillage increases the TN content of the soil [56]. This may be due to shallow tillage promoting the development of surface root systems, which efficiently provided more root carbon to the soil [57].

The soil inorganic N content indicates the N supply capacity of the soil, which is significantly influenced by different tillage and fertilization patterns in the soil, affecting NO_3-N and NH_4-N [58]. In this study, the inorganic N content was higher in 2019 than in 2020 under each treatment in the 0–20 cm soil layer, while the soil NO_3-N content was higher under the organic fertilizer treatment in the 20–40 cm. This is contrary to the results of Geng et al. [59]. The high inorganic N content in 2019 may have been due to the additional precipitation during 2019 compared to 2020, which resulted in more nitrogen leaching. The results of Han J et al. showed that the application of organic fertilizer could improve soil fertility to increase soil NO_3-N. The results of this study are consistent with them, and the soil NO_3-N content showed an increase in organic fertilizer better than N fertilizer under the same tillage method in 2020 [60]. The higher NH_4-N content of soil under STF treatment in this study may be due to the fact that organic fertilizer contains a large amount of effective carbon sources, which can increase microbial biomass and activity and promote more NH_4-N assimilation by microorganisms into the soil's active organic N pool [61]. The efficiency of N fertilizer use plays a critical role in efficient fertilizer application, which balances crop yields, economic returns, and environmental sustainability [62]. In the present study, and in agreement with Devkota et al., the annual N fertilizer use efficiencies for both the wheat and maize were better for the additional organic fertilizer treatment than the nitrogen fertilizer treatment [63]. The efficiency of N fertilizer use decreased significantly with a greater application of N, which may have been due to the high mineral N content that remained in the pre-sown soil of wheat that reduced the N application response.

4.4. Evaluation of Tillage and Fertilizer Application on Crop Yields and Economic Benefits

It was shown that the application of organic fertilizers played a key role in improving the soil structure, nutrient content, sustainable yield growth, and high economic efficiency [64–66]. This study revealed that, in agreement with previous studies, crop yields were higher in the treatment with additional organic fertilizer than in the treatment with conventional fertilizer [54]. Regression analysis showed a significant negative correlation between yield and bulk density. This may have been due to the application of organic fertilizer, which optimized the soil physical properties, reduced the soil bulk density, and increased the porosity, all of which were conducive to the growth of crop roots and nutrient absorption, leading to higher yields [19,42]. Correlation analysis showed a positive correlation between yield and water content. Depending on the tillage practice, the structure of the soil was affected, which in turn impacted the soil water content, and ultimately crop yields [43]. The total annual yields of wheat and maize in this study were lowest under the no-till treatment. This was due to the adverse effects of no-till, which can lead to soil compaction, difficult weed control, and organic matter and soil nutrient stratification, which translate into reduced crop yields [67,68].

As a developing country, individuals in the poorer areas of China still rely on agriculture for the majority of their income, with the proceeds from crops being used for their children's education, as well as health and food expenses for family members. Research has found that cash crops have a significantly positive effect on farm household incomes and that the per capita income of farmers who do not grow cash crops is 3909 CNY lower than that of farmers who grow cash crops [69]. Enhancing the economic efficiency of crops requires making them more productive while reducing farm input costs. Not only can appropriate tillage and fertilization patterns effectively improve crop yields, they can also create maximum economic value for farmers. The increased application of organic fertilizer was effective for enhancing crop yields. Therefore, in this study, the organic fertilizer patterns increased the highest benefits for farmers under the same tillage treatment. There were greater mechanical inputs for the deep tillage treatment under the same fertilizer application treatment, and long-term deep tillage treatments resulted in insignificant increases in crop yields and thus insignificant differences in returns compared to shallow tillage. Due the low yields under no-till treatments, the return is lower; thus, the recommended tillage and fertilization pattern to ensure higher crop yields and farmer profits is shallow tillage + organic fertilizer.

5. Conclusions

In this study, we investigated the effects of different tillage and fertilization practices on soil physical properties, soil organic carbon, nitrogen, crop yields, and economic efficiency. Based on the analysis of soil physical and chemical properties over two years, the additional application of organic fertilizer was found to be effective at increasing the soil water content, reducing the soil bulk density, and effectively increasing the proportion of <0.25 mm aggregates when compared with conventional fertilization. It was noticeable that in terms of soil organic carbon and nitrogen contents, the organic fertilizer treatment was better than the nitrogen fertilizer treatment, and the N use efficiency of shallow tillage was higher under the additional organic fertilizer treatments. The results of the study also revealed that the STF treatment had the highest crop yields and farmer profitability, which resulted in our recommending the cropping practice of NCP with a tillage layer of 20 cm or more and additional organic fertilizer.

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