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The Effects of Tillage Systems and Cover Crops on Soil Quality and Soybean Yield

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Abstract: Implementing management practices that minimize environmental impact while maintaining high crop yields is essential to achieve sustainable agricultural production. This study conducted a field trial within a soybean system to evaluate the responses of crop yield, residue decomposition, soil organic carbon (SOC) stock, and soil total nitrogen (STN) stock to varying tillage [moldboard tillage (MP) vs. no-tillage (NT)] and cover crop [hairy vetch (Vicia villosa Roth, HV) vs. rye (Secale cereal, RY)] management practices. The results showed no significant difference in soybean economic yield between MP and NT. However, NT demonstrated a higher SOC stock (0–30 cm), exceeding MP by 4.0% in 2020 and 8.2% in 2021. STN stock (0–30 cm) under NT also surpassed that of MP by 3.3% in 2020 and 3.6% in 2021. No significant differences were observed in soybean yield, SOC stock, and STN stock between HV and RY. Compared to NT, MP accelerated the decomposition of cover crop residues. Moreover, the decomposition of RY was more difficult than that of HV. These findings suggest that NT enhances soil carbon and nitrogen sequestration without compromising yield, positioning it as a sustainable practice for soybean systems, particularly when integrated with RY cover crops.

Keywords: conservation tillage; cover crop; soil organic carbon; soil total nitrogen; residue decomposition

Citation: Hunag, Q.; Gong, Y.; Li, P.; Dewi, R.K.; Komatsuzaki, M. The Effects of Tillage Systems and Cover Crops on Soil Quality and Soybean Yield. *Agriculture* **2024**, *14*, 2119. https://doi.org/10.3390/agriculture14122119

Academic Editor: Pedro A. Casquero

Received: 30 October 2024
Revised: 16 November 2024
Accepted: 21 November 2024
Published: 22 November 2024

1. Introduction

Given the challenges of global climate change, population growth, and resource scarcity, ensuring the security of food, feed, and fiber while minimizing environmental impact has become a critical focus for agricultural system development [1]. Evidence from extensive long-term field experiments reveals that the productivity and environmental impact of cropping systems vary with different agricultural management practices [2–4]. In the current context of frequent extreme weather events, certain conventional agricultural practices, such as intensive tillage and monocropping, may exacerbate the environmental impacts of agricultural systems, thereby hindering the development of sustainable agriculture [1,5].

Conventional tillage, primarily consisting of rotary tillage and plowing, has been widely adopted in agriculture for its benefits in loosening soil and improving aeration [6]. However, intensive tillage heightens the risk of organic matter loss and soil erosion, resulting in nutrient depletion and degradation of the ecological environment [7]. No-tillage

(NT) is a critical management strategy in conservation agriculture, which minimizes soil disturbance and protects soil organic matter within macroaggregates, thereby slowing its decomposition [8,9]. Some studies have reported that NT effectively reduced the mineralization of soil organic carbon (SOC), significantly improving SOC stock [10,11]. Moreover, NT mitigates soil nitrogen (N) loss by providing both physical and biochemical protection to N-mineral complexes, resulting in an increase in soil total nitrogen (STN) stock [12,13]. In addition to its benefits for soil, crop productivity is also a crucial factor to consider when adopting NT in agricultural production systems. Despite numerous studies investigating the effects of NT on crop yields, conclusions remain controversial regarding whether NT increases, maintains, or decreases yields [4,14]. Some studies reported that conventional tillage demonstrated a relative advantage in production, resulting in higher yields compared to NT [4,15]. However, a long-term tillage experiment conducted in Northeast China reported that NT significantly increased grain yield and yield stability [14]. These conflicting results indicate that the response of crop yields to NT is complex and variable, influenced by factors such as soil texture, crop type, and straw management [16,17]. Further and more in-depth discussions are necessary to better understand the impact of NT on crop yields.

Besides NT, cover crop treatment is another key component of conservation agriculture, with a well-established history of application [18]. After termination, cover crops can serve as green manure in agricultural systems, significantly affecting the dynamics of SOC and STN [19]. However, the ecological functions provided by cover crops may vary depending on their varieties. Gramineous cover crops, which produce high biomass residue, are commonly used to enhance SOC accumulation and sequestration [20]. On the other hand, legume cover crops, due to their biological N-fixation ability, provide greater N supplementation to the soil, leading to an increase in STN stock [21]. Similarly, the response of main crop yields to cover crops is also influenced by the types of cover crops used. For instance, in the Argentinian Pampas, corn yields decreased when following non-legume cover crops, while they increased after legume cover crops [22]. Therefore, identifying an appropriate cover crop management strategy is essential for enabling farmers to maximize both crop yields and environmental benefits.

Cover crop residue, as one of the main sources of soil organic matter, plays a vital role in carbon (C) sequestration and nutrient cycling through its decomposition [23]. The decomposition of cover crop residue is a complex biogeochemical process closely related to the environmental conditions of the residue and its inherent properties [24]. The cover crop residues' quality, such as their initial C content, N content, and C/N ratio, is a key driver of decomposition dynamics and significantly influences the decomposition rate [25]. Non-legume cover crops tend to have slower residue decomposition compared to legume cover crops [26,27]. Moreover, agronomic practices, including tillage, also affect the decomposition dynamics of cover crop residue. [28–30]. Thus, it is necessary to gain a deeper understanding of cover crop decomposition dynamics to determine suitable cover crop species under different agricultural management practices.

Previous studies on cover crop residue decomposition typically focused on investigating the decomposition dynamics of various cover crop residues in different environments [25–27]. Additionally, many publications have discussed the effect of NT and cover crop management on crop yields, SOC stock, or STN stock [31–33]. However, there is still insufficient research linking cover crop residue decomposition to the responses of crop yields, SOC stock, and STN stock under NT and cover crop management.

Therefore, we analyzed a soybean cropping system under different tillage practices and various cover crop management strategies in the Kanto region of Japan, which has a prevailing humid subtropical climate. Specifically, the aims of this study were to (1) compare the crop performance under various tillage and cover crop practices; (2) investigate the decomposition dynamics of cover crop residues under different treatments; (3) measure the SOC stock and STN stock of treatments; and (4) analyze the relationships among crop yields, SOC stock, STN stock, and the decomposition dynamics of cover crop residues. The findings of this study will provide a theoretical basis for farmers in selecting appropriate tillage and cover crop management strategies, thereby enabling the sustainable achievement of both high crop productivity and environmental benefits within agricultural production systems.

2. Materials and Methods

2.1. Experiment Site Description

A two-year field experiment was conducted from June 2020 to May 2022 at the soybean farmland of the Center for International Field Agriculture Research and Education, Ibaraki University, Japan (36°02′ N, 140°12′ E). The site has a humid subtropical climate, with a total precipitation of 2581.5 mm and an average air temperature of 15.6 °C during the experimental period [34]. The monthly mean precipitation and air temperature at the study site are shown in Figure 1. The soil at the site is classified as Andosol based on the World Reference Base for Soil Resources and has a sandy loam texture. The bulk density, carbon content, total nitrogen, available phosphorus, exchangeable potassium, exchangeable calcium, exchangeable magnesium, CEC, and pH at 0–30 cm soil were as follows: 0.63 g cm^{-3}, 3.8%, 4.5 g kg^{-1}, 63 mg kg^{-1}, 220 mg kg^{-1}, 1300 mg kg^{-1}, 125 mg kg^{-1}, 32 cmol kg^{-1} and 6.5, respectively.

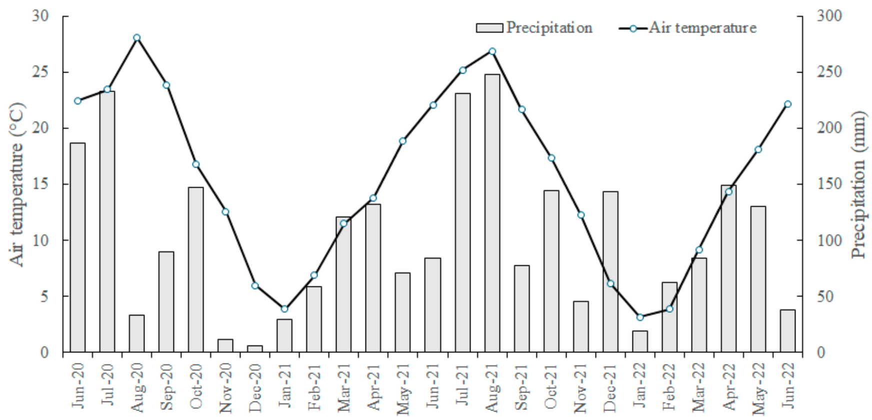

Figure 1. Monthly air temperature and precipitation during the experiment period.

2.2. Experiment Design and Field Management

This study adopted a split-plot design with four replications. Specifically, two tillage methods [moldboard plowing (MP) vs. NT] served as the main factor while two cover crop management practices [hairy vetch (*Vicia villosa* Roth, HV) vs. rye (*Secale cereal*, RY)] constituted the split factor. The main plot measured 54 m^2 (3 × 18 m), while the sub-plot covered an area of 18 m^2 (3 × 6 m).

The cultivation period of soybean (cv. Sachiyutaka) was from early July to November. Soybean was sown at a seeding density of 60 kg ha^{-1} using an NT direct seeder with a row width of 0.3 m. In early November, HV (cv. Mameseku) and RY (cv. Ryokusei) were seeded manually in their corresponding plots as winter cover crops at seeding rates of 50 kg ha^{-1} and 100 kg ha^{-1}, respectively. Subsequently, in the following May, all cover crops were terminated and crushed in the field using a flail mower. After being crushed, cover crop residues were returned to the field, and left on the surface in the NT plots, while in the MP plots, they were incorporated into the soil through tillage. Moreover, the farmland is left fallow each June to allow for recuperation and regeneration. Summer tillage and autumn tillage were conducted in the MP plots immediately after the termination of cover crops and after soybean harvest, to a depth of 0.3 m. This experimental site adhered to the principles of organic farming, and no pesticides, herbicides, or fertilizers were used during the experimental period.

2.3. Crop Sampling and Measurement

In late May, HV and RY were sampled from the center of the corresponding plot using a 0.25 m^2 quadrat. Prior to harvest, soybean samples were collected from the center of each plot using a 0.6 m^2 quadrat on 5 November 2020 and 2 November 2021. After being dried in an oven (60 °C for 72 h), the plant samples were weighed for biomass analysis. Sub-samples of soybean biomass were threshed, and the grains were weighed to determine the soybean yield. Additionally, sub-samples of the oven-dried cover crops were ground into a powder and passed through a 2 mm mesh sieve. After that, the carbon and nitrogen content of HV and RY were quantified using a C/N analyzer (JM3000, J-Science Lab, Kyoto, Japan).

2.4. Soil Sampling and Analysis

Soil samples were collected on 21 October 2020 and 19 October 2021, prior to harvest, a soil sampling cylinder (30 cm in length and 5 cm in diameter) was used to assess the SOC and STN stocks. The soil core samples were divided into four depth intervals (0–2.5 cm, 2.5–7.5 cm, 7.5–15 cm, and 15–30 cm) using manual cutting, and the bulk density of each layer was measured. Sub-samples of soil from each layer for SOC and STN analysis were air-dried, ground, and passed through a 2 mm mesh sieve. The samples were then oven-dried at 105 °C for 72 h, and the SOC and STN content were measured using a C/N analyzer (JM3000, J-Science Lab, Kyoto, Japan). Following the equivalent soil mass method [35], the SOC/STN stock was determined by incorporating the SOC/STN content, soil bulk density, and soil depth.

2.5. Decomposition Analysis of Cover Crop Residues

Litter bags containing cover crop residue were installed after soybean sowing in July 2021 to monitor cover crop decomposition during the soybean growing season [29]. Each litter bag was constructed from nylon with 1 mm mesh and measured 100 cm^2 (10 cm × 10 cm). The litter bags in the HV and RY plots were filled with HV and RY residues, respectively, with weights corresponding to the 2020 cover crop biomass of 2.6 Mg ha^{-1} for HV and 8.7 Mg ha^{-1} for RY. The initial weight of HV and RY litter bags was recorded before installation in the farmland, with bags placed on the surface in NT plots and buried 30 cm underground in MP plots. A total of five litter bags were placed in each plot and collected at 1, 2, 4, 8, and 12 weeks after installation. Residue samples collected from the litter bags after decomposition were washed and oven-dried at 60 °C for 72 h to determine their final weight. The remaining mass proportion of residue at each decomposition stage was calculated by comparing the initial weight to the final weight. Cover crop residue decomposition was analyzed by fitting the observed mass proportions to a two-parameter exponential decay model [29,36]. The decay model is as follows:

$$M_t = M_f \times e^{(-K \times t)} + \left(100 - M_f\right)$$

where M_t represents the percentage of remaining mass or nutrient content, M_f denotes the percentage of the initial material that decomposes at the decomposition rate K, and t is the time elapsed since the litter bags were placed in the field.

2.6. Statistical Analysis

Statistical analyses of the experimental data were conducted using Statistix 8 (Analytical Software, Tallahassee, FL, USA), Hitplot (https://hiplot.com.cn, accessed on 15 October 2024), and JMP 14 (SAS Institute Inc., Cary, NC, USA). Analysis of variance (ANOVA) was conducted using a split-plot model to examine the effects of tillage, cover crop, and their interaction on biomass and yield of crops, SOC stock, STN stock, as well as the parameters M_f and K. Furthermore, relationships among these parameters were analyzed using Pearson correlation analysis with Hitplot. The impact of cover crop management on the C content, N content, and C/N ratio of cover crops was evaluated using an independent samples *t*-test. A least significant difference (LSD) test was performed at a significance level of $p < 0.05$ to compare the mean values of different treatments and identify significant differences among them. Model fitting was conducted separately for each combination of tillage method and cover crop management using the MODEL procedure in JMP 14. Additionally, the coefficients of determination (R^2) and root mean square errors (RMSE) generated from the model fitting were utilized to assess model accuracy.

3. Results

3.1. SOC and STN

Apart from the 0–30 cm depth, SOC stock at other depths (0–2.5 cm, 0–7.5 cm, and 0–15 cm) was significantly affected by the tillage method (Table 1). Both in 2020 and 2021, SOC stocks under NT at these depths were significantly improved compared to MP, with increases ranging from 12.2% to 81.0%. At the depth of 0–30 cm, although not significant, NT tended to improve SOC stock, with NT showing a 4.1% higher SOC stock than MP in 2020 and 8.2% higher in 2021. Although cover crop treatment had no significant effect on SOC stock, RY tended to increase SOC stock compared to HV. In this study, except at the 0–2.5 cm and 0–15 cm depths in 2021, RY consistently showed higher SOC stock than HV, with increases ranging from 1.1% to 9.1%.

The tillage method had a significant effect on the STN stock at depths of 0–2.5 cm, 0–7.5 cm, and 0–15 cm (Table 2). At these depths, STN stocks under NT significantly exceeded those under MP in both 2020 and 2021, showing increases ranging from 13.0% to 77.7%. Moreover, NT tended to exhibit higher STN stock at the depth of 0–30 cm, being 3.2% higher in 2020 and 3.6% higher in 2021 compared to MP. The STN stock was significantly affected by cover crop treatment at a depth of 0–15 cm in 2020, with a significant increase of 8.9% under RY compared to HV. Aside from this depth, there was no significant effect of cover crop treatment on STN stock at other depths throughout the experimental period. Additionally, STN stock under HV was 8.2% lower than under RY in 2020 and 3.2% lower in 2021, although the difference was not significant.

Table 1. Effect of tillage and cover crop on soil organic carbon (SOC) stock across different depths.

Factor	2020				2021			
	0–2.5 cm	0–7.5 cm	0–15 cm	0–30 cm	0–2.5 cm	0–7.5 cm	0–15 cm	0–30 cm
	(Mg ha^{-1})							
Tillage								
MP	7.7 b	23.2 b	46.4 b	84.4 a	7.6 b	22.4 b	46.2 b	87.1 a
NT	13.9 a	30.8 a	52.0 a	87.8 a	13.2 a	30.7 a	52.7 a	94.3 a
Cover crop								
HV	10.5 a	25.8 a	47.5 a	84.2 a	10.4 a	26.4 a	49.7 a	90.0 a
RY	11.1 a	28.2 a	50.9 a	88.0 a	10.4 a	26.7 a	49.3 a	91.4 a
ANOVA significance								
Tillage (T)	***	**	*	ns	***	**	*	ns
Cover crop (CC)	ns	ns	ns	ns	ns	ns	ns	ns
T × CC	ns	ns	ns	ns	ns	ns	ns	ns

MP: moldboard plowing; NT: no-tillage; HV: hairy vetch; RY: rye. ns indicates no significant effect. *, **, and *** indicate significance at the 0.05, 0.01, and 0.001 probability levels, respectively. Different letters following the values denote significant differences among treatments at $p < 0.05$ (LSD test).

Table 2. Effect of tillage and cover crop on soil total nitrogen (STN) stock across different depths.

Factor	**2020**				**2021**			
	0–2.5 cm	**0–7.5 cm**	**0–15 cm**	**0–30 cm**	**0–2.5 cm**	**0–7.5 cm**	**0–15 cm**	**0–30 cm**
	(Mg ha^{-1})							
Tillage								
MP	0.7 b	2.2 b	4.5 b	8.4 a	0.6 b	1.8 b	3.7 b	6.9 a
NT	1.3 a	3.0 a	5.1 a	8.7 a	1.1 a	2.5 a	4.3 a	7.1 a
Cover crop								
HV	1.0 a	2.5 a	4.6 b	8.2 a	0.8 a	2.1 a	4.0 a	6.9 a
RY	1.0 a	2.7 a	5.0 a	8.9 a	0.8 a	2.2 a	4.0 a	7.1 a
ANOVA significance								
Tillage (T)	***	**	*	ns	***	**	*	ns
Cover crop (CC)	ns	ns	ns	ns	ns	ns	ns	ns
T × CC	ns	ns	ns	ns	ns	ns	ns	ns

MP: moldboard plowing; NT: no-tillage; HV: hairy vetch; RY: rye. ns indicates no significant effect. *, ** and *** indicate significance at the 0.05, 0.01, and 0.001 probability levels, respectively. Different letters following the values denote significant differences among treatments at $p < 0.05$ (LSD test).

3.2. Crop Performance

In 2020, soybean biomass was significantly affected by the tillage method, with a 44.9% increase in NT compared to MP (Table 3). Similarly, in 2021, the soybean biomass under NT was 5.2% higher than that under MP, although the increase was not significant. Moreover, RY tended to have a higher soybean biomass than HV, with increases reaching 4.9% in 2020 and 14.3% in 2021, respectively. Compared to MP, while not significant, the yield of soybeans under NT was 24.3% lower in 2020 and 30.4% lower in 2021. Cover crop treatment demonstrated varying effects on soybean yield across different years. Although not significant, the RY treatment showed a 6% lower soybean yield than HV in 2020 and exceeded HV by 29.4% in 2021.

Table 3. Effects of tillage and cover crop on soybean biomass and soybean yield.

Factor	**2020**		**2021**	
	Soybean Biomass	**Soybean Yield**	**Soybean Biomass**	**Soybean Yield**
	(Mg ha^{-1})			
Tillage				
MP	6.9 b	3.7 a	5.8 a	2.3 a
NT	10.0 a	2.8 a	6.1 a	1.6 a
Cover crop				
HV	8.2 a	3.3 a	5.6 a	1.7 a
RY	8.6 a	3.1 a	6.4 a	2.2 a
ANOVA significance				
Tillage (T)	*	ns	ns	ns
Cover crop (CC)	ns	ns	ns	ns
T × CC	ns	ns	ns	ns

MP: moldboard plowing; NT: no-tillage; HV: hairy vetch; RY: rye. ns indicates no significant effect. * indicates significance at the 0.05 probability level. Different letters following the values denote significant differences among treatments at $p < 0.05$ (LSD test).

In the present study, there was no significant effect of the tillage system or the interaction between tillage and cover crop on cover crop biomass (Table 4). Conversely, cover crop treatments significantly affected the cover crop biomass during the experiment period. The cover crop biomass of the HV treatment was significantly lower than that of the RY treatment, showing a decrease of 69.2% in 2020 and 51.8% in 2021, respectively. Cover crop variety had no significant effect on the C content of cover crops in 2020 (Table 5). However, in 2021, the C content of RY was significantly higher than that of HV, with an increase of 2.3%. The N content of the cover crop was significantly affected by the cover crop variety, with that under RY being 55.6% in 2020 and 65.0% lower in 2021 than that under HV, respectively. Also, cover crop variety significantly affected the C/N ratio of cover crops. Compared to HV, RY showed a higher cover crop's C/N ratio, with increases of 153.8% in 2020 and 154.8% in 2021.

Table 4. Cover crop biomass under varying tillage and cover crop management practices.

Tillage	Cover Crop	2020	2021
		(Mg ha^{-1})	
MP	HV	1.7 b	2.7 b
	RY	9.2 a	9.7 a
NT	HV	3.7 b	4.6 ab
	RY	8.2 a	5.4 ab
ANOVA significance			
Tillage (T)		ns	ns
Cover crop (CC)		***	*
T × CC		ns	ns

MP: moldboard plowing; NT: no-tillage; HV: hairy vetch; RY: rye. ns indicates no significant effect. * and *** indicate significance at the 0.05 and 0.001 probability levels, respectively. Different letters following the values denote significant differences among treatments at $p < 0.05$ (LSD test).

Table 5. Carbon (C) content, nitrogen (N) content, and C/N ratio of different cover crops.

Year	Cover Crop	C Content	N Content	C/N Ratio
		(%)	(%)	
2020	HV	43.8	1.8	26.0
	RY	44.3	0.8	66.0
	Significance	ns	***	***
2021	HV	44.4	2.0	32.1
	RY	45.4	0.7	81.8
	Significance	**	**	**

HV: hairy vetch; RY: rye. ns indicates no significant effect. ** and *** indicate significance at the 0.01 and 0.001 probability levels, respectively.

3.3. Decomposition of Cover Crop Residue

The decomposition cover crop residue varied under different tillage methods and cover crop treatments (Figure 2). The decay model for cover crop residue showed a good fit of biomass decomposition as a function of time, with R^2 values exceeding 0.94 for all treatments (Table 6). The parameters M_f and K are the key constants in the decay model. A higher value of M_f indicates a more complete decomposition of the residue, while a higher K value signifies a faster rate of decomposition. ANOVA results indicated that tillage methods, cover crop treatments, and their interaction significantly affected the M_f of the decomposition model. For the same cover crop treatment, MP resulted in higher M_f under both HV and RY than under NT, with a 1.1% increase under HV and a 27.6% increase under RY compared to NT, respectively. Meanwhile, under the MP system, the Mf of HV was 5.2% higher than that of RY. A similar trend was observed in the NT system, where HV increased M_f by 32.9% compared to RY. The K value of the decomposition model was also significantly affected by tillage methods, cover crop treatments, and their interaction. For HV treatment, the K value under NT was 68.0% lower than that under MP. In the case of the RY treatment, NT exhibited a 40.2% lower K value compared to MP.

Moreover, compared to RY, HV led to 158.6% and 38.2% increase in *K* value under MP and NT, respectively.

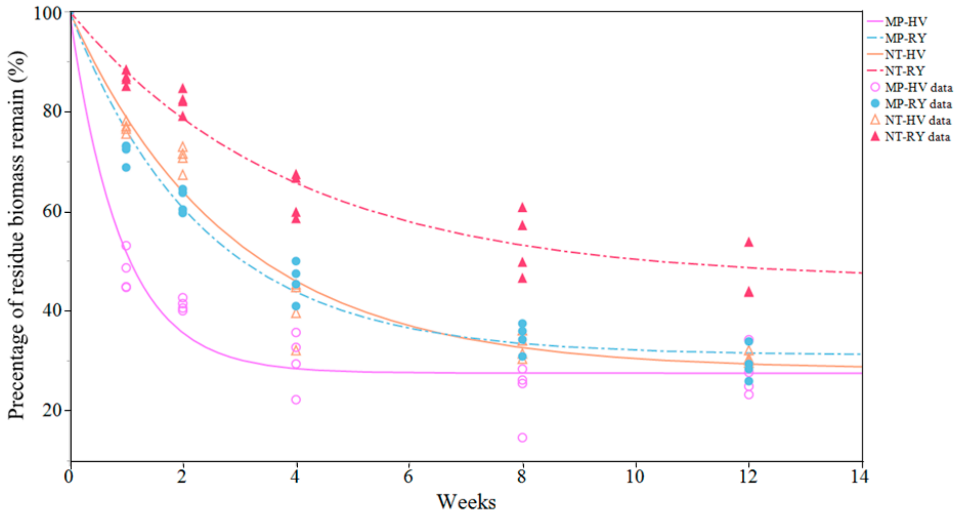

Figure 2. The proportion of mass remaining in litter bags after installation. Lines on the graph represent simulated decay model data, while points indicate observed values from litter bags. MP: moldboard plowing; NT: no-tillage; HV: hairy vetch; RY: rye.

Table 6. Parameter estimates and model fit data for the decay model of biomass decomposition.

Tillage	Cover Crop	Biomass Model Parameter Estimates				Model Fit	
		M_f	Standard Error	K	Standard Error	RMSE	R^2
MP	HV	72.48 a	1.53	1.10 a	0.11	5.18	0.96
MP	RY	68.87 a	1.40	0.42 b	0.03	3.44	0.98
NT	HV	71.72 a	2.16	0.35 b	0.03	4.67	0.97
NT	RY	53.95 b	2.67	0.25 b	0.03	4.22	0.95
ANOVA significance							
Tillage (T)		*		**			
Cover crop (CC)		**		***			
T × CC		*		**			

MP: moldboard plowing; NT: no-tillage; HV: hairy vetch; RY: rye; RMSE: root mean square errors; R^2: coefficients of determination. *, ** and *** indicate significance at the 0.05, 0.01, and 0.001 probability levels, respectively. Different letters following the values denote significant differences among treatments at $p < 0.05$ (LSD test).

3.4. Correlation Analysis

Soybean yield was significantly and positively correlated with soybean biomass and STN stock (0–30 cm) (Figure 3). Conversely, soybean yield showed a significant negative correlation with SOC stock (0–30 cm). In addition, significant negative correlations were observed between cover crop biomass and *K* value as well as M_f of the decomposition model. Similarly, SOC stock (0–30 cm) was significantly and negatively correlated with the *K* value of the decomposition model. However, there was a significant positive correlation between *K* and M_f of the decomposition.

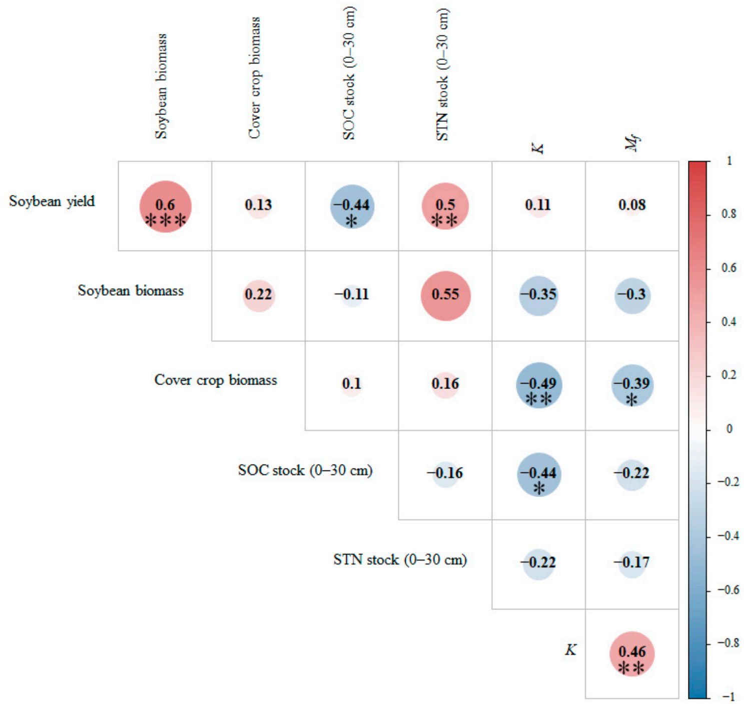

Figure 3. Correlation analysis conducted among soybean yield, soybean biomass, cover crop biomass, SOC stock (0–30 cm), STN stock (0–30 cm), *K* value, and M_f. Red and blue, respectively, indicate positive and negative correlations between the two variables. *, ** and *** indicate significance at the 0.05, 0.01, and 0.001 probability levels, respectively.

4. Discussion

4.1. SOC and STN Were Affected by NT and Cover Crop

Soil macroaggregates are crucial for the accumulation of SOC [35,36]; however, they are typically broken up during tillage, which accelerates the decomposition of the organic matter they protect [37]. In contrast, NT minimizes soil disturbance and provides a stable environment that protects macroaggregates [38,39]. MP inverts surface soil and incorporates surface carbon into deeper soil layers through plowing, resulting in lower SOC content in topsoil compared to NT [40,41]. Furthermore, NT has been shown to reduce SOC mineralization in the topsoil, thereby increasing the stability of SOC [10,11]. Our findings showed that NT significantly increased SOC stock in the surface soil (0–30 cm) compared to MP, consistent with previous studies conducted on the same site [33,42]. Previous studies found that NT exhibits greater STN stock than MP, which is consistent with our findings [43,44]. The reduction in soil erosion and surface runoff under NT effectively mitigates N loss in farmland, leading to a higher STN stock compared to MP [45,46]. Moreover, through its improvements in soil structure and porosity [47], NT enhances the activity of N-fixing microorganisms [48] and promotes the immobilization of N-containing compounds by soil minerals [49], thereby maintaining high STN stock.

The adoption of cover crops can enhance SOC stock by increasing C inputs to soil [23], while this change is affected by the quantity and quality of cover crops [50]. Several studies found that planting grass cover crops, such as RY, contributes greater SOC increases compared to legume cover crops [31,51]. However, another reported the increases in SOC in legume cover crops were greater than those in grass cover crops [52]. Our findings indicated that there was no significant difference between the SOC stock under HV and RY, despite the higher biomass input from RY. Grass cover crops often exhibit a higher

C/N ratio, requiring more time to convert biomass into SOC [53,54]. Meanwhile, decomposer organisms demonstrate low C use efficiency in the residues with a high C/N ratio, resulting in a greater loss of C through respiration rather than its stabilization in the soil [55]. Legume cover crops, with their biological N-fixation capacity, can enhance N accumulation in both the plants and the soil by capturing N from the atmosphere [56]. Generally, cropping systems that incorporate legume cover crops have higher STN stocks compared to those that use grass cover crops [57]. In the present study, the difference in STN stock under different cover crop treatments was non-significant. We found that HV showed higher N content but lower biomass than RY, leading to comparable nitrogen accumulation in biomass. Consequently, the similar total N inputs to the soil from both HV and RY caused comparable STN stocks.

4.2. Crop Performance Was Affected by NT and Cover Crop

Since the 1960s, the adoption of NT practice has steadily increased worldwide, with at least 125 Mha farmland currently implementing NT practice [58]. Several studies reported that crop category was the key factor affecting crop yield response to NT [59,60]. The yields of wheat and corn were highly sensitive to the effects of NT, while legume crop yields under NT showed little difference compared to those under conventional tillage [59]. In the present study, the difference in soybean yields between NT and MP was not significant, consistent with previous findings [61]. Meanwhile, our data showed that NT significantly increased the soybean biomass compared to MP. NT practices have been reported to significantly improve soil health, which benefits crop growth [62,63]. We speculate that NT has a positive effect on soybean growth during the vegetative stage, while its impact on reproductive growth is not significant.

Similar to tillage practices, the impact of cover crop adoption on main crop yields remains under debate. While some studies have shown that rotating with cover crops can enhance main crop yields [64,65], others have reported no significant effects, or even negative impacts, on main crop yields [66,67]. A meta-analysis reported that the impact of cover crop management on main crop yields was significantly influenced by cover crop species [68]. Due to the benefits of biological N-fixation, legume cover crops typically result in higher main crop yields compared to non-legume cover crops [22,69]. For instance, in corn production systems, corn yields were higher when rotated with hairy vetch (legume cover crop) compared to rotations with oat or radish (non-legume cover crop) [70]. However, in this study, no significant difference in soybean yield was observed between the HV (legume cover crop) and RY (non-legume cover crop) treatment, consistent with previous findings [71].

4.3. Effect of Tillage and Cover Crop on Residue Decomposition

Conventional tillage typically accelerates the decomposition of plant litter in soil relative to NT [72,73]. A study conducted in Maryland reported that cover crop residues decomposed greatly faster under conventional tillage than under NT [74]. In this study, both HV and RY demonstrated a more rapid and complete decomposition under MP compared to NT. A point of view claimed that tillage accelerated decomposition by increasing close contact between buried residues and soil microbes [75,76]. Furthermore, tillage promotes the proliferation of particular decomposers, such as saprotrophic fungi, whose increased abundance is positively correlated with the accelerated decomposition of plant residues [73]. The initial C/N ratio of the residue of plant residue is one of the primary drivers of decomposition [77,78], with cover crop species that have a high C/N ratio decomposing more difficult than those with a low C/N ratio [74,76]. The C content of HV and RY was comparable, whereas HV exhibited significantly higher nitrogen content than RY, thereby demonstrating a lower C/N ratio in HV compared to RY. Moreover, RY has been found to contain higher fiber fractions compared to HV, which likely impeded the degradation processes in RY [29,79]. Previous studies found that HV decomposed significantly faster than RY [29,76], which aligns with the present findings.

4.4. The Correlation Between Soil Quality and Soybean Yield

The results of correlation analysis indicated that no significant effect was observed on cover crop decomposition rate to soybean yield in the present study. Cover crop residues release substantial C and N during decomposition [26,76], while not all this C and N is converted into stable compounds that can be sequestered in the soil [80,81]. In this study, we monitored the loss of residue biomass over time and built a decay model for its decomposition. However, the impact of C and N released from residue decomposition affects the C and N cycles in soil remains unclear. Consequently, future studies with isotope tracer methods to mark and track the carbon and nitrogen from cover crop residues during decomposition may be needed to investigate the processes by which these unstable C and N are sequestered into the soil.

5. Conclusions

Sustainable agricultural development requires achieving a balance between high yields and environmental benefits. This study investigated the response of crop yield and soil quality under different tillage and cover crop practices from the perspective of straw decomposition. In terms of the cover crops selection, no significances were observed in soybean yield, SOC stock, and STN stock between HV and RY while the residue decomposition of HV was faster and more complete compared to RY. The decomposition of both HV and RY residues was slowed under NT practice, resulting in a longer duration of mulching in NT plots, which helps mitigate soil erosion. NT can significantly improve the SOC stock and STN stock in the soybean system while maintaining comparable yields to MP, indicating that NT is a promising practice for achieving sustainable soybean production. Our findings provide a data basic for the benefits of NT and cover crop application in soybean production, promoting sustainable agriculture development. Additionally, further studies monitoring C and N from cover crop residue under different tillage systems are still needed to better understand how they can influence the soil C and N cycles.

Author Contributions: Q.H.: conceptualization, investigation, data curation, formal analysis, methodology, visualization, writing—original draft; Y.G.: investigation, data curation, formal analysis, writing—review and editing; P.L.: investigation, data curation; R.K.D.: investigation; M.K.: supervision, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: Part of this work was funded by a grant from the Tojuro Iijima Foundation for Food Science and Technology.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data are available from the corresponding author upon reasonable request.

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

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