アジアにおける保全農業が土壌炭素貯留に及ぼす影響のメタ解析とそのモデル化

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はじめに

国際連合食糧農業機関（FAO） は、増大する世界の人口を養う食料を生産し、気候変動に対応するため、世界の農民は今すぐ、より持続可能で生産性の高い耕作システムに転換しなければならない（FAO 2009)、ことを指摘して以来、世界各国で保全農業（CA: Conservation Agriculture）に関する圃場研究が進められている。CA の基本ルールとしては、①不耕起あるいは省耕うん、②カバークロップなどの植生の被覆、および③輪作に多様性確保があげられている（FAO 2017)。これら CA の農法に関する慣行農法との比較研究は欧米を中心に進められているが、アジアにおける保全効果についての検証は少ない。

本研究では、アジア諸国で報告されている査読済みの出版物から、不耕起など保全耕うんと慣行耕うん体系との土壌炭素貯留や作物生産性について比較し、アジアにおける保全農業の効果について検証する。このメタ解析研究では、不耕起体系と慣行耕うん体系での土壌炭素含有量、土壌炭素貯留量、乾燥密度、平均団粒径およびその他の土壌特性を評価する。さらに大学農場内に設置したモデル圃場実験により、アジアモンスーンによる気象特性と小農による農業環境特性の中で、土壌炭素貯留と農業生産の持続性について特に土壌水分保全の点から評価を行う。

これらの検討により、今まで大規模農業を中心とした欧米での検証が主流となっていたＣＡの効果について、アジア地域における小規模かつ集約的な農業生産の場面での CA の効果について明らかとしたい。

１）アジアにおける保全農業が土壌炭素貯留に及ぼす影響のメタ解析

メタ解析に使用する文献は Web of Science と Google Scholar を使用し、 検索に使用するキーワードには、「不耕起」、「耕起」、「土壌の質」、および各アジアの国名が含めた。査読論文は、以下の基準を使用して選択した。a）農業生産現場で実施された調査研究、 b）選択された論文には、不耕起と慣行耕起を比較するデータが含まれていることとした。データは、公開された記事の表から取得し、Get-Data Graph Digitizer（バージョン 2.24）を使用して図から間接的に取得した。

図１アジアにおける保全農業と慣行農業との炭素貯留量に関する研究調査地点（現時点で６６地点網羅）

このメタ解析研究では、不耕起体系と慣行耕うん体系での土壌炭素含有量、土壌炭素貯留量、乾燥密度、平均団粒径およびその他の土壌特性を評価した（図１）。 さらに、メタ解析では、さまざまな土壌の層別、土壌型、および気候地域で不耕起を採用した後の土壌特性の変化を検討した。具体的には、各圃場実験の各変数の平均、標準偏差（SD)、およびサンプルサイズ（n）を抽出し、RevMan5.2 を使用してメタ分析を行った。ここで不耕起と慣行耕うんとの間の変化率は、次の式のように計算した。

変化率 (%) = 100× (MDNT-MDCT)/MDCT

ここで MDNT および MDCT は、不耕起および慣行耕うんの平均値を示す。

以上の調査をもとに、アジアにおける不耕起栽培などの保全耕うんの効果を検証した結果、慣行農法とＣＡによる土壌炭素量の比較では、ＣＡで土壌別、気候帯別に関わらず土壌炭素貯留量の増加が認められた（図２)。一方、作物収量については、ＣＡと慣行農業との差異は大豆及び小麦では差異が認められず、とうもろこし及び水稲ではＣＡにより作物収量が低減した。これらの結果は、ＣＡは作物の増収技術とはならないが、土壌を保全する効果が著しく高いことが、アジア地域においても認められることが明らかとなった。

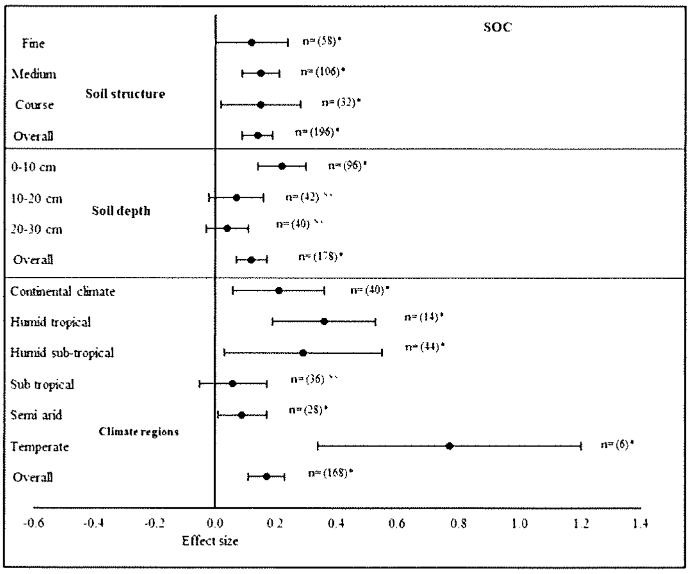

図2アジアにおける保全農業と慣行農業との炭素貯留量の差違。土壌炭素は、土壌タイプ、土壌深さ、気候帯によって保全農業の効果は大きく異なる。

２）モデル圃場におけるＣＡの土壌水分保持効果に関する検証

不耕起栽培とカバークロップの組み合わせによるＣＡは、土壌表面のほぼすべての物理的な撹乱を排除し、土壌の凝集力と有機炭素（SOC）を増加させる気候対応型の農業実践であるが、日本の火山灰土壌における長期のＣＡシステムの SOC と土壌水保持（SWR）への応答はよく取り上げられていない。この研究は、ライムギと裸地を組み合わせた不耕起およびプラウ耕システムの SOC、活性炭（AC)、耐水性団粒、平均団粒径（MWD)、容積重量、易分解性有機物（AC)、および SWR に与える影響を評価することを目的とした。不耕起栽培は、0-2.5 cm および 2.5-5 cm の深さでの>4 mm および 2 mm の団粒、0-15 cm の間

の団粒に関連する炭素、圃場容水量、および0から15 cmの間のSWRを有意に増加させた。ライムギカバークロップは、不耕起栽培およびプラウ耕の両方で2.5-5 cmおよび5-10 cmの深さで団粒に関連する炭素と10-15 cmの深さでSWRを有意に増加させた。不耕起栽培とライムギを組み合わせた場合、表層でのSOCとAC、およびすべての土壌深さでの体積含水率が有意に増加しました。パス解析によれば、不耕起栽培ではSOCとMWDが容易に植物が利用可能な水（EPAW）および圃場容水量と相関しており、これがSWRの増加の主な要因となっていた。したがって、不耕起栽培は圃場表面の作物山さによる被覆を増加させることで、土壌の蒸発を減少させ、SOC含有量とSWRを増加させ、プラウ耕よりも土壌の微細団粒をマクロ団粒に結びつけることが認められた。これらの結果から、ライムギをカバークロップとして用いた不耕起栽培は、気候変動による干ばつの影響を軽減する効果的な気候対応型農業実践となることが期待される。

まとめ

アジアで行われた土壌保全に関する研究では、不耕起栽培（CA）と従来の慣行農法を比較した結果、CAにおいて土壌炭素量が増加しました。この増加は土壌の種類や気候帯に関係なく観察されました。一方、作物収量については、大豆と小麦ではCAと慣行農法の間に差異は見られませんでしたが、とうもろこしと水稲ではCAにより作物収量が低下しました。この研究から、CAは主に土壌保全に寄与し、作物の増収には直接的な影響を与えないことがわかりました。またモデル圃場での検討結果からCAは土壌の団粒形成や水保持力を高め、気候変動による干ばつの軽減に役立つことが期待されます。特にライムギをカバークロップとして組み合わせたCAは効果的な気候対応型農業実践として注目されます。

これらの検討により、いままで大規模農業を中心とした欧米での検証が主流となっていたCAの効果について、アジア地域における小規模かつ集約的な農業生産の場面でのCAの効果について有意性を認めた。

発表論文

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No-tillage and rye cover crop systems improve soil water retention by increasing soil organic carbon in Andosols under humid subtropical climate

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ABSTRACT

No-tillage (NT) combined with a cover crop is a climate-smart agricultural practice that eliminates nearly all physical disturbance of the soil surface and increases soil aggregation and soil organic carbon (SOC); however, the response of SOC and soil water retention (SWR) to long-term NT and cover crops systems in the volcanic ash Andosol soil of Japan has not been well addressed. This study aimed to evaluate the effect of NT and moldboard plow (MP) tillage systems combined with rye (RY) and fallow (FA) cover crop treatments on SOC, active carbon (AC), water-stable aggregates, aggregate stability index, mean weight diameter (MWD), bulk density, aggregate-associated carbon, and SWR. NT significantly increased the > 4 and 2 mm aggregates, aggregate-associated C at the 0–2.5 and 2.5–5 cm depths, field capacity, and SWR between 0 and 15 cm. RY cover crops significantly increased aggregate-associated carbon at the 2.5–5 and 5–10 cm depths in both NT and MP and SWR at the 10–15 cm depth. NT combined with RY significantly increased SOC and AC in the surface layer and volumetric water content at all soil depths. Path analysis revealed that SOC and MWD were correlated with easily plant-available water (EPAW) and field capacity under the NT system and is the primary reason for the observed increase in SWR. Thus, the NT system increased plant residue, reduced soil evaporation, increased SOC content and SWR, and bonded soil microaggregates into macroaggregates better than the MP system. The use of an RY-based NT system is an effective climate-smart agriculture practice that reduces the drought effects brought on by climate change.

1. Introduction

Soil organic carbon (SOC) is one of the most important soil components and is a key indicator of soil quality and function that improves the structural stability of soil and helps to mitigate climate change (Rocci et al., 2021). Restoring soil organic matter enhances plant water availability, resilience against drought-related yield losses, and contributes to both climate change mitigation and adaptation (Lal, 2020; Paul et al., 2023). Generally, land-use management practices can cause SOC to be lost or gained (Zhu et al., 2021). Land conversion from native ecosystems to cropland can result in a considerable loss of carbon, ranging from 0.5 to more than 2 megagrams (Mg) of carbon per hectare per year (Davidson and Ackerman, 1993; Ogle et al., 2005). Thus, agricultural management practices that increase SOC accumulation are important in climate change mitigation (Smith et al., 2007).

No-tillage (NT) practices enhance soil carbon sequestration and multiple agroecosystem services (Chan et al., 2002; Komatsuzaki and Ohta, 2007) by alleviating soil disturbance and maintaining crop residue on the soil surface. The NT system in Andosols has been demonstrated to decrease soil organic matter (SOM) decomposition, enhance soil aggregation, and improve soil biological structures by increasing fungal biomass (Nakamoto et al., 2012). Consequently, the accumulation of SOC contributes to improved soil aggregation, bulk density (BD), water retention, and crop productivity (Hashimi et al., 2020; Huang et al., 2020; Koga and Tsuji, 2009). SOC accumulation in the soil aids in the formation of macroaggregates, which physically protects SOC from

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decomposition (Sekaran et al., 2021) and increases the long-term SOC storage capability of soil (Aziz et al., 2013). Furthermore, soil aggregation is associated with higher levels of SOM, water infiltration, aeration, and nutrient availability in soil (Nichols and Toro, 2011). In sustainable agriculture, NT effectiveness is mostly dependent on the previous plant residue input rate (Derpsch et al., 2014). Conversely, intensive tillage systems, including moldboard plow (MP), in Andosol soil can be destructive and can lead to decreased soil aggregate stability, and soil fertility by increasing O_2 availability to microbes, which speeds up the rate of organic matter decomposition (Koga and Tsuji, 2009; Nakamoto et al., 2012). However, limited studies are available regarding the effect of MP on soil water retention (SWR) in volcanic ash Andosol soil of Japan.

According to Koga et al. (2020), Andosol soil, which has volcanic ash and humus as its main constituents and parent material, makes up the majority of the 47% of Japan's farmland. Because of its high soil carbon content, low pH, and creation of the aluminum-humus complex, Andosol soil has a stronger potential to store carbon in the soil, a feature rarely found in other soil groups (Miyazawa et al., 2013). Low BD is another distinctive feature of the Andosol soil in this area, which is essential in defining soil structure, porosity, and water infiltration capacity (Rahman et al., 2008). However, Takahashi et al. (2010) found that SOC buildup in Andosols may sometimes be unstable and impacted by changes in land use, which results in a significant loss of SOC. For instance, 80% of farmers in Japan cultivate their crops using rotary tillage, which reduces soil aggregates and SOC (Gong et al., 2021a). Though winter cereals have vanished from the area, winter fallowing is still a frequent practice in upland fields, despite the region's environment being conducive to double crop rotation with the main crop in the summer and cover crops in the winter (Miyazawa et al., 2013). As a result, preserving the SOC in Andosols requires both significant inputs of carbon and sustainable land management (Koga et al., 2020).

The main purpose of growing cover crops is to enhance the physical attributes of the soil and prevent soil erosion by covering soil surfaces with living vegetation. The amount of cover crop residue left on the soil surface is largely dependent on the termination method and the C:N ratio of the cover crop at the time of termination (Lynch et al., 2016). Higashi et al. (2014) reported that RY cover crops have high biomass and provide a good source of SOC content in Andosol under humid subtropical conditions. In another study, a long-term NT system combined with cover crops increased surface layer SOC and aggregate stability and reduced soil compaction (Blanco-Canqui et al., 2011). Thus, NT systems and cover crops are recognized as smart agriculture practices (Bai et al., 2019). However, there is a lack of comprehensive documentation on the long-term effects of NT and cover crop management on soil aggregation and SWR in Andosols under humid subtropical climate conditions, where plant growth is frequently reliant on the soil's water storage capacity. Consequently, it is crucial to assess the impact of NT and cover crop systems on soil aggregation and SWR. These factors significantly influence soil structure stability and crop growth, particularly during drier seasons.

Many parts of the world, including Asia, have monsoon climate conditions and are highly vulnerable to drought. Various climate zones in Asia (e.g., tropical, arid, and continental climates) are experiencing altered monsoon characteristics due to climate change, including drought conditions that effect crop production (Chen et al., 2004; Kim et al., 2020). Increasing the water storage capacity of soil reduces the negative impacts of such droughts. Several studies on nonvolcanic soil have confirmed that the high amount of plant residue left on the surface layer of soil in NT systems reduces evaporation and increases the soil's water retention capacity (Kumar et al., 2012; Sekaran et al., 2021). Despite the benefits of NT and cover crops on soil quality and climate mitigation, it has not yet been adequately documented how SOC and SWR responds to climate change and different tillage practices in humid subtropical climate conditions. Thus, the effect of different tillage systems and cover crops on Andosol soil requires further study. The objectives of this study were to examine the effect of the long-term use of different tillage and cover crop management systems on the physical and chemical properties of soil. Specifically, we investigated SOC, active carbon (AC), water-stable aggregates, BD, mean weight diameter (MWD), aggregate-associated carbon in different soil aggregate sizes, and SWR. We also performed a path analysis to determine how SOC and MWD affect field capacity and easily available water content in the Andosol soil of Japan.

2. Materials and methods

2.1. Site description, and experimental design

This experiment began in 2002 at the Center for International Field Agriculture Research and Education, Ibaraki University, Japan (36°02′N 140°12′ E). The experimental site has a humid subtropical climate suitable for double crop rotation for main crops in summer and covers crops in winter, with an annual air temperature of 15.6 °C and an annual rainfall of 1390 mm (Japan Meteorological Agency, 2022). The soil of the Kanto region of Japan developed from volcanic ash and is classified as a typical Andosol soil in which the texture of the upper surface is sandy loam, and the clay content increases gradually with depth (Kanda et al., 2018).

The experiment was performed as a split-plot design with four replications that consisted of two tillage systems (NT and MP) with two cover crop treatments of winter rye (RY; *Secale cereale*), and fallow (FA; *native weeds*) as the split factor. The native weeds primarily consisted of *Lolium* × *hybridum* Hausskn and *Bromus catharicus* Vahl (Gong et al., 2021b). The main plot had dimensions of 54 m^2 (3 × 18 m), whereas the sub-plot measured 18 m^2 (3 × 6 m).

2.2. Experimental farming practices

The tillage and cover crop systems were implemented with upland rice from 2002 to 2007 and soybeans from 2008 to 2021. The MP treatment plot involved two rounds of tillage operations each year using a mounted plow (RQY141C; Sugano Co., Ltd.) to achieve a tillage depth of approximately 28 cm. For the summer MP treatment, tillage was performed after terminating the cover crop. For the autumn MP treatment, tillage was conducted following soybean harvesting, typically in early November.

The RY cover crop was sown by hand at a rate of 100 kg ha^{-1} every year in November and allowed to grow for 7 months. In early June of the following year, the RY cover crop was mowed by flail mower in both the NT and MP plots. In the NT plot, the residue of the RY cover crop remained on the top layer of the soil. In contrast, in the MP plot, the residue was incorporated into the soil to a depth of 28 cm through plowing. After these operations, all the plots were left fallow until late June. From 2002–2007, upland rice (*Oryza sativa* L. cv. Yumenohatamochi) was sown with a NT seeder (MJSE18–6, Mitsubishi, six rows, 1.8 m wide) in late April at a seeding rate of 50 kg ha^{-1}. Following the harvest of upland rice, the rice residue was returned to the soil as an organic amendment. Soybean seeds (var: Sachiyutaka) were sown using a NT seeder manufactured by Mitsubishi Co., Ltd. (model: MJSE 18–6) in six rows that were 1.8 m wide, using a seeding rate of 50 kg ha^{-1}. Throughout the experiment, no pesticides or herbicides were applied to control pests, diseases, or weeds. However, during the soybean seedling stage, manual weeding was performed 3–4 times in all plots to manage weed growth. Additionally, to prevent potential damage caused by hares, an electric wire fence was installed around the soybean field. The fence was activated during the nighttime hours. In late October, the soybeans were harvested using a bush cutter. The harvested soybeans were then threshed outside the field, and the soybean residue was not returned to the field. Farming practices for this field were similar from 2002 to 2007 for upland rice and from 2008 to 2021 for soybean cultivation. The average cover crop biomass input, above-ground upland rice and soybean biomass, upland rice yield, and soybean yield for the experimental site are presented in Table 1.

2.3. Soil samples collection

Soil samples were collected from each plot at a depth of 0–20 cm in December 2021 to measure the water-stable aggregates and total and active C, and to perform BD analyses. After harvesting, the soil samples were cut with a sharp knife into five layers of 0–2.5, 2.5–5, 5–10, 10–15, and 15–20 cm. For total and active C analysis, soil samples were passed through a 2 mm sieve to remove any undesirable plant residue. The samples were air dried, then subsamples of these were dried at 105 °C for 72 h to measure the soil total C and N.

Samples were also collected from each plot in sets of five stainless ring samplers in a steel cylinder (5 cm diameter) at five different depths (0–2.5, 2.5–5, 5–10, 10–15, and 15–20 cm) to determine the soil water retention curve (SWRC). All samples were carefully moved from the field to the laboratory, where they were carefully stored until the SWRC measurements were performed.

2.4. Soil analyses

2.4.1. Soil chemical analyses

Soil total C and N were analyzed using a CN analyzer (JM3000, J Science Lab, Japan). For soil active C analysis, 2.5 g of air-dried soil was placed into a 50 ml centrifuge tube with 20 ml of 0.02 mol $KMnO_4$ solution. The centrifuge was then shaken for 2 min before the soil solution was centrifuged at 4000 rpm for exactly 10 min. To make standard solutions we further diluted 0.02 mol $KMnO_4$ and made 0.005 mol, 0.01 mol and distilled water consider as 0 mol. To measure standard solution and samples, we placed 0.5 ml standards and samples of each solution in a new 50 ml centrifuge tube and then added distilled water to 50 ml and shook well before the absorbance was measured at 550 nm using mass spectrometry (Weil et al., 2003). Active C was calculated by the following formula:

$$AC = [Ci - (a + b \times absorbance)] \times MC \times \left(\frac{V_{sol}}{W_s}\right)$$

where C_i is the initial solution concentration (0.02 mol L^{-1}), a is the intercept, b is the slope of the standard curve, MC is the mass of carbon (9000 mg, 0.75 mol) that is oxidized by 1 mol of MnO_4 changing from Mn_{7+} to Mn_{4+}, V_{sol} is the volume of $KMnO_4$ solution reacted (0.02 L), and Ws is the weight of soil used (2.5 g).

2.4.2. Soil physical analyses

To determine soil BD and water content, the soil subsamples were weighed and dried in an oven at 105 °C for 72 h and then weighed again. BD was calculated as dry soil weight (g)/soil volume (cm^3) in each layer (McKenzie et al., 2002). For water-stable aggregates, briefly, 10 g of fresh soil was placed in the center of the top sieve of the stack of five sieves with decreasing mesh sizes (4, 2, 1, 0.5, and 0.25 mm, respectively). The sieves were placed in water for 30 mins and then were placed in clean water and vertically shaken 60 times at a rate of one shake per second. Afterwards, the sieves were placed in a steel cup and dried in an oven at 105 °C for 72 h. Finally, the soil was weighed again to determine the dry soil amount. The values were adjusted to a dry soil weight based on the weight and initial soil moisture content of each sample. The dry soil weights were used to calculate the water-stable aggregate distribution (WSAD%), MWD, and aggregate stability index (ASI) per the following equations, respectively (Kemper and Chepil, 1965):

$$WSAD\% = \frac{wi}{\sum wi} \times 100$$

$$MWD = \sum_{i=1}^{n} (xiwi)$$

$$ASI\% = \frac{(yi - zi)100}{yi}$$

where xi is the mean diameter of each class (mm), wi is the weight of the aggregates of each class, yi represents the dry soil samples, and zi represents < 0.25 mm aggregate weight.

2.4.3. Water retention curve measurement

For SWRC analysis, the ring samples were sealed with gauze and placed in water for 24 h for saturation. The sample in each saturated ring from below the gauze was transferred to filter paper and gradually dewatered to the matric potentials of 0, 6.2, 33, and 100 kPa using the hanging water column method and pressure plate method for each pressure. The samples were dewatered for a minimum of 72 h to ensure that the water effluent was completely stopped at each pressure. The samples were then weighed and turned before the next pressure step was performed. In the final step, all the samples had been dried in an oven at 105 °C for 48 h. Afterwards, the soil BD and volumetric water content measurements were calculated. Volumetric water content (θ) at field capacity (FC) (at pF = 1.8 or 6.2 kPa) was measured according to (Hohenbrink et al., 2023; Wessolek et al., 2008) and easily plant-available water (EPAW) was calculated by (pF 1.8 – pF 3.01).

2.5. Statistical analysis

Data were analyzed using StatView for Windows version 5.0.1 (SAS Institute, USA). Analysis of variance was performed to analyze the SOC and AC contents, SOC accumulation, water-stable aggregates distribution, aggregate-associated carbon content, MWD, volumetric water content, BD, aggregates stability index, and SWR. The Tukey–Kramer test was performed to assess the differences between the treatments. A multiple regression of path analysis was also performed using a structural equation model to evaluate the direct and indirect effects of SOC,

Table 1
Effect of tillage and cover crop on average cover crop biomass input, aboveground upland rice biomass, aboveground soybean biomass, upland rice, and soybean yield after a 19-year experiment.

Treatments	Cover crop biomass	Upland rice biomass	Soybean biomass	Upland rice yield	Soybean yield
(Mg ha^{-1})					
	(2003–2021)	(2003–2007)	(2008–2021)	(2003–2007)	(2008–2021)
NT	4.96	4.24	7.13	2.0	2.58
MP	4.45	4.28	6.44	2.13	2.73
Tillage	ns	ns	ns	ns	ns
FA	2.28 b	4.12	7.12	2.05	2.77
RY	8.48 a	4.2	6.42	2.03	2.69
Cover crop	* **	ns	ns	ns	ns

Data from 2003 to 2018 was obtained from (Wulanningtyas et al., 2021).
* ** indicate significance at $p < 0.001$. NS indicates no significant difference. The different letters in the columns indicate significant differences between the treatments at $p < 0.05$.

AC, MWD and BD on FC and to determine the total water content. The path analysis was performed using AMOS software (IBM SPSS AMOS 28.0). The fitness of the path analysis was examined using a nonsignificant chi-square test ($P > 0.05$), chi-square ratio of degrees of freedom (CMIN/DF < 3), normed fit index (NFI < 0.90), root mean square error of approximation (RMSEA < 0.08), and standard RMR (SRMR < 0.05) (Schermelleh-Engel et al., 2003).

3. Results

3.1. SOC, AC, and SOC accumulation

SOC and AC concentrations were 61.2% and 28.3%, respectively, and were significantly higher in NT than in MP at the 0–2.5 cm depth and the 2.5–5 cm depth (26.9% and 12.2% higher, respectively; Fig. 1a, c). At the 10–15 cm and 15–20 cm depths, SOC was significantly higher by 16.1% and 17.5% in MP than in NT, respectively. AC was 14.2% higher in MP than in NT at the 10–15 cm depth. The RY cover crop significantly increased SOC content at the 2.5–5 cm depth only, which was 7.9% higher than in FA (Fig. 1b). The RY cover crop did not have a significant effect on SOC and AC at other soil depths compared to FA. Overall, SOC was significantly higher by 12.9% in the NT system compared to the MP system (Fig. 2a) at the 0–20 cm soil depth. At this depth, we observed that NT had no significant effect on AC (Fig. 2b). At the 0–20 cm soil depth, the RY cover crop did not have a significant effect on SOC and AC. NT significantly increased SOC accumulation at all depths, except for 0–20 cm (Table 2). The average SOC accumulation was 34.8% and 25.1% higher in NT than in MP at the 0–2.5 and 2.5–5 cm depths, respectively. The average SOC accumulation was 17.2% and 9.8% at the depths of 0–10 and 0–15 cm. At 0–20 cm, neither the tillage nor cover crop system affected SOC accumulation. However, no significant differences in all soil layers were observed between RY and FA.

3.2. Soil aggregate size distribution, stability, and aggregate-associated carbon

Tillage significantly influenced the distribution of soil aggregate sizes (Fig. 3). At all depths, the > 4 mm macroaggregate fraction was significantly higher in NT than in MP. The 2 mm aggregates fraction was significantly higher in NT at the 0–2.5, 2.5–5, and 5–10 cm depths. The > 4 mm aggregate fraction was 187.6% higher in NT-RY than in MP-RY at 0–2.5 cm. This parameter was even more effective at the 10–15 cm depth, which was 211.1% higher in NT-RY than in MP-RY. Tillage had a significant effect on the 0.5 and 0.25 mm aggregate fractions at a depth of 0–2.5 cm with a decrease by 5.7% and 47.2% in NT-RY than MP-RY, respectively. NT significantly increased the > 4 and 2 mm aggregates at the 0–20 cm depth compared to MP, whereas MP significantly increased the 0.25 mm aggregates fraction.

MWD and ASI contents were significantly influenced by the tillage system at all depths (Table 4). At the 0–2.5 and 2.5–5 cm soil depths, the average MWD was 100.0% and 78.8% higher in NT than in MP, respectively. At these depths, the difference for ASI was 27.2% and 27.8% higher in NT than in MP, respectively. A similar trend was obtained at the 15–20 cm depth; NT significantly increased MWD and ASI by 61.2% and 74.4% more than MP, respectively. At the 0–20 cm depth, MWD and ASI were significantly increased by NT compared to MP. The RY cover crop also significantly increased ASI only in the MP system, which was 17.1% higher than FA at a depth of 10–15 cm.

Both tillage and cover crop had a significant effect on aggregate-associated carbon at various soil depths (Fig. 4). The amounts of aggregate-associated carbon were significantly higher at depths of 0–2.5, 2.5–5, and 5–10 cm for all aggregate size classes in the NT system compared to the MP system. In contrast, the depths of 10–15 and

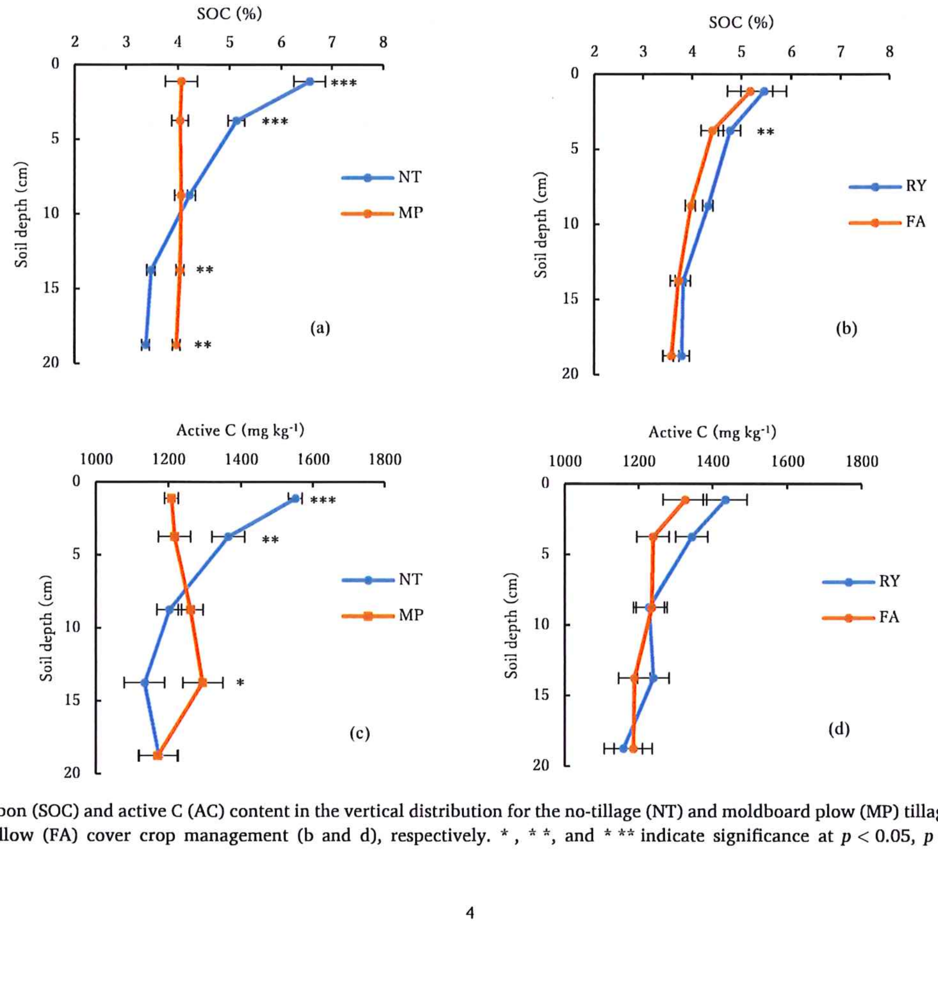

Fig. 1. Soil organic carbon (SOC) and active C (AC) content in the vertical distribution for the no-tillage (NT) and moldboard plow (MP) tillage systems (a and c) and under rye (RY) and fallow (FA) cover crop management (b and d), respectively. *, **, and *** indicate significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

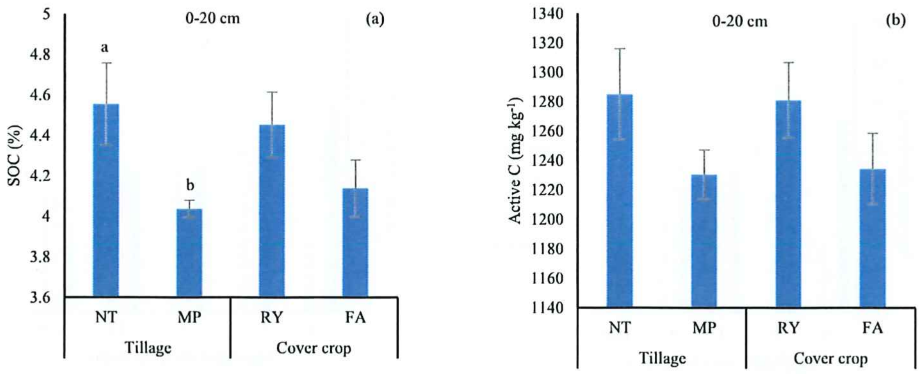

Fig. 2. Soil organic carbon (a) and active C (b) as influenced by tillage (NT: no-tillage; MP: moldboard plow) and cover crop system (RY: rye; FA: fallow) at a soil depth of 0–20 cm. The different letters above the error bars indicate significant differences between the treatments at $p < 0.05$.

Table 2
SOC sequestration at various cumulative soil depths as influenced by tillage and cover crop system.

SOC sequestration (Mg ha^{-1})						
Tillage	Cover crop	Depths (cm)				
		0–2.5	0–5	0–10	0–15	0–20
NT	RY	9.5 a	17.6 a	31.1 a	42.9 a	54.0
	FA	8.7 a	16.7 a	28.9 a	40.9 ab	52.4
MP	RY	7.0 b	13.8 b	26.4 b	39.9 bc	54.0
	FA	6.5 b	13.6 b	24.8 b	36.4c	49.9
ANOVA Significance						
Tillage (T)		* *	* *	* *	*	ns
Cover crop (C)		ns	ns	ns	ns	ns
T × C		ns	ns	ns	ns	ns

* and * * indicate significance at $p < 0.05$ and $p < 0.01$, respectively. NS indicates no significant difference. The different letters in the columns indicate significant differences between the treatments at $p < 0.05$

15–20 cm had higher aggregate-associated carbon in the MP system compared to the NT system. At the 0–2.5 cm depth, the average SOC content in the > 4 and 2 mm-sized aggregates were 55.1% and 65.4% higher in NT than MP, respectively. Aggregate size also affected SOC content. At depths of 0–2.5 and 2.5–5 cm, NT had significantly higher SOC content in the > 4 mm-sized aggregates compared to the 0.5 mm aggregates (12.4% and 14.4%, respectively). NT displayed significantly higher SOC contents at these depths when the > 4 mm-sized aggregates were compared to the 0.25 mm aggregates (28.7% and 27.9%, respectively).

The average amount of SOC contents in the > 4, 2, 0.5, and 0.25 mm aggregates were 16.1%, 8.0%, 11.8%, and 12.1% higher in NT than MP, respectively, at the depth of 0–20 cm. The RY cover crop also had a significant effect on aggregate-associated carbon at the 2.5–5, 5–10, and 10–15 cm soil depths. In NT at the 2.5–5 cm soil depth, the RY cover crop significantly increased the SOC content compared to the FA treatment in the > 4, 1, 0.5, and 0.25 mm aggregates under the NT system at a soil depth of 2.5–5 cm (21.2%, 11.1%, 14.3%, and 19.5% higher than FA, respectively). The RY cover crop in the MP plot also displayed a significantly increased amount of SOC in the > 4, 1, 0.5, and 0.25 mm aggregates (7.4%, 14.5%, 12.8%, and 12.5% higher than FA, respectively). The RY cover crop significantly increased the SOC contents in the 1 mm aggregates at the 0–20 cm soil depth (6.6% and 12.5% higher than FA in NT and MP, respectively).

3.3. BD and volumetric water content

The soil BD and water content data are presented in Table 3. The NT treatment significantly decreased BD compared to MP at the 0–2.5 and 2.5–5 cm depths. In the NT plot, BD was significantly decreased by 16.4% compared to MP at the 0–2.5 cm depth. In NT, the highest BD was obtained in the range of 0.69 g cm^{-3} at the 10–15 cm depth, whereas the highest soil BD in MP was obtained in the range of 0.74 g cm^{-3} at the 2.5–5 cm soil depth. The cover crops had no significant effect on the soil BD at any depth. Both the tillage and cover crop systems had a significant effect on the soil volumetric water contents at all depths. The highest water content occurred at the 0–2.5 cm soil depth in the NT-RY treatment at 0.44 cm^3 cm^{-3}. The second highest water content was the NT-FA treatment at 0.43 cm^3 cm^{-3}. The RY cover crop significantly increased the water content in both tillage systems at all depths, except for the 10–15 cm depth in NT. In both NT-RY and NT-FA, the lowest volumetric content was obtained at the 10–15 cm depth of 0.39 cm^3 cm^{-3}. Similarly, the MP-FA treatment also showed the lowest volumetric water content of 0.39 cm^3 cm^{-3} at the same (10–15 cm) depth.

3.4. SWR and storage

SWR was significantly affected by the tillage system used at all depths, except for the 15–20 cm depth (Fig. 5). The NT system increased the average volumetric water content, which was 5.0% and 7.5% under 0 and 6.2 kPa pressure, respectively, at a depth of 0–2.5 cm. In NT, the average volumetric water content increased by 7.0% and 5.0% under 33.0 and 100.0 kPa, respectively, compared to MP at the 2.5–5 cm depth. The NT system also significantly increased the average volumetric water content at the 5–10 cm depth at 6.2, 33.0, and 100.0 kPa compared to MP, which was 5.0%, 5.5%, and 4.0%, respectively. In MP, the RY cover crop significantly increased the volumetric water content at 10–15 cm depth at the saturated point and 33.0 kPa compared to FA. At 10–15 cm depth, the NT system significantly increased the average volumetric water content by 8.0%, 6.8%, and 6.7% under 6.2, 33.0, and 100.0 kPa, respectively, compared to MP. There was no significant difference in volumetric water content between tillage and cover crop treatment at 15–20 cm depth. Thus, at the overall depth of 0–20 cm, the NT system significantly increased the average volumetric water content by 3.9%, 4.9%, and 4.1% under 6.2, 33.0, and 100.0 kPa, respectively, compared to MP.

The NT system significantly enhanced volumetric water content at FC under 6.2 kPa suction compared to the MP system at all depths except for 15–20 cm depth (Fig. 6a). The highest volumetric water content at FC was enhanced at the depth of 10–15 cm (8.0% higher), followed by 0–2.5 cm (7.5% higher), compared to MP. EPAW was not significantly affected by the tillage system (Fig. 6b).

3.5. Cover crop, soybean, and upland rice biomass and yield

The tillage and cover crop systems had different effects on cover crop biomass. The tillage system did not impact the average cover crop

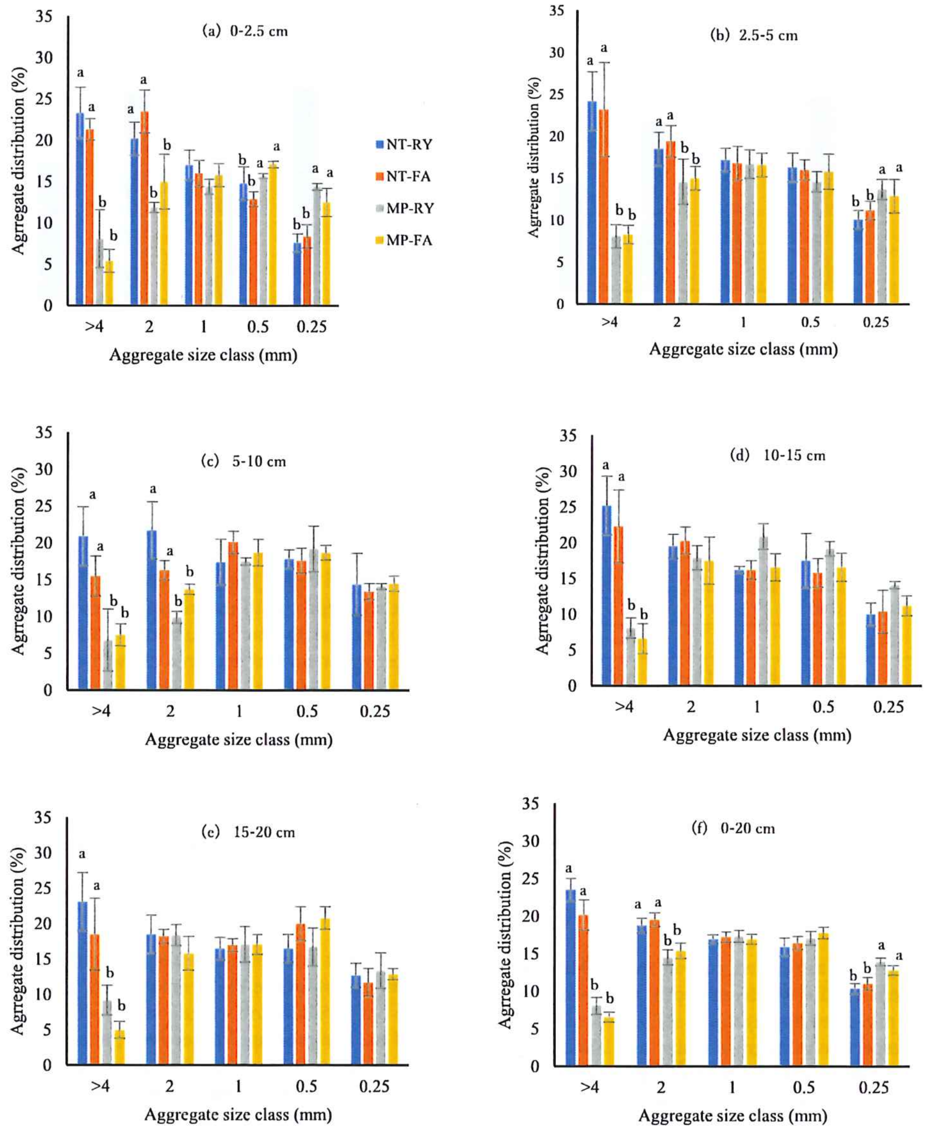

Fig. 3. Soil water-stable aggregate size distribution (%) for the no-tillage (NT) system with rye (RY; NT-RY) and fallow (FA; NT-FA) and for the moldboard plow (MP) tillage system with RY (MP-RY) and FA (MP-FA) treatments at 0–2.5, 2.5–5, 5–10, 10–15, 15–20, and 0–20 cm depths. The different letters above the error bars indicate significant differences between the treatments at $p < 0.05$.

biomass from 2003 to 2021. However, the cover crop system had a significant influence on cover crop biomass, as shown in Table 1. Specifically, the average cover crop biomass for the RY treatment from 2003 to 2021 was 271.9% higher than the FA treatment. Neither the tillage system nor the cover crop system had significant effects on soybean above-ground biomass or yield. Similarly, when considering the average data from 2003 to 2007, neither the tillage system nor the cover crop system had a noteworthy impact on upland rice biomass and yield.

3.6. Relationship between soil variables

A path analysis was performed to assess the direct and indirect relationships of SOC and AC with MWD, BD, FC, and EPAW (Fig. 7). SOC was positively correlated with MWD and EPAW, whereas AC was negatively correlated with BD. MWD had direct positive effects on FC, which suggests that SOC and MWD were the key factors affecting SWR. We determined that the path analysis displayed an overall goodness of fit based on the p-value (0.88), CMIN/DF (0.38), NFI (0.97), RMSEA (0.001), and SRMR (0.036) values.

4. Discussion

4.1. Tillage effect on SOC, soil structure stability, and SWR

Conventional tillage induces soil disturbance and disruption of soil aggregates, exposing the protected SOC to microbial decomposition and thus depleting SOC from the soil through CO_2 emissions (Six et al., 2004). Using an NT management system can mitigate greenhouse gas emissions through soil carbon sequestration in the soil (Follett, 2001). Our results showed that long-term NT practices significantly increase SOC and AC contents in the surface layer of Andosol soil in Japan and reduce SOC content in the 10–20 cm layer compared to MP. This indicates that tillage systems affect SOC distribution in the soil profile (Fig. 1a & c). This result is consistent with Rahman et al. (2008), who reported that NT for 41 years increased SOC content in the 0–10 cm layer in Andosol soil. A recent meta-analysis study in Asia by Hashimi

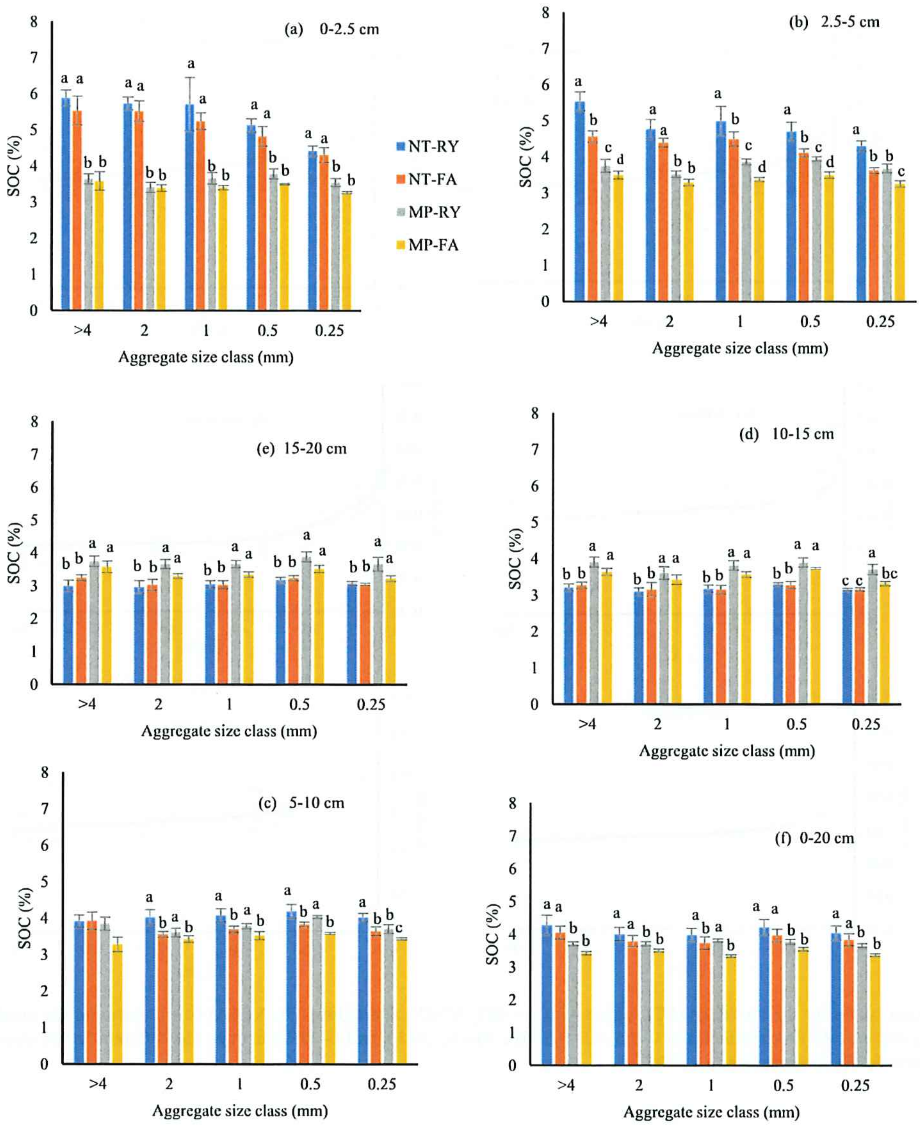

Fig. 4. Aggregate-associated soil organic carbon (SOC) in different sizes of soil water-stable aggregates for the no-tillage (NT) system with rye (RY; NT-RY) and fallow (FA; NT-FA) cover crops and the moldboard plow (MP) tillage system with RY (MP-RY) and FA (MP-FA) treatments at 0–2.5, 2.5–5, 5–10, 10–15,15–20, and 0–20 cm depths. The different letters above the error bars indicate significant differences between the treatments at $p < 0.05$.

Table 3
Soil bulk density and volumetric water content (cm^3 cm^{-3}) at different soil depths as influenced by tillage and cover crop systems.

Tillage	Cover crop	Bulk density (g cm^{-3})						Volumetric water content (cm^3 cm^{-3})					
		Depth (cm)											
		0–2.5	2.5–5	5–10	10–15	15–20	0–20	0–2.5	2.5–5	5–10	10–15	15–20	0–20
NT	RY	0.56 b	0.62 b	0.62 a	0.68 a	0.65 b	0.62 a	0.44 a	0.43 a	0.42 a	0.39 b	0.40 a	0.42 a
	FA	0.56 b	0.64 b	0.60 ab	0.69 a	0.68 ab	0.63 a	0.43 b	0.41 b	0.40 b	0.39 b	0.39 b	0.41 b
MP	RY	0.66 a	0.64 b	0.59 b	0.65 ab	0.68 ab	0.64 a	0.41c	0.41 b	0.41 ab	0.41 a	0.40 a	0.41 b
	FA	0.68 a	0.74 a	0.59 b	0.59 b	0.71 a	0.66 a	0.39 d	0.39c	0.39c	0.39 b	0.39 b	0.39c
ANOVA Significance													
Tillage (T)		* *	* *	* *	* *	* *	ns	* **	* **	* **	* **	* **	* *
Cover crop (C)		ns	*	ns	ns	ns	ns	* **	* **	* **	* **	* **	* *
T × C		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* * and * ** indicate significance at $p < 0.01$ and $p < 0.001$, respectively. NS indicates no significant difference. The different letters in the columns indicate significant differences between the treatments at $p < 0.05$.

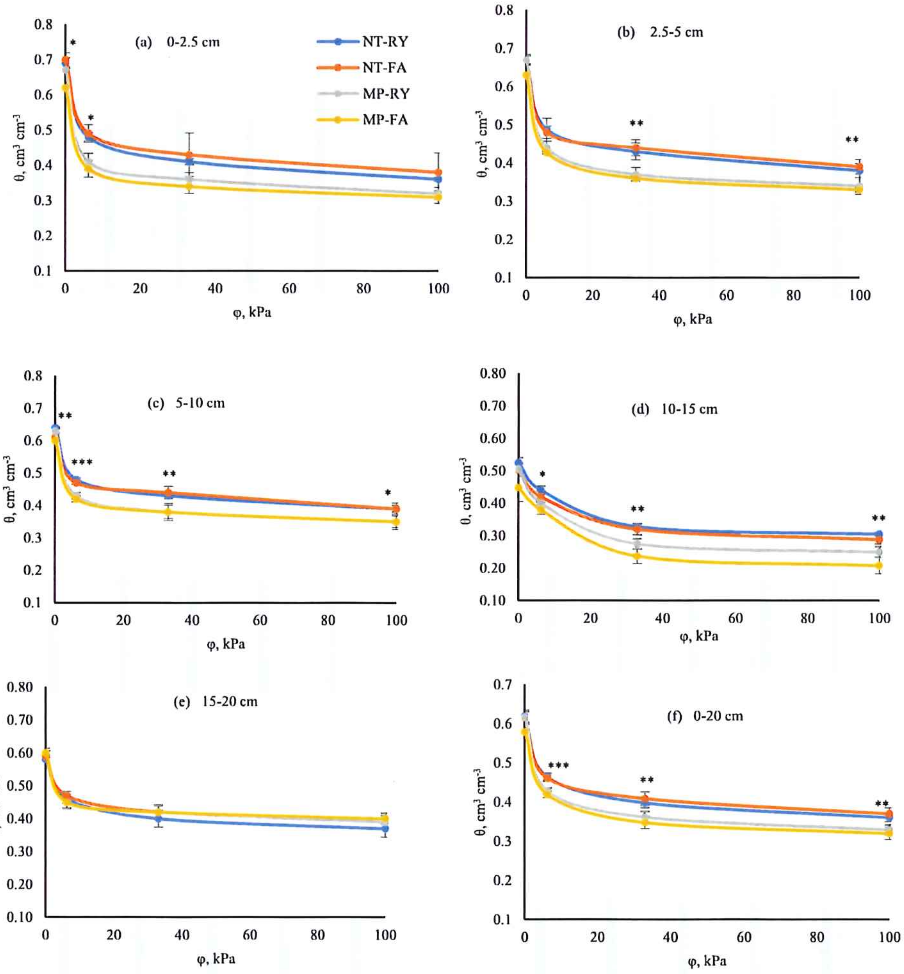

Fig. 5. Soil water retention curves for the no-tillage (NT) system with rye (RY; NT-RY) and fallow (FA; NT-FA) cover crops and the moldboard plow (MP) tillage system with RY (MP-RY) and FA (MP-FA) treatments at 0–2.5, 2.5–5, 5–10, 10–15, 15–20, and 0–20 cm depths. The different letters above the error bars indicate significant differences between the treatments at $p < 0.05$.

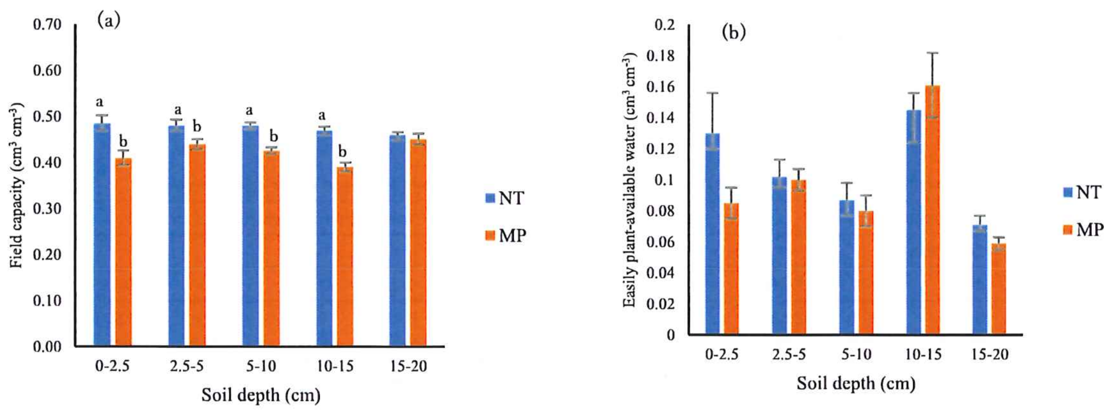

Fig. 6. Effect of tillage system on volumetric water content at field capacity (a) and easily plant-available water content (b) at different soil depths. The different letters above the error bars indicate significant differences between the treatments at $p < 0.05$.

et al. (2023) also observed that NT only significantly increased the SOC content in the 0–10 cm depth compared with conventional tillage (CT).

In NT systems, a high amount of SOC and AC contents in the surface layer may be linked with higher plant residues and reduced soil disturbance (Guo et al., 2020). In contrast, Mazzoncini et al. (2016) found that long-term NT practices in a Mediterranean climate significantly increased SOC content in the 0–30 cm soil layer over 28 years. This increase was attributed to a higher input of crop residues compared to CT. Therefore, the changes in SOC content are influenced by the balance between organic carbon input and the mineralization process, as

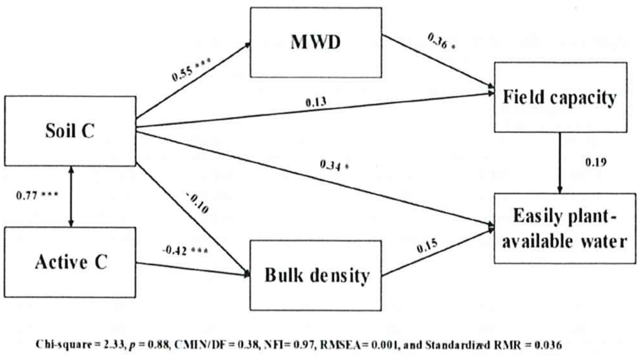

Fig. 7. The path analysis by AMOS depicts the direct and indirect effects of SOC and AC on MWD, bulk density, field capacity, and easily plant-available water content. The numbers associated with single-headed arrows are standardized path coefficients (*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$). The overall goodness of fit for this path analysis was determined when $p > 0.05$, CMIN/DF < 3.0, NFI < 0.90, RMSEA < 0.08, and SRMR < 0.05.

highlighted by Grandy et al. (2013).

In our study, NT significantly increased SOC accumulation in both the surface layer and the sublayer (0–15 cm; Table 2). Thus, the plant residue mulch in the surface layer of the soil in the NT system and the improved soil structural stability in the sublayer enhanced SOC accumulation. SOC decomposition and accumulation depend on climate conditions (Fang et al., 2022). He et al. (2011) reported that NT significantly increased SOC accumulation under continental climate conditions by 16% in the 0–10 cm layer 11 years after the conversion from CT to NT. In this study, SOC accumulation was significant at 17.2% compared to MP 19 years after the conversion from MP to NT at the 0–10 cm layer. This difference could have been caused by a faster rate of plant residue decomposition at our site since our study site had humid subtropical climate conditions. This long-term (19 years after the conversion from MP to NT) research demonstrates that NT systems considerably boost SOC sequestration compared to MP at 0–15 cm soil depth, even if the long-term sequestration rate of SOC under NT may decrease. Our results are congruent with those of research conducted in a sandy loam Eutric Cambisol soil (Martínez et al., 2016), which found that NT did not improve SOC accumulation in the 0–20 cm soil depth compared to MP. In the Asia, recent meta-analysis research likewise found no discernible difference between NT and CT in terms of SOC accumulation in a 10–30 cm soil depth (Hashimi et al., 2023). The high availability of O_2 in the MP system provides soil microorganisms increased access to soil aggregates, which increases the rate of SOM decomposition and significantly decreases SOC accumulation in soil (Sithole et al., 2019).

In NT systems, crop residue retention combines microaggregates to form macroaggregates that improves SOC storage for long periods of time (Song et al., 2019; Xiao et al., 2021). In previous study, the presence of macroaggregates were mainly associated with decomposing plant residues and hyphae (Wang et al., 2016). In this study, the NT system showed a significant increase in the amount of aggregate-associated C in the in > 4 and 2 mm aggregate fractions compared to the 0.25 mm aggregates in the surface layer (Fig. 4a & b). Ji et al. (2019) also confirmed that the NT system mainly contributed to the high amount of SOC contents in the macroaggregates due to the system's crop residue retention at the surface layer and minimal soil disturbance. The NT practice led to a significant increase in > 4 mm and 2 mm water-stable aggregates by 198.6% and 28.1%, respectively, at a soil depth of 0–20 cm compared to the MP practice (Fig. 3f). This finding strongly indicates that reducing soil disturbance through primary tillage operations and retaining crop residues on the soil surface effectively mitigates the impact of raindrops and enhances the stability of large macroaggregates in Andosol soil (Arai et al., 2018). Macroaggregates are mainly developed from microaggregates, and studies have reported that the fungal substrate induces respiration combined with the glomalin produced by arbuscular mycorrhizal fungi in NT systems played an important role in bonding and stabilizing soil aggregates (Hashimi et al., 2020; Liu et al., 2020). In contrast, intensive tillage systems, such as CT, and mechanical disturbance break up macroaggregates, resulting in an increase in microaggregates (Sekaran et al., 2021).

According to our findings (Table 4), the presence of the active fraction of SOM within the macroaggregates and the slower rate of organic matter breakdown were detected in the NT in comparison to MP (Finn et al., 2016). Our findings supported those of Arai et al. (2013), who found that in the Andosol in the Kanto area of Japan, NT with RY cover crops promoted high MWD by providing both aggregate forming and stabilizing agents. These results suggest that using long-term NT practices improves and maintains the stability of the soil structure due to the retention of crop residues and minimal soil disturbance.

In our study, the surface layer NT displayed a lower BD than that of the MP system (Table 3), which might be linked to the higher SOC contents observed. According to meta-analysis research, > 12 years of NT practices had no significant impact on BD, but 6–12 years of NT practices elevated BD (Li et al., 2020). Due to their low BD, high porosity, and high capacity for SOC accumulation, volcanic Andosols constitute a special kind of soil (Dahlgren et al., 2004). Similar results were reported by Hashimi et al. (2019), who found that the SOC concentration was the strongest contributor to the reduced BD in the Andosol. The crop residue in the NT system decreases water evaporation, SOC loss, and soil erosion, which helps increase soil moisture (Zheng et al., 2018). In our investigation, the bulk soil volumetric water content was significantly increased in the NT system compared to MP (Table 3). Furthermore, NT increases volumetric water content by preventing the soil from undergoing direct exposure to solar radiation and decreasing the soil temperature in the surface layer (Li et al., 2022).

Our results indicate that the NT system significantly increases SWR at various soil water pressures at all soil depths, except for 15–20 cm (Fig. 5). This is ascribed to the macroporosity in NT systems improves soil structure by allowing water to better penetrate the soil profile compared to CT practices (Page et al., 2019). In MP, farm heavy machinery can break up soil aggregates and destroy soil structure and the desired pore space, which affects the soil infiltration rate (Radford and Thornton, 2011). Our findings, however, do not support Hati et al. (2021) observation that CT enhanced the SWR of dry-sieved aggregates (2–5 mm) at matric potentials of − 10, − 30, and − 60 kPa more than NT. The disparity in SOC content and climatic conditions may be the cause of this anomaly. Sekaran et al. (2021) confirmed that higher SOC and macroaggregate contents in NT systems improve SWR in silt loam soil. Olness and Archer (2005) also concluded that increasing SOC content by 1% increases the available water content to plants by 2–5% in soil. In this study, SOC content was increased at the overall 0–20 cm depth by 0.47% and FC and EPAW were increased by 5.2% and 1.1%, respectively (Fig. 6a & b). At the 0–2.5 cm and 10–15 cm depths, respectively, we discovered that the NT treatment considerably enhanced the volumetric water content at FC by 7.5% and 8.0% compared with the MP treatment. Increases in SOM and soil aggregation are to blame for the observed increases in water retention at FC. According to Emerson (1995), raising SOC in soil increased water at a matric potential of − 10 kPa. Thus, SOM accumulation in the soil can improve the climate resilience of agroecosystems. The magnitude of the increase in plant available water content may also depend on the initial SOM amount and soil texture (Lal, 2020). Land management, soil structure, and pore-size distribution strongly affect the amount of SOM in the soil, which directly influences SWR (Rajkai et al., 2015). Thus, we conclude that the NT system increased SOC, macroaggregates, and MWD which are associated with high amounts of FC and EPAW, which can reduce the risks associated with drought conditions.

Table 4
Mean weight diameter (MWD) and aggregate stability index (ASI) at different soil depths as influenced by tillage and cover crop systems.

Tillage	Cover crop	MWD (mm)						ASI (%)					
		Depth (cm)											
		0–2.5	2.5–5	5–10	10–15	15–20	0–20	0–2.5	2.5–5	5–10	10–15	15–20	0–20
NT	RY	1.65 a	1.65 a	1.50 a	1.67 a	1.61 a	1.60 a	83.5 a	87.3 a	82.6 a	88.3 a	85.7 a	85.7 a
	FA	1.57 a	1.57 a	1.27 a	1.56 a	1.47 a	1.47 a	82.2 a	86.6 a	82.9 a	84.8 a	84.4 a	84.4 a
MP	RY	0.82 b	0.89 b	0.78 b	1.02 b	0.91 b	0.90 b	64.5 b	67.6 b	73.1 b	80.1 b	70.9 b	70.9 b
	FA	0.79 b	0.91 b	0.89 b	0.89 b	0.86 b	0.86 b	65.8 b	68.4 b	67.5 b	68.4c	69.4 b	69.4 b
ANOVA Significance													
Tillage (T)		* **	* **	* **	* *	* **	* **	* **	* **	* **	* **	* **	* **
Cover crop (C)		ns	ns	ns	ns	ns	ns	ns	ns	ns	* *	ns	ns
T × C		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

* * and * ** indicate significance at $p < 0.01$ and $p < 0.001$, respectively. NS indicates no significant difference. The different letters in the columns indicate significant differences between the treatments at $p < 0.05$.

4.2. *Cover crop effect on SOC, soil structure stability, and SWR*

According to DeLaune et al. (2019), cover crops have been acknowledged for their capacity to fix and sequester atmospheric C and N and lessen the consequences of climate change. According to our findings, the RY cover crop considerably enhanced the SOC content between 2.5 and 5 cm deep, but not below that depth (Fig. 1b). According to Gong et al. (2021a), RY cover crops may improve soil SOC stock due to their increased biomass and C:N ratio. In subtropical humid climate conditions, cover crops increased soil total nitrogen, which suggests that cover crops can effectively retain more nitrogen within the cycling pool, thereby reducing its loss through leaching (Hubbard et al., 2013). The addition of cover crops also increased SOC (Koudahe et al., 2022).

The RY cover crop had no discernible impact on SOC sequestration in our investigation at any depth (Table 2), and as we did not calculate BD using the equivalent soil mass approach, it's possible that we missed SOC accumulated differences. However, in our research, the aggregates-associated C in 2 mm, 1 mm, 0.5 mm, and 0.25 mm at the 2.5–5, 5–10, and 10–15 cm soil layers in both MP and NT considerably changed as a result of the RY cover crop; however, the impact was greater in the NT treatment as compared to MP. These findings imply that the RY cover crop promotes SOC incorporation into aggregates and may act as a reliable C sink by slowing the rate at which SOC decomposes inside aggregates. However, once microaggregates C are encapsulated within macroaggregates, they are stabilized and resistant to further decomposition (McCarthy et al., 2008). Microaggregates C are formed as a result of the microbial decomposition of SOM within macroaggregates and are relatively less labile than the macroaggregate SOM. These findings showed that RY cover crops may improve SOC stability in microaggregates in Andosol soil, which would result in higher SOC sequestration.

The size distribution of the aggregates was not significantly affected by the RY cover crop in the current research, although RY did improve the 4 mm and 2 mm aggregates at the 5–10 cm soil depth; however, the improvements were not statistically significant. According to Yao et al. (2022), exchangeable Ca^{2+} played a significant role in soil aggregation and showed a favorable link with MWD. Wulanningtyas et al. (2021) observed that employing RY cover crops had no appreciable impact on exchangeable Ca^{2+} at our experimental location. One of the potential explanations for the lack of a discernible impact on soil aggregation might be the decrease in exchangeable Ca^{2+} concentration. The RY cover crop in our research marginally increased MWD, but these changes were not statistically significant (Table 4). But in the MP system, we only discovered that the RY cover crop had a substantial impact on ASI at a soil depth of 10–15 cm. In MP systems, cover crops are incorporated into the soil and secrete cementing agents, such as polysaccharides and organic acid, during the decomposition process, which further improves the structural stability of the soil (Liu et al., 2022) and that would helped to recover the structural stability of the soil that was lost due to tillage. According to Blanco-Canqui (2018), using cover crops reduced soil bulk density for a longer period of time; however, in our investigation, RY cover crops only significantly affected BD at 2.5–5 cm in the MP system (Table 3). According to Chalise et al. (2019), employing RY cover crops decreased soil BD at a depth of 0–5 cm in silty loam soil. Although the soil used for this research is Andosol, which has a low BD and high porosity, it is unique (Koga et al., 2020). Comparing our soil's BD to that of Jacobs et al. (2022), who discovered that the BD was two times greater under NT and cover crop management schemes in non-Andosol soil, our soil's BD was lower. This could be the result of unique physical, chemical, and mineralogical characteristics that aren't present in the majority of other soil types.

The RY cover crop also significantly improved the volumetric water content in both tillage systems (Table 3). While crop residue retention and a smaller amount of disturbance in NT systems increases soil water content, the large pores and low amount of macroaggregates increases gravitational drainage and decreases water content in CT systems (Kahlon et al., 2013).

In MP, the RY cover crop substantially enhanced the volumetric water content at 10–15 cm depth at the saturated point and 33.0 kPa compared to FA (Fig. 5d). Basche et al. (2016) revealed that NT with cover crops boosted water retention at FC. In order to boost SOC (Kätterer et al., 2011) and soil aggregate stability (Ali et al., 2023), it was discovered that the contribution of cover crop roots was more significant than the incorporation of above-ground plant leftovers. By encouraging the production of soil aggregates, which enhance water penetration and storage, these roots serve a critical role in improving soil structure stability. In contrast, the RY cover crop in our research increased aggregate-associated C, the ASI, and volumetric water content, at various soil depths. Therefore, our findings imply that cover crops, via raising aggregate-associated C and soil structural stability, play a critical role in improving SWR in the root zone.

4.3. *Relationship between soil variables*

In this study, a path analysis indicated that SOC was positively correlated with MWD and EPAW (Fig. 7), which indicates that SOC accumulation can improve the structural stability of soil and EPAW in NT crop production systems. We also observed that MWD had direct positive effects on FC, indicating that high SOC contents in the surface layer combined with low levels of soil disturbance in NT systems significantly improves the macroaggregate and SWR levels in soil. Ayoubi et al. (2021) and Redmile-Gordon et al. (2020) also found a positive correlation between SOC and MWD, indicating that SOC is vital for improving MWD and soil structural stability. Our pathways analysis showed that BD was negatively correlated with SOC and AC, which indicated that SOC content is key to improving soil BD and SWR. SOC has a relatively higher water retention capacity due to its high porosity and low BD (Lal, 2020). We conclude that SOC and MWD were the key factors affecting SWR and that the structural stability of soil can be improved by combining these factors. In addition, SOC and MWD can also reduce soil erosion and dust emissions caused by intensive tillage practices.

5. Conclusion

Most climate zones throughout the Asian monsoon region are affected by climate change and show significant changes in soil drought characteristics due to irregular precipitation and water budgets. Our long-term NT system in Andosol soil outperformed the MP system in terms of increased SWR, SOC content, soil macroaggregates, and structural stability. These findings indicated that the use of an NT system can potentially recover the lost SOC and structural stability found in soils that have undergone continuous MP. The RY cover crop significantly increased aggregate-associated C in both the NT and MP systems, and this will further increase SOC accumulation and structure stability. Andosol soil has low bulk density, and the NT system further decreased BD in the surface layer of the soil and increased MWD, the ASI, and the water content at all soil depths. Furthermore, the pathway analysis results showed that SOC and MWD influence EPAW and FC. Our results showed that at the depth of 0–2.5 cm in the NT system, FC and EPAW were increased by 7.5% and 4.5%, respectively, compared to MP. In MP, the RY cover crop significantly increased the volumetric water content at the 10–15 cm depth compared to FA. Thus, an NT system combined with the RY cover crop can increase SWR by increasing the SOC content and improving the structural stability of soil. In addition, NT-RY could be a climate-smart agriculture management tool to address the irregular rainfall distribution brought on by drought and to more effectively use soil water reservoirs to stabilize crop yield in drought conditions. Our findings provide a new direction for further research to determine how the quality and quantity of SOM and the microbial community affect soil aggregate formation and improve SWR to at least the 0–30 cm layer.

CRediT authorship contribution statement

Rahmatullah Hashimi: Methodology, Software, Investigation, Data curation, Writing – original draft. **Qiliang Huang:** Data curation, review. **Ratih Kemala Dewi:** Data curation, review. **Junko Nishiwaki:** Supervision, Methodology, Writing – review & editing. **Masakazu Komatsuzaki:** Conceptualization, Methodology, Supervision, Writing – review & editing, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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