

Article

Organic Fertilizer and Deep Tillage Synergistically Regulate Soil Physicochemical Properties and Aggregate-Associated Distribution of Carbon and Nitrogen in Dryland Foxtail Millet Fields

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Abstract

Foxtail millet (*Setaria italica* L.), a typical dryland crop, has a high nutrient uptake capacity, which can lead to rapid soil nutrient depletion. Establishing soil conservation strategies compatible with the high yield traits of hybrid millet is crucial. Although organic fertilization and deep tillage are proven measures for maintaining soil productivity, their effects on dryland crops like millet remain understudied. This study investigated Zhangzagu 10 under five treatments: rotary tillage without fertilization (RT), rotary tillage with compound fertilizer (RTC), rotary tillage with organic fertilizer (RTO), deep tillage with organic fertilizer at 20–30 cm (DT1O), and deep tillage with organic fertilizer at 30–40 cm (DT2O). Soil physicochemical properties were measured at seven sampling periods and four tillage layer depths in a two-year field experiment. Compared to RT, RTO increased organic carbon and total nitrogen in mechanically stable macro-aggregates (0–20 cm) by up to 141.2% and 135.14%, respectively. Corresponding increases in water-stable aggregates reached 105.9% for organic carbon and 193.33% for total nitrogen. RTO also enhanced the pH buffering capacity of the topsoil while reducing soil bulk density and solid volume fraction in the surface layer during the late growth stages of foxtail millet. Combining organic fertilization with deep tillage (DT1O and DT2O) further optimized subsoil (20–40 cm) structure, increasing macro-aggregate content and stability, with effects intensifying at greater tillage depths. The integration of organic fertilization and deep tillage synergistically improved soil structure and nutrient distribution, offering a sustainable approach for dryland foxtail millet production.

Keywords: soil pH buffering capacity; soil bulk density; soil three-phase; mechanically stable aggregate; water-stable aggregate



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1. Introduction

Foxtail millet (*Setaria italica* L.), characterized by high photosynthetic capacity [1], resilience to environmental stresses, and efficient water utilization [2], is a predominant crop in China's arid and semi-arid ecosystems [3]. The vigorous nutrient uptake capacity of foxtail millet sustains production under low fertility conditions at the cost of potential soil nutrient depletion or imbalance [4,5]. The application of organic fertilizers and deep tillage,

as traditional yet effective approaches for improving soil structure and enhancing soil fertility, has been extensively studied in other crops. However, in traditional agricultural systems, additional inputs such as heavy organic fertilizer application and deep tillage were previously considered economically unfeasible for foxtail millet as a dryland and minor crop. The recent expansion of high-yielding hybrid foxtail millet production [6,7], which places greater nutrient demands on the soil, has intensified the need for conservation strategies that are both agronomically effective and economically feasible. However, a critical knowledge gap persists regarding the synergistic effects of organic fertilizer and deep tillage on key soil physicochemical properties, such as pH buffering capacity, three-phase equilibrium, aggregate stability, and the distribution of associated carbon and nitrogen. Elucidating these synergistic mechanisms is essential to develop sustainable management practices that can reconcile the high yield potential of modern hybrids with the preservation of soil health in these fragile agroecosystems.

Organic fertilizer induces pH elevation in acidic soils for acidification alleviation [8] and pH reduction in alkaline systems [9], while simultaneously enhancing of pH buffering capacity [10]. Organic fertilizer application improves the three-phase balance of soil [11], increases soil porosity and field water-holding capacity, while reducing bulk density [12,13]. Its application also promotes soil aggregate formation, compensating for tillage-induced aggregate disruption [14], with a consequent increase in macro-aggregate fraction [15]. Additionally, organic fertilization contributes to organic carbon accumulation in cultivated soils [16,17], resulting in elevated organic carbon levels in size-fractionated mechanically stable aggregates [18,19] and water-stable aggregates [20,21]. Total nitrogen content in soil and aggregates is increased [19–23] by applying organic fertilizer, with concurrent improvement in nitrogen use efficiency [24,25].

Most studies indicate that deep tillage reduces soil pH [26,27], while conflicting evidence demonstrates pH elevation [28], nonsignificant effects [29] or site-dependent variations [30]. Deep tillage fractures the plow pan and incorporates subsoil into surface layers, concurrently reducing bulk density, enhancing porosity, and optimizing water-air dynamics [31–33]. Meanwhile, the phase equilibrium is adjusted by boosting gas and liquid phases while shrinking the solid phase [34]. Deep tillage boosts aggregate stability [35,36], elevates macro-aggregate content [37,38], and yields higher mean weight diameter (MWD) and geometric mean diameter (GMD) compared to conventional tillage [37,39]. Deep tillage enhances organic carbon accumulation in subsoil [40], yet accelerates topsoil organic carbon depletion [31,41]. Prolonged deep tillage further compromises soil structural integrity and exacerbates organic carbon losses [42,43]. The combination of long-term organic fertilization with deep tillage can promote a comprehensive increase in organic carbon stocks throughout the entire soil profile [44]. Deep tillage enhances soil nutrient storage capacity [45], promotes a more uniform nutrient distribution across soil layers [46], and improves nitrogen use efficiency [47,48]. Deep tillage significantly enhances nitrogen accumulation in subsurface soil layers [49,50], yet may exacerbate nitrogen leaching losses [51].

In surface soil horizons, intensive tillage operations coupled with vigorous microbial activity markedly accelerate organic matter mineralization [52,53]. Consequently, organic amendments applied via rotary or shallow tillage exhibit limited efficacy in augmenting soil organic carbon stocks, particularly under short-term application regimes [54]. In low-fertility soils where foxtail millet is typically cultivated, deep tillage might cause structural degradation beyond crop tolerance thresholds [43,55]. Notably, the strategic integration of organic fertilizer with deep tillage appears to synergistically enhance soil conditions, thus potentially optimizing the growth environment for millet production. Foxtail millet exhibits distinct nutrient acquisition patterns and tillage adaptability compared to other

crops, further complicated by its sensitivity to continuous monoculture. Given the practical challenges in establishing long-term field trials for millet, this study conducted a two-year fixed-site experiment. We hypothesize that the integrated application of organic fertilizer with deep tillage will induce a spatiotemporal optimization of the soil environment. Specifically, we posit that this management strategy will not only enhance key physicochemical properties during critical growth stages and throughout the soil profile but will also achieve improvements comparable to or greater than those observed with the conventionally practiced rotary tillage combined with compound fertilizer.

To test this central hypothesis, we focused on five critical soil properties and processes, aiming to: (i) quantify the spatiotemporal dynamics of soil pH and pH buffering capacity under different management regimes; (ii) evaluate the improvements in soil physical structure, specifically bulk density, porosity, and the solid–liquid–gas phase equilibrium; (iii) determine the enhancements in soil aggregate stability, including the content of macro-aggregates and their mean weight diameter; (iv) assess the profile distribution of organic carbon concentration within different size classes of soil aggregates; (v) elucidate the retention and redistribution of total nitrogen associated with aggregates throughout the soil profile.

2. Materials and Methods

2.1. Experimental Site Description

The field experiment was conducted at Yujiazhuang Village (112°53′46″ E, 38°35′04″ N), Shoulu Township, Dingxiang County, Xinzhou City, a representative site in the north-central part of Shanxi Province, China. The region is characterized by a temperate semi-arid continental monsoon climate. The mean annual temperature is 8.7 °C, with a frost-free period of approximately 150 d and an annual precipitation of 413 mm. The field experiment was conducted during 2020 and 2021 in the same plot. The preceding crop was continuous maize cultivated for five years under 15–20 cm rotary tillage. Prior to the experiment, the topsoil (0–20 cm) was identified as a Haplic Luvisol (World Reference Base for Soil Resources, WRB, 2015) with a sandy loam texture comprising 55.4% sand, 26.8% silt, and 17.8% clay, and had chemical properties as detailed in Table S1. Meteorological data during the foxtail millet growing season (10 May–15 October) are shown in Figure 1.

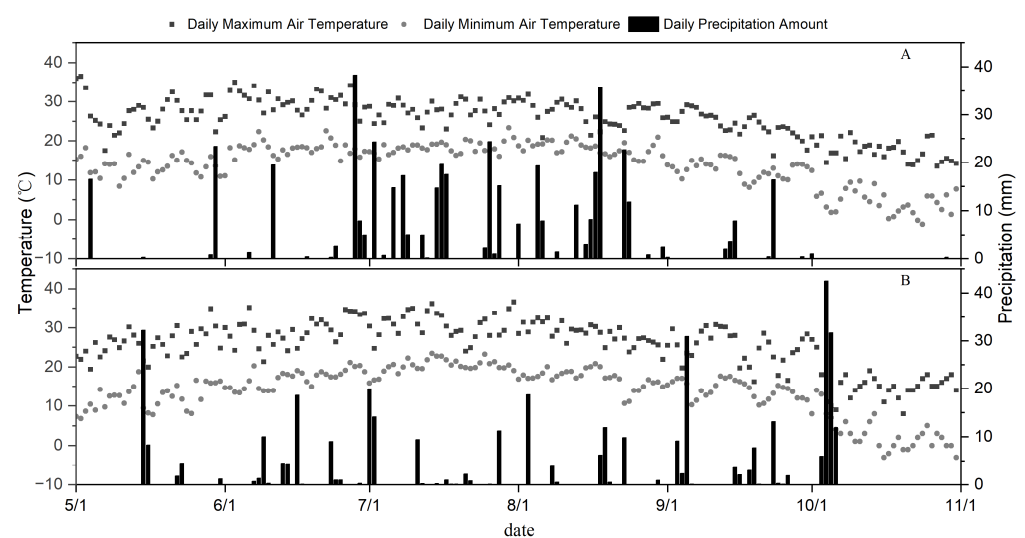


Figure 1. Precipitation and air temperature during the growing season of foxtail millet in the experimental field in 2020 (A) and 2021 (B).

2.2. Field Experimental Design

This experiment was a two-year fixed-site trial, employing a randomized complete block design (RCBD) with treatments randomly assigned to plots at the initiation of the experiment in 2020; the same plot layout was maintained for the subsequent year (2021). The experiment comprised five treatments: rotary tillage without fertilization (RT, serving as the non-fertilized control), rotary tillage with compound fertilizer (RTC, representing the conventional high-yield management practice), rotary tillage with organic fertilizer (RTO), deep tillage with organic fertilizer at 20–30 cm (DT1O), and deep tillage with organic fertilizer at 30–40 cm (DT2O). Each treatment was replicated three times, resulting in a total of 15 experimental plots. To minimize edge effects, all sampling was conducted within the central area of each plot, maintaining a buffer zone of at least 1 m from the plot boundaries. Field implementation details are provided in Table 1. A 100-horsepower tractor with a 1500 mm rear wheel track was employed, coupled with a 1500 mm wide rotary tiller and a 1400 mm wide hydraulic reversible plow. Tillage depth was adjusted by regulating plow blade penetration. The test cultivar was Zhangzagu 10, a locally promoted foxtail millet variety. Sowing was conducted using a four-row planter at 5 cm depth, with 8 rows per plot, 50 cm row spacing, 25 m row length, and a 100 m² plot area. Post-thinning plant spacing was maintained at 20 cm. Compound fertilizer (28% N, 7.9% P, 1.7% K) was applied at 600 kg/ha, a rate determined by local high-yielding foxtail millet production practices. Separately, well-decomposed sheep manure (a type of Farmyard Manure, FYM) was applied at 30,000 kg/ha as organic fertilizer, with its application rate aligned with common practices for staple crops while considering cost control. The detailed characteristics of the manure are provided in Supplementary Table S2.

Table 1. Details of the experimental treatments.

Treatment	Practices
RT	Rotary tiller operation at 15–20 cm depth without fertilizer application
RTC	Rotary tiller operation at 15–20 cm depth with basal application of 600 kg/ha compound fertilizer
RTO	Rotary tiller operation at 15–20 cm depth with basal application of 30,000 kg/ha organic fertilizer
DT1O	Moldboard plowing followed by harrowing at 20–30 cm depth with basal application of 30,000 kg/ha organic fertilizer
DT2O	Moldboard plowing followed by harrowing at 30–40 cm depth with basal application of 30,000 kg/ha organic fertilizer

2.3. Measurements and Methods

Soil samples were collected from each plot on 12 June (0612), 2 July (0702), 22 July (0722), 11 August (0811), 31 August (0831), 20 September (0920), and 10 October (1010), approximately corresponding to the millet growth stages of seedling, jointing, booting, heading, early grain-filling, mid grain-filling, and late grain-filling (with slight interannual variations in key phenological phases). At each sampling time, new soil profile pits were excavated within the pre-defined sampling area of each plot. Soil samples were collected from depths of 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm. To prevent cross-contamination between layers, the soil profile face was carefully cleaned with a trowel before sampling each successive layer.

2.3.1. Soil pH and pH Buffering Capacity

A 25 g aliquot of air-dried soil (sieved through a 1 mm mesh) was weighed into a 50 mL beaker. Subsequently, 25 mL of CO₂-free distilled water was added, and the mixture was intermittently stirred for 30 min to ensure complete soil dispersion before measuring the pH of the suspension using a Leici PHS-3C pH meter (Leici, Shanghai, China).

Additionally, two 25 g subsamples of air-dried soil (1 mm sieved) were separately placed into two 50 mL beakers. Each subsample was mixed with 25 mL of CO₂-free distilled water, followed by the addition of 0.5 mL of 0.1 mol·L^{−1} HCl or 0.5 mL of

0.1 mol·L⁻¹ NaOH, respectively. After 30 min of stirring, the pH of each solution was measured with a pH meter [56,57]. The pH buffering capacity (pHBC) was then calculated as:

$$\text{pHBC} = \frac{1}{\frac{(pH_{NaOH} - pH_o) + (pH_o - pH_{HCl})}{2}} = \frac{2}{(pH_{NaOH} - pH_{HCl})} \quad (1)$$

2.3.2. Soil Three-Phase Composition

Soil samples were collected from four depth layers (0–10, 10–20, 20–30, and 30–40 cm) using the cutting ring method (100 cm³ ring volume). The cutting rings containing undisturbed soil samples were carefully transported intact to the laboratory to avoid compaction. The following direct measurements were obtained:

The total weight of the ring with moist soil (M1).

The total volume of the solid and liquid phases (V) was directly measured using a DIK-1150 soil three-phase meter (Daiki, Konosu, Japan).

After oven-drying at 105 °C for 24 h, the weights of the ring with dry soil (M2) and the empty ring (M3) were measured.

The three-phase parameters were then calculated using the following equations:

$$\text{Solid mass : } S = M2 - M3 \quad (2)$$

$$\text{Wet mass : } W = M1 - M3 \quad (3)$$

$$\text{Water mass : } M = W - S \quad (4)$$

$$\text{Water volume : } V_l = \frac{M}{1\text{g/cm}^3} \quad (5)$$

$$\text{Volumetric water content : } M_v = V_l \quad (6)$$

$$\text{Air volume : } V_a = 100 - V \quad (7)$$

$$\text{Air – filled porosity : } A = V_a \quad (8)$$

$$\text{Solid volume : } V_s = V - V_l \quad (9)$$

$$\text{Solid volume fraction : } S_v = V_s \quad (10)$$

$$\text{Total porosity : } P = 100 - V_s \quad (11)$$

$$\text{Bulk density : } BD = \frac{S}{100} \quad (12)$$

2.3.3. Soil Aggregate Stability

For each sample, 100 g of air-dried undisturbed soil with an intact structure was weighed for dry sieving to determine mechanically stable aggregate (MSA) composition. Then, 50% of each aggregate fraction from dry sieving (totaling 50 g) was subjected to wet sieving to analyze water-stable aggregate (WSA) distribution. All sieved fractions were retained for further analysis. Aggregate size proportions were calculated as follows [38]:

$$w_i = \frac{m_i}{\sum_{i=1}^n m_i} \times 100\% \quad (13)$$

Aggregate stability was evaluated by the mean weight diameter (MWD) and geometric mean diameter (GMD). The calculation formulas were as follows [37]:

$$\text{MWD} = \sum_{i=1}^n \frac{r_{i-1} + r_i}{2} \times w_i \quad (14)$$

$$\text{GMD} = e^{\sum_{i=1}^n \ln\left(\frac{r_{i-1} + r_i}{2}\right) \times w_i} \quad (15)$$

In the formula, m_i and w_i represent the mass of aggregates retained on the i -th sieve and the mass percentage, respectively. r_i represents the aperture size (mm) of the i -th sieve, and n denotes the total number of sieves.

2.3.4. Soil Organic Carbon

The soil samples from each aggregate fraction after dry and wet sieving were ground to pass through a 100-mesh sieve. The content of soil mechanically stable aggregate organic carbon (MSAOC) and water-stable aggregate organic carbon (WSAOC) was determined by the potassium dichromate external heating method [58] and expressed in g kg^{-1} .

2.3.5. Soil Total Nitrogen

The aggregates were ground to pass a 100-mesh sieve ($150 \mu\text{m}$). The total nitrogen content was determined by Kjeldahl digestion followed by the salicylate-hypochlorite method [59], and analyzed mechanically stable aggregate total nitrogen (MSATN) and water-stable aggregate total nitrogen (WSATN) using a SmartChem 200 autoanalyzer (AMS Alliance, Frépillon, France), with results in g kg^{-1} .

2.4. Data Processing Methods

Data are presented as the mean $\pm$ standard error of three biological replicates ($n = 3$). Statistical analyses were performed using SAS 9.4 (SAS Institute Inc., Cary, NC, USA), with a predetermined significance level of $\alpha = 0.05$ for all tests. No technical replicates were performed.

A one-way analysis of variance (ANOVA) was conducted independently for each combination of sampling time and soil depth to assess the effect of treatment. Prior to ANOVA, the normality of the model residuals was tested using the Shapiro–Wilk test, and the homogeneity of variances was assessed using Levene’s test.

Regardless of the outcome of the overall ANOVA F-test, Tukey’s Honest Significant Difference (HSD) post hoc test was applied to all treatment pairs within each time-depth combination. This uniform approach allowed for a consistent letter-based labeling convention across all figure panels. When no significant differences were found, all treatments were assigned the same lower-case letter. Figures were performed using Origin Pro 2021 software.

3. Results

3.1. Effects of Organic Fertilizer Application and Deep Tillage on Soil pH and pH Buffering Capacity

The variations in soil pH and pH buffering capacity (pHBC) are presented in Figure 2. At the early growth stage (seedling stage, 12 June), soil pH in the topsoil (0–20 cm) was significantly higher in the organic fertilizer treatments (RTO, DT1O, DT2O) than in the RT and RTC treatments. For instance, in the 0–10 cm layer on 12 June 2020, the pH under RTO was 6.1% and 6.0% higher than under RT and RTC, respectively. This initial pH elevation was more pronounced in 2021. However, a marked decrease in pH was observed in the deep tillage with organic fertilizer treatments (DT1O and DT2O) by the jointing stage (early July), after which the differences in pH among treatments diminished during the mid to late growth stages (booting to grain-filling).

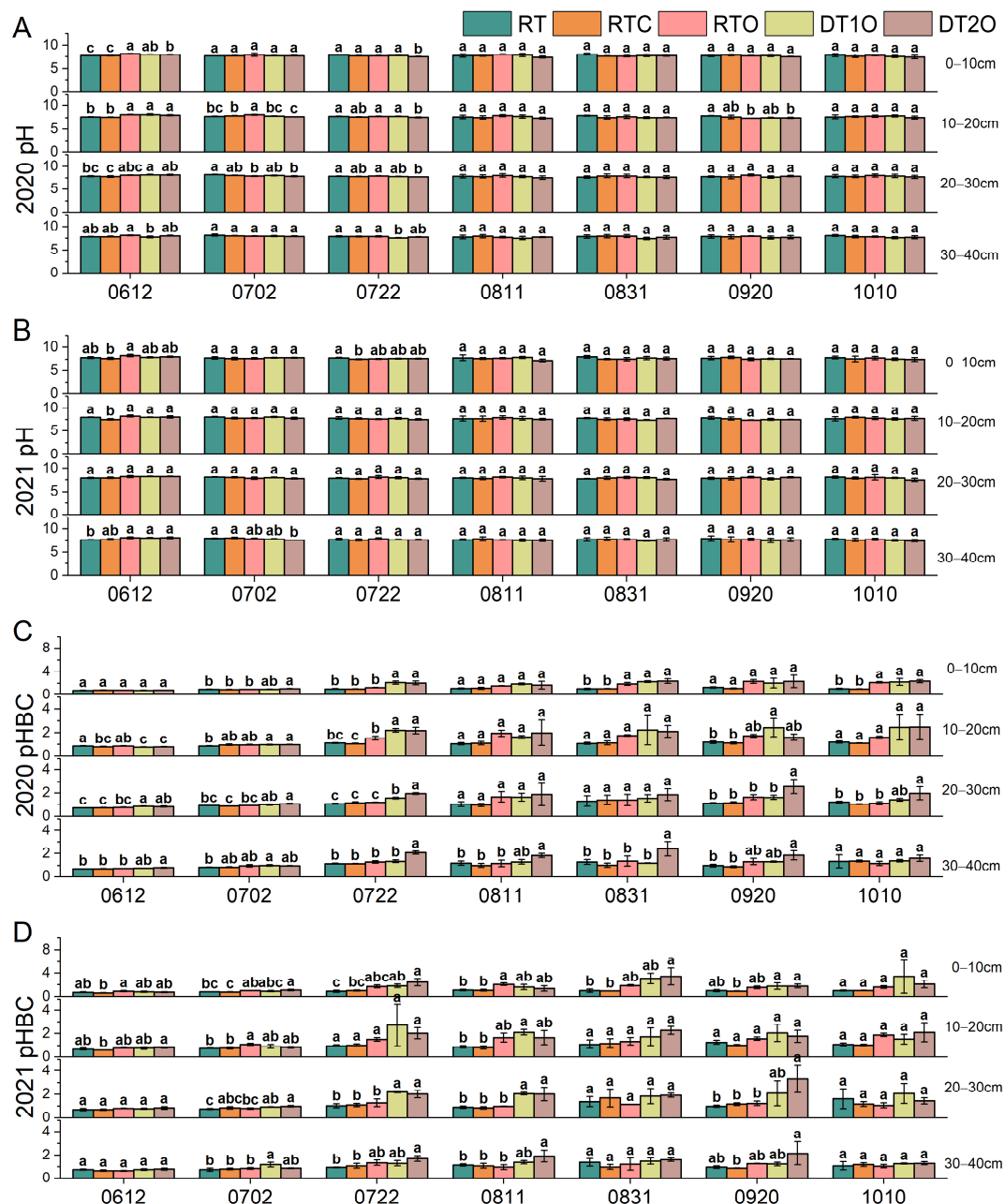


Figure 2. The soil pH ((A): 2020; (B): 2021) and pH buffering capacity (pHBC; (C): 2020; (D): 2021). across sampling times and depths. Data are expressed as the mean $\pm$ SE ($n = 3$). Values followed by different lowercase letters are significantly different at $p < 0.05$ level among different treatments under the same sampling time and soil depth. RT: rotary tillage (15–20 cm depth) without fertilization; RTC: rotary tillage with compound fertilizer; RTO: rotary tillage with organic fertilizer; DT10: deep tillage (20–30 cm depth) with organic fertilizer; DT20: deep tillage (30–40 cm depth) with organic fertilizer.

The application of organic fertilizer, either alone or combined with deep tillage, significantly enhanced the soil's pH buffering capacity (pHBC), with the effects becoming more substantial as the growing season progressed. In the surface layer (0–10 cm), RTO increased pHBC by 43.5% compared to RT on 11 August 2020. The most substantial improvement was observed under DT20, which increased pHBC by 245.5% in the same layer on 31 August 2021. Furthermore, the enhancements in pHBC were not confined to the topsoil. The deep tillage with organic fertilizer treatments (DT10 and DT20), particularly DT20, significantly increased pHBC in the 20–40 cm subsurface layers compared to all

other treatments during the mid to late growth stages. For example, on 20 September 2020, DT2O increased pHBC by 132.7% in the 20–30 cm layer compared to RT, and by 123.9% in the 30–40 cm layer on the same date in 2021.

3.2. Effects on Soil Bulk Density, Total Porosity, and Three-Phase Composition

The effects of treatments on soil bulk density (BD) and total porosity (P) are presented in Figure S1. Meanwhile, the dynamics of the soil three-phase composition (i.e., A: Air-filled porosity; Mv: Volumetric water content; Sv: Solid volume fraction) are illustrated in Figure 3. During the mid to late growth stages of foxtail millet (from jointing to maturity, 22 July to 10 October), the RTO treatment significantly reduced BD in the 0–10 cm layer compared to both RT and RTC. While DT1O and DT2O initially exhibited higher BD than RTO in the 0–10 cm layer during early growth stages (seedling stage, 12 June to 2 July), their BD showed a decreasing trend in the subsequent mid to late stages. Notably, in the 20–40 cm layer, DT1O and DT2O consistently maintained significantly lower BD than RT and RTC throughout the experimental period.

In the 0–10 cm layer during 2020, RTO significantly increased A compared to RT on 22 July, 31 August, and 20 September, with the maximum increase (21.6%) occurring on 31 August (early grain-filling). Relative to RTC, RTO enhanced A by 13.2% and 31.3% on 31 August and 20 September, respectively. In deeper soil layers (20–40 cm), DT1O and DT2O generally showed higher A than RTO, exemplified by DT1O's 9.7% increase over RTO in the 20–30 cm layer on 12 June 2020. However, in the 0–10 cm layer, DT1O and DT2O displayed lower A, with DT2O showing a 30.1% reduction compared to RTO on 12 June 2020.

In the 0–10 cm soil layer during 2020, RTO significantly increased Mv by 13.9% compared to RT on 12 June. In the 30–40 cm soil layer of 2020, DT1O and DT2O markedly enhanced Mv relative to RT on 11 August. However, in the 30–40 cm layer of 2021, DT1O and DT2O significantly reduced Mv compared to RT on both 22 July and 11 August.

Organic fertilizer significantly reduced Sv during late growth stages. For instance, on 20 September 2020, RTO decreased Sv by 15.6% and 11.2% compared to RT and RTC, respectively, in the 0–10 cm layer. DT1O and DT2O generally exhibited lower Sv than RTO in the 20–40 cm layer, with this effect being more pronounced in 2021—for example, DT2O showed 16.2% lower Sv than RTO in the 20–30 cm layer on 10 October. P demonstrated inverse trends to Sv.

3.3. Effects on Soil Aggregate Stability

As shown in Figure 4, RTO significantly increased the proportion of 2–5 mm mechanically stable aggregates (MSAs) compared to RT in the 0–10 cm layer on 31 August 2020 and 2 July 2021. RTO showed significantly higher proportions of 2–5 mm MSA than RTC on 31 August 2020 (0–10 cm) and 12 June 2020 (20–30 cm). On 2 July 2021 (0–10 cm) and 22 July 2021 (30–40 cm), DT1O exhibited higher 2–5 mm MSA than RTO. On 20 September 2020 (20–30 cm), 2 July 2021 (0–10 cm), 20 September 2021 (0–10 cm), and 31 August 2021 (10–20 cm), DT2O significantly increased 2–5 mm MSA over RTO. Conversely, on 31 August 2021 (0–10 cm) and 20 September 2021 (0–10 cm and 10–20 cm), RTO had significantly lower <0.25 mm MSA than RTC. Similarly, on 31 August, 22 July, and 10 October 2021 (20–40 cm), DT1O and DT2O reduced <0.25 mm MSA compared to RTO. Overall, organic fertilization and deeper tillage tended to promote the formation of larger, more stable aggregates (2–5 mm) and reduce the proportion of the smallest, least stable fraction (<0.25 mm). RTO significantly improved mean weight diameter (MWD, Figure S2) over RT on 12 June 2020 (0–10 cm), 2 July 2021 (0–10 cm), and 11 August 2021 (10–20 cm). DT2O showed higher MWD than RTO on 20 September 2020 (20–30 cm) and

31 August 2021 (20–40 cm). The geometric mean diameter (GMD) followed a similar trend to MWD.

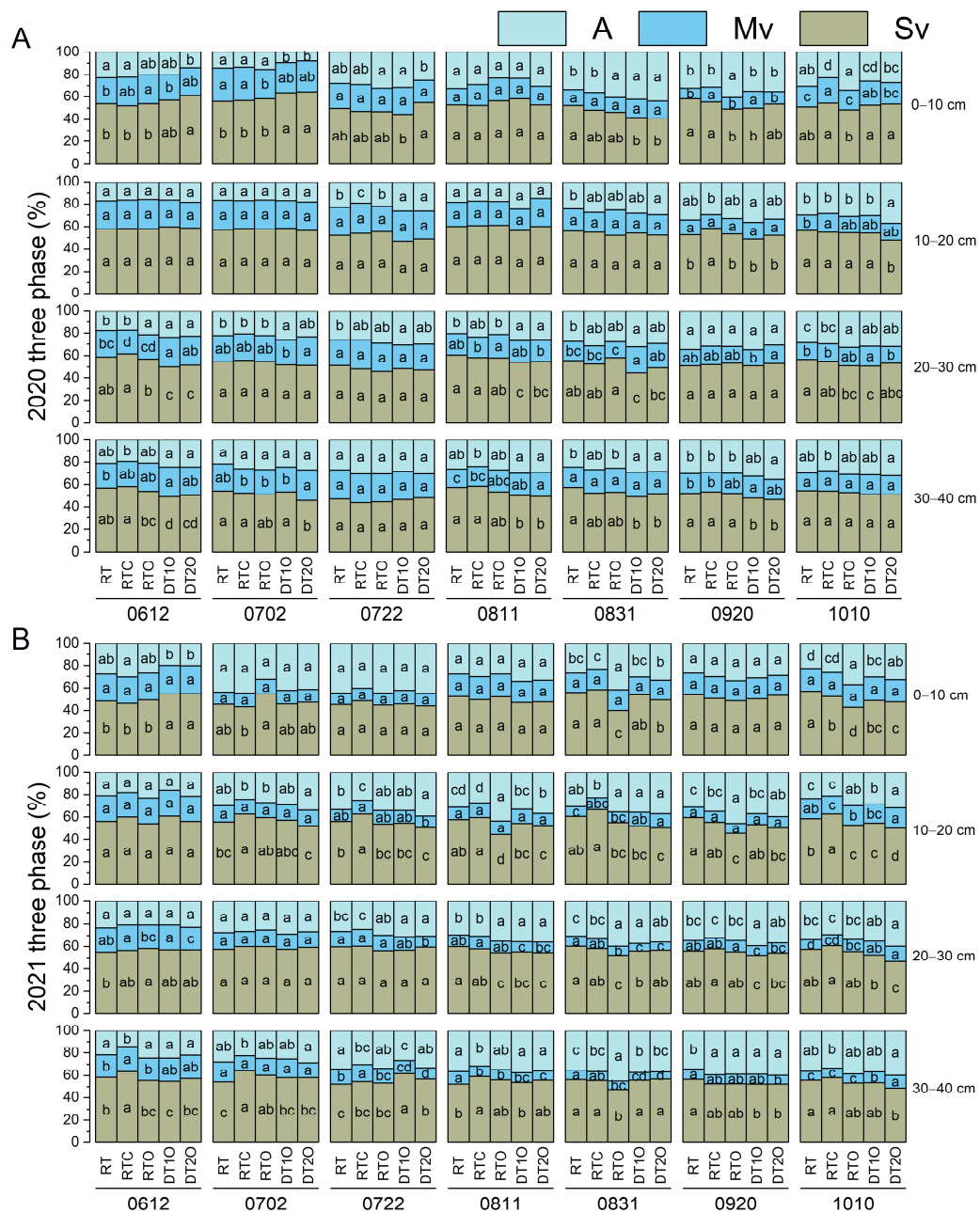


Figure 3. The soil three phase ((A): 2020; (B): 2021) across sampling times and depths. Data are expressed as volume percentages (%), determined via the cutting-ring method (see Section 2.3.2), and represent the mean $\pm$ SE ($n = 3$). Values followed by different lowercase letters are significantly different at a $p < 0.05$ level among different treatments under the same sampling time and soil depth. RT: rotary tillage (15–20 cm depth) without fertilization; RTC: rotary tillage with compound fertilizer; RTO: rotary tillage with organic fertilizer; DT1O: deep tillage (20–30 cm depth) with organic fertilizer; DT2O: deep tillage (30–40 cm depth) with organic fertilizer. A: Air-filled porosity; Mv: Volumetric water content; Sv: Solid volume fraction.

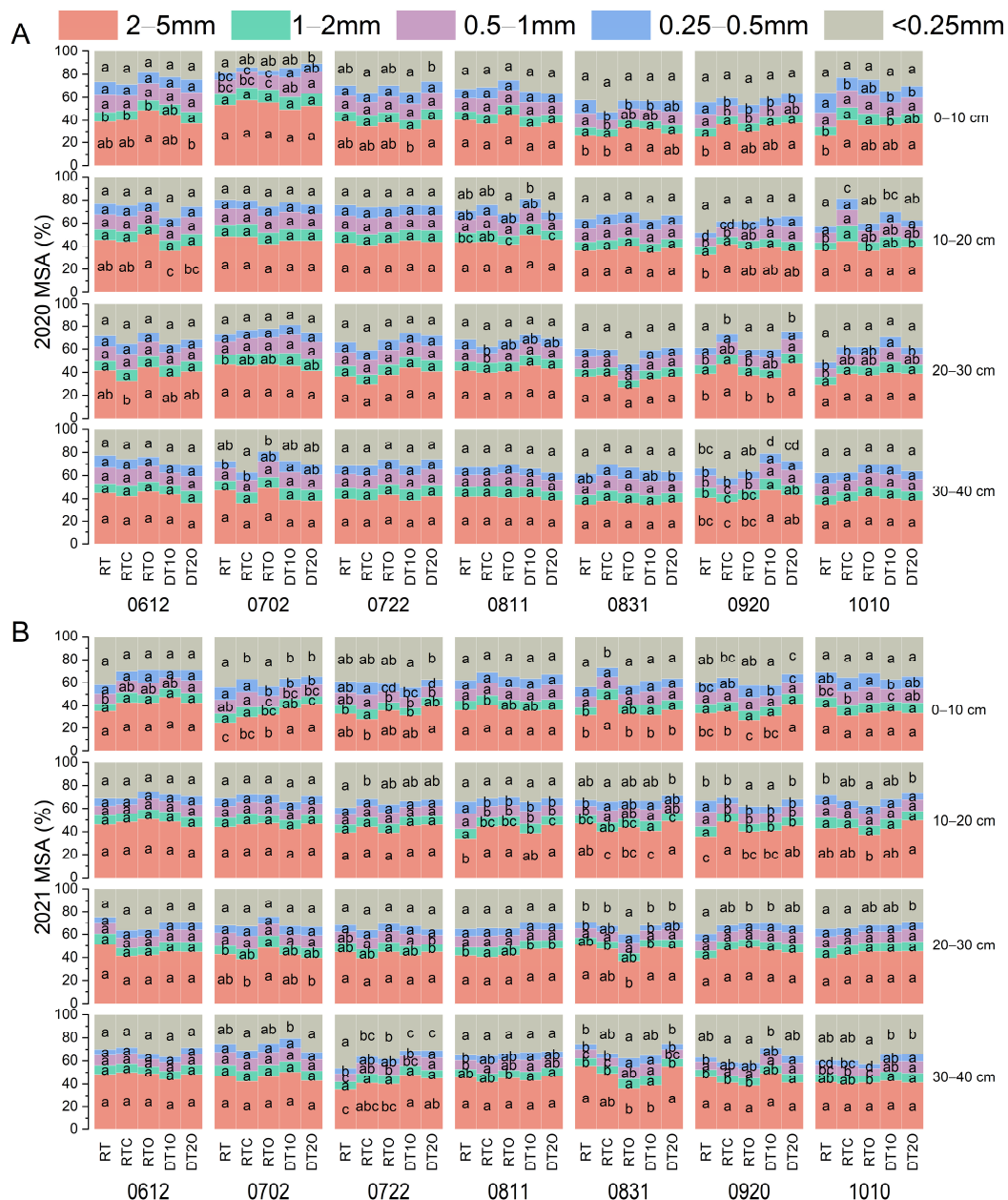


Figure 4. The soil mechanically stable aggregates (MSAs; (A): 2020; (B): 2021) across sampling times and depths. Data are expressed as the mean $\pm$ SE ($n = 3$). Values followed by different lowercase letters are significantly different at a $p < 0.05$ level among different treatments under the same sampling time and soil depth. RT: rotary tillage (15–20 cm depth) without fertilization; RTC: rotary tillage with compound fertilizer; RTO: rotary tillage with organic fertilizer; DT10: deep tillage (20–30 cm depth) with organic fertilizer; DT20: deep tillage (30–40 cm depth) with organic fertilizer.

Regarding water-stable aggregates (WSAs, Figure 5), RTO increased >2 mm WSA over RT on 12 June and 20 September (both in the 10–20 cm layer in 2020). RTO also surpassed RTC in >2 mm WSA on 12 June and 22 July 2021 (10–20 cm). DT10 and DT20 generally increased >2 mm WSA over RT and RTC in the 0–20 cm layer, while in 20–40 cm, DT10 and DT20 often exceeded RTO during 2021. However, the size distribution of water-stable aggregates varied considerably with sampling time and depth. As for the stability indices, DT20 significantly increased MWD compared to RT on multiple sampling dates (Figure S3). For instance, on 10 October 2020, the 10–20 cm layer showed higher MWD under DT20; on 12 June 2020, the 20–30 cm layer exhibited the same trend. In 2021, DT20 exhibited higher MWD than RT on 2 July in the 0–10 cm layer, on 12 June in the 10–30 cm layer, on

20 September in both the 10–20 cm and 30–40 cm layers, and on 10 October in the 30–40 cm layer. DT1O also frequently demonstrated higher MWD than RT. The trends for GMD were consistent with those for MWD.

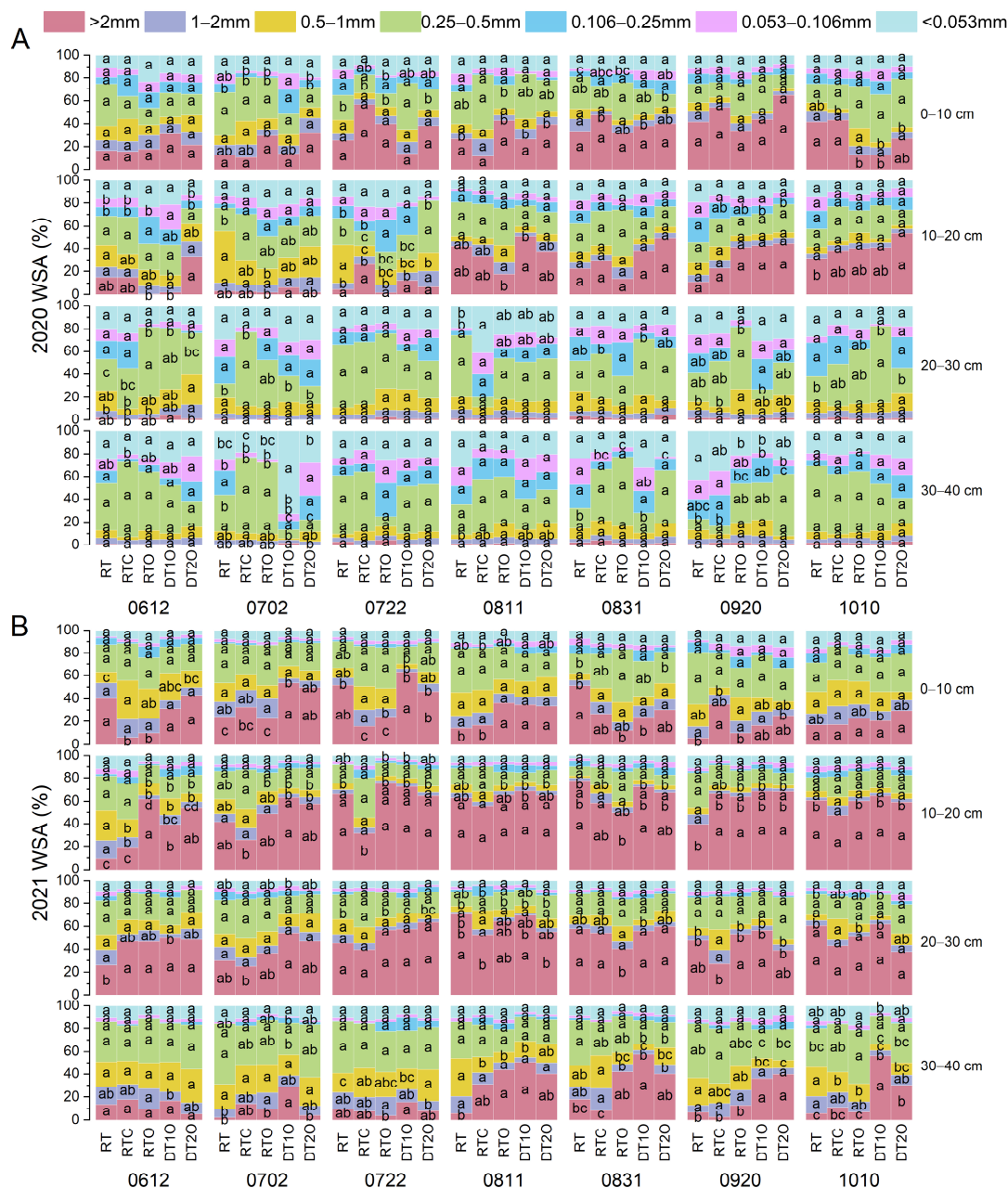


Figure 5. The soil water-stable aggregate (WSA; (A): 2020; (B): 2021) across sampling times and depths. Data are expressed as the mean $\pm$ SE ($n = 3$). Values followed by different lowercase letters are significantly different at a $p < 0.05$ level among different treatments under the same sampling time and soil depth. RT: rotary tillage (15–20 cm depth) without fertilization; RTC: rotary tillage with compound fertilizer; RTO: rotary tillage with organic fertilizer; DT1O: deep tillage (20–30 cm depth) with organic fertilizer; DT2O: deep tillage (30–40 cm depth) with organic fertilizer.

3.4. Effects on Aggregate-Associated Organic Carbon

The distribution of soil organic carbon within mechanically stable aggregates (MSAOC) and water-stable aggregates (WSAOC) under different treatments is shown in Figure 6 and Figure 7, respectively. In the 0–20 cm soil layer during most sampling periods, RTO significantly increased MSAOC compared to RT and RTC. Specifically, the

>2 mm fraction MSAOC increased by 4.7–69.8% over RT and –7.1–62.5% over RTC; the 0.25–2 mm fraction increased by –3.8–141.2% over RT and 5.6–80.0% over RTC; and the <0.25 mm fraction increased by 12.3–107.3% over RT and 5.6–62.4% over RTC. In the 20–30 cm layer, DT1O generally exhibited higher MSAOC than RTO, with increases of 4.7–69.8% (>2 mm), 2.0–59.2% (0.25–2 mm), and –18.7–39.7% (<0.25 mm). In the 30–40 cm layer, DT2O surpassed RTO in MSAOC, showing increases of –5.2–36.8% (>2 mm), –2.9–49.5% (0.25–2 mm), and –17.2–24.6% (<0.25 mm).

In the 0–20 cm soil layer, RTO significantly enhanced WSAOC compared to RT and RTC, showing increases ranging from –7.8–99.2% for RT and –8.0–73.5% for RTC in the >0.25 mm aggregate fraction. Similarly, the 0.053–0.25 mm fraction exhibited increases of –12.4–105.9% (RT) and –5.8–60.6% (RTC), while the <0.053 mm fraction showed increases of 6.1–83.6% (RT) and –6.3–76.5% (RTC). In the 20–30 cm layer, DT1O demonstrated superior WSAOC accumulation relative to RTO, with increases of 4.7–69.8%, 2.0–59.2%, and –18.7–39.7% in the >2 mm, 0.25–2 mm, and <0.25 mm fractions, respectively. Furthermore, in the 30–40 cm layer, DT2O exhibited higher WSAOC than RTO, with increases ranging from –12.0–107.3% (>2 mm), –6.3–81.0% (0.25–2 mm), and 1.0–99.6% (<0.25 mm).

3.5. Effects on Aggregate-Associated Total Nitrogen

Figures 8 and 9 show the total nitrogen content in mechanically stable aggregates (MSATN) and water-stable aggregates (WSATN), respectively. In the topsoil (0–20 cm), both RTC and RTO significantly increased MSATN compared to RT. RTO was particularly effective, consistently enhancing MSATN across all aggregate size fractions throughout most of the growing season. The increases under RTO relative to RT ranged from 9.09% to 135.14% in the >2 mm fraction, 8.70% to 86.67% in the 0.25–2 mm fraction, and 11.54% to 96.23% in the <0.25 mm fraction. While RTO showed significantly higher MSATN than RTC only on 12 June and 4 July, no significant differences were observed between RTO and RTC during other sampling periods. In the 20–30 cm soil layer, DT1O generally exhibited significantly higher MSATN than RTO, with increases of –3.2–35.2% (>2 mm), –10.6–62.7% (0.25–2 mm), and –10.0–48.8% (<0.25 mm). In the 30–40 cm layer, DT2O surpassed RTO in MSATN, showing increases of –9.1–79.1% (>2 mm), –1.7–100.0% (0.25–2 mm), and 4.0–106.0% (<0.25 mm).

A similar trend was observed for total nitrogen in WSATN in the topsoil (0–20 cm). During most sampling intervals in the 0–20 cm layer, RTO markedly increased WSATN relative to RT, with increases of 9.09–135.14% in the >2 mm fraction, 8.70–86.67% in the 0.25–2 mm fraction, and 11.54–96.23% in the <0.25 mm fraction. Notably, RTO generally exhibited higher WSATN than RTC, with particularly significant improvements observed in the <0.25 mm fraction at 10–20 cm depth. In the subsurface layer (20–30 cm), DT1O demonstrated greater WSATN relative to RTO, showing increases in the range of 9.3–58.8%, –25–43.2%, and –13.1–65.9% for the >2 mm, 0.25–2 mm, and <0.25 mm aggregate fractions, respectively. In the deeper soil profile (30–40 cm), DT2O treatment outperformed RTO in WSATN accumulation, with relative improvements of 19.4–100% (>2 mm), 2.5–57.5% (0.25–2 mm), and –13.7–97.0% (<0.25 mm).

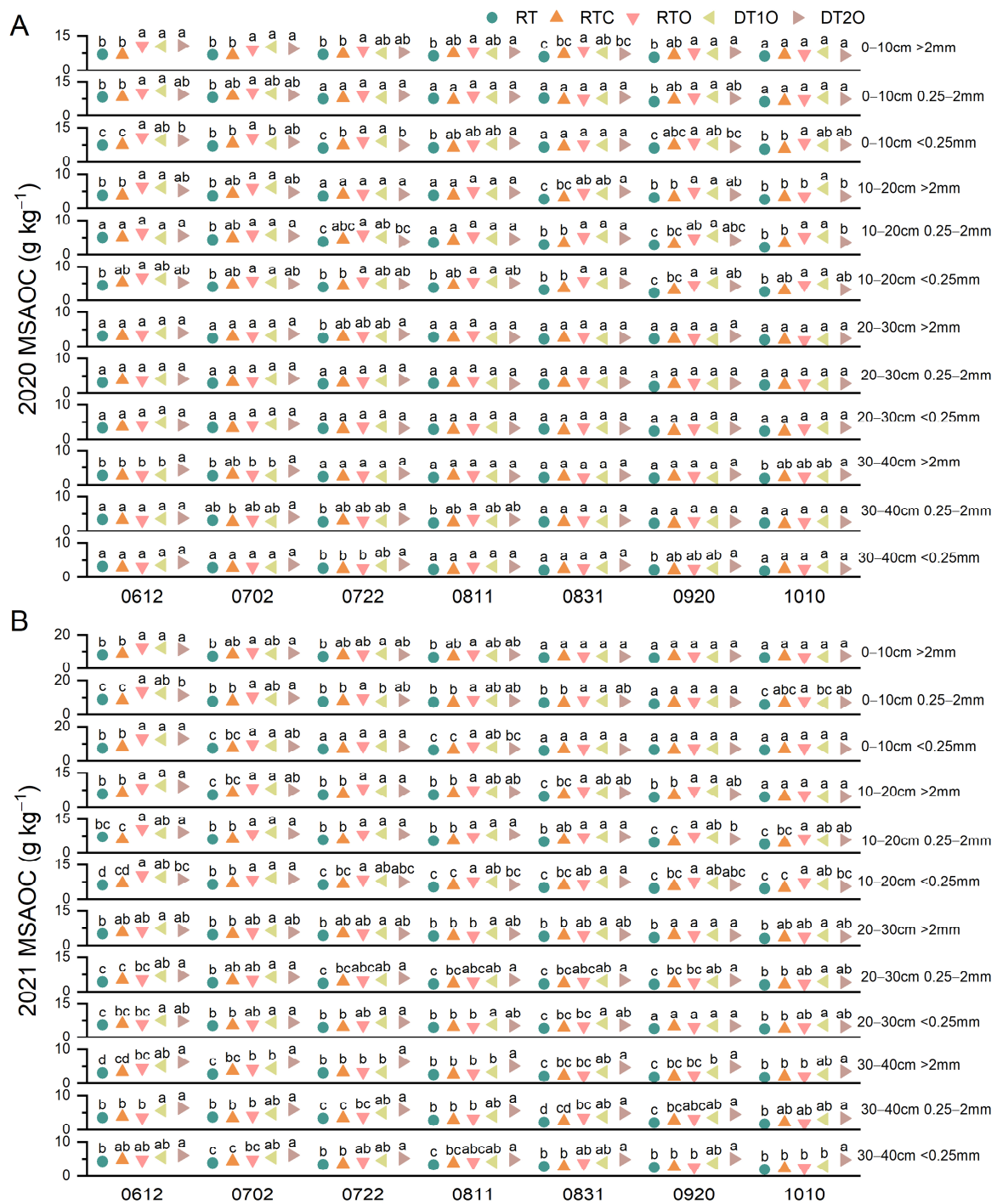


Figure 6. The soil mechanically stable aggregate organic carbon (MSAOC; **(A)**: 2020; **(B)**: 2021) across sampling times and depths. Data are expressed as the mean $\pm$ SE ($n = 3$). Values followed by different lowercase letters are significantly different at a $p < 0.05$ level among different treatments under the same sampling time and soil depth. RT: rotary tillage (15–20 cm depth) without fertilization; RTC: rotary tillage with compound fertilizer; RTO: rotary tillage with organic fertilizer; DT1O: deep tillage (20–30 cm depth) with organic fertilizer; DT2O: deep tillage (30–40 cm depth) with organic fertilizer.

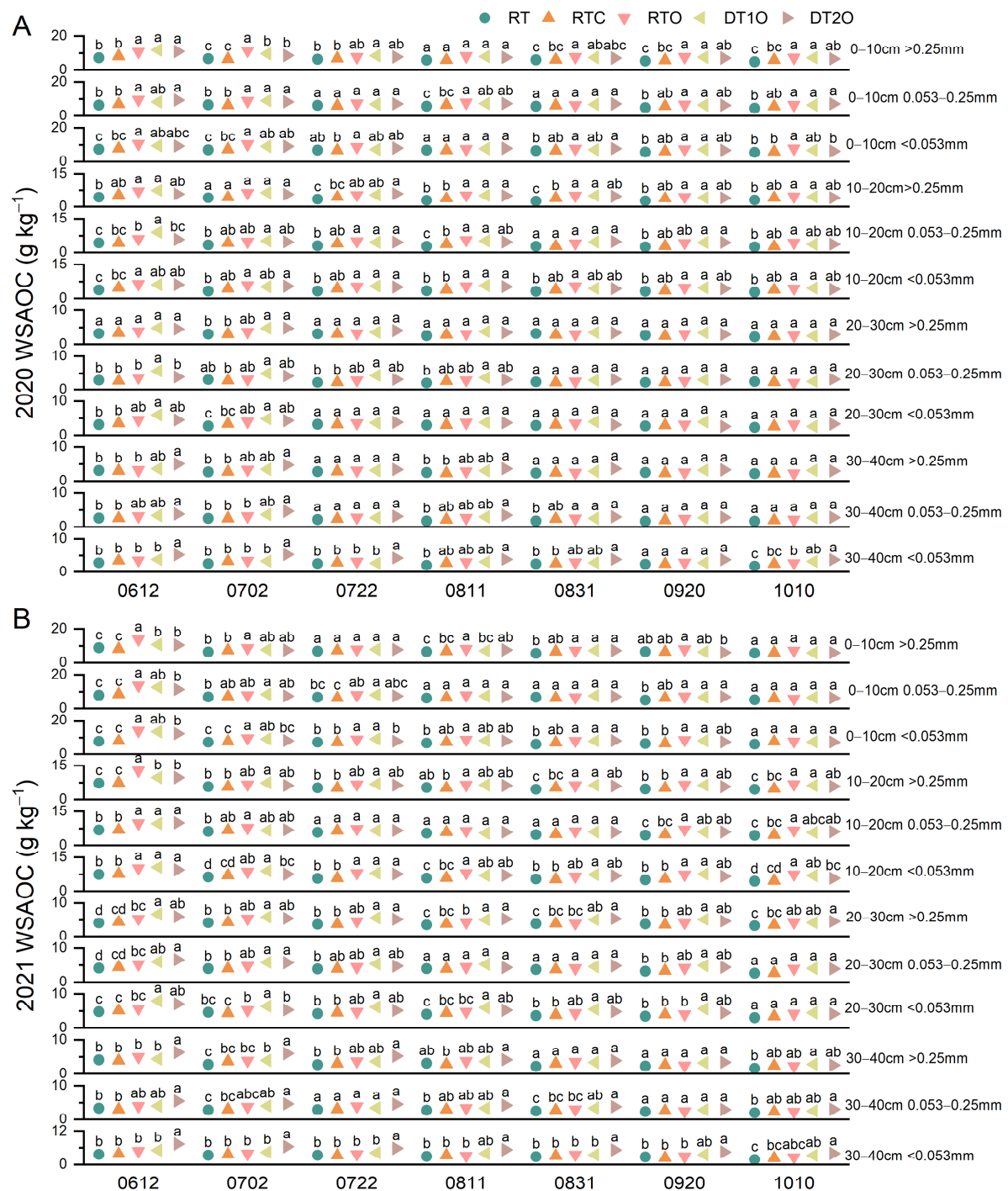


Figure 7. The soil water-stable aggregate organic carbon (WSAOC; (A): 2020; (B): 2021) across sampling times and depths. Data are expressed as the mean $\pm$ SE ($n = 3$). Values followed by different lowercase letters are significantly different at a $p < 0.05$ level among different treatments under the same sampling time and soil depth. RT: rotary tillage (15–20 cm depth) without fertilization; RTC: rotary tillage with compound fertilizer; RTO: rotary tillage with organic fertilizer; DT1O: deep tillage (20–30 cm depth) with organic fertilizer; DT2O: deep tillage (30–40 cm depth) with organic fertilizer.

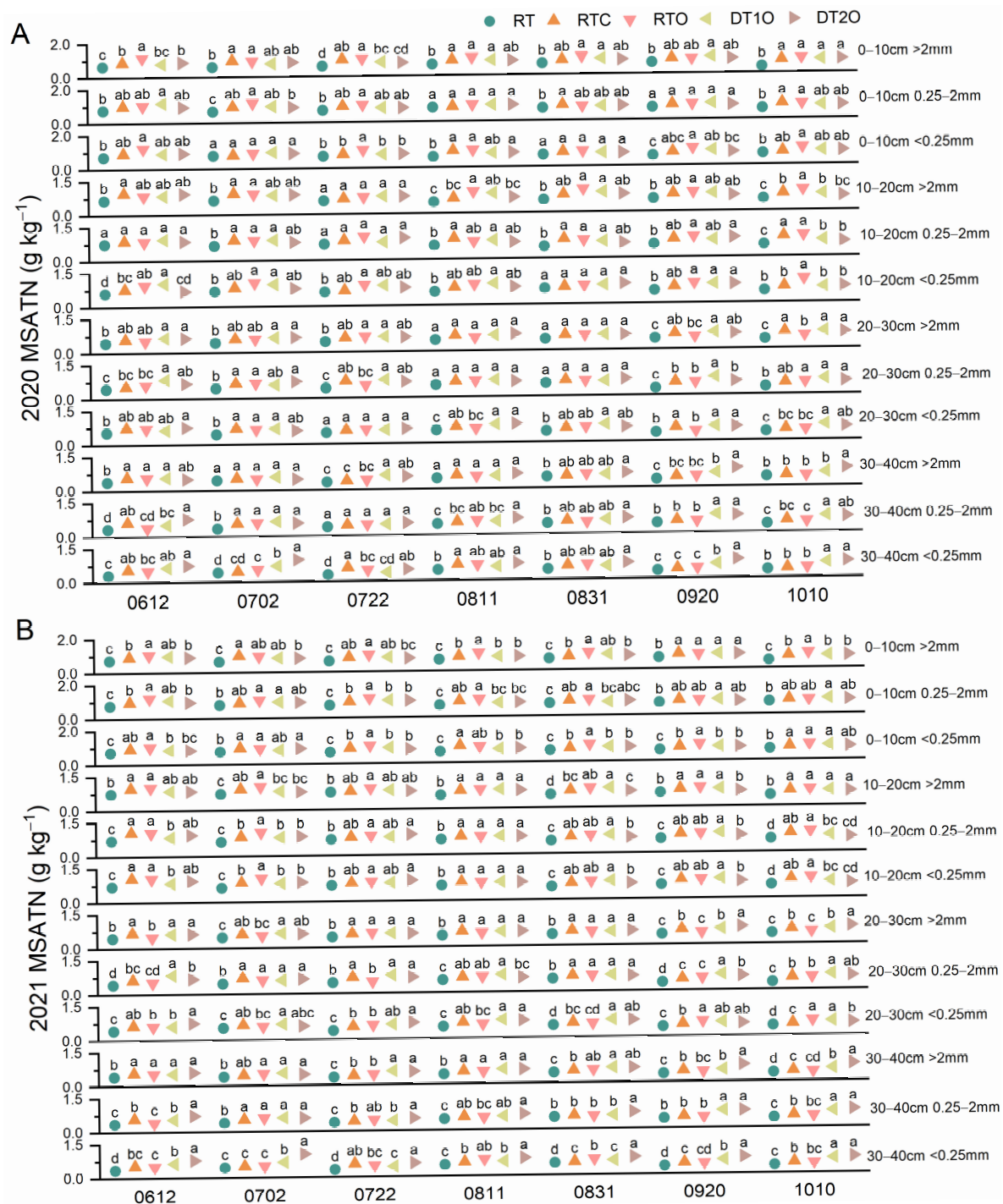


Figure 8. The soil mechanically stable aggregate total nitrogen (MSATN; (A): 2020; (B): 2021) across sampling times and depths. Data are expressed as the mean $\pm$ SE ($n = 3$). Values followed by different lowercase letters are significantly different at a $p < 0.05$ level among different treatments under the same sampling time and soil depth. RT: rotary tillage (15–20 cm depth) without fertilization; RTC: rotary tillage with compound fertilizer; RTO: rotary tillage with organic fertilizer; DT1O: deep tillage (20–30 cm depth) with organic fertilizer; DT2O: deep tillage (30–40 cm depth) with organic fertilizer.

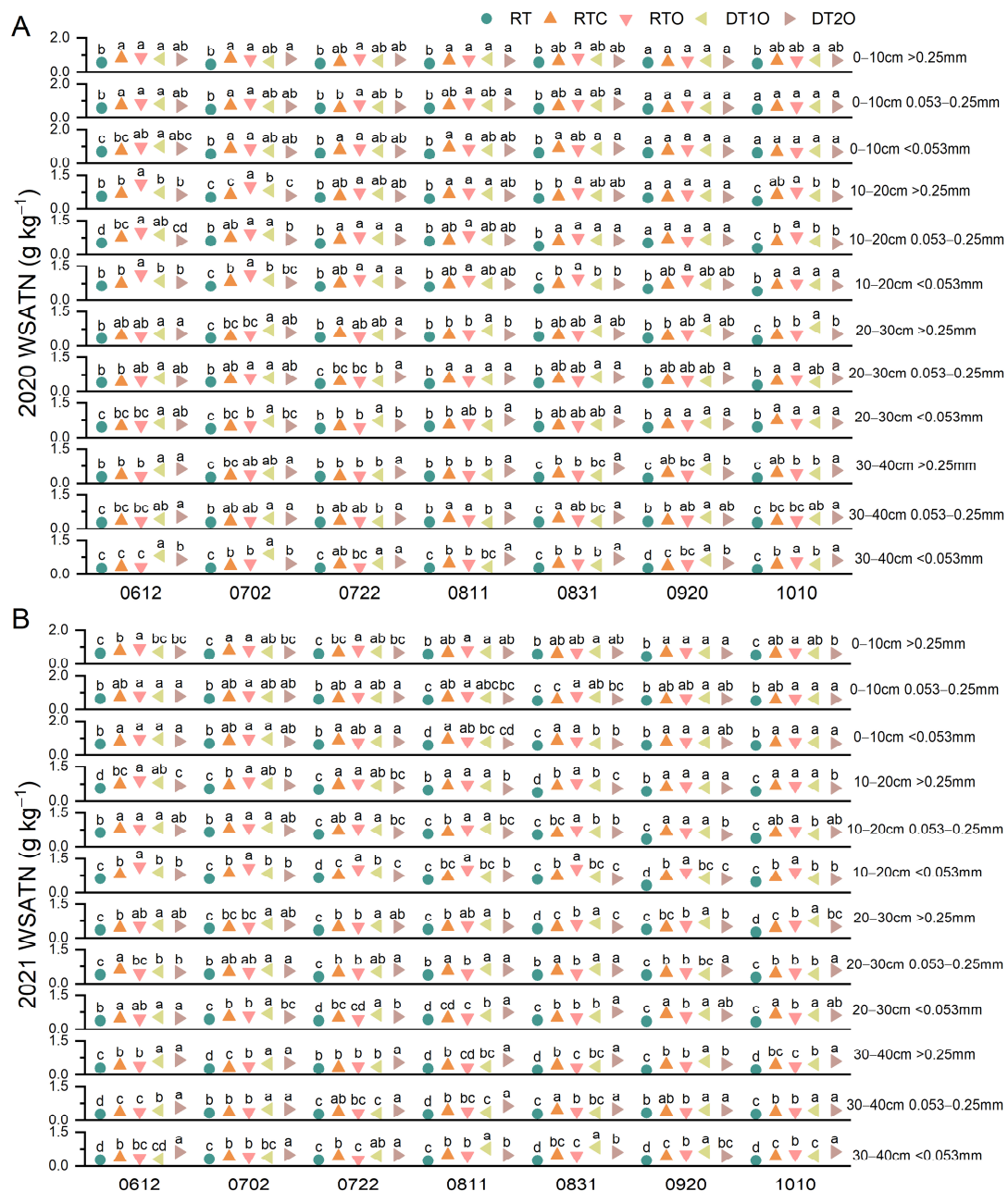


Figure 9. The soil water-stable aggregate total nitrogen (WSATN; (A): 2020; (B): 2021) across sampling times and depths. Data are expressed as the mean $\pm$ SE ($n = 3$). Values followed by different lowercase letters are significantly different at a $p < 0.05$ level among different treatments under the same sampling time and soil depth. RT: rotary tillage (15–20 cm depth) without fertilization; RTC: rotary tillage with compound fertilizer; RTO: rotary tillage with organic fertilizer; DT1O: deep tillage (20–30 cm depth) with organic fertilizer; DT2O: deep tillage (30–40 cm depth) with organic fertilizer.

4. Discussion

4.1. Deep Tillage Facilitates Organic Fertilizer Downward Migration and Co-Regulates Spatial Distribution of Soil pH and Buffering System

This study demonstrated that alkaline sheep manure application could temporarily elevate soil pH, resulting in significantly higher pH values in the early growth stage (12 June) RTO treatment compared to RT or RTC, which aligns with findings by Wang [60] and Song [61]. Notably, the deep tillage treatments DT1O and DT2O exhibited significant pH decreases on 2 July, potentially attributable to organic acid production during organic mat-

ter mineralization [62,63]. As the growing season progressed, inter-treatment differences diminished, a phenomenon linked to accelerated organic matter decomposition, enhanced root activity, and possibly greater influence from environmental variables (e.g., temperature and precipitation fluctuations) during mid-to-late growth stages. This observation corroborates previous studies highlighting environmental regulation of organic fertilization effects on soil pH dynamics [64].

The ability of organic fertilizers to improve soil pHBC has been widely demonstrated [8,65,66]. Our results further revealed that deep tillage combined with organic fertilization significantly improved pHBC, showing progressive enhancement during the growing season. This progressive improvement can be attributed to two main factors: the gradual establishment of stable humus-based buffer systems following organic fertilizers application [67,68], coupled with the increasing contribution of millet root systems to soil buffering capacity development throughout the growing season. Furthermore, the deep tillage practice itself played a crucial role in modifying the vertical distribution of this buffering capacity. Particularly noteworthy was DT2O's performance in 30–40 cm subsoil layers, demonstrating that deep tillage facilitates organic fertilizer downward migration, thereby expanding the spatial distribution range of the buffering system into deeper profiles.

4.2. Organic Fertilizer Combines with Deep Tillage to Decrease Bulk Density and Optimize Soil Three-Phase Composition

The results demonstrate that organic fertilizer application significantly improved soil physical properties. Compared with RT, organic fertilizer treatments (RTO, DT1O, DT2O) markedly reduced soil bulk density (BD) and increased total porosity (P), particularly during mid-to-late growth stages, consistent with previous findings [69–72]. During late growth stages, DT1O and DT2O exhibited lower BD and higher P than RTO, corroborating earlier report [32,33,41,73]. However, in early growth stages, surface soil BD in DT1O and DT2O was higher than in RTO, primarily due to reduced soil structure disruption from moldboard plowing.

The integration of deep tillage with organic fertilization (DT1O, DT2O) further optimized the soil three-phase ratio, as evidenced by a significant increase in air-filled porosity (A) and a concurrent decrease in solid volume fraction (Sv) within the 20–40 cm layer. This finding supports the established view that deep tillage ameliorates subsoil structure [34]. Moreover, the most substantial improvement in the air phase was observed under the DT2O treatment in the 30–40 cm layer, confirming that deep tillage to a depth of 40 cm is particularly effective in disrupting the plow pan. Notably, while existing studies suggest organic fertilization [74,75] or deep tillage [48,76] can enhance water use efficiency or soil water content, and some argue only their combination significantly improves saturated hydraulic conductivity; however, our study observed no significant standalone effect of organic fertilizer on volumetric water content (Mv). Furthermore, deep tillage's impact on Mv showed distinct interannual variation: it appeared to enhance water storage during the relatively wet August of 2020 but may have promoted deeper water uptake by the crop during the drought conditions in August 2021. This highlights the context-dependent nature of deep tillage effects on soil water dynamics, effectively creating an adaptive water regulation capacity within the soil profile.

4.3. Organic Fertilizer and Deep Tillage Synergistically Enhance Macroaggregate Content and Stability

It is generally accepted that organic fertilizer application significantly increases the proportion of mechanically stable aggregates (MSAs) and water-stable aggregates (WSAs) in large-size fractions [77–79], while enhancing the mean weight diameter (MWD) and geometric mean diameter (GMD) of aggregates and reducing the percentage of small-sized

aggregates [79]. However, some studies have reported contradictory findings, showing that organic fertilizer may decrease the content of >2 mm MSA [80], increase the proportion of medium-sized aggregates (0.25–2 mm) [19] or reduce the MWD of WSA [81]. For instance, Guo et al.'s research demonstrated that animal manure had no significant effect on aggregate formation in northern China's soils [82]. Regarding tillage practices, multiple studies [83–85] have indicated that deep tillage alone can adversely affect soil aggregate formation. In the present study, compared with RT and RTC treatments, RTO only significantly increased the content of large-sized aggregates in surface soil during limited sampling periods. This limited effect underscores the challenge of maintaining stable macroaggregates under frequent rotary tillage disturbance. In contrast, DT1O and DT2O exhibited more pronounced effects. This discrepancy may be attributed to the following mechanisms: First, the rotary tillage process itself causes substantial disturbance to surface soil structure, which is unfavorable for the stable existence of macroaggregates in topsoil [86,87]. Second, while organic fertilizer application provides binding agents necessary for macroaggregate formation [88,89], the deep tillage combined with organic fertilizer treatments distribute these cementing substances and form aggregates throughout different depths of the plow layer when bringing subsoil to the surface [90]. Additionally, deep tillage promotes root growth into deeper soil layers [37], and root development or exudates may also facilitate aggregate formation [91–93]. The discrepancies among different studies may be attributed to the fact that the formation and stabilization of soil aggregates are also influenced by a combination of environmental factors, including soil texture, climatic conditions, and crop growth. As observed in this study, if prolonged drought occurs during the early growth stage of foxtail millet, the surface soil under rotary tillage remains loose for an extended period. Conversely, heavy rainfall rapidly induces surface compaction in rotary-tilled soil, resulting in significant variations in aggregate structure under identical treatments. This observed sensitivity to weather conditions underscores the context-dependent nature of aggregate stability and reinforces the value of management practices that enhance resilience, such as the deep tillage and organic fertilizer combination.

4.4. Deep Tillage Promotes Organic Fertilizer-Induced Carbon Accumulation in Subsoil Aggregates

In this study, the variation patterns of mechanically stable aggregate organic carbon (MSAOC) and water-stable aggregate organic carbon (WSAOC) were generally consistent. The RTO treatment exhibited significantly higher organic carbon content in the 0–20 cm soil layer compared to RT and RTC, confirming the enhancing effect of organic fertilizer on aggregate-associated organic carbon [77,94,95]. We propose that this enhancement is primarily achieved through the physical protection pathway of carbon stabilization, wherein the added organic amendments serve as binding agents that promote the formation and stability of macroaggregates, effectively encapsulating organic carbon within their structure and reducing its accessibility to decomposers. In semi-arid or arid environments where the inherent soil carbon sequestration potential is relatively low [96], the fact that the jointing to grain-filling stages of foxtail millet coincide with the warm-rainy season further accelerates the decomposition and transformation of organic fertilizers [97,98], consequently resulting in a progressive decline in soil aggregate organic carbon content during the growing season. Organic carbon in the >20 cm tillage layer constitutes a critical component of the soil carbon pool [99,100]. The DT1O and DT2O treatments demonstrated significantly higher organic carbon content in the 20–40 cm layer than RTO, aligning with studies highlighting deep tillage's role in breaking plow pans and promoting vertical carbon migration [83,101,102]. This process effectively leverages the deeper soil layers as a reservoir for long-term carbon storage. Due to the relatively anoxic conditions [103], distinct microbial communities [104] and lower biodegradability [105], deeper soil layers may be more conducive to long-term

carbon stabilization than surface soils [106]. Notably, the impact of deep tillage on surface (0–20 cm) organic carbon remains debated [31]. For instance, studies by Zhang [107] and Tong [108] reported reduced surface aggregate organic carbon under deep tillage, whereas our study observed minimal significant differences between RTO and DT1O/DT2O in the 0–20 cm layer. This discrepancy could be attributed to the fact that in our system, the incorporation of a large quantity of organic fertilizer likely compensated for the mineralization initially stimulated by tillage disturbance, underscoring the importance of combined management for carbon balance. While deep tillage facilitates carbon accumulation in subsoil, it may also induce carbon loss through soil disturbance [109]. Detectable increases in organic carbon occur only when accumulation outweighs losses, underscoring the efficacy of combining deep tillage with organic fertilizer for soil carbon sequestration [44]. The synergy emerges because deep tillage creates a more extensive physical matrix for carbon storage throughout the profile, while organic fertilizer simultaneously provides the necessary substrates to fuel this storage process and promotes aggregate formation that protects carbon from mineralization. Additionally, we observed a consistent decrease in organic carbon content with soil depth [84,110], a trend not easily reversed even by deep tillage. Although organic carbon differences among aggregate size classes were mostly non-significant in this study, prior research suggests that macroaggregates (>0.25 mm) respond more sensitively to organic inputs, with newly sequestered carbon primarily stored in these fractions [111,112]. In contrast, microaggregates (0.053–0.25 mm) show greater improvements in deeper layers under deep tillage [84], a phenomenon requiring further validation.

4.5. Deep Tillage Combined with Organic Fertilizer Enhances Nitrogen Retention

Regarding nitrogen distribution, the RTO treatment demonstrated significantly higher mechanically stable aggregate total nitrogen (MSATN) and water-stable aggregate total nitrogen (WSATN) within the 0–20 cm soil layer compared to RT, reaching levels comparable to RTC. This indicates that organic fertilizer application promotes nitrogen accumulation across all aggregate size fractions [19,113–115]. The advantage of RTO in enhancing aggregate-associated nitrogen persisted even in the 20–40 cm layer, potentially due to nitrogen leaching [116]. Notably, DT1O and DT2O exhibited more pronounced effects on total nitrogen accumulation in subsurface soils, suggesting that deep tillage strengthens nitrogen retention in deeper soil layers [83,102,117,118]. It is noteworthy that RTO, DT1O, and DT2O uniformly increased total nitrogen content in all aggregate size classes, which contrasts with findings by Xue [119] (reporting organic fertilization primarily enriched >2 mm WSATN) and Kong [84] (observing deep plowing favored <0.25 mm fractions). These differences underscore that the synergy between organic fertilizer and deep tillage uniquely enhances nitrogen retention across the entire soil profile and aggregate size spectrum, rather than selectively enriching specific fractions.

The synergistic improvements in soil physicochemical properties reported in this study were ultimately translated into significant agronomic benefits. The integrated organic fertilizer and deep tillage treatments significantly enhanced foxtail millet grain yield and improved grain quality parameters, such as protein and Ash content (Table S3). Correlation analysis further revealed that foxtail millet yield and quality parameters were significantly correlated with a range of key soil physicochemical indicators (Table S4). Furthermore, the PCA-Random Forest analysis identified that the yield and quality improvements were primarily driven by changes in soil physicochemical properties during the early growth stages and within the deeper soil layers (Table S5). Limitations and future perspectives: (1) Given foxtail millet's intolerance to continuous cropping, future studies should investigate the long-term effects of organic fertilizers and deep tillage on millet field soils by designing millet-legume/gramineous crop rotation systems. (2) The mechanistic understanding

remains insufficient regarding pH buffer system formation following organic fertilizer application and the contribution of root exudates to soil aggregate formation. Priority research directions should include the transformation processes between humic acids and humates, their coupling with microbial activities, and the dynamics of root metabolites during different millet growth stages. (3) Although conducted in representative dryland millet production areas, certain treatment effects may have been obscured by environmental variability such as precipitation. Multi-location, multi-year trials incorporating diverse agroecological conditions are needed to enhance the generalizability of findings. Additionally, the use of continuous soil sensor networks to monitor moisture and temperature could provide higher-resolution data to better elucidate the environmental drivers of the observed treatment effects. (4) Future research should also focus on the spatiotemporal dynamics of key biological drivers, such as microbial community composition, enzyme activity and root exudation profiles, to mechanistically explain the observed synergistic improvements in soil structure and carbon sequestration.

Based on our findings, we recommend that farmers in dryland millet regions adopt deep tillage (30–40 cm) combined with organic fertilizer (30,000 kg/ha sheep manure) to improve subsoil structure, enhance water and nutrient retention, and sustain long-term productivity. Policymakers may consider subsidizing organic inputs and promoting customized deep tillage equipment to support the adoption of these practices.

5. Conclusions

This study demonstrates that management practices integrating organic fertilizer and deep tillage significantly improved soil quality in dryland foxtail millet production systems. The application of organic fertilizer under rotary tillage effectively enhanced the soil's pH buffering capacity within the 0–20 cm layer, increased aggregate-associated organic carbon and total nitrogen content, and improved soil physical structure by reducing bulk density while increasing total porosity and air-filled porosity during critical mid-to-late growth stages. The synergistic combination of organic fertilizer with deep tillage further extended these benefits to deeper soil layers (20–40 cm), with more pronounced improvements observed at greater tillage depths. This integrated approach significantly optimized the soil three-phase composition, enhanced the formation and stability of macro-aggregates, and promoted the distribution and retention of organic carbon and total nitrogen throughout the soil profile. These improvements in soil physicochemical properties and aggregate-associated nutrient distribution create a more favorable root environment for foxtail millet growth in dryland conditions.

Our findings provide scientific evidence that the strategic integration of organic fertilizers with appropriate tillage depth represents a sustainable soil management strategy for dryland foxtail millet production. This approach effectively addresses the challenges of soil nutrient depletion and structural degradation while supporting the high-yield potential of modern hybrid millet varieties.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture15232419/s1>, Figure S1: The soil bulk density (A: 2020; B: 2021) and total porosity (C: 2020; D: 2021) across sampling times and depths; Figure S2: The mean weight diameter (MWD; A: 2020; B: 2021) and geometric mean diameter (GMD; C: 2020; D: 2021) of the soil mechanically stable aggregates (MSA) across sampling times and depths; Figure S3: The mean weight diameter (MWD; A: 2020; B: 2021) and geometric mean diameter (GMD; C: 2020; D: 2021) of the soil water-stable aggregate (WSA) across sampling times and depths; Table S1: Initial chemical properties and the analytical methods for the topsoil (0–20 cm) before the experiment; Table S2: Moisture, organic carbon and NPK content of the sheep manure organic fertilizer in 2020 and 2021; Table S3: Yield and grain quality of foxtail millet under different treat-

ments; Table S4: Correlations between Foxtail Millet Grain Yield and Quality Attributes with Soil Physicochemical Properties; Table S5: Key Soil Drivers of Integrated Crop Performance Identified by PCA-Random Forest Analysis.

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Abbreviations

The following abbreviations are used in this manuscript:

RT	Rotary tillage without fertilization
RTC	Rotary tillage with compound fertilizer
RTO	Rotary tillage with organic fertilizer
DT1O	Deep tillage with organic fertilizer at 20–30 cm
DT2O	Deep tillage with organic fertilizer at 30–40 cm
pHBC	pH buffering capacity
Mv	Volumetric water content
A	Air-filled porosity
Sv	Solid volume fraction
BD	Bulk density
P	Total porosity
MSA	Mechanically stable aggregates
WSA	Water-stable aggregate
MWD	Mean weight diameter
GMD	Geometric mean diameter
MSAOC	Mechanically stable aggregate organic carbon
WSAOC	Water-stable aggregate organic carbon
MSATN	Mechanically stable aggregate total nitrogen
WSATN	Water-stable aggregate total nitrogen

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