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Responses of Soil Profile Hydrology, Structure and Microbial Respiration to Organic Amendments Under Different Tillage Systems on the Loess Plateau

Lili Zhao [1], Lusheng Li [1,*], Xiangjie Chen [1], Yanbin Li [1], Jiankun Ge [1] and Xiaowen Wang [2,3]

[1] School of Water Conservancy, North China University of Water Resources and Electric Power, Zhengzhou 450046, China; zhaolili@ncwu.edu.cn (L.Z.); x20231010033@stu.ncwu.edu.cn (X.C.); liyb101@163.com (Y.L.); gejiankun@ncwu.edu.cn (J.G.)
[2] High-Tech Key Laboratory of Agricultural Equipment and Intelligence of Jiangsu Province, Jiangsu University, Zhenjiang 212013, China; wangxiaowen@ujs.edu.cn
[3] School of Agricultural Engineering, Jiangsu University, Zhenjiang 212013, China
* Correspondence: lilusheng@ncwu.edu.cn

Abstract: The combined effects of tillage and organic amendments on microbial respiration and its contribution to soil hydraulic conductivity are still uncertain in the 0–40 cm layer of a loess soil. We conducted a two-year field experiment to explore the effects of organic amendments, tillage and their interaction on soil microbial respiration, aggregate stability, pore parameters, and hydraulic conductivity on the Loess Plateau. Three tillage methods (conventional tillage (CT), deep tillage (DT) and no tillage (NT)) plus five fertilizer treatments (mineral fertilizer (control) alone and along with 20 t ha^{-1} wheat straw (MWS), wheat husk (MWH), farmyard soil (MFS) and bioorganic fertilizer (MBF)) were set up as experimental treatments. The findings demonstrated that the organic amendments significantly increased the soil microbial respiration and saturated hydraulic conductivity compared to the control in the 0–10 cm and 10–20 cm layers. Soil microbial respiration had indirect effects on hydraulic conductivity by improving the water aggregate stability and macroporosity. Additionally, the interaction effects of tillage and organic amendments on the pore and hydrological parameters were significant in the 20–40 cm layer. NT-MBF resulted in the greatest saturated hydraulic conductivity, which was directly correlated with the soil's strong pore organization. Given the issue of subsurface soil compaction in our study area, it is recommended that local farmers adopt NT-MBF to enhance the soil's microbial, structural and hydrological properties.

Keywords: hydraulic conductivity; microbial respiration; aggregate stability; pore connectivity; sustainable practices

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1. Introduction

Hydraulic conductivity has a substantial influence on soil quality, along with the ecosystem services that the soil provides [1,2]. Soil hydraulic conductivity controls soil water infiltration, redistribution, drainage and evaporation and determines the roots' water absorption and crop growth [3]. A soil's hydraulic conductivity is primarily determined by its structure, which may govern a variety of physical, chemical and biological activities; in turn, it is also shaped by these activities [4,5]. The soil structure is regarded as a crucial indicator in assessing the functionality of soil [6,7], and it is usually described in terms of aggregates or pore spaces [8]. From an aggregate perspective, the soil structure is characterized by the dry and wet sieving of soil aggregates to assess their size, shape, grade and stability [9]. Dry sieving indicates the soil aggregates' resilience against mechanical disruption, whereas wet sieving demonstrates the soil aggregates' resistance to dispersion [3]. The soil quality is generally improved by increasing the fraction of large aggregates (>0.25 mm) [10]. Soil aggregate stability denotes the capacity of aggregates to withstand disintegration caused by factors such as tillage, water-borne abrasion and wind erosion [11]. Soil aggregate stability can indicate the soil organic carbon content, biological activity and the transfer processes of water and air [12]. Diminished aggregate stability and reduced hydraulic conductivity may cause intense soil erosion and additional land degradation processes [6]. The pore space indicates the hierarchical organization of soil pore systems [6,8], which are physically delineated by the pore size, shape and spatial distribution, thereby facilitating the derivation of the pore connectivity [5]. A soil's hydraulic conductivity is strongly influenced by its macroporosity, as well as the continuity and connectivity within the pore network [13]. Various factors have the potential to influence the soil structure and hydraulic conductivity, including tillage [14,15], machinery-induced compaction [16,17] and organic amendments [18]. Therefore, assessing these properties under different conditions is crucial in understanding the essential functions of soil.

Sustainable intensification strategies for soil improvement emphasize minimal mechanical soil disturbance and the application of organic amendments, which are pivotal in optimizing the soil structure and enhancing the hydraulic conductivity [1,19]. However, studies citing the impacts of tillage on hydraulic conductivity remain difficult to comprehend due to inconsistent reports. Some researchers have reported that tillage has a positive effect in elevating the soil hydraulic conductivity [20], whereas other researchers have reported a decrease in soil hydraulic conductivity [21,22]. The soil structure affects the hydrological properties of soils [14]. Therefore, tillage, by reshaping the soil aggregate and pore structure, concurrently changes the soil hydraulic conductivity [19]. Conservation tillage increases the hydraulic conductivity via higher aggregation stability and lower soil bulk density by increasing the soil organic carbon content [2,4]. For example, no-tillage systems improve the distribution and connectivity of soil pores, along with enhancing the hydraulic conductivity, because the soil structure is altered [23]. However, the hydraulic conductivity is ultimately reduced with intensive tillage [24]. The repeated passage of heavy machinery can disrupt root systems and biological processes, destroying the macropore network and decreasing the hydraulic conductivity [17,21]. The multifaceted influence of tillage systems on soil hydraulic conductivity requires further study.

Organic amendments significantly contribute to the regulation of soil's hydraulic properties by modifying the soil structure [3,25]. Various organic materials, including compost, crop residues and manure, can enhance the soil quality [26,27]. Compost and crop residues are particularly popular for soil amendment due to their ready availability and accessibility [28,29]. Compost- and crop residue-amended soil had more water-stable aggregates and greater macroporosity, leading to higher hydraulic conductivity than that of non-amended soil, with a greater increase at higher application rates [25]. Notably, soil aggregates can physically protect organic carbon from microbial decomposition, thereby reducing microbial respiration, with a pronounced effect in the upper soil layers [30]. Conversely, organic amendments increase the soil organic carbon and macropores, providing adequate nutrients, oxygen and space for soil microorganisms, thus promoting soil microbial respiration [31]. Most studies have concentrated on soil organic carbon, microbial respiration, aggregate sizes and stability, pore parameters and hydraulic conductivity, yet the variations in these properties differ significantly across various tillage practices. Importantly, the potential interactions among these parameters have not been fully considered.

Soil degradation is one of the primary constraints restricting agricultural development in the loess soils of the Loess Plateau, China [32]. This stress impact is exacerbated by unsustainable soil management practices [33]. Intensive conventional tillage (rotary tillage without straw retention) destroys the soil structure's stability, hinders biological activity and lowers the hydraulic conductivity [34]. Furthermore, heavy agricultural machinery has caused subsurface compaction. Compaction adversely impacts soil by diminishing the pore volume, reducing the pore connectivity and causing anisotropic alterations in water and air movement [17]. Currently, scientists are exploring ways to improve the soil structure and hydrology. The individual impacts of tillage or organic amendments on soil hydraulic conductivity have been studied extensively at the Loess Plateau [17,35,36]. Nevertheless, few studies have been conducted to clarify the integrated impacts of tillage and organic amendments on the soil hydraulic conductivity and its correlation with microbial respiration, especially across the soil profile. Therefore, assessing the influence of tillage strategies combined with organic amendments on the soil profile's microbial respiration and its relationship with hydraulic conductivity may help managers to make better judgments. In this context, the purposes of this research were (1) to investigate the impacts of tillage and organic amendments on the microbial respiration, structure and hydraulic conductivity of the soil profile in the loess soil of the Southern Loess Plateau and (2) to explore the direct and indirect effects of microbial respiration, the aggregate stability and the pore properties (i.e., macroporosity and pore organization) on the hydraulic conductivity in response to various tillage practices and the addition of organic amendments in field conditions, specifically at the soil depths of 0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm.

2. Materials and Methods

2.1. Experimental Site

Summer maize and winter wheat rotation field experiments were conducted from 2014 to 2016 in Yangling (34°17′ N, 108°04′ E, altitude 506 m), Shaanxi Province, China. This region is a typical dryland agricultural area at the southern edge of the Loess Plateau, with a semi-arid to sub-humid climate. The average annual air temperature and precipitation are 13 °C and 632 mm, respectively. Precipitation throughout the year is mainly concentrated between July and September. The daily rainfall amounts and air temperatures during the experimental period are shown in Figure 1. These data were sourced from the Yangling National Weather Station, situated approximately 50 m west of the experimental site. The soil at the site is loess-derived silty clay loam (eum-orthic anthrosols). Table 1 shows the basic soil physicochemical parameters evaluated before the experiment. The maize cultivar Zhengdan 958 (June–October) and the wheat cultivar Xiaoyan 22 (October–June) were planted in the experimental field.

Table 1. Basic physicochemical properties of the tested soil at 0–40 cm.

Parameter	Depth (cm)			
	0–10	10–20	20–30	30–40
Texture (international system)	Clay loam	Clay loam	Silty clay loam	Silty clay loam
Sand (0.02–2 mm) (%)	38.24	36.65	30.51	30.47
Silt (0.002–0.02 mm) (%)	43.80	44.22	46.71	48.69
Clay (<0.002 mm) (%)	17.96	19.12	22.78	24.90
Bulk density (g·cm^{-3})	1.32	1.44	1.68	1.70
Total porosity (%)	50.29	46.03	36.99	35.96
Field capacity (cm^3·cm^{-3})	0.322	0.328	0.308	0.314
Organic carbon (g kg^{-1})	8.75	8.04	7.28	6.42
Electric conductivity (1:5) (dS m^{-1})	0.36	0.25	0.27	0.22
Soil pH (1:5)	8.56	8.57	8.55	8.58

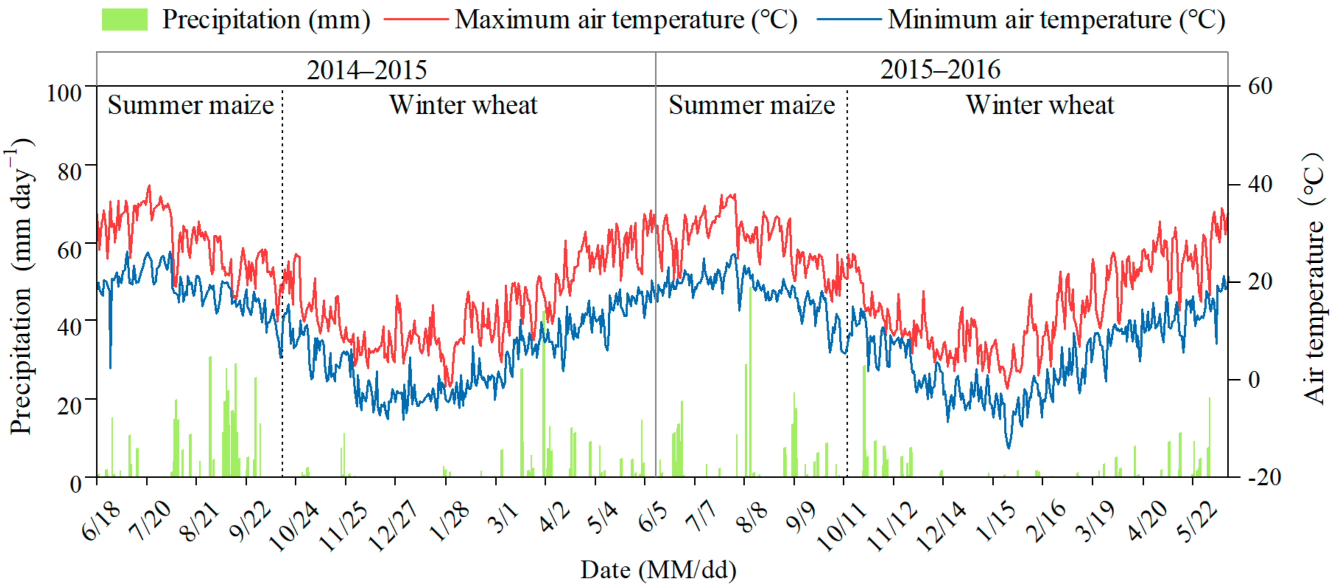

Figure 1. Daily precipitation and air temperatures during the 2014–2015 and 2015–2016 summer maize–winter wheat rotation. The dashed line is used to distinguish the summer maize season from the winter wheat season.

2.2. Experimental Design

The field experiment included tillage treatments and organic amendments. Tillage treatment was considered as the main effect, with organic amendments as a split-plot effect, in a complete randomized experimental design (Table 2). Each sub-plot was 7.5 m × 4 m = 30 m^2 and the trial area was 0.27 ha. The experiment used three tillage methods, namely conventional tillage (CT), deep tillage (DT) and no tillage (NT). Each tillage method included five fertilizer treatments: a control with only mineral fertilizer, as well as mineral fertilizer combined with wheat straw (MWS), wheat husk (MWH), farmyard soil (MFS) and bioorganic fertilizer (MBF). In total, fifteen treatments with three replications were established. The experiment was carried out in a fixed field configuration at the same site.

Table 2. Field experimental layout.

	NT			CT			DT	
Control	MWS	MFS	MBF	MWH	Control	MBF	MWS	MFS
MWS	MWH	MBF	MFS	Control	MWH	MWS	MBF	Control
MWH	MFS	Control	MWS	MBF	MFS	MWH	MFS	MBF
MBF	Control	MWS	MWH	MFS	MWS	MFS	Control	MWH
MFS	MBF	MWH	Control	MWS	MBF	Control	MWH	MWS

Note: CT, conventional tillage; DT, deep tillage; NT, no tillage. Control, mineral fertilizer; MWS, mineral fertilizer with wheat straw; MWH, mineral fertilizer with wheat husk; MFS, mineral fertilizer with farmyard soil; MBF, mineral fertilizer with bioorganic fertilizer.

CT involved ploughing and harrowing the soil twice to a 15 cm depth for the preparation of the seed bed. DT involved ploughing with a moldboard plow to a depth of 30 cm and disking to a depth of 10 cm to prepare the seed bed. NT involved manually seeding into undisturbed soil. Regarding the organic amendment treatments, the management details are reported in Table 3. The wheat straw was chopped into segments of 2 cm. The wheat husk was milled down to 2 mm. The farmyard soil was prepared using a standard ratio of 80% decomposed sheep manure to 20% soil by weight, adhering to the local conventional production methods. The bioorganic fertilizer was crafted by blending farmyard soil with a microbial agent, which was supplied by the Sino Green Agri-Biotech Company in Beijing, China, at a rate of 60 kg ha^{-1} with 2 × 10^{8} cfu g^{-1} of live bacteria. Table 4 lists the nutrients and dry bulk densities of the organic materials. The mineral fertilizer was urea (46% N) and diammonium phosphate (18% N, 46% P_2O_5) in all fertilizer treatments. The mineral fertilizer was applied at a ratio of 6:4 for basal to supplemental fertilization during every summer maize season and at a ratio of 10:0 during each winter wheat season, following the local farmers' practices. All organic materials were applied as the basal dressing before planting in each growing season for both maize and wheat crops. The irrigation schedule complied with regional agricultural customs.

Table 3. Organic amendment treatments in the 2014–2015 and 2015–2016 summer maize–winter wheat seasons.

Crop	Management				Control	MWS	MWH	MFS	MBF
Maize	Mineral fertilizer	Basal fertilizer	Date (Y/M/D)	2014			2014/06/18		
				2015			2015/06/15		
			N rate (kg ha^{-1})		102	102	102	102	102
			P_2O_5 rate (kg ha^{-1})		102	102	102	102	102
		Supplemental fertilizer	Date (Y/M/D)	2014			2014/08/08		
				2015			2015/08/05		
			N rate (kg ha^{-1})		68	68	68	68	68
			P_2O_5 rate (kg ha^{-1})		68	68	68	68	68
		Total fertilizer	N rate (kg ha^{-1})		170	170	170	170	170
			P_2O_5 rate (kg ha^{-1})		170	170	170	170	170
	Organic materials		Date (Y/M/D)	2014			2014/06/18		
				2015			2015/06/15		
			Type			Wheat straw	Wheat husk	Farmyard soil	Bioorganic fertilizer
			Rate (t ha^{-1})		0	20	20	20	20
	Irrigation		Date (Y/M/D)	2014			2014/07/30		
				2015			2015/07/27		
			Method				Flood irrigation		
			Amount (mm)				75		
	Precipitation (mm)		2014				381.3		
			2015				278.2		
Wheat	Mineral fertilizer		Date (Y/M/D)	2014–2015			2014/10/20 2015/10/20		
				2015–2016			2015/10/20		
			N rate (kg ha^{-1})		150	150	150	150	150
			P_2O_5 rate (kg ha^{-1})		110	110	110	110	110
	Organic materials		Date (Y/M/D)	2014–2015			2014/10/20 2015/10/20		
				2015–2016			2015/10/20		
			Type			Wheat straw	Wheat husk	Farmyard soil	Bioorganic fertilizer
			Rate (t ha^{-1})		0	20	20	20	20
	Irrigation		Date (Y/M/D)	2014–2015			2015/01/08 2015/10/20		
				2015–2016			2016/01/10		
			Method				Flood irrigation		
			Amount (mm)				75		
	Precipitation (mm)		2014–2015				239.4		
			2015–2016				218.5		

Note: Control, mineral fertilizer; MWS, mineral fertilizer with wheat straw; MWH, mineral fertilizer with wheat husk; MFS, mineral fertilizer with farmyard soil; MBF, mineral fertilizer with bioorganic fertilizer.

Table 4. Physicochemical characteristics of the applied organic materials.

Material	Cellulose (%)	Organic Carbon (g kg^{-1})	Total N (g kg^{-1})	C/N Ratio	Total P (g kg^{-1})	Total K (g kg^{-1})	Dry Bulk Density (g·cm^{-3})
Wheat straw	36.32	432.44	10.84	39.95	1.65	9.71	0.074
Wheat husk	24.89	396.99	20.44	19.43	5.41	6.20	0.137
Farmyard soil	18.25	190.30	11.63	16.46	3.02	6.49	0.474
Bioorganic fertilizer	17.96	184.19	12.98	14.21	3.19	6.27	0.325

2.3. Sampling and Measurements

Soil samples were collected from the top 40 cm depth at 10 cm intervals by mixing four subsamples from each plot in June 2016 before the winter wheat harvest. The air-dried samples were crushed to pass through a 0.15 mm sieve for the measurement of soil organic carbon (SOC) using the dichromate oxidation method [3]. Soil microbial respiration (MR) was quantified on fresh soil samples using the incubation–alkaline absorption method over seven days at 75% of the water holding capacity and 25 °C [25]. The CO_2 evolved was trapped in 0.1 M NaOH, followed by titration with a standard HCl solution [37]. To evaluate the decomposability of the organic amendments across various tillage systems, the mineralization quotient (qmC) was calculated from the measurements of the SOC and the cumulative value (168 h) of CO_2 evolution, using the following formula: qmC = mg CO_2–C/mg SOC [25,37]. The qmC represented the fraction of SOC mineralized throughout the entire incubation period (168 h).

Some soil samples were utilized to test the aggregate stability with the dry and wet sieving methods. Fresh soil samples were carefully treated to eliminate dead organisms, undecomposed materials and roots. Then, these soil samples were gently broken into around 10 mm pieces manually and air-dried. Air-dried soil (200 g) was passed through a series of five sieves using a horizontal shaker (JH-200, Xinxiang, China), which caused the sieves to oscillate horizontally. The sieve sizes were 5, 2, 1, 0.5 and 0.25 mm, respectively. The distribution of dry aggregate sizes was determined by weighing the soil aggregates remaining on each sieve and those that were collected below the 0.25 mm sieve [38]. The analysis of water-stable aggregates was conducted using 50 g air-dried samples, which were prepared by separating dry aggregates of various sizes according to their percentage distribution in the sieves. These soil samples were placed on a series of sieves with mesh sizes of 5, 2, 1, 0.5 and 0.25 mm, which were fitted to a soil aggregate analyzer (QD24-DIK-2001, Kounosu, Japan). After this, the stacked sieves along with the samples were soaked in water and subjected to shaking for 15 min at an oscillation frequency of 30 cycles/min with an amplitude of 35 mm [38]. Finally, the aggregate size distribution was obtained by drying and weighing the soils remaining on each sieve.

The percentage of aggregate destruction (PAD, %) was calculated as follows:

$$\text{PAD} = \frac{w_d - w_w}{w_w} \times 100\% \quad (1)$$

where W_d is the weight ratio of dry-sieved soil > 0.25 mm and W_w is the weight ratio of wet-sieved soil > 0.25 mm.

The mean weight diameter (MWD) was estimated using the formula [39]

$$\text{MWD} = \frac{\sum_{i=1}^{n} \overline{X}_i W_i}{\sum_{i=1}^{n} W_i} \quad (2)$$

where $\overline{X_i}$ is the mean diameter of the sieve, mm; W_i is the proportion of aggregates retained on the i^{th} sieve, %; and n is the number of sieves.

The aggregate size distribution was modeled using a power-exponential distribution [3,40]:

$$M(< d) = \lambda d^{\gamma} \left(1 - e^{-(d/d_r)}\right) \tag{3}$$

where $M(<d)$ is the cumulative frequency of aggregates sized less than d, %; d is the sieve size, mm; and λ, γ and d_r are fitting parameters.

Minimally disturbed soil cores (100 cm^3) were sampled from 0 to 40 cm at 10 cm increments to assess the soil pore and hydrology characteristics. The soil cores were saturated with water to determine their saturated hydraulic conductivity, employing the constant head method for the measurement. The hanging water column method was then used to drain the soil cores at a soil matric potential of −10 kPa. Each sample was weighed and then oven-dried at 105 °C for 24 h. The volumetric water content at −10 kPa was calculated based on the weight loss of the soil cores during oven drying. The macroporosity was deduced by calculating the difference between the volumetric water content at −10 kPa and the total porosity. Soil total porosity was evaluated according to the soil bulk density and soil particle density. Air permeability was measured on the same cores as above at −10 kPa using the one-dimensional steady-state method [41].

Pore organization (PO) was used to obtain more insights into the soil pore characteristics [42]:

$$\text{PO} = k_a / \varepsilon_a \tag{4}$$

where k_a is the air permeability at −10 kPa, μm^2, and ε_a is the macroporosity at −10 kPa. A high PO indicates high continuity [14].

2.4. Statistical Analysis

The main effects and interactions of the tillage and organic amendments on the soil microbial respiration and structural and hydrological properties were analyzed by two-way analysis of variance (ANOVA). The means were compared by Duncan's multiple range test ($p < 0.05$). To link soil microbial respiration, aggregates and pores with hydrology, we selected a set of 23 predictor variables to perform Pearson's correlation analysis. The variables encompassed soil microbial parameters (SOC, MR and mqC), the soil aggregate size distribution (>5 mm, 2–5 mm, 1–2 mm, 0.5–1 mm, 0.25–0.5 mm and >0.25 mm) determined by both dry and wet sieving, aggregate stability indicators (PAD, MWD determined by dry and wet sieving), pore characteristics (total porosity, macroporosity, air permeability and PO) and the soil saturated hydraulic conductivity. Structural equation modeling (SEM) was conducted to elucidate how the soil MR affects the soil hydraulic conductivity through the soil aggregate and pore properties, using AMOS 26.0 (Chicago, IL, USA). The CHI/DF < 3, chi-squared test (p) > 0.05, a root mean square error of approximation (RMSEA) < 0.08 and a comparative fit index (CFI) > 0.9 were adopted to fit the SEM [43]. Statistical analysis was performed with SPSS 20.0 (IBM-SPSS, Inc., Chicago, IL, USA). Drawing, non-linear fitting, heat plot correlation and principal component analysis (PCA) were performed using Origin 2021 (OriginLab, Northampton, MA, USA). The PCA was performed to thoroughly assess the differences among the combined treatments regarding the soil hydraulic conductivity and corresponding soil parameters.

3. Results

3.1. Soil Organic Carbon

The tillage methods exerted a significant ($p < 0.05$) influence on the SOC, but only within the upper 10 cm soil depth (Table 5). Compared with DT, CT and NT resulted in higher SOC values ($p < 0.05$). However, in comparison with DT, both CT and NT presented slightly lower SOC values at 10–40 cm, although these changes were not obvious ($p > 0.05$). Regardless of the tillage method, the mean SOC content was significantly ($p < 0.05$) greater under the organic amendments compared to the control at 0–40 cm. The significant differences were mainly found at the 0–20 cm depth. At these depths, MWS performed better than MWH, MFS and MBF, although its advantages were generally not obvious ($p > 0.05$).

Table 5. Responses of soil organic carbon to tillage and organic amendments at 0–40 cm.

Treatment		SOC (g kg^{-1})				
		0–10 cm	10–20 cm	20–30 cm	30–40 cm	0–40 cm
Tillage						
	CT	10.88 ± 1.31 a	9.27 ± 0.85	7.64 ± 0.55	6.75 ± 0.56	8.63 ± 0.51
	DT	9.92 ± 1.04 b	9.33 ± 0.94	7.77 ± 0.70	6.83 ± 0.62	8.47 ± 0.47
	NT	11.50 ± 1.51 a	8.92 ± 0.77	7.59 ± 0.66	6.60 ± 0.45	8.65 ± 0.54
Organic amendments						
	Control	8.88 ± 0.73 b	8.31 ± 0.64 b	7.45 ± 0.57	6.55 ± 0.44	7.80 ± 0.09 c
	MWS	11.89 ± 1.18 a	9.83 ± 0.67 a	7.77 ± 0.49	6.83 ± 0.70	9.08 ± 0.20 a
	MWH	11.40 ± 1.05 a	9.54 ± 0.68 a	7.86 ± 0.78	6.78 ± 0.65	8.90 ± 0.30 a
	MFS	10.88 ± 1.05 a	9.06 ± 0.73 a	7.71 ± 0.47	6.76 ± 0.61	8.60 ± 0.27 b
	MBF	10.77 ± 1.10 a	8.96 ± 0.78 a	7.55 ± 0.81	6.71 ± 0.32	8.50 ± 0.33 b
Two-way ANOVA (p values)						
	T	0.000 **	0.298 (ns)	0.771 (ns)	0.598 (ns)	0.117 (ns)
	O	0.000 **	0.003 **	0.760 (ns)	0.903 (ns)	0.000 **
	T × O	0.550 (ns)	0.990 (ns)	0.999 (ns)	1.000 (ns)	0.991 (ns)

Different letters indicate significant differences at $p < 0.05$. T, tillage method; O, organic amendment. **, significant at $p < 0.01$; ns, non-significant. CT, conventional tillage; DT, deep tillage; NT, no tillage. Control, mineral fertilizer; MWS, mineral fertilizer with wheat straw; MWH, mineral fertilizer with wheat husk; MFS, mineral fertilizer with farmyard soil; MBF, mineral fertilizer with bioorganic fertilizer. SOC, soil organic carbon.

3.2. Microbial Respiration

Regarding soil MR, significant variations were observed with the tillage methods and organic amendments, but their interaction had no significant impact on the soil MR (Figure 2, Table 6). Comparisons among the tillage methods suggested that DT and NT experienced significantly ($p < 0.05$) greater mean values of soil MR than CT in 0–40 cm. Similar changes were found at 0–10 cm, 20–30 cm and 30–40 cm. Significantly ($p < 0.05$) greater MR was observed only in DT rather than CT at 10–20 cm. Under all tillage systems, the organic amendment treatments produced significantly ($p < 0.05$) greater mean values of soil MR compared to the control at 0–40 cm. With MBF, we observed the greatest increase in CO_2 emissions ($p < 0.05$).

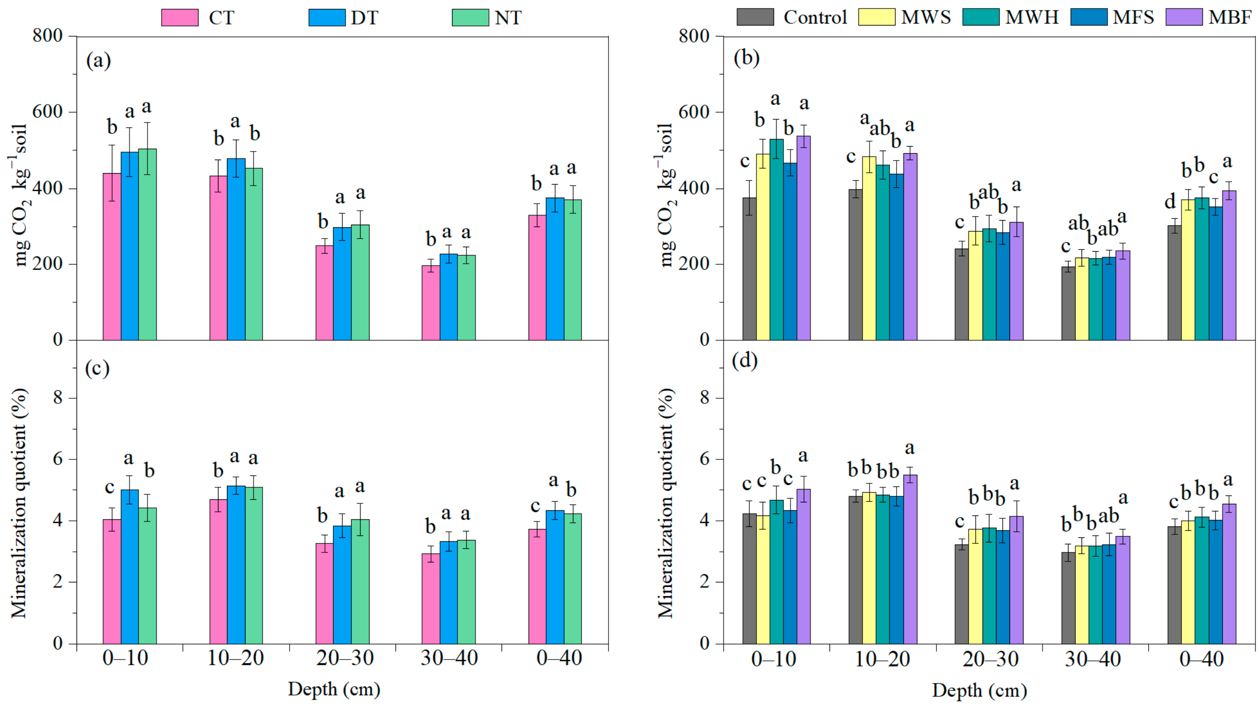

Figure 2. Responses of soil microbial respiration (**a**,**b**) and mineralization quotient of organic carbon (**c**,**d**) to tillage and organic amendments at 0–40 cm. Different letters indicate significant differences at $p < 0.05$. CT, conventional tillage; DT, deep tillage; NT, no tillage. Control, mineral fertilizer; MWS, mineral fertilizer with wheat straw; MWH, mineral fertilizer with wheat husk; MFS, mineral fertilizer with farmyard soil; MBF, mineral fertilizer with bioorganic fertilizer.

Table 6. Results of two-way ANOVA for soil microbial and structural properties at 0–40 cm.

p Value		MR (mg CO_2 kg^{-1} Soil)	*q*mC (%)	MWD (mm)		Total Porosity (%)	Macroporosity (%)	k_a (μm^2)	PO (μm^2)
				Dry Sieve	Wet Sieve				
0–10 cm	T	0.000 **	0.000 **	0.000 **	0.000 **	0.023 *	0.002 **	0.009 **	0.031 *
	O	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **
	T × O	0.996 (ns)	0.456 (ns)	0.000 **	0.713 (ns)	0.857 (ns)	0.118 (ns)	0.423 (ns)	0.184 (ns)
10–20 cm	T	0.002 **	0.000 **	0.000 **	0.001 **	0.000 **	0.002 **	0.271 (ns)	0.005 **
	O	0.000 **	0.000 **	0.000 **	0.000 **	0.001 **	0.000 **	0.000 **	0.000 **
	T × O	0.731 (ns)	0.923 (ns)	0.030 *	0.067 (ns)	0.641 (ns)	0.075 (ns)	0.870 (ns)	0.010 *
20–30 cm	T	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **
	O	0.000 **	0.000 **	0.000 **	0.000 **	0.248 (ns)	0.000 **	0.000 **	0.000 **
	T × O	0.350 (ns)	0.240 (ns)	0.118 (ns)	0.384 (ns)	0.186 (ns)	0.005 **	0.048 *	0.004 **
30–40 cm	T	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **
	O	0.001 **	0.007 **	0.000 **	0.000 **	0.054 (ns)	0.000 **	0.000 **	0.000 **
	T × O	0.893 (ns)	0.983 (ns)	0.045 *	0.056 (ns)	0.186 (ns)	0.009 **	0.000 **	0.000 **
0–40 cm	T	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **	0.001 **
	O	0.000 **	0.000 **	0.000 **	0.000 **	0.045 *	0.000 **	0.000 **	0.000 **
	T × O	0.837 (ns)	0.672 (ns)	0.096 (ns)	0.597 (ns)	0.488 (ns)	0.016 *	0.309 (ns)	0.017 *

MR, microbial respiration; *q*mC, mineralization quotient; MWD, mean weight diameter; k_a, air permeability; PO, pore organization. T, tillage method; O, organic amendment. *, significant at $p < 0.05$; **, significant at $p < 0.01$; ns, non-significant.

The *q*mC was also significantly ($p < 0.05$) impacted by the tillage methods and organic amendments (Figure 2, Table 6). Relative to CT, DT and NT significantly ($p < 0.05$) increased the *q*mC across all investigated depths. At these depths, MBF had the highest *q*mC among all organic treatments, which was significant ($p < 0.05$), regardless of the tillage method.

3.3. Aggregate Size Distribution and Stability

Figure 3 and Table S1 show the soil aggregate size distributions acquired through the dry and wet sieving analysis. The comparison of the macroaggregates (>0.25 mm) from dry and wet sieving showed that the PAD values were 34.84%, 48.96%, 53.59% and 56.09% at 0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm under CT, respectively (Table 7). CT had the lowest soil PAD at 0–10 cm among the three tillage systems. However, compared to CT, DT and NT significantly ($p < 0.05$) decreased the soil PAD in deeper soil layers. The soil PAD in DT was 1.62%, 2.62% and 2.92% lower than in CT, whereas that in NT was 6.05%, 8.29% and 5.28% lower than in CT at the 10–20 cm, 20–30 cm and 30–40 cm layers, respectively. The organic amendments generally reduced the soil PAD in all layers, with PAD values of 32.19–55.22% in amended soils versus 39.01–55.28% in non-amended soils. On average, the organic amendments significantly ($p < 0.05$) decreased the soil PAD compared to the control at 0–40 cm, where the MWS treatment had the lowest soil PAD values. The lowest values for the MWS treatment mostly occurred at 0–10 cm. The tillage and organic amendment interactions also revealed that CT-MWS attained the lowest soil PAD (29.15%) at 0–10 cm (Table S2, $p < 0.05$). Conversely, the PAD values for NT-MBF were the lowest at 10–20 cm (41.07%, $p < 0.05$), 20–30 cm (41.60%, $p > 0.05$) and 30–40 cm (46.77%, $p > 0.05$).

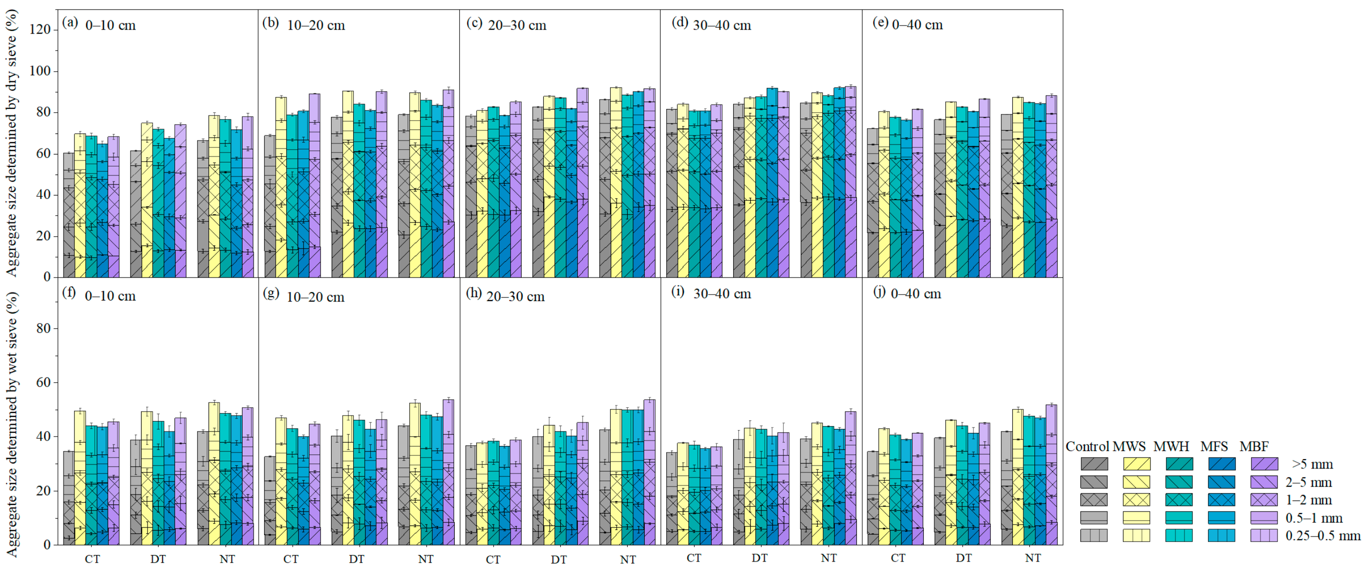

Figure 3. Responses of macroaggregate size distribution, determined by dry (**a**–**e**) and wet (**f**–**j**) sieving analysis, to tillage and organic amendments at 0–40 cm. CT, conventional tillage; DT, deep tillage; NT, no tillage. Control, mineral fertilizer; MWS, mineral fertilizer with wheat straw; MWH, mineral fertilizer with wheat husk; MFS, mineral fertilizer with farmyard soil; MBF, mineral fertilizer with bioorganic fertilizer.

The mean weight diameter values determined from dry sieving (dry MWD, 1.72–4.04 mm) were larger than those acquired from the wet sieving analysis (wet MWD, 0.70–1.38 mm) in all soil layers (Figure 4, Table 6, $p < 0.05$). In both the dry and wet sieving analysis, the MWD was significantly affected by the tillage method. Compared with CT, DT and NT significantly increased the MWD by 7.61–30.50% and 6.62–34.60%, respectively. In the wet sieving analysis, NT also significantly increased the mean MWD value by 7.8% relative to that of DT at the 0–40 cm soil layer.

Table 7. Responses of the percentage of aggregate destruction to tillage and organic amendments at 0–40 cm.

Treatment		PAD (%)				
		0–10 cm	10–20 cm	20–30 cm	30–40 cm	0–40 cm
Tillage						
	CT	34.84 ± 4.93 b	48.96 ± 3.12 a	53.59 ± 2.66 a	56.09 ± 2.36 a	48.37 ± 2.19 a
	DT	36.63 ± 2.34 a	47.35 ± 2.35 b	50.97 ± 1.79 b	53.17 ± 3.02 b	47.03 ± 1.56 a
	NT	35.14 ± 2.11 b	42.91 ± 2.29 c	45.29 ± 3.58 c	50.81 ± 3.03 c	43.54 ± 2.10 b
Organic amendments						
	Control	39.01 ± 3.22 a	48.38 ± 3.92 a	51.79 ± 2.70	55.28 ± 2.93 a	48.62 ± 2.51 a
	MWS	32.19 ± 2.86 c	45.06 ± 3.11 b	49.60 ± 3.74	51.80 ± 3.07 b	44.66 ± 1.93 c
	MWH	36.45 ± 1.32 b	44.98 ± 2.29 b	49.76 ± 4.85	52.00 ± 2.50 b	45.80 ± 2.09 bc
	MFS	34.86 ± 2.86 b	47.01 ± 3.35 ab	49.74 ± 4.40	55.22 ± 2.50 a	46.71 ± 2.40 b
	MBF	35.18 ± 2.66 b	46.59 ± 4.68 ab	48.86 ± 6.19	52.49 ± 4.87 b	45.78 ± 3.71 bc
Two-way ANOVA (*p* values)						
	T	0.030 *	0.000 **	0.024 *	0.000 **	0.000 **
	O	0.000 **	0.009 **	0.204 (ns)	0.001 **	0.000 **
	T × O	0.000 **	0.046 *	0.474 (ns)	0.063 (ns)	0.019 *

Different letters indicate significant differences at $p < 0.05$. T, tillage method; O, organic amendment. **, significant at $p < 0.01$; *, significant at $p < 0.05$; ns, non-significant. CT, conventional tillage; DT, deep tillage; NT, no tillage. Control, mineral fertilizer; MWS, mineral fertilizer with wheat straw; MWH, mineral fertilizer with wheat husk; MFS, mineral fertilizer with farmyard soil; MBF, mineral fertilizer with bioorganic fertilizer. PAD, percentage of aggregate destruction.

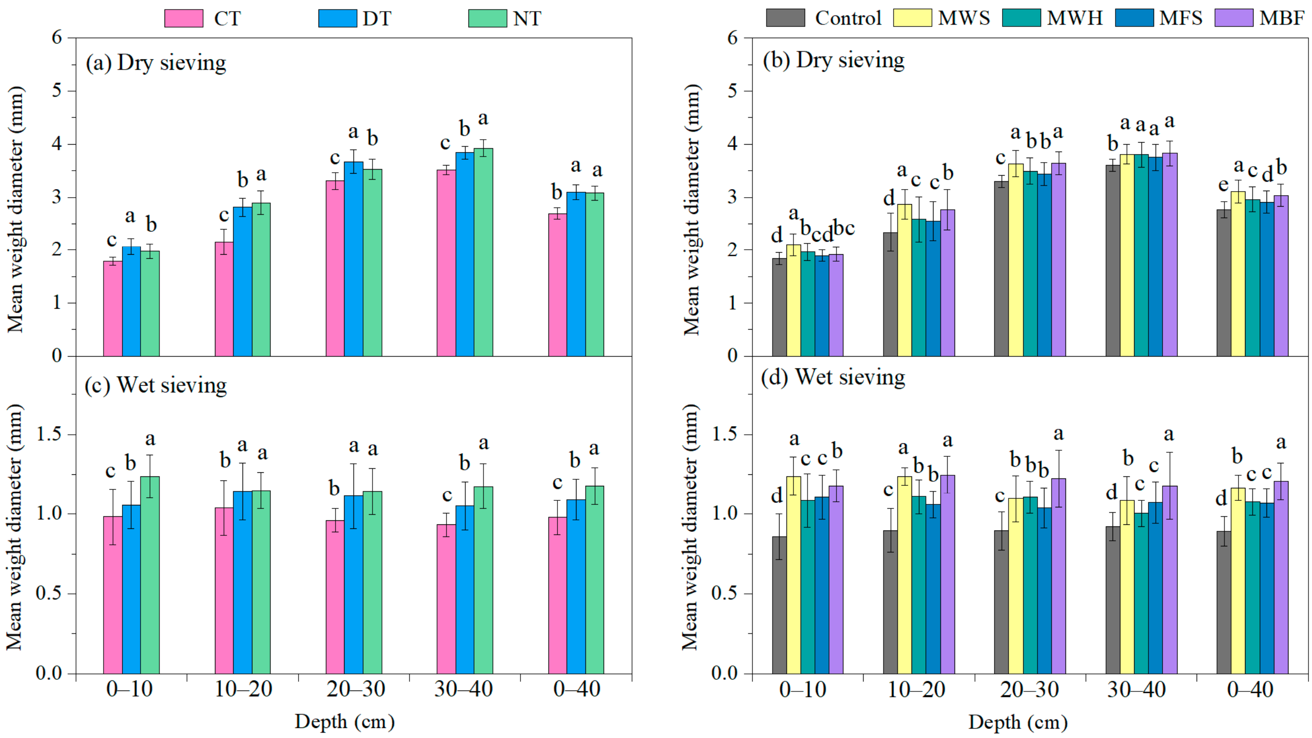

Figure 4. Responses of the mean weight diameters of aggregates, obtained by dry and wet sieving analysis, to tillage and organic amendments at 0–40 cm. Different letters indicate significant differences at $p < 0.05$. CT, conventional tillage; DT, deep tillage; NT, no tillage. Control, mineral fertilizer; MWS, mineral fertilizer with wheat straw; MWH, mineral fertilizer with wheat husk; MFS, mineral fertilizer with farmyard soil; MBF, mineral fertilizer with bioorganic fertilizer.

Regardless of the tillage method, the application of organic amendments significantly ($p < 0.05$) impacted the dry MWD and wet MWD. The dry MWD significantly ($p < 0.05$) increased after the addition of organic amendments (1.96–3.83 mm) in comparison with the control (1.83–3.60 mm), except for the MFS treatment at 0–10 cm (Figure 4b). The dry MWD in the MWS treatment was significantly ($p < 0.05$) greater than those in the MWH, MFS and MBF treatments at 0–20 cm. In addition, both the MWS and MBF treatments had higher MWD values than the other organic amendments at 20–30 cm ($p < 0.05$). Regarding the wet MWD, the control soil also had the lowest values (0.86–0.92 mm), whereas the amended soils had significantly ($p < 0.05$) higher values (1.00–1.25 mm) (Figure 4d). Higher wet MWD values were obtained in the MWS and MBF treatments than in the MWH and MFS treatments at 0–20 cm ($p < 0.05$). Notably, the MBF treatment alone exhibited the highest wet MWD values at 20–40 cm ($p < 0.05$).

Significant interactions between tillage and organic amendments were observed at depths of 0–10 cm, 10–20 cm and 30–40 cm in the dry sieving analysis (Table S3, $p < 0.05$). DT-MWS had the greatest dry MWD values at 0–10 cm. At 10–20 cm, NT-MBF achieved the highest dry MWD value. Meanwhile, the highest dry MWD in NT-MBF was obtained at 30–40 cm, which was significant. In the wet sieving analysis, the interactions between the tillage and organic amendments were not obvious ($p > 0.05$).

The power-exponential distribution model was used to match the aggregate size distributions for both dry and wet sieving (Figure 5). The statistical characteristics for the good fit data are shown in Table S4. The coefficient of determination (R^2) ranged from 0.92 to 1.00 (average of 0.97), while the root mean square error (RMSE) varied between 0.008 and 0.04 (average of 0.02). These findings demonstrate that the power-exponential model adequately described the distributions of the dry and wet sieving aggregates in the organically modified soils under various tillage systems. The γ values changed from 0.002 to 0.59, with an average of 0.22. Larger γ values indicate a more left-skewing distribution. The skewness for various treatments of dry or wet soil aggregates was generally similar at each soil depth in the present study. In addition, the values of d_r ranged from 0.003 to 2.13, with an average of 0.30. Organic amendments generally had lower d_r values for wet aggregates in all soil layers under the different tillage systems, but the differences were not obvious. Smaller values of d_r indicate a greater frequency of macroaggregates. For example, the soil aggregates exhibited sizes of >5 mm, 2–5 mm and 1–2 mm according to the wet sieve analysis (Figure 3f–j).

3.4. Soil Porosity Fractions

The tillage systems significantly affected the total porosity (Figure 6a,b, Table 6) and macroporosity (>30 μm) (Figure 6c,d, Table 6) at the four investigated depths ($p < 0.05$). At the 0–20 cm depth, CT had generally greater total porosity compared to DT and NT, whereas both CT and DT tended to have significantly greater macroporosity than NT ($p < 0.05$). At the depth of 20–40 cm, NT resulted in the greatest total porosity and macroporosity (NT > DT > CT). In general, the organic amendments increased the total porosity and macroporosity relative to those of the control. A significant variation in total porosity was detected at 0–20 cm, where MWS and MWH had higher total porosity than the MFS and MBF treatments. The advantages of the MWS and MWH treatments were significant ($p < 0.05$) at 0–10 cm, yet non-significant at 10–20 cm ($p > 0.05$). However, significant effects of the organic amendments on the macroporosity were generally found across all soil depths compared with those of the control ($p < 0.05$). On average, MWS resulted in significantly ($p < 0.05$) greater macroporosity than the other organic amendments at 0–40 cm. The benefits of MWS on the macroporosity were mostly noticeable at 0–10 cm, whereas MBF resulted in a similar improvement to MWS in the macroporosity at larger depths.

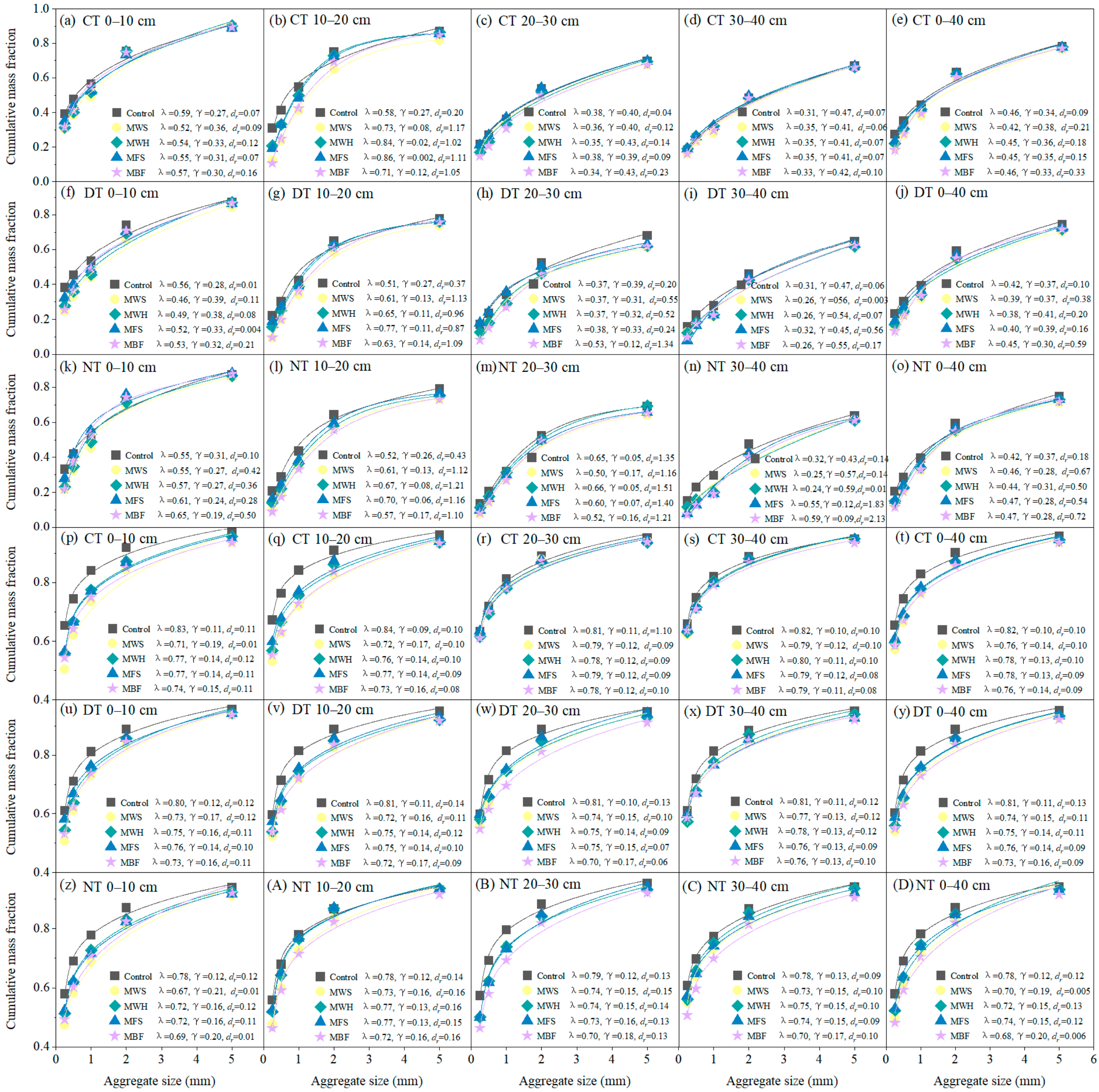

Figure 5. The dry (**a**–**o**) and wet (**p**–**D**) sieving aggregate size distribution fitted by power-exponential distribution models.

The air permeability was significantly ($p < 0.05$) impacted by tillage at all soil depths except the 10–20 cm depth (Figure 6e,f, Table 6). At the 0–10 cm depth, CT and DT resulted in significantly ($p < 0.05$) larger air permeability than NT. However, at depths of 20–30 cm and 30–40 cm, NT produced significantly ($p < 0.05$) larger air permeability than CT and DT (NT > DT > CT). As a result, the mean value of air permeability was the largest under NT in 0–40 cm ($p < 0.05$). The organic amendments significantly influenced the air permeability across all depths ($p < 0.05$). Compared to the control, the organic amendment treatments significantly ($p < 0.05$) enhanced the air permeability by 31.26–367.89% (except for MFS at 0–10 cm). Among the organic amendment treatments, the air permeability was significantly ($p < 0.05$) higher for MWS and MWH than for MFS and MBF (MWH > MWS > MBF > MFS) at 0–20 cm, while it decreased in the order MBF > MFS > MWH > MWS at 20–40 cm

($p < 0.05$). On average, MWS and MWH had significantly larger air permeability than MFS (119.36% and 173.52%) and MBF (75.61% and 118.97%) at 0–40 cm.

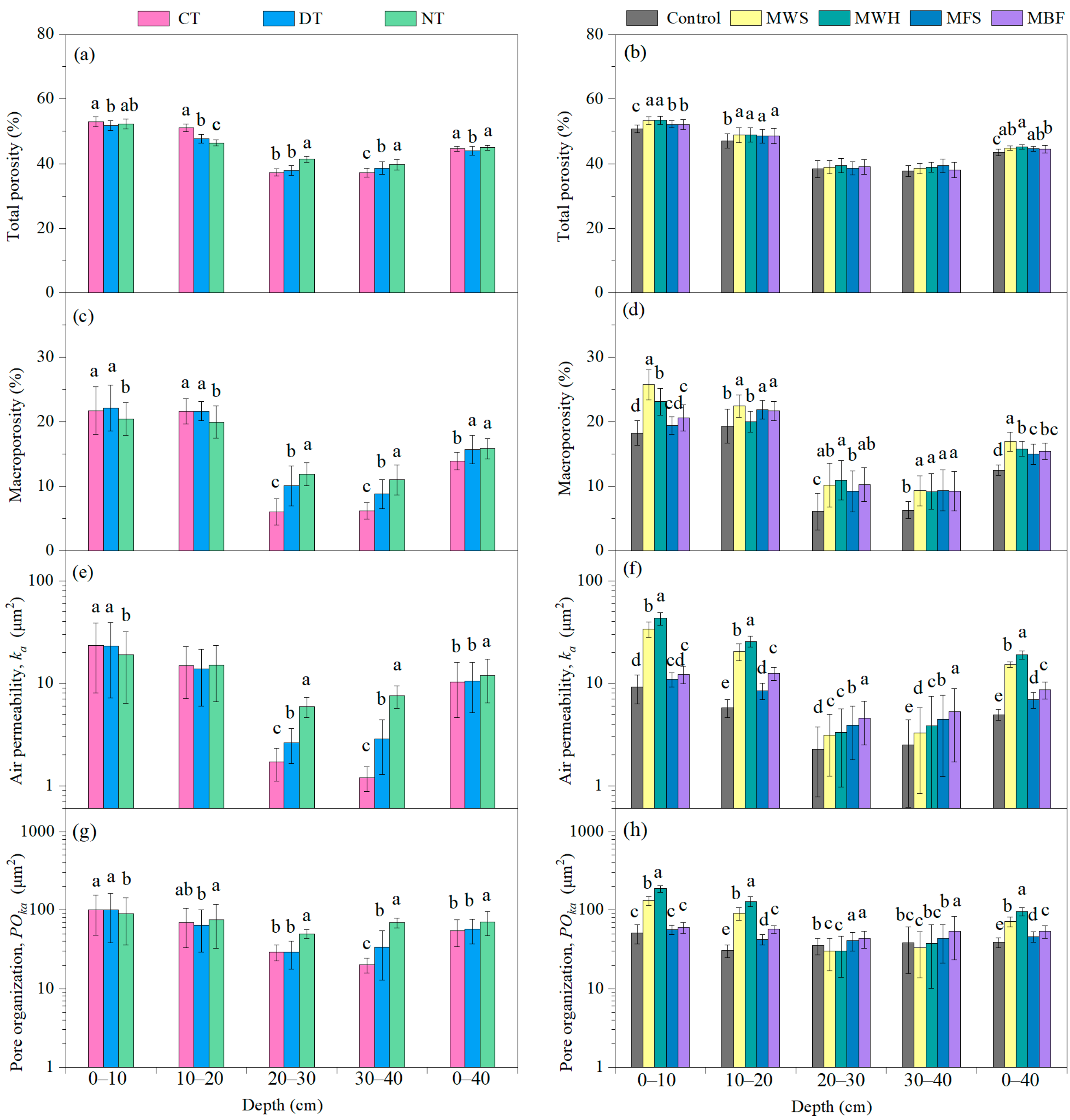

Figure 6. Responses of soil total porosity (**a**,**b**), macroporosity (**c**,**d**), air permeability (**e**,**f**) and pore organization (**g**,**h**) to tillage and organic amendments at 0–40 cm. Different letters indicate significant differences at $p < 0.05$. No letter annotation indicates no significant difference. CT, conventional tillage; DT, deep tillage; NT, no tillage. Control, mineral fertilizer; MWS, mineral fertilizer with wheat straw; MWH, mineral fertilizer with wheat husk; MFS, mineral fertilizer with farmyard soil; MBF, mineral fertilizer with bioorganic fertilizer.

The PO continuity index exhibited significant ($p < 0.05$) differences in both the tillage systems and organic amendments at all depths (Figure 6g,h, Table 6). At 0–10 cm, the PO was the highest in CT, followed by DT and NT. At deeper soil depths, NT produced the highest PO. The organic amendments also increased the PO compared to the control. MWS and MWH resulted in significantly ($p < 0.05$) higher PO values than MFS and

MBF at 0–20 cm. However, the opposite results were recorded at a depth of 20–40 cm (MBF > MFS > MWH > MWS). On average, MWS and MWH had significantly ($p < 0.05$) larger PO values than MFS (55.99% and 109.62%) and MBF (33.60% and 79.54%) at 0–40 cm. The interaction effects of tillage and organic amendments on the pore characteristics were evident at the 20–30 cm and 30–40 cm depths, with NT-MBF showing higher macroporosity, air permeability and PO values than the other treatments (Table S5).

3.5. Soil Hydraulic Properties

The soil saturated hydraulic conductivity (*Ks*) was remarkably influenced by the tillage practices and organic amendments across all depths (Table 8). At the 0–20 cm depth, CT had the highest *Ks* values compared to DT and NT ($p < 0.05$). In contrast, DT and NT had higher *Ks* values than CT (NT > DT > CT) at 20–40 cm ($p < 0.05$). Compared to the control, the organic amendments significantly ($p < 0.05$) increased *Ks* by 43.79%~431.92% at 0–20 cm. Among all of the organic amendments, the *Ks* values for MWS and MBF were significantly ($p < 0.05$) greater than those for MWH (53.26–269.92%) and MFS (49.12–259.93%). At a depth of 20–40 cm, greater *Ks* values were found only for MBF and MFS compared to the control (MBF > MFS > control, 27.75–130.04%, $p < 0.05$). On average, the *Ks* values decreased in the order of MWS > MBF > MFS > MWH > control. Interaction effects between tillage and organic amendments on *Ks* were found at all depths (Table S6). CT-MWS and DT-MWS were found to be more effective treatments in terms of increasing the *Ks* values compared to other combined treatments at the depth of 0–10 cm. However, this advantage was mostly exhibited in the CT-MBF and NT-MBF treatments at the 10–20 cm depth, with NT-MBF displaying the greatest *Ks* values at the 20–30 cm and 30–40 cm depths.

Table 8. Responses of soil saturated hydraulic conductivity to tillage and organic amendments at 0–40 cm.

Treatment	*Ks* (cm h^{-1})				
	0–10 cm	**10–20 cm**	**20–30 cm**	**30–40 cm**	**0–40 cm**
Tillage					
CT	20.02 ± 15.68 a	18.67 ± 10.57 a	0.50 ± 0.22 c	0.56 ± 0.09 c	9.94 ± 5.67 a
DT	18.97 ± 16.18 b	16.91 ± 9.22 c	1.12 ± 0.49 b	1.16 ± 0.39 b	9.54 ± 5.47 b
NT	11.32 ± 4.23 c	17.98 ± 10.32 b	1.82 ± 0.58 a	1.90 ± 0.32 a	8.26 ± 3.66 c
Organic amendments					
Control	7.33 ± 1.10 d	7.12 ± 0.66 e	0.83 ± 0.42 d	0.99 ± 0.44 c	4.07 ± 0.32 e
MWS	38.99 ± 16.25 a	22.86 ± 1.81 b	0.93 ± 0.45 cd	1.13 ± 0.56 c	15.98 ± 3.90 a
MWH	10.54 ± 1.37 c	11.62 ± 1.03 d	1.00 ± 0.56 bc	1.06 ± 0.60 c	6.06 ± 0.29 d
MFS	10.83 ± 1.77 c	13.25 ± 1.07 c	1.06 ± 0.61 b	1.28 ± 0.62 b	6.61 ± 0.47 c
MBF	16.15 ± 1.41 b	34.40 ± 1.90 a	1.92 ± 0.88 a	1.57 ± 0.78 a	13.51 ± 0.52 b
Two-way ANOVA (*p* values)					
T	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **
O	0.000 **	0.000 **	0.000 **	0.000 **	0.000 **
T × O	0.000 **	0.005 **	0.000 **	0.001 **	0.000 **

Different letters indicate significant differences at $p < 0.05$. T, tillage method; O, organic amendment. **, significant at $p < 0.01$. CT, conventional tillage; DT, deep tillage; NT, no tillage. Control, mineral fertilizer; MWS, mineral fertilizer with wheat straw; MWH, mineral fertilizer with wheat husk; MFS, mineral fertilizer with farmyard soil; MBF, mineral fertilizer with bioorganic fertilizer. *Ks*, soil saturated hydraulic conductivity.

3.6. Soil Hydraulic Conductivity and Its Relationship with Soil MR and Soil Structure

Pearson correlation coefficients were used to reveal the relationship between soil MR, soil aggregates, soil pores and *Ks* at different soil depths (Figure 7). *Ks* was slightly ($p > 0.05$) correlated with soil MR, whereas it was significantly ($p < 0.05$) correlated with the soil PAD, dry MWD, porosity, macroporosity and k_a at the 0–10 cm soil depth. The SEM analysis also demonstrated that MR had an indirect, rather than direct, influence on the *Ks* changes at the 0–10 cm depth (Figure 8). Soil MR primarily influenced *Ks* by modifying the soil's water-stable aggregates and macroporosity. Importantly, the macroporosity exerted a direct positive effect on the *Ks* changes at 0–10 cm ($p < 0.05$). Similarly, soil MR had an indirect effect on *Ks* at a 10–20 cm depth, where *Ks* was positively correlated with the MWD and macroporosity. Furthermore, direct positive correlations between the macroporosity and *Ks* were found at a depth of 20–40 cm, with standardized coefficients of 0.35 at 20–30 cm and 0.45 at 30–40 cm, respectively ($p < 0.05$). Additionally, direct positive correlations between the PO and *Ks* were detected, with standardized coefficients of 0.52 at 20–30 cm and 0.55 at 30–40 cm, respectively.

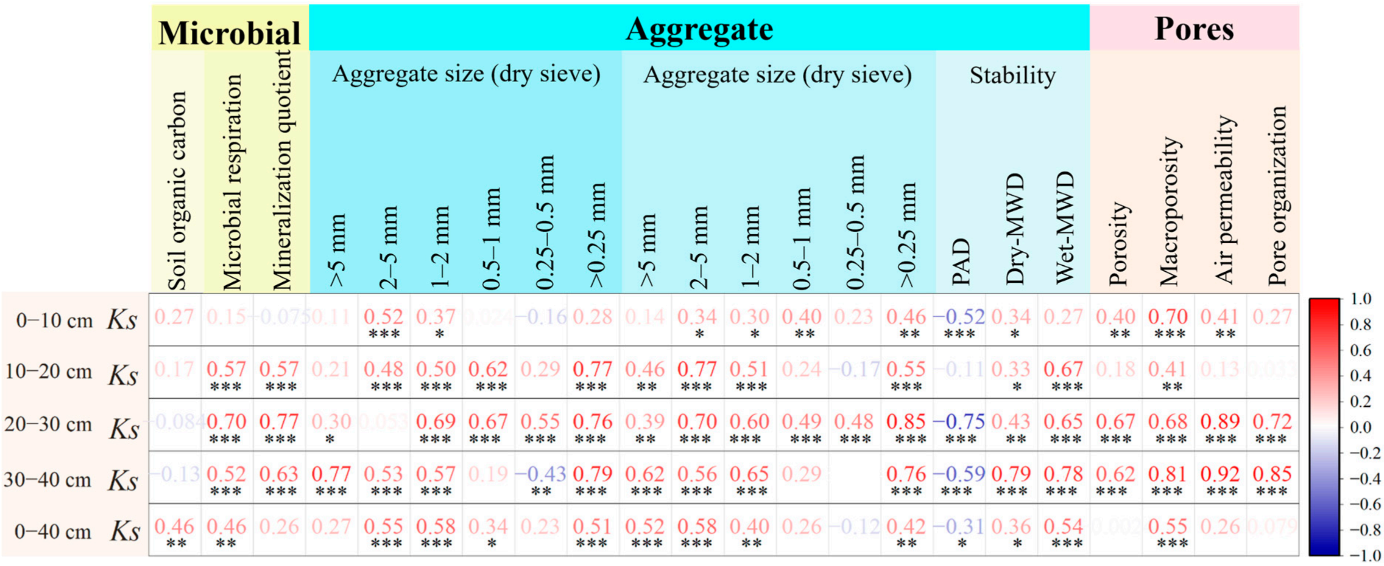

Figure 7. Heatmap indicating Pearson's correlations between soil microbial respiration, soil aggregates, soil pores and soil saturated hydraulic conductivity across all depths. PAD, percentage of aggregate destruction; Dry-MWD, mean weight diameter of aggregates obtained by dry sieving analysis; Wet-MWD, mean weight diameter of aggregates obtained by wet sieving analysis; *Ks*, soil saturated hydraulic conductivity. ***, significant at $p < 0.001$; **, significant at $p < 0.01$; *, significant at $p < 0.05$.

A PCA biplot was constructed to integrate the thirteen variables and evaluate the overall effects of the combined treatments on the soil microbial respiration, structure and *Ks* (Figure 9). In the PCA, three principal components having eigenvalues >1 contributed to 83.9% of the variation in the selected variables at 0–10 mm and 87.7% of the variation at 10–20 cm. Most of the experimental variance was explained by the first two principal components at the 20–30 cm (87.5%) and 30–40 cm (87.5%) depth. The PCA figure further illustrates the correlation results between *Ks* and soil MR and the soil structure at each depth. Interestingly, the combined treatments were located in different regions of the factor space due to different loads in the variables. The DT-MWS treatment demonstrated the best comprehensive improvement in the selected soil properties at 0–10 cm, attributed to the highest scores for PC1 (SOC, dry->0.25 mm, wet->0.25 mm, wet MWD, macroporosity, *Ks*) and PC3 (PAD, dry MWD, k_a and PO). Additionally, the DT-MWS treatment was identified as the most effective at 10–20 cm, primarily due to obtaining the highest score for PC1 (MR, *q*mC, dry->0.25 mm, wet->0.25 mm, dry MWD and wet MWD). However, the NT-MBF treatment emerged as the most effective in enhancing the selected properties, primarily due to obtaining the highest score for PC1 at the 20–40 cm depth. The PCA also revealed that combined mineral fertilizer and CT had the lowest comprehensive scores across all soil depths.

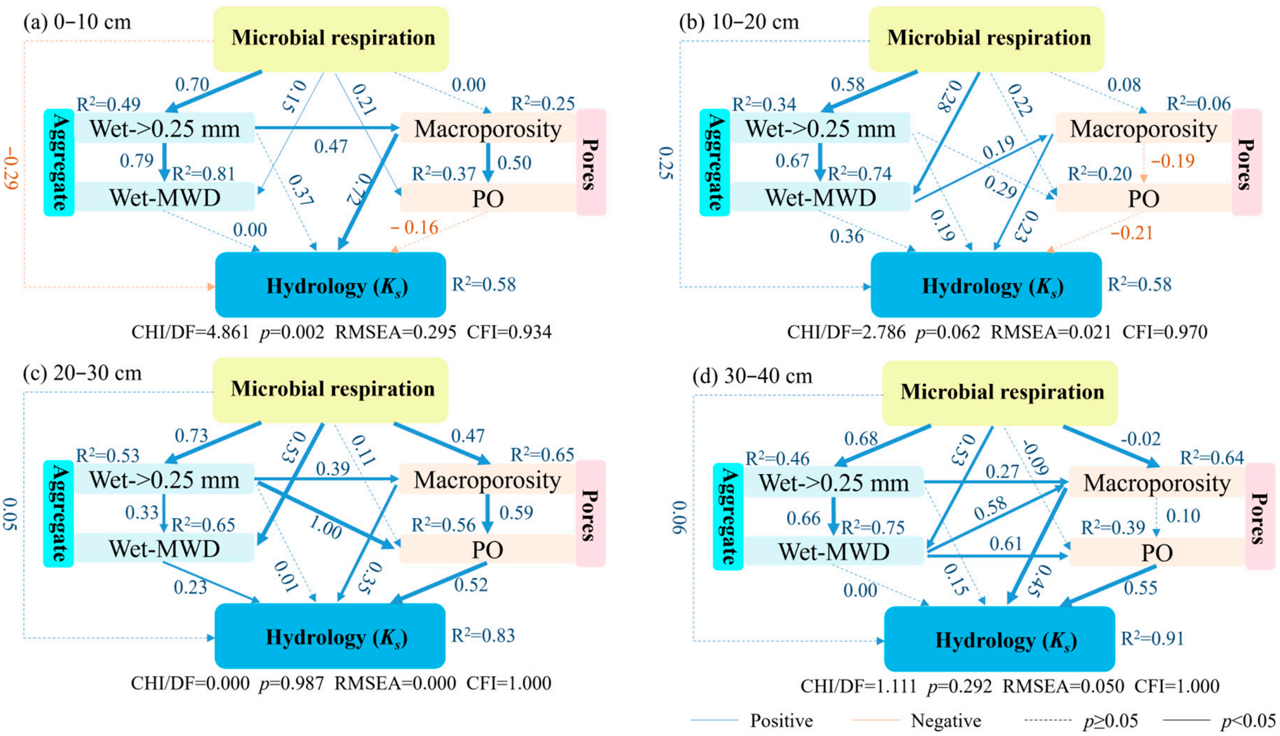

Figure 8. The direct and indirect effects of soil microbial respiration, aggregates and pores on the saturated hydraulic conductivity at 0–10 cm (**a**), 10–20 cm (**b**), 20–30 cm (**c**) and 30–40 cm (**d**). The blue and orange arrows indicate positive and negative relationships, respectively. The solid and dashed arrows indicate significant and non-significant relationships, respectively. The numbers adjacent to the arrows represent the path coefficients, while the thickness of the arrows denotes the strength of the significant standardized path coefficient. R^2 indicates the proportion of variance explained by all predictors. RMSEA, root mean square error of approximation; CFI, comparative fit index; Wet->0.25 mm and Wet-MWD, >0.25 mm soil aggregates and the mean weight diameter obtained by wet sieving analysis; PO, pore organization; *Ks*, soil saturated hydraulic conductivity.

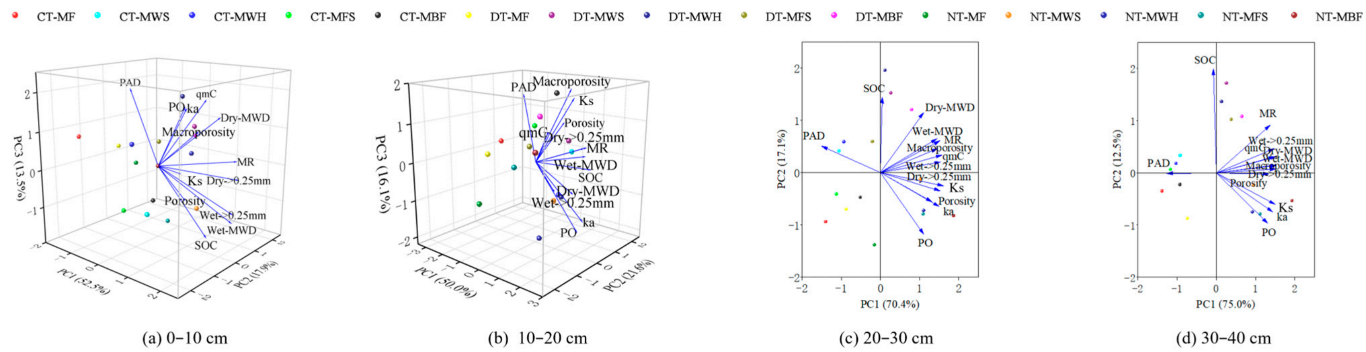

Figure 9. Principal component analysis of soil properties for different treatment combinations of tillage and organic amendments in all soil layers. SOC, soil organic carbon; MR, microbial respiration; *q*mC, mineralization quotient; Dry->0.25 mm and Wet->0.25 mm, >0.25 mm soil aggregates obtained by dry and wet sieving analysis; PAD, percentage of aggregate destruction; Dry-MWD and Wet-MWD, mean weight diameter obtained by dry and wet sieving analysis; k_a, air permeability; PO, pore organization; *Ks*, soil saturated hydraulic conductivity. CT, conventional tillage; DT, deep tillage; NT, no tillage. MF (control), mineral fertilizer; MWS, mineral fertilizer with wheat straw; MWH, mineral fertilizer with wheat husk; MFS, mineral fertilizer with farmyard soil; MBF, mineral fertilizer with bioorganic fertilizer.

4. Discussion

4.1. Effects of Tillage Systems and Organic Amendments on Soil Microbial Respiration

Tillage and organic amendments are the predominant practices employed to influence the SOC and MR [44]. Both tillage and no tillage induce losses in the SOC, with no tillage exerting a more significant negative impact [45]. However, the application of organic amendments can enrich the SOC under tillage systems [46]. Our study revealed that organic amendments showed a more significant effect on the mean values of the SOC than tillage at the 0–40 cm depth (Table 5). One reason for this phenomenon is the addition of organic matter through organic amendments [30]. Additionally, organic amendments stimulated plant root growth and increased root residues, which were additional sources of SOC accumulation [33]. The organic amendments primarily enriched the SOC in the 0–20 cm layer, mostly owing to the depth at which the organic materials were mixed during tillage [45]. The organic materials carried more C in the 0–10 cm soil layer under CT (tillage depth around 15 cm), whereas the same dose of organic materials mostly remained on the surface of the soil under NT. DT (tillage depth around 30 cm) could incorporate the amendments into deeper soil depths. This also explains why the SOC was significantly higher in CT and NT than in DT at 0–10 cm. Our results are in agreement with the findings of Govednik et al. [47]. In terms of the organic amendments, MWS had greater SOC content than MWH, MFS and MBF, predominantly due to the higher organic carbon content of wheat straw (Table 4). A significant linear correlation was observed between the C input and SOC ($r = 0.849$, $p < 0.05$) [45].

In our study, the organic amendments increased the mean MR values compared with the control (Figure 2a,b). Our findings are consistent with the observations of previous researchers, who discovered that applying organic materials might provide additional sources of energy and nutrients [48]. More energy and nutrients induce the development of various microbiota, increasing the microbial diversity and stimulating CO_2 emissions in soils [25]. Additionally, the comparative analysis in our study suggested that MBF had the highest levels of MR. Various organic materials with differing resistant organic components yield a diversity of decomposition rates [30]. For example, organic materials' decomposability was controlled by their C/N ratio, with a lower ratio resulting in a faster rate of C mineralization and CO_2 generation [34]. Hence, the low C/N ratio (Table 4) was most likely responsible for the high MR levels in MBF, as well as the highest *q*mC (Figure 2c,d). Compared with CT, NT greatly enhanced the soil surface microbial activity and MR by retaining organic matter on the surface soil. The retained organic matter also enhanced SOC mineralization and released CO_2 via the "priming effect" in the surface soil [49]. The positive priming effect not only stimulated MR but also increased the *q*mC under NT. Some studies have reported that the "priming effect" of organic amendments is difficult to observe in the deeper soil under NT [43]. However, our results indicated that NT promoted soil MR and the *q*mC at 20–40 cm. Although NT did not have higher SOC than CT, it improved the total porosity, macroporosity and PO in the subsurface soil. The better pore structure created a favorable environment for extracellular enzyme activities [29]. Liu et al. [49] reported the same trend between enzyme activity and carbon mineralization. Meanwhile, DT significantly increased the MR and mqC compared to CT in both the surface and subsurface soils. The higher SOC and better pore connectivity also promoted organic carbon mineralization and increased MR under DT at the 10–40 cm depth compared to CT. However, CT had lower MR at 0–10 cm than NT and DT, although this depth contained a high concentration of organic materials. Frequent tillage under CT disintegrated the macroaggregates, resulting in more microaggregates to preserve the organic matter. Consequently, this accelerated SOC retention and reduced CO_2 production [46,50].

4.2. Effects of Tillage Systems and Organic Amendments on Soil Structure

Soil aggregates and soil pore characteristics are the primary indicators used to assess the soil structure, which influences soil nutrients and water transport [3]. For tillage, CT disintegrated macroaggregates and disrupted the pore network through strong mechanical forces from consecutive rotary tillage [51]. Combining CT and organic amendments could effectively mitigate the negative effects on the soil structure in the surface soil but not in the subsurface soil [18]. We observed that CT had the lowest PAD at 0–10 cm and the largest total porosity at 10–20 cm (Table 7 and Figure 6). However, DT and NT significantly decreased the PAD and increased the MWD of dry and wet sieving aggregates at 20–40 cm. A lower PAD and higher MWD generally led to larger soil aggregates and greater soil stability [3,52]. Moreover, greater aggregate stability would produce a better soil pore structure, with higher total porosity, macropores, PO and air permeability. Mechanical modifications of the soil profiles in DT could decrease the bulk density and enrich the SOC [53], thereby increasing the proportions of macroaggregates and macropores in the subsurface soil [54]. The little or no soil disturbance caused by NT promoted microaggregation to form macroaggregates and then improved the soil aggregate stability, thus enhancing the pore radius, biotic macropores and pore connectivity [50].

The enhanced structural stability and optimized pore properties are largely due to the addition of organic amendments [3,5,14,25]. Compared with the control, the organic amendments significantly decreased the mean PAD values and increased the mean MWD values for both dry and wet sieving in the 0–40 cm soil layer (Table 7 and Figure 4). The incorporation of organic materials provided organic colloids for soil aggregates, thus increasing the proportion of macroaggregates and improving the soil aggregate stability [55]. This was confirmed by the positive correlation between the MWD and C input [52]. Additionally, the total porosity, macroporosity, air permeability and PO were generally increased by the addition of organic materials (Figure 6). Li et al. [3] also indicated that the short-term application of compost and corn stover improved the CT-measured pores and their connectivity in comparison with inorganic fertilization. This phenomenon could be caused by a variety of mechanisms. A given dose of organic material applied to soils could dilute denser soil mineral fractions, which leads to a decrease in soil bulk density and an increase in macropores [56]. Moreover, organic materials could increase the humic acid concentration, which may also increase the total porosity and macroporosity [28]. Lastly, the improved pore structure might be attributed to the deposition of organic acids and polysaccharides derived from organic materials, which facilitate the binding of soil mineral particles with organic components, thereby promoting the formation of soil aggregates. Moreover, the improvement in the soil structure could be ascribed to the organic amendment types [25]. MWS had the highest MWD values for dry and wet sieving compared to the other amendment treatments at 0–20 cm, while MBF improved the MWD more than the other organic amendments at 20–40 cm. Wheat straw generally remained in the topsoil, owing to its lower bulk density (Table 4) compared to other organic materials. This would lead to the best improvement in the aggregates and macropores of the surface soil under MWS. However, the improvement in the soil structure caused by MBF might be accomplished by more vigorous roots [26,57], continuous biopores [18] and soil MR and the decomposability of bioorganic fertilizer in the subsurface soil. The great MR and decomposability of bioorganic fertilizer also enhanced the pore connectivity [25]. The significant interaction effect between the tillage methods and organic amendments on the pore characteristics at depths of 20–40 cm was remarkable. NT-MBF had the largest macroporosity, air permeability and PO, improving the air and water transport properties.

4.3. Microbial Respiration and Soil Structure's Impacts on Soil Hydraulic Properties

The soil hydraulic properties describe the physical aspects of the soil that enable air and water to be stored and transmitted. Tillage significantly affected the soil profile's hydraulic conductivity. The highest *Ks* values were found in CT at 0–20 cm and in NT at 20–40 cm, respectively (Table 8). Under CT, a large amount of organic amendment was added to the 0–10 cm soil layer, increasing the macroaggregates (>5 mm, 2–5 mm and 1–2 mm) and MWD for wet sieving [51]. Enhancing the soil aggregation resulted in an optimized pore distribution, thereby augmenting the *Ks* [58]. However, frequent tillage led to subsurface soil compaction and altered the soil structure, ultimately decreasing the conductivity under CT [20]. Under NT, all organic materials were retained in the soil surface, yet the highest saturated hydraulic conductivity was recorded in the subsurface soil compared with CT (Table 8). This could be due to the increased biological activity in subsurface soil [21]. The hydraulic conductivity increased as the soil MR and *q*mC increased (Figure 7). Higher soil microbial activity resulted in more water-stable aggregates (>1 mm), following the greater MWD, which in turn increased the soil macroporosity [25]. More macropores provide more space and air for crop root systems and microflora, which are advantageous for the hydraulic conductivity [21]. The hydraulic conductivity of saturated and nearly saturated soils is presumably governed by macropores, accounting for 53% of the total water flow [59].

Higher *Ks* values were observed in the organic amendment treatments than in the control, being especially significant at the 0–20 cm depth (Table 8). This phenomenon could be attributed to the greater MR, macroaggregates and macroporosity promoted by the addition of organic materials (Figure 7). Chichongue et al. [60] and Eze et al. [61] found that an increase in SOC not only stimulated biological activity but also promoted soil aggregation, thereby improving the soil's pore connectivity and hydrological properties. Yazdanpanah et al. [25] also revealed significant positive relationships between the MR, mqC, water-stable aggregates, porosity, macroporosity and hydraulic conductivity following the application of compost and alfalfa residue. Importantly, variations in pore size exerted a significant direct influence on *Ks* (Figure 8). Li et al. [3] showed that the *Ks* values were enhanced with the application of organic materials owing to the increase in soil macropores. Consistently, a simultaneous increase in macroporosity and hydraulic conductivity was observed by Abdollahi et al. [14] and Li et al. [62]. Thus, the improved *Ks* values in MWS within the 0–20 cm depth are attributable primarily to the greater macroporosity compared to the MWH and MFS treatments. Nevertheless, the presence of macroporosity in MWS did not yield a significant enhancement in the *Ks* values at the 20–40 cm depth when compared to the control. This discrepancy might be attributed to reduced pore connectivity. Direct positive correlations between PO and *Ks* were also detected by Schlüter et al. [20] and Thotakuri et al. [63]. Hence, the high *Ks* values of MBF might be caused by the strong PO at 20–40 cm as compared to the organic amendments.

Understanding the mechanisms controlling soil hydraulic conductivity in response to organic amendments and tillage practices is critical in improving soil's hydrological conditions, alleviating soil degradation and combating soil compaction [14,25,62]. Our study demonstrated that the conventional practices aggravated subsurface soil compaction on the Loess Plateau. DT-MWS and NT-MBF had the greatest comprehensive improvement effects on the soil's microbial respiration, structure and hydrology at the 0–20 cm and 20–40 cm depths, respectively (Figure 9). Improving the surface soil hydraulic conductivity is important, but overlooking subsurface compaction impedes deep water infiltration. Hence, our study recommends the application of NT-MBF to effectively improve the soil hydraulic conductivity by enhancing the soil microbial respiration and increasing the soil macropores and pore connectivity. We hope that our findings offer a theoretical basis for local farmers to achieve enhanced soil hydrology. However, the scope of our study was limited by its relatively short duration, which did not extend beyond five years [49]. Further investigation would be essential to elucidate the long-term, combined impacts of tillage and organic amendments on the soil profile, microbial respiration, structure and hydrology, as well as the complex interactions among these elements.

5. Conclusions

The two-year application of organic amendments and tillage methods significantly affected the soil hydrology, structure and microbial respiration. Organic amendments significantly improved the *Ks* at 0–10 cm and 10–20 cm, which was linked to enhanced MR by modifying the water-stable aggregates and macroporosity. MWS generally showed a lower PAD and higher MWD and macroporosity, leading to greater *Ks* values compared to MWH and MFS. The PCA revealed that DT-MWS resulted in the best comprehensive improvement in the selected soil properties at the 0–10 cm and 10–20 cm depths. Significant interactions between tillage and the organic amendments were found for *Ks*, macroporosity and PO at 20–40 cm. NT-MBF was the best treatment due to producing the highest *Ks*, macroporosity and PO values, which were significant. The soil macroporosity and PO were directly correlated with *Ks*, especially PO. Considering the problem of subsurface soil compaction in our study region, NT-MBF would be the recommended treatment for local farmers.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy15010250/s1, Table S1: Responses of macro-aggregate-size distribution, determined by dry- and wet sieving analysis, to organic amendments and tillage systems in 0–40 cm. Table S2: The interaction of tillage and organic amendments on the percentage of aggregate destruction in 0–40 cm. Table S3: The interaction of tillage and organic amendments on the mean weight diameter of aggregates obtained by dry sieving analysis in 0–40 cm. Table S4: The fitting parameters and goodness-of-fit criteria for different aggregate-size distribution models. Table S5: The interaction of tillage and organic amendments on soil pore structure in 0–40 cm. Table S6: The interaction of tillage and organic amendments on soil saturated hydraulic conductivity in 0–40 cm.

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