



Soil aggregation influences soil drought degree after long-term organic fertilization in red soil

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Received: 6 April 2021 / Accepted: 8 February 2022 / Published online: 23 February 2022
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Abstract

Fertilization is an effective approach to improve aggregation of red soil (Ultisol). However, the effect of soil aggregation after long-term organic or mineral fertilization on red soil drought degree during intermittent seasonal drought remains unclear. The objective of this study was to examine the effect of long-term fertilization on soil aggregation (aggregate size distribution and stability) and aggregate-binding agents, and to determine the relationship between aggregation and soil drought degree (D) during wet and dry years. Red soil was continuously applied with manure, NPK + straw, or NPK for 21 years. Surface soil water content (SWC), D , aggregate size distribution, wet aggregate stability, and aggregate-binding agents contents (Fe oxides and soil organic carbon (SOC)) were determined in 2017 (normal wet year), 2019 (dry year), and 2020 (above average wet year). The results showed that manure and NPK + straw treatments resulted in greater SWC variation than the control, especially a sharper SWC decline than control under dry conditions. The results indicated that D values varied with climatic conditions, and that manure and NPK + straw resulted in higher D values than NPK in the normal wet year and dry year, while an opposite trend was observed in the above-average wet year. The D value peaked to 1 in a 70-day dry spell in 2019, while it peaked to 0.7 in < 10-day dry spell in other years. The variation in D can be explained by aggregation due to a significant negative correlation between D and the 2–0.25 mm aggregate size fraction ($-0.58 < r < -0.64$, $p < 0.05$). In the dry year (2019), the low proportion of 2- to 0.25-mm size aggregates under manure and NPK + straw treatments was significantly correlated with a lower SOC and amorphous Fe oxide content, which might explain their greater D values. Generally, long-term organic fertilization aggravated D during drought periods. The results of this study will contribute to the sustainable management of red soils.

Keywords Aggregate stability · Fe oxides · SOC · Soil water

Introduction

Drought, as one of the major natural hazards around the world, limits crop yield and causes great economic losses for agriculture (Lesk et al. 2016). The seasonal drought of Ultisols (locally named red soils in China) is a relative drought in subtropical climate, and it is spatio-temporally characterized by intermittent short-term water shortage accompanied by a shallow-soil-layer available water shortage (Wang

et al. 2016; Small and Raizada 2017; Minaduola et al. 2021). The extent of soil water content deficit during a drought period was exacerbated by low soil aggregate stability of red soil (He et al. 2018). When the water deficit in a seasonal drought of clayey red soil lasted for more than 12 days, it resulted in serious damage to maize growth in rain-fed agriculture (Chen et al. 2010; Lin et al. 2016; Wang et al. 2016).

The severity of seasonal drought in clayey red soil can be related to the soil structural properties. A high proportion of poorly available soil water between -330 and -1500 kPa water potential was reported to be the origin of high sensitivity of clayey red soils to drought (D'Angelo et al., 2014). Low available water storage in red soil was caused by micro-aggregation properties which facilitated downward water transfer (Zhang and Zhang 1995; Assi et al. 2019; He et al. 2019). Similarly, a soil with high percentage of 2- to 1-mm aggregates was also found to result in a faster increase in soil

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matric potential during soil drying process than the same soil inoculated with arbuscular mycorrhizal fungi, indicating a faster soil water depletion rate (Chen et al. 2020). Therefore, the role of soil aggregation must be considered during soil water retention and depletion processes.

However, soil aggregation may vary with climate due to differences in aggregate-binding agents (mainly organic matter, oxides, and calcite), thus altering soil water retention and depletion. Several studies have reported the significant effect of seasonal climate changes on soil water dynamics as a result of aggregate dispersion and reduced soil porosity in rainy seasons, and formation of aggregates and large pores in dry seasons (Kursar et al. 1995; He et al. 2018). During seasonal climate changes, changes in soil organic matter (SOM) and Fe oxides may be responsible for the changes in soil aggregation and water retention/depletion (Zhu et al. 2010; Xue et al. 2019). For example, abrupt precipitation after drought has been shown to stimulate the decomposition of organic fertilizers (De Neve and Hofman 2002), reduce SOM content (Wang and Cao 2020), and accelerate the transformation of Fe oxides (Su et al. 2001), all which affect aggregate stability and water retention. Seasonal changes in soil aggregation due to different climatic conditions may result in different levels of drought (Assi et al. 2019).

Drought is usually considered a gradual, evolving process, and the drought intensity is determined by how fast the soil water availability changes. When soil water loss continues and reaches a certain maximal level, the extent of water deficiency can be expressed by a term “drought degree (D).” The higher the D value, the greater stress the drought poses, and the more irreversible damage it causes to plants (Chen et al. 2010). However, few studies have investigated soil water dynamics and soil drought degree development characteristics from a climatic perspective with long-term fertilization. Therefore, the objectives of this research were to (1) investigate red soil aggregate stability in relation to SOM and Fe oxide content within different aggregate size fractions after long-term fertilization (manure, NPK + straw, NPK, CK) in 3 years with varying climatic conditions; and (2) to elucidate the mechanism involved in how soil aggregation affects soil drought degree (D).

Materials and methods

Study site and research design

This study was conducted at an experimental station (30°01'N, 114°21'E) affiliated with the Huazhong Agricultural University in the southeast of Hubei, China. The local area has an annual mean temperature of 16.8 °C and annual mean precipitation of 1300 mm. The predominant rain season is from April to July. The red soils in the study site are

developed from Quaternary red clay and are classified as Ultisols in the USDA Soil Taxonomy system.

The research design was a completely randomized block design with four treatments and three replicates (a total of 12 plots). Each plot had the dimensions of 7 m by 3 m. The four treatments were (1) chicken manure (manure) (10,000 kg ha⁻¹, NPK > 5%, soil organic matter > 45%), (2) NPK plus rice straw (NPK + straw) (NPK + 1666 kg ha⁻¹ rice straw, rice straw length within 4–6 cm), (3) inorganic fertilizers (NPK) (N: 175 kg ha⁻¹, CO(NH₂)₂; P: 150 kg ha⁻¹, Ca(H₂PO₄)₂·2H₂O; K: 115 kg ha⁻¹, KCl), and (4) control (CK, without amendments). Amendments were applied annually for 21 years from 1998 to 2019. From 1998 to 2015, the plots were annually planted with maize (*Zea mays* L.) at a rate of 5 plants m⁻². From 2016 to 2020, the study was not seeded and weeds were controlled by spraying herbicide. Meteorological data from 2017 to 2020 were obtained from a climate station in the study site (Fig. 1). Soil samples (0–10 and 10–30 cm) in 2016 were analyzed for soil texture, bulk density, organic matter content, pH, field capacity (FC), wilting point (WP), and soil available N, P, and K content (Table 1).

Soil water content monitoring

The soil water content (SWC) from a depth of 0–10 cm was monitored considering great SWC variation in this depth in seasons in three different precipitation years, including a normal wet year 2017, a dry year 2019, and an above average wet year 2020 in one out of 3 replicate plots of each treatment using probes (WS SMEC 300 SM/EC/Temp Sensor). The SWC was monitored every 15 min, and the data were recorded by a data logger (Watchdog 2400, Spectrum Technologies, Inc.).

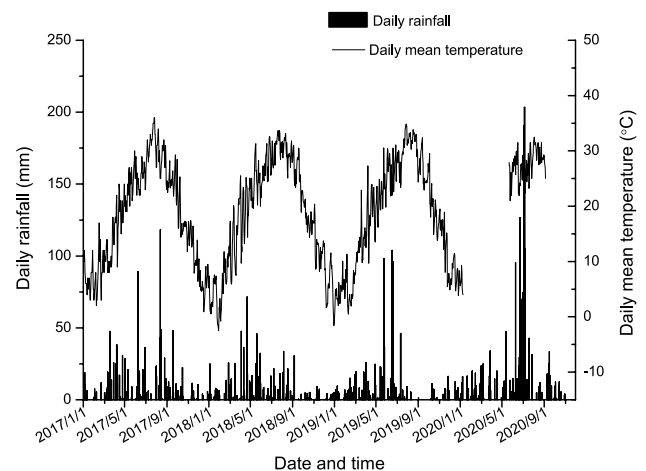


Fig. 1 The precipitation and temperature from year 2017 to 2020 in the research site

Table 1 Basic soil properties (0–10 and 10–30 cm) under different long-term fertilization treatments

Treatments	Soil depth (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (cm ⁻³)	Saturated SWC (cm ⁻³)	Field capacity (cm ³ cm ⁻³)	Wilting point (cm ³ cm ⁻³)	pH	Alkaline hydrolysis N (mg kg ⁻¹)	Available P (mg kg ⁻¹)	Available K (mg kg ⁻¹)	Soil organic matter (g kg ⁻¹)
NPK + straw	0–10	27.4 ± 0.0a	51.7 ± 2.1b	20.9 ± 2.1ab	1.35 ± 0.0b	0.49 ± 0.0a	0.39 ± 0.0a	0.29 ± 0.0a	6.7 ± 0.1a	58.5 ± 2.4b	31.0 ± 0.9b	135 ± 14.0ab	13.9 ± 0.1b
NPK		26.6 ± 0.2a	50.3 ± 0.8b	23.1 ± 1.0a	1.46 ± 0.1a	0.45 ± 0.0b	0.35 ± 0.0b	0.24 ± 0.0b	6.4 ± 0.1b	57.4 ± 2.5b	34.3 ± 2.8b	109 ± 10.5b	10.9 ± 0.1b
Manure		15.5 ± 0.1c	62.0 ± 0.1a	22.5 ± 0.0a	1.32 ± 0.0b	0.50 ± 0.0a	0.39 ± 0.0a	0.27 ± 0.0a	6.3 ± 0.1b	87.6 ± 6.1a	58.1 ± 2.9a	158 ± 5.2a	17.1 ± 0.2a
CK		23.3 ± 0.3b	53.9 ± 0.2b	22.8 ± 0.1a	1.35 ± 0.0b	0.49 ± 0.0a	0.33 ± 0.0b	0.24 ± 0.0b	6.7 ± 0.1a	60.6 ± 9.4b	16.7 ± 4.5c	80.8 ± 5.7c	7.30 ± 0.1c
NPK + straw	10–30	27.3 ± 0.3a	45.8 ± 0.1b	26.9 ± 0.1a	1.50 ± 0.0a	0.43 ± 0.0b	0.37 ± 0.0a	0.21 ± 0.0a	6.2 ± 0.3a	49.0 ± 5.8a	20.6 ± 2.0b	90.3 ± 3.1b	12.7 ± 0.01b
NPK		17.4 ± 2.2b	55.7 ± 2.1a	26.8 ± 0.0a	1.48 ± 0.0a	0.44 ± 0.0b	0.36 ± 0.0a	0.20 ± 0.0a	5.8 ± 0.0a	46.8 ± 5.5a	28.9 ± 2.7a	70.3 ± 2.5c	10.3 ± 0.1b
Manure		19.5 ± 0.2b	51.6 ± 2.2a	28.9 ± 2.0a	1.46 ± 0.0a	0.45 ± 0.0b	0.36 ± 0.0a	0.20 ± 0.0a	6.0 ± 0.1a	53.1 ± 5.5a	31.5 ± 2.8a	108 ± 6.1a	16.5 ± 0.1a
CK		23.7 ± 0.0a	49.5 ± 0.0b	26.8 ± 0.0a	1.44 ± 0.0b	0.50 ± 0.0a	0.37 ± 0.0a	0.21 ± 0.0a	6.3 ± 0.1a	41.6 ± 3.1a	9.3 ± 0.6c	53.8 ± 2.9d	7.1 ± 0.1c

Different lowercase letters indicate each soil parameter was significantly different within treatments at the same depth

Soil relative water content (SRWC) was also calculated as the ratio of measured SWC to field capacity. The SRWC in 10-cm-deep soils was used to distinguish different soil drought levels, including severe drought (SRWC < 45%), heavy drought (45% < SRWC < 55%), moderate drought (55% < SRWC < 65%), and slight drought (65% < SRWC < 70%) (Jin et al. 2014).

Soil drought degree (D)

Soil drought intensity (*I*) is reflected by the relationship between depletion and supply of soil water as in Eq. 1.

$$I = 1 - e^{(1+a)} \tag{1}$$

where the value of *I* always falls within [0, 1] because the empirical regression parameter *a* < -1 in the process of soil drying. The parameter *a* is calculated as the slope of a function between the cumulative amount of relative soil water depletion (*y*) and the remaining transpirable water (*lnx*).

The hazard of soil drought on plants is influenced not only by *I* but also by the drought duration, which accumulates progressively. Therefore, a term “soil drought degree (*D*)” indicates accumulation level of progressive soil drying; it is expressed as in Eq. 2 (Chen et al. 2010)

$$D = 1 - \frac{x_1}{x_0} e^{(-\Sigma')} \tag{2}$$

where *x*₀ is the maximal value of transpirable water in a soil layer, which is calculated as the soil field capacity minus the air-dried soil water content; and *x*₁ is the initial transpirable water amount at the beginning of soil water monitoring. *D* is the value falling within [0, 1], and a larger *D* value means a higher soil drought degree and a more severe water stress on the crop.

In this study, the SWC was used to calculate *D* (data from July 17 to 31, 2017; August 14 to 24, 2017; August 1 to Octpber 10 2019; August 25 to September 4, 2020, with a continuous rain absence of > 10 days).

Soil wet aggregate stability and binding agent measurement

Soil aggregate stability was assessed by determining the wet aggregate stability and calculating the aggregate mean weight diameter (MWD) (Six et al. 2000). Soil aggregate samples were collected from at least three random sampling points from the 0- to 10-cm soil depth in 2017, 2019, and 2020 under each treatment. Samples from three random sampling points in each plot were mixed, air dried, crushed along the natural cracks at appropriate soil water content, and dry sieved through 8 mm sieves. The 100 g aggregates (< 8 mm) were submerged in distilled water

for 10 min, and then the aggregates were transferred to a series of sieves with successively reducing mesh diameter (5, 2, 0.25, and 0.053 mm) which were submerged into water to gently shaken 20 times with 2-cm amplitude vertical vibration. The aggregates remaining on each sieve were collected and dried at 40 °C for at least 48 h to obtain for each of the aggregate size classes. Among all the aggregate size classes, > 0.25 mm aggregates were classified as macroaggregate. The aggregate mean weight diameter (MWD) was calculated according to Eq. 3.

$$MWD = \sum_1^{n+1} \frac{r_{i-1} + r_i}{2} \times m_i \quad (3)$$

where r = aperture of the i th mesh (mm), $r_0 = r_1$, and $r_n = r_{n+1}$; m_i indicates the mass of aggregates remaining on i th sieve; n represents number of the sieves.

The content of soil Fe oxides (free, chelated, and amorphous) and soil organic carbon (SOC) in each aggregate size class were determined. The “free” Fe (Fe_d) oxides were extracted with citrate-bicarbonate-dithionite; chelated Fe (Fe_p) oxides were extracted with sodium pyrophosphate; and amorphous Fe (Fe_o) oxides were extracted by the ammonium oxalate at pH 8.5 according to Bao (1999). The extracted Fe in solution was determined by atomic absorption spectrophotometry (Agilent Technologies 200 Series AA). The SOC was determined by the $K_2Cr_2O_7$ - $FeSO_4$ oxidation method (Bao 1999).

Statistical analysis

The differences in soil aggregate properties among the fertilizer treatments were assessed using Fisher’s least significant difference (LSD) test ($\alpha = 0.05$). Pearson correlation was used to assess the relationship between aggregate MWD and binding agents (Fe oxides and SOC) using all data across the 3 years. The correlation between I and D values and aggregate size class percentage were also analyzed for each year.

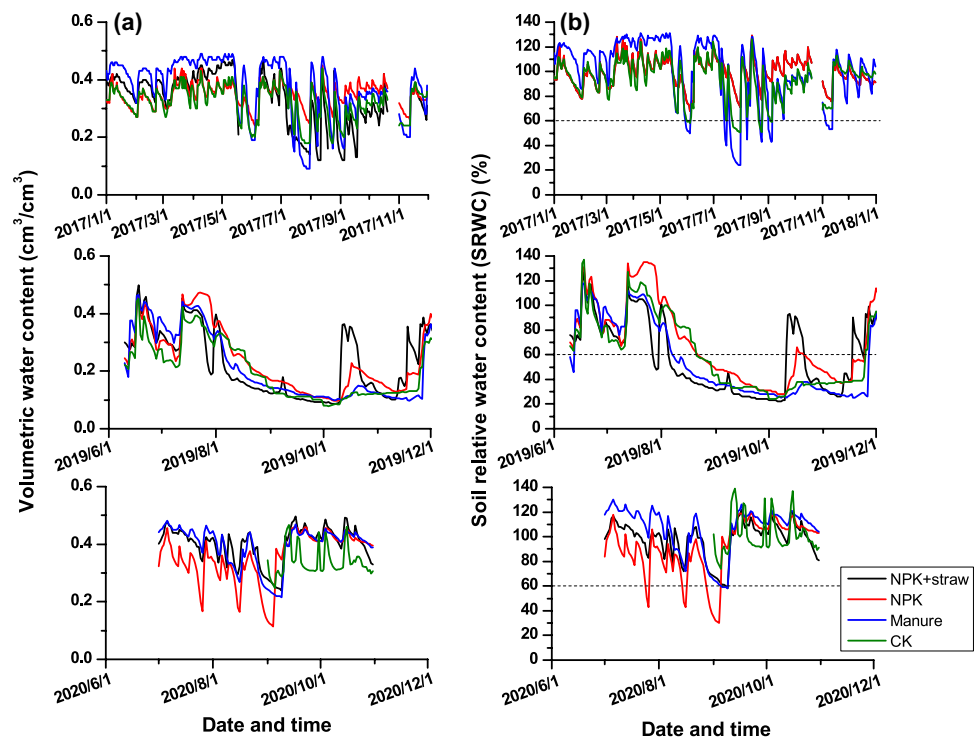
Results

Soil water dynamic pattern under various treatments

Compared to the control, NPK + straw and manure treatments significantly increased soil FC and WP, whereas NPK treatment resulted in medium higher FC and WP values. Difference between FC and WP among treatments resulted in the available water content (AWC) in an order of NPK + straw > manure > NPK (Table 1). However, the soil water retention properties were insufficient to reveal the dynamic process of gradual development of drought. Therefore, the SWC and SRWC were taken into consideration to reflect the hydric history.

The SWC fluctuated frequently with rainfall and dropped to various degrees in the continuous absence of rainfall (Fig. 2a). The SWC in control ranged from 0.18 to 0.44 $cm^3 cm^{-3}$

Fig. 2 The soil water dynamics at depth of 0–10 cm under long-term fertilization treatment in 2017, 2019, and 2020; **a** the soil volumetric water content and **b** the soil relative water content (SRWC)



in 2017, 0.06 to 0.45 $\text{cm}^3 \text{cm}^{-3}$ in 2019, and 0.25 to 0.47 $\text{cm}^3 \text{cm}^{-3}$ in 2020. However, the organic treatments (manure and NPK + straw) generally resulted in higher SWC values and greater SWC variations than CK in period of continuous absence of rainfall in 2017 and 2020. The application of manure and NPK + straw increased SWC in wet seasons but decreased it in dry seasons, indicating that the organic fertilizer application might aggravate the drought. For example, from July 17 to 31, 2017, manure treatment showed 77% decrease in SWC, whereas the CK had a 52% decrease. However, in a dry year 2019, both manure and NPK + straw treatments displayed a greater decline in SWC than CK from August 1 to September 1, whereas an opposite trend was observed from September 1 to October 10.

Under all the treatments, the change trend of SRWC was similar as that of SWC across 3 years (Fig. 2b). The $\text{SRWC} < 70\%$ generally was observed from August to October every year, especially in 2019, which was consistent with seasonal climatic drought. Since both SRWC and SWC were insufficient to reflect total soil drying history, soil drought degree (D) was further examined from August to October in the surveyed 3 years.

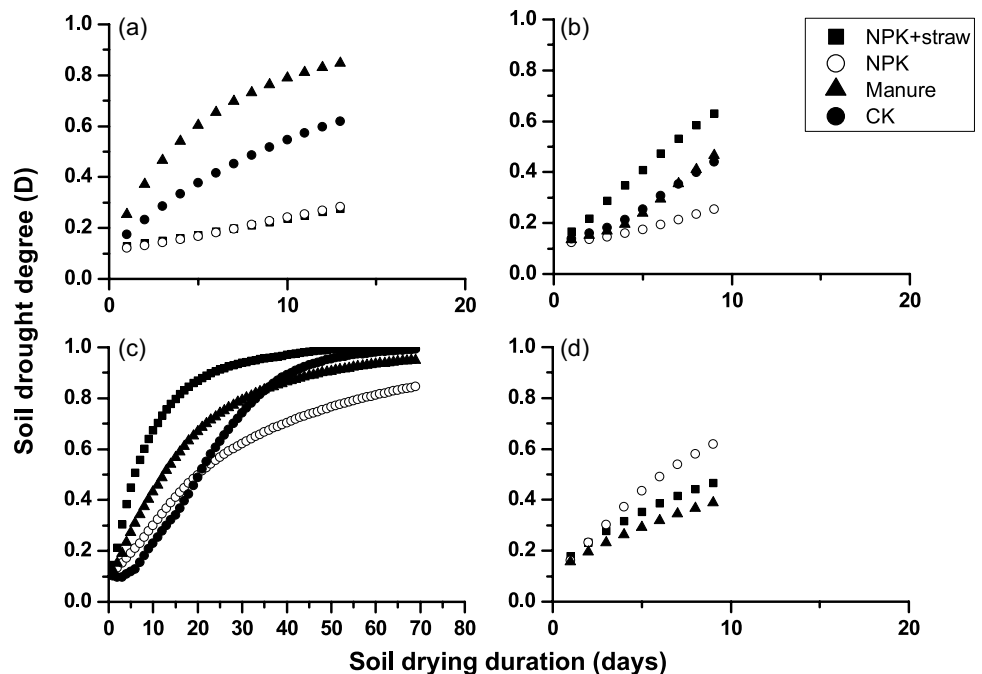
Soil drought degree (D) in seasonal drought period

Maximum D values under different treatments showed different orders across years. Generally, under manure and NPK + straw treatments, the D values were higher and increased at a faster rate compared with CK at the same year in 2017 and 2019 (Fig. 3). In July 17–31, 2017

(normal wet year), higher D values (0.25–0.85) were observed under manure treatment than CK (0.18–0.62) (Fig. 3a).

In 2019 (dry year), D values under all the fertilization treatments were divided into two stages during a long 70-day spell of drying (Fig. 3c). In the 1st stage (the first 20 days), D displayed in an order of NPK + straw > manure > NPK > CK. The three fertilization treatments displayed a faster increase in D values than CK treatment (from 0.10 to 0.49), with D values increasing from 0.15 to 0.85 for NPK + straw, from 0.11 to 0.47 for NPK, and from 0.13 to 0.63 for manure, respectively. In the 2nd stage (the remaining 50 days), D values displayed in an order of NPK + straw > manure > CK > NPK. The D values in CK treatment increased more rapidly and finally reached 1, exceeding those in manure and NPK treatment groups, indicating that non-fertilization treatment might aggravate the drought hazard when the drying lasted for a long time. At the end of 2nd stage, almost all the maximum D values reached 1, which further confirmed the presence of a serious drought event in 2019. In 2020 (above average wet year), D values were similar under various treatments (< 0.70) and the order of D values under fertilization treatments was different from that in 2017 and 2019 (Fig. 3d). Generally, D values under treatments were dependent on climate change, and the organic treatments (manure and NPK + straw) resulted in relatively higher D values, while NPK treatment resulted in the lowest D values in the normal wet year and dry year.

Fig. 3 The pattern of soil drought degree (D) under each type of long-term fertilization in the selected dry spell with continuous absence of rainfall **a** 2017/7/17–2017/7/31, **b** 2017/8/14–2017/8/24, **c** 2019/8/1–2019/10/10, and **d** 2020/8/25–2020/9/4



Soil aggregates and corresponding binding agents

The proportions of the various aggregate size classes differed across treatments over the 3 years (Fig. 4). In each year, the 2- to 0.25-mm aggregates were dominant for CK and NPK treatment, while > 5-mm aggregates were dominant for manure and NPK + straw treatments. The 2- to 0.25-mm aggregate percentage was significantly lower in fertilization treatment than in CK (34.1 to 45.6%) with an order of manure (17.1–25.2%) < NPK + straw (19.6–32.1%) < NPK (33.1–34.1%) < CK (Fig. 4). In contrast, the percentage of > 5 mm aggregates was significantly higher in fertilization treatment than in CK, with an order of manure > NPK + straw > NPK > CK (Fig. 4). The effects of fertilization treatments on > 5-mm and 2- to 0.25-mm aggregate size class also varied significantly with hydrological years. Finally, different aggregate size distributions resulted in various MWD values.

The SOC content decreased in aggregate size classes but did not significantly differ in climatic conditions for all treatments (Fig. 5). Amorphous Fe oxides (Fe_o) were significantly higher in < 2-mm aggregate size than that in > 2-mm aggregate size and was significantly lower in dry year 2019 than that in other years at the same aggregate size class (Fig. 5). The SOC in all aggregate size classes was significantly positively correlated with the MWD (Table 2). The Fe_o content in > 5-mm and 0.25- to 0.053-mm aggregate classes was also positively correlated with the MWD ($r=0.64^{**}$ and $r=0.56^{**}$, respectively) (Table 2).

Relationship between aggregate size classes and D

The 2- to 0.25-mm aggregate percentage was significantly negatively correlated with average *D* values with $r = -0.58$ in 2017, -0.64 in 2019, and -0.60 in 2020 (Table 3). In addition, aggregate percentages (0.25–0.053 mm) in 2019 and that (> 5 mm) in 2020 were also significantly correlated with *D* values. Generally, 2- to 0.25-mm aggregate played major roles in determining *D* values.

Discussion

Effect of SOC and Fe oxides on aggregate under fertilization over years

Our study highlighted the important effect of SOC and amorphous Fe oxides in the aggregates (> 5 mm and 0.25–0.053 mm) on highly weathered red soil aggregation (Table 2). This result was in line with the previous findings that tropical soil macro-aggregate stability was mainly affected by high contents of oxides (Fe, Al, and silicon) (Liu et al. 2013; Peng et al. 2015; Yin et al. 2016). Different degrees of variation in amorphous Fe oxides content in climatic conditions under fertilization treatments were another important reason for aggregation change in years.

In our study, aggregate size distribution varied with fertilization treatments due to variation of SOC and Fe oxide contents. The manure treatment had the highest contents of SOC and amorphous Fe oxides and thus promoted the highest macro-aggregate parentage and MWD (Fig. 5). The

Fig. 4 Soil aggregate size distribution and MWD under fertilization treatment during the selected dry spell in 3 years. Different lower-case letters indicate significant differences among aggregate size percentage under the same fertilizer treatment; different capitalized letters indicate significant differences of aggregate size percentage among fertilizer treatment under the same size of aggregate or significant differences of MWD among years under the same fertilizer treatment

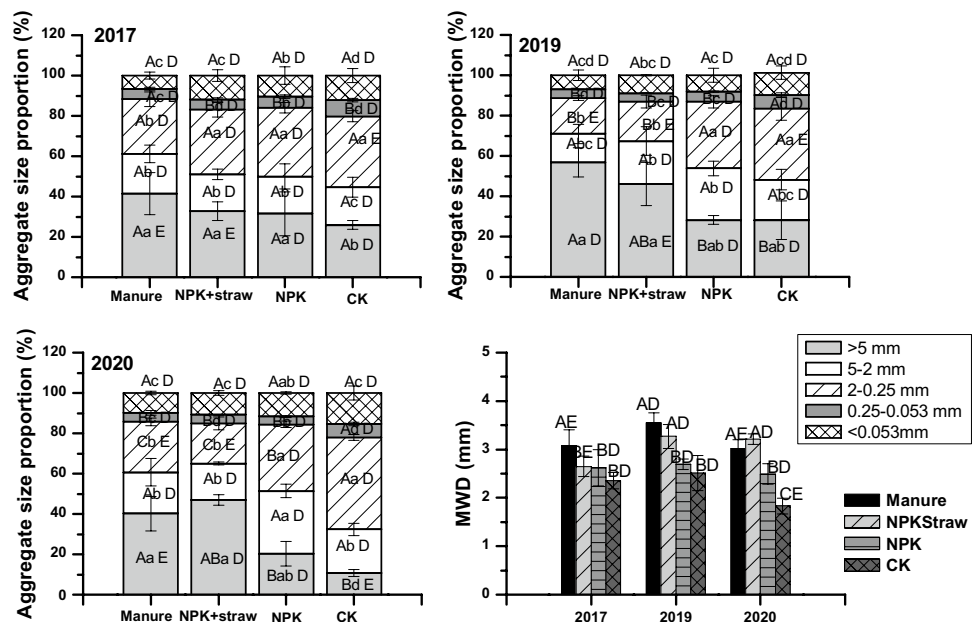


Fig. 5 The content of SOC and amorphous Fe oxides (Fe_o) on each size of aggregate under fertilization treatment during the selected dry spell over years. Different capitalized letters indicate significant differences of SOC or Fe_o content among fertilizer type under the same size of aggregate. Different lower-case letters indicate significant differences of SOC or Fe_o content among 3 years under the same treatment

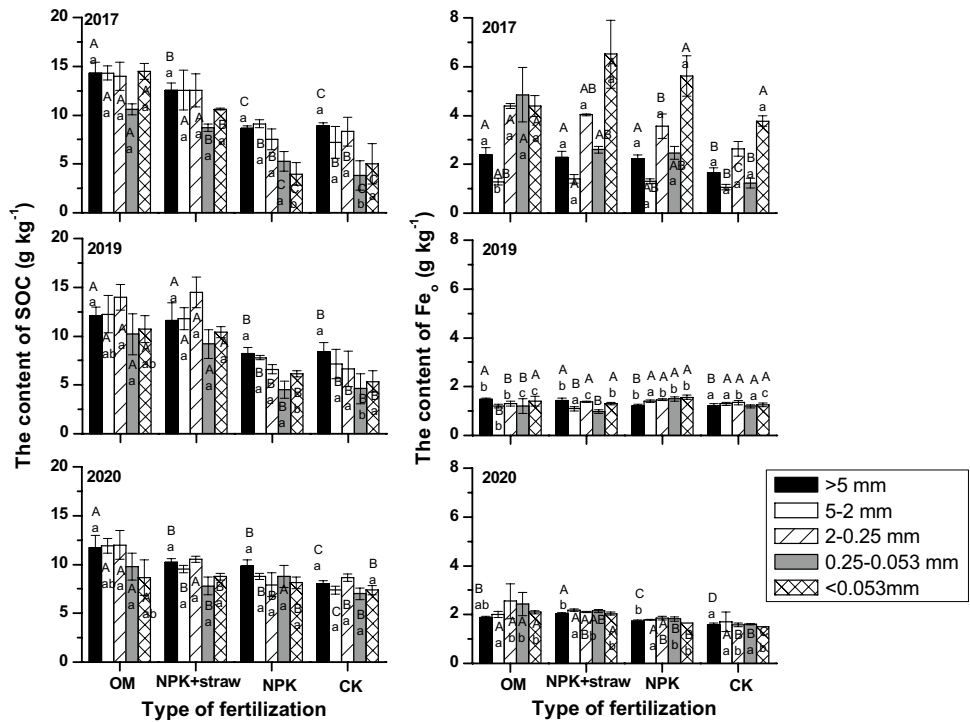


Table 2 Pearson correlation coefficients of the relationship between soil wet aggregate stability (MWD) and the content of the cementing agents (soil organic carbon (SOC), free-form iron oxides (Fe_d), chelated iron oxides (Fe_p), and amorphous iron oxides (Fe_o)) on each aggregate size fraction

Aggregate fraction (mm)	SOC	Fe _d	Fe _p	Fe _o
> 5	0.50**	0.44*	-0.12	0.64**
5–2	0.52**	0.38	0.23	0.30
2–0.25	0.54**	0.20	0.09	0.33
0.25–0.053	0.50**	0.15	0.13	0.56**
<0.053	0.49**	0.07	-0.11	0.08

*Significant when *p* < 0.05; ** significant when *p* < 0.01

results agreed with a previous study that showed that the oxides were the most important factor controlling the aggregate stability in Ultisols (Peng et al. 2015). High content of SOC after long-term manure treatment also might be the second most important factor stimulating red soil aggregation by indirectly generating organic-oxide complex (chelated Fe oxides) (Barbieri et al. 2014; He et al. 2019). Similar to manure treatment, the NPK + straw treatment resulted in similar high aggregate stability of red soil due to similar increment in contents of SOC and Fe oxides. The NPK treatment brought about low content of these binding agents, which was similar to CK, thereby resulting in similar aggregate size distribution and MWD in our study.

Aggregate size distribution also varied with hydrological years. Higher percentages of > 5-mm and 2- to 0.25-mm aggregates were observed in 2019 than in 2017 and 2020, which might be due to the fact that long duration of drought followed by abrupt wetting in 2019 promoted the transformation of the phases of Fe oxides and SOC, thus enhancing the formation of macro-aggregates and large pores. Firstly, the duration of continuous wetting or drying influences the content of amorphous Fe oxides (Fe_o) and SOC. Long period of soil waterlogging in a rice field has been reported to increase the content of amorphous Fe oxides from about one to hundreds of mg L⁻¹ (Kumar 1981). Similarly, long-term soil wetting resulted in a maximal increase by 214% in Fe_o, but soil drying led to a decrease by 60% in Fe_o in the same red paddy soil (Su et al. 2001). In our study, a 70-day continuous soil drying spell in 2019, rather than short-term drying spells in 2017 and 2020, would be a dominant reason for lower content of amorphous Fe oxides in 2019 than in 2017 and 2020 (Fig. 5). A long drying event in dry year 2019 also likely resulted in the lower content of SOC (Fig. 5) and its weak impact on aggregate size (Table 2), probably because abrupt rainfall after long period of drought stimulated the soil respiration rate rapidly to reduce the content of SOC (Wang and Cao 2020). Secondly, the moisture difference brought by wetting/drying cycles under fertilization treatments influenced Fe_o content due to different degrees of oxidation/reduction. Greater moisture difference under organic treatments contributed to lower content of Fe_o. This

Table 3 Pearson correlation coefficients of the relationship between aggregate size class %; wet aggregate stability (MWD); and the min, max, and average values of drought intensity (*I*) and drought degree (*D*)

Year	Aggregate size class %	<i>I</i> min	<i>I</i> max	<i>I</i> avg	<i>I</i> median	<i>D</i> min	<i>D</i> max	<i>D</i> avg	<i>D</i> median
2017	> 5 mm	0.36	0.43	0.40	0.40	0.41	0.30	0.34	0.34
	5–2 mm	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
	2–0.25 mm	–0.54	–0.60*	–0.57*	–0.57*	–0.59*	–0.47	–0.58*	–0.55*
	0.25–0.053 mm	0.18	0.07	0.12	0.12	0.09	0.28	0.21	0.20
	<0.053 mm	–0.49	–0.54	–0.52	–0.52	–0.52	–0.45	–0.48	–0.48
	MWD	0.43	0.51	0.48	0.48	0.49	0.36	0.41	0.41
2019	> 5 mm	0.22	–0.28	–0.26	–0.38	0.39	0.26	0.50	0.22
	5–2 mm	0.25	0.02	0.01	0.00	0.12	–0.31	–0.21	–0.25
	2–0.25 mm	–0.41	0.25	0.22	0.40	–0.56*	–0.32	–0.64*	–0.60*
	0.25–0.053 mm	–0.59*	0.55*	0.55*	0.69*	–0.77*	0.11	–0.75	0.10
	<0.053 mm	–0.18	0.53	0.53	0.54	–0.41	0.31	0.07	0.33
	MWD	0.34	–0.38	–0.35	–0.49	0.52	0.18	0.50	0.15
2020	> 5 mm	–0.72*	–0.67*	–0.77*	–0.80*	0.33	–0.75*	–0.69*	–0.69*
	5–2 mm	0.47	0.44	0.50	0.51	–0.17	0.49	0.46	0.46
	2–0.25 mm	0.63*	0.58	0.70*	0.73*	–0.46	–0.70*	–0.60*	–0.60*
	0.25–0.053 mm	–0.17	–0.18	–0.15	–0.14	–0.17	–0.16	–0.18	–0.17
	<0.053 mm	0.36	0.37	0.34	0.33	0.21	0.35	0.36	0.36
	MWD	0.73*	0.68*	0.78*	0.81*	0.35	0.76*	0.70*	0.70*

finding is supported by the findings of Li et al. (2021) which showed incorporation of O₂ to the soil with 70% water inhibited the conversion of crystalline Fe oxides into amorphous Fe oxides (Fe_o) due to good oxidation. Therefore, the low content of amorphous Fe oxides and slightly lower content of SOC would be responsible for the lower percentage of 2- to 0.25-mm aggregates in 2019 than in 2017 and 2020.

Influence of aggregates on soil drought degree with climate change

Long-term organic fertilization significantly increased FC than that in NPK and CK, but did not significantly improve the available water due to its slightly lower clay percentage. The soil drought degree was aggravated under organic treatments compared to NPK and CK in years 2017 and 2019, but opposite trend existed in above-average wet year 2020 (Fig. 3). This can be related with the aggregate properties among fertilizer treatments.

The difference in drought degree between fertilization treatments was related to the different properties of soil aggregates. Firstly, the decrease in soil macro-aggregate portion was reported to be responsible for an increase in water infiltration rate (Stehlik et al. 2019; Zhang et al. 2020). A low 2- to 0.25-mm macro-aggregate fraction after organic treatment might allow a fast surface soil water infiltration and surface water depletion. Secondly, the lowest percentage of 2- to 0.25-mm macro-aggregates under organic treatments was also probably responsible for

the increased water evaporation because soil evaporation was enhanced when soil aggregates are disintegrated (Peng et al. 2007; Li et al. 2017; Lal 2020). Disintegration of macro-aggregate changes soil pore architecture, thus modifying soil least limiting water range (LLWR), because the LLWR upper limits (field capacity, air-filled porosity) and LLWR lower limits (wilting point, soil resistance) are all pore-associated properties (de Moura et al. 2021). In our study, dominant 150- to 300- μ m-diameter pores in organic fertilizer-treated soils relative to 30- to 75- μ m pores in CK (Fig. S1) allowed greater water evaporation during drought period and wetting/drying cycles (Kursar et al. 1995; Reynolds et al. 2009; Ma et al. 2015). With the wetting/drying cycles continue, these large pores would become more rigid in organic-treated soils due to decreased shrinkage index (Peng et al. 2007), allowing preferential evaporation of water in pores (around 100 μ m) (Smith et al. 2017). Similarly, Lu et al. (2019) have reported that high proportion of the pores with high soil pore throat area, pore channel length, and pore network diameter under pig manure treatment are favorable for water evaporation and infiltration.

Our data indicated that the effect of fertilization on *D* depended on the climate change. In dry year (2019), *D* values were obviously influenced by fertilization types with the order of manure > NPK + straw > CK > NPK ranking in terms of *D* values (Fig. 3). In dry year, sudden rainfall after long-term drought can stimulate the soil respiration rapidly to greatly reduce SOC (Wang and Cao 2020) and amorphous

Fe oxide content (Kumar 1981), probably resulting in low aggregate (2–0.25 mm) stability and high soil water loss under organic treatments. The effect of slightly higher clay percentage under NPK on decline in water depletion rate and lower *D* values overtook the effect of aggregate on *D*.

Climate change modified the effect of organic matter on soil aggregate pores and soil water retention. In our study, although SOC content in each particle-sized aggregate showed no significant changes over the 3 years, there existed differences in SOC functional group percentages among various particle-sized aggregates, and SOC functional groups can regulate soil water hydrophobicity and soil water storage (Rasool et al. 2010; Zheng et al. 2021). In our study, the ratios of hydrophobic-C to hydrophilic-C were small and were about 1.08 for NPK + straw treatment and 1.04 for other treatments (Supplemental Table S1). But a small change of hydrophobic-C/hydrophilic-C might result in substantial change in soil water, as reported in Qu et al. (2019) that the increase of ratio of hydrophobic-C/hydrophilic-C from 1.04 to 1.07 for chicken manure treatment was accompanied with a great soil water variation. Besides, the hydrophobic groups of organic carbon have been reported to point outward, thus aggravating soil water repellency with the extension of drought time (Mamedov et al. 2016; Vogelmann et al. 2017), indicating that water repellency might play an important role in determining the rate of soil water loss.

Long-term organic fertilization generally resulted in faster developing rate of *D* and higher *D* values than inorganic treatment in the red soil, which might be attributed to the low percentage of 2- to 0.25-mm aggregates, and this low percentage might further be due to the low amorphous Fe oxides and SOC in dry year. As reported by Chen et al. (2010), when *D* values were above the threshold values of 0.68 and 0.70 in consecutive drought, maize yield was seriously impaired. In our study, under NPK + straw, manure, NPK, and CK, it took about 10, 20, 30, and 30 days for *D* values to go beyond 0.70, respectively, indicating that organic fertilization promoted faster increase in *D* values in seasonal drought. Our results suggested that the index of *D* value will be helpful in the red soil management in subtropical areas to promote sustainable land use. However, it should be noted that the index *D* has its limitation for predicting intermittent seasonal soil drought.

Conclusions

Manure and NPK + straw treatments resulted in a greater SWC variation than NPK and CK. The *D* values based on SWC depletion varied with fertilization treatments and climatic conditions. *D* displayed higher values under organic treatments than under inorganic treatments in normal wet

year 2017 and dry year 2019, but an opposite trend was observed in above average wet year 2020. The aggregate properties were responsible for the *D* variations, which was confirmed by a significant negative correlation between *D* and 2- to 0.25-mm aggregate size fraction. A decline in the proportion of 2- to 0.25-mm aggregates under manure and NPK + straw treatments relative to NPK and CK was responsible for the increased SWC variations and high *D* values in 2019. Under the organic treatments, the decline in aggregate (2–0.25 mm) portion might be attributed to the decline in the contents of amorphous Fe oxides and SOC in 2019 relative to other years. Generally, organic fertilization aggravated soil drought manifested by higher *D* values and its faster developing rate in normal wet year and dry year. This study provides reference for predicting soil fertility in response to climate change in terms of soil drought degree and SWC variation.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12517-022-09660-9>.

Acknowledgements Special thanks to Sihan Lai and Xiaoyan Wang who helped to analyze part of soils. The aid from the reviewers and editors to improve the paper is highly appreciated. Great gratitude goes to linguistic Prof. Ping Liu from Huazhong Agricultural University for her work at English editing and language polishing.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Mingxuan Yang, Bige Chen, Jiamin Zhao, and Waqar Ali. The first draft of the manuscript was written by Yangbo He and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This research was supported by National Natural Science Foundation of China (41601219, 2016) and the Hubei Provincial Natural Science Foundation (2019CFB517, 2019).

Data availability Data can be supplied if requested.

Code availability No software code.

Declarations

Consent to participate All authors agreed to participate.

Consent for publication All authors agreed for publication.

Conflict of interest The authors declare that they have no competing interests.

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