Soil Biology & Biochemistry 43 (2011) 590–599

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

journal homepage: www.elsevier.com/locate/soilbio

Soil biophysical controls over rice straw decomposition and sequestration in soil: The effects of drying intensity and frequency of drying and wetting cycles

Shui-Hong Yao [a,c], Bin Zhang [a,b,*], Feng Hu [c]

[a] State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, P.O. Box 821, Nanjing 210008, PR China
[b] Key Laboratory of Plant Nutrition and Nutrient Cycling of Ministry of Agriculture of China, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, PR China
[c] Institute of Soil Ecology, College of Natural Resource and Environment, Nanjing Agricultural University, Nanjing 210079, PR China

ARTICLE INFO

Article history:
Received 19 May 2010
Received in revised form
22 November 2010
Accepted 24 November 2010
Available online 18 December 2010

Keywords:
Wetting and drying cycles
Microbial biomass
Microbial community
Organic matter decomposition
Soil pore-size distribution
Soil aggregation
Soil water repellency

ABSTRACT

Although it is well known that fluctuations in soil moisture affect the decomposition of organic matter, few studies have provided direct evidence of the underlying biophysical mechanisms. Cycles of wetting and drying (W/D) may not only alter soil pore structure, but also stimulate a proliferation of fungi, since these organisms are typically less affected by drought stress than bacteria, and hence the development of fungal-induced soil water repellency. The biophysical interaction between these processes is likely to influence the decomposition of organic matter amendments to soil and carbon sequestration. By using soil cores amended with rice straw, the objectives of this study were to determine the effects of drying intensity and frequency of W/D cycles on decomposition rate after rewetting, soil pore-size distribution, soil microbial biomass (SMB) and soil water repellency, and to assess their biophysical interaction. One W/D cycle consisted of wetting a soil core from the bottom for 1.5-days at −0.03 kPa followed by 1.5, 3.5 or 6.5 days of drying in open air at 25 ± 2.5 °C. This resulted in different intensities of drying and frequencies of W/D cycles over a 120-d incubation period. The decomposition rate decreased with repeated W/D cycles and increasing drying intensity, particularly between the 3rd and 9th W/D cycles. The SMB-C concentration and soil water repellency peaked at the 3rd W/D cycle. The peak size of the SMB-C concentration was larger in the drier soils and soil water repellency was significantly related to SMB-C concentration ($R = 0.57$, $P = 0.025$). The soil with the strongest drying treatment had a greater concentration of particulate organic carbon (POC) and the lowest C:N ratio in POC. Although the decomposition rate was significantly correlated to the concentration of soil organic carbon (SOC) ($P < 0.01$), POC ($P < 0.01$) and SMB-C ($P < 0.05$), stepwise regression analysis further identified that it was largely correlated to soil pore characteristics. The decrease in the decomposition rate in the drier soil was largely explained by the increase in macropores >300 μm in diameter ($R = 0.98$). The results suggest that an increased drying intensity or a longer duration of drying after rainfall or irrigation may favour SOC sequestration through inhibiting decomposition of amended residue. This may be due to the formation of macropores and their subsequent stabilization via fungal growth and fungal-induced soil water repellency.

1. Introduction

Multiple wetting and drying (W/D) cycles impose inconsistent effects on soil microbial activity. Many studies suggest that W/D cycles can accelerate organic matter decomposition relative to that under constant and optimum conditions (e.g. Miller et al., 2005; Wu and Brookes, 2005), while others demonstrate contradictory results (Franzluebbers et al., 1994; Mikha et al., 2005). Two main mechanisms on the substrate source of pulse decomposition have been debated in the literature: either microbial or non-microbial substrates supplied as pulses upon wetting (Xiang et al., 2008; Borken and Matzner, 2009). Microbial substrates include dead microbes (Bottner, 1985), microbial extracellular polymeric substrates (Bottner, 1985; Van Gestel et al., 1993) and intracellular osmo-regulatory solutes (Fierer and Schimel, 2003) released due to physiological responses of microbes to suddenly changed

* Corresponding author. State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, P.O. Box 821, Nanjing 210008, PR China. Tel.: +86 10 82106719; fax: +86 10 82106225.
E-mail address: bzhang@caas.ac.cn (B. Zhang).

0038-0717/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.soilbio.2010.11.027

environments. Non-microbial substrates become more available due to aggregate destruction (Hallett et al., 2001) and differential swelling (Cosentino et al., 2006). If the pulse decomposition results from microbial derived C, then this can lead to deceleration of soil organic carbon (SOC) loss with W/D cycling. If, however, the pulse in respiration is from increased availability of physically protected SOC, then this could have the net effect of accelerating decomposition and a decrease in SOC sequestration. Previous studies have shown either the microbial source dominating over the substrate source (Fierer and Schimel, 2003; Mikha et al., 2005), or the opposite (Miller et al., 2005; Wu and Brookes, 2005; Xiang et al., 2008). Some other work has shown the microbial source supply to be initially dominant, and later the substrate supply to be dominant (Saetre and Stark, 2005).

Multiple W/D cycles promote soil aggregation through physical and microbial processes. Wetting and drying cycles alter hydraulic stresses and then cause increases in soil rigidity and stability (Rajaram and Erbach, 1999) because of swelling and shrinkage in the soil volume (Mullins et al., 1992) and the rearrangement of soil particles and pores (Horn and Dexter, 1989; Li et al., 2004; Bresson and Moran, 2004). Drying suppresses the activity and biomass of soil microorganisms (Halverson et al., 2000) and may shift community structure towards a greater proportion of fungi, since these organisms are typically less affected by drought stress than bacteria (Jensen et al., 2003). Fungal growth may improve soil aggregation either through the direct binding effects of fungal hyphae (Kaiser et al., 2000) or the development of soil water repellency (Ritz and Young, 2004; Cosentino et al., 2006; Zhang et al., 2007). Soil water repellency has the indirect effect of diminishing slaking stresses from the build-up of air-pressure in soil pores (Piccolo and Mbagwu, 1999). Moreover, soil water repellency influences water distribution in soil (Bauters et al., 1998) and then induces spatial inaccessibility of SOC for water and microbes (Six et al., 2002; Von Lützow et al., 2006; Lamparter et al., 2009). Although soil water repellency was indirectly linked to soil organic matter decomposition, Piccolo and Mbagwu (1999) demonstrated that the addition of hydrophobic substances could reduce the CO_2 losses of an agricultural soil by 30%.

The soil pore system influences the accessibility of SOC to water and microbes due to its large heterogeneity and its influences on the location and distribution of microorganisms, water and air (Young and Ritz, 2000). Recent studies, either by regression analysis between pore volume and SOC concentration (Strong et al., 2004) or by comparing C mineralization rate of soils with contrasting pore volume and SOC concentration (Yoo et al., 2006a), suggest that the decomposition rate can differ among various pore-size classes. Strong et al. (2004) reported that the decomposition rate was fastest in intermediate sized pores of 15–60 μm. Slower decomposition rates in the macropores (60–300 or >300 μm) were attributed to limited microbial activity due to extreme desiccation (Strong et al., 2004; Yoo et al., 2006b). In water-filled micropores (<30 μm or <4 μm), decomposition was suppressed due to water saturation (Yoo et al., 2006b). Most work to date has considered the soil pore system to be static, but it is known to be dynamic with changes with repeated W/D cycles and drying intensity. Using X-ray tomography, De Gryze et al. (2006) measured changes in soil pore characteristics associated with W/D cycles and attributed these changes to observed fungal mediation. More intense drying or a longer duration after wetting may cause stronger stresses not only on soil physical structure (Le Bissonnais, 1996), but also on the microbial community (Fierer and Schimel, 2003).

There is contradictory evidence on the effects of the intensity or duration of drying on organic matter mineralization (e.g. Fierer and Schimel, 2002; Mikha et al., 2005; Miller et al., 2005; Zhang et al., 2007; Xiang et al., 2008). Most of these studies, however, did not control or measure changes in soil volumes during W/D treatments, so interpretation of the impact of changes in the soil pore systems is not possible. As a change in soil pore system may influence substrate availability and microbial processes, it may provide crucial evidence that explains why previous studies had inconsistent results. Pore structure changes may be a major mechanism controlling the effects of fluctuations in soil moisture on the decomposition and sequestration of organic matter in soil.

We hypothesized that changes in the soil pore system, soil microbial processes and their biophysical interaction associated with W/D cycles would influence the decomposition of organic matter amendments to soil. A degraded soil with little soil organic carbon was amended with rice straw. This alternative use of rice straw is preferred to burning in paddy fields, which has become a serious problem in Southeastern Asia due to the immediate release of smoke and CO_2 to the atmosphere. Soil cores filled with the soil–rice straw mixture were subjected to different drying intensities and frequencies of W/D cycles during an incubation experiment lasting 120 days. By using the constrained soil cores amended with rice straw, the objectives of this study were to determine the effects of drying intensity and frequency of W/D cycles on the decomposition rate after rewetting, soil pore-size distribution, soil microbial biomass (SMB), and soil water repellency, and to assess their biophysical interaction. The overarching aim was to advance our understanding how soil moisture fluctuations due to changes in rainfall pattern associated with climate change and irrigation schedule may influence SOC dynamics, and the underlying mechanisms.

2. Materials and methods

2.1. Research site and soil core preparation

Soil was sampled near the Ecological Experimental Station of Red Soil, Chinese Academy of Sciences in Yingtan, Jiangxi Province of China (116° 5′ 30″E, 28° 5′ 30″N). The average annual rainfall at the station is 1785 mm, about 50% of which falls from March to early July. The soils in the region are subjected to frequent cycles of wetting and drying and severe drought in the dry season.

Soil samples were taken from 0 to 100 mm depth in the A horizon of land that has been cropped with peanut (*Arachis hypogaea* L.) for over 10 years. The soil derived from Quaternary red clay and was classified as an Alumi-Orthic Acrisol according to FAO/UNESCO (1988) or Udic Kandiusltults according to USDA soil taxonomy (Soil Survey Staff, 2010). It has a SOC concentration of 3.6 g kg^{-1}, pH in water of 5.4 and is rich in clay (455 g kg^{-1}) and sesquioxides, with a concentration of iron oxides of about 60 g kg^{-1}. The dominant clay minerals are kaolinite with some hydromica and vermiculite. Air-dried soil and rice straw passed through a 2-mm sieve were thoroughly mixed at a rate of 30 g straw kg-$soil^{-1}$. The application rate of rice straw in the upland soil corresponded to about one quarter of rice straw production per hectare in a typical rice paddy field. The rice straw contained 370 g organic C kg^{-1}, and 10.1 g-N kg^{-1}. The soil–rice straw mixture was filled into 100 cm^3 cylinders (23 mm in diameter and 59 mm high) by every 10 mm depth and compacted with a flat-face piston to a bulk density of 1.2 Mg m^{-3}. The bulk density was similar to the field condition at sampling. The bottom ends of soil cores were covered with nylon nets with 50-μm apertures.

2.2. Incubation experiment

The experimental treatments and sampling intervals are listed in Table 1. There were three different intensities of drying, coupled with sampling after different numbers of wetting and drying cycles.