Biophysical controls over mineralization and sequestration of amended organic carbon in soil: Effects of intensity and frequency of drying and wetting cycles

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Abstract
Global climate change may enhance temporal and spatial variability of precipitation, which would likely increase frequency, intensity or both of wetting and drying (W/D) cycles in soils and then affect organic matter mineralization and SOC sequestration, but the direction of the change is still unclear. The objectives of this study were to assess the long-term effects of frequency and intensity W/D cycles on (1) soil water retention and pore size distribution, (2) main microbial agents and soil water repellency (3) organic matter mineralization rate and C sequestration. Soil physical properties such as porosity and pore size distribution, soil water content near saturation (-0.03 kPa) and soil microbial properties such as, soil water repellency, microbial biomass and its C:N are strongly affected by the number and intensity of W/D cycles. The bio-physical properties were correlated from each other and Soil mineralization rate of amended rice straw were also significantly correlated to the physical and biological properties. Such interaction resulted in the particulate fraction of organic carbon in soil being affected by the intensity of W/D cycles, suggesting that the increasing intensity of W/D cycles would enhance carbon sequestration through soil aggregation in a long run although it stimulates the Birch effect for a short time.

Key Words
Birch effect, W/D cycles, carbon sequestration, global climate change, soil biophysics

Introduction

Sequestration of soil organic carbon (SOC) has been considered as an important strategy to mitigate global climate (Lal, 2004). Many studies have been done on the rate and potential of SOC sequestration as affected by land use and soil management. However, the effect of global climate change on SOC sequestration is unclear. As model simulation predicted (IPCC, 2007), global climate change does not only cause the global warming, but also likely enhance the temporal and spatial variability of precipitation. The enhanced temporal and spatial variability of precipitation would likely increase frequency, intensity or both of wetting and drying (W/D) cycles in soils. Rewetting a dry soil causes a pulse of respiration (the "Birch effect"; Birch, 1958) and that the specific moisture status of soils is a key factor controlling organic matter decomposition (Orchard and Cook, 1983). Therefore, such increases in frequency and/ or intensity of W/D cycles in soils may affect organic matter mineralization and consequently SOC sequestration, but the direction of the change is still unclear (Borken and Matzner, 2009). Two mechanisms of the Birch effect should have dramatically different effects on SOC dynamics, particularly through multiple W/D cycles (Xiang et al., 2008). The microbial biomass mechanism suggests a reduction in SOC mineralization and an increase in SOC sequestration over time, while the substrate supply mechanism suggests an increase in the amount of SOC available to microbial attack and a decrease in SOC sequestration potential over time. Multiple W/D cycles can promote soil aggregation through both physical and microbial processes (Tisdall and Oades 1982), which has been considered as important mechanisms for physical sequestration of SOC (Six et al., 2002) because it can cause spatial inaccessibility of SOC for water and microbes (Lamparter et al. 2009). However, there are few supportive studies that demonstrate the feedback effects of soil aggregation on organic matter mineralization and the concomitant effects on SOC sequestration. We hypothesized that frequency and intensity of W/D cycles affect the microbiologically mediated soil aggregation, which in turn influences organic matter decomposition and physical protection of organic C through modification of soil pore size distribution. With extending incubation time to 120 days, the objectives of this study were to assess the long-term effects of frequency and intensity W/D cycles on (1) soil water retention and pore size distribution, (2) main microbial agents and soil water repellency (3) organic matter mineralization rate and C sequestration.

Methods

Soil sampling and core preparation

A soil derived from Quaternary red clay (Alumi-Orthic Acrisol or Udic Kandiusltult) was sampled, ground (<2 mm), air-dried and mixed with rice straw at a rate of 30 g straw/kg-soil. The mixture was filled into 100 cm^3 cylinders (46.4 mm in diameter and 59 mm high) to the field measured bulk density (1.2 Mg/m^3). The soil cores were covered at the lower end with nylon nets with 53 µm apertures for pre-incubation during which period the soil cores were placed sand box at a -0.03 kPa water potential for 7 d at 25°C to reduce priming effect and ensure the same initial conditions before the incubation experiment under wetting and drying cycles (W/D). W/D cycles were performed for a 1.5-*d* wetting at -0.03 kPa following with 1.5, 3.5 or 6.5- *d* drying, resulting in 40-W/D cycles in low drying intensity (S-LD), 24-W/D cycles in middle drying intensity (S-MD) and 15-W/D cycles in strong drying intensity (S-SD) treatments. Wetting was carried out from the bottom surface in airtight 1100 ml jars filled with 100 mm deep sand and with a -30 mm water table where soil respiration rate was measured. Drying was carried out in open air at 25 °C in the temperature controlled laboratory after the soil cores were moved out of the jars.

Incubation and experimental treatments

Three fixed soil cores before and after wetting on the sand table (-30 mm) were weighed and used to measure mineralization rate (SRR) at the sampling intervals. A set of nine soil cores were randomly sampled to ensure triplicates for each measurement at the same interval. The sampling was more frequent at the earlier stage than the later stage during the incubation period as changes in microbial activity and soil porous structure were expected to be stronger at the earlier stage. A set of three soil cores was used to measured soil microbial biomass (SMB) C and N, while another set of three soil cores was used first to measure soil water repellency (SWR) and then sampled to measure soil organic carbon (SOC), dissolved organic matter (DOC) and particulate organic carbon (POC). The remaining three soil cores were reserved in sealed, cool and dark condition till the end of the incubation to measure soil core volume and then soil water retention curve (SWRC) for calculation of pore size distribution.

Measurements

Soil cores after wetting at -0.03 kPa were weighed to calculate near saturation volumetric soil water content, θ_s as an indication of changes in soil pore characteristics. Soil core volume after drying was measured by determining changes in water volume after immersing the soil cores sealed with para film into pure water. The soil core volume measured was used to correct total soil porosity and porosities of different pore size classes. Soil pore size distributions are calculated from the water retention curves by applying Jurin's law The pore size classes were <1, 1-10, 10-30, 30-300 and > 300 µm corresponding to the soil water potentials of -300, -100, -60, -30, -10, -0.3 kPa for the soil water retention curve measurements.
To estimate soil respiration rate the evolved C-CO_2 trapped in 0.3 mol/L NaOH in the head space of the airtight jar was measured by titration with 0.1 M HCl following the addition of $BaCl_2$ (Bekku et al., 1997) during the 1.5 day rewetting period at the sampling times. The jars were vented every 12 hours by removing lids for about 2 minutes during the time when NaOH solution was replaced. Soil microbial biomass (SMB) C and N concentrations were measured using the chloroform fumigation-extraction method (Joergensen et al., 1995). SWR was then calculated following the approach of Hallett & Young (1999). Particulate fractionation of organic carbon was performed using a dense solution (1.8 Mg/m^3) following Sohi et al. (2001).

Results

Volumetric shrinkage of soil cores occurred along the metal ring wall within early 70 days of the incubation period and the magnitude of shrinkage followed the order S-SD> S-MD>S-LD. The median pore size fractions (10-30 µm) decreased with the increasing number of W/D cycles. The fractions of 30-300 and < 10 µm were conversely correlated with each other and to θ_s (Figure 1).

SRR during rewetting decreased over time during the incubation period (Figure 2) and the decay fitted well ($R^2 > 0.94$) to the first order exponential function. The estimated basal decomposition rate and decreasing amplitude was not influenced by drying intensity, but the decay constant was very significantly ($P < 0.01$) lower for S-LD than S-MD and S-SD, between which there was no significant difference.

SMBC and SWR correspondingly changed with increasing number and intensity of W/D cycles (Figure 3). SWR and SMBC in all treatments were significantly correlated when the SMB-C measured at the first wetting was not included (R^2 =0.80, $P < 0.001$).

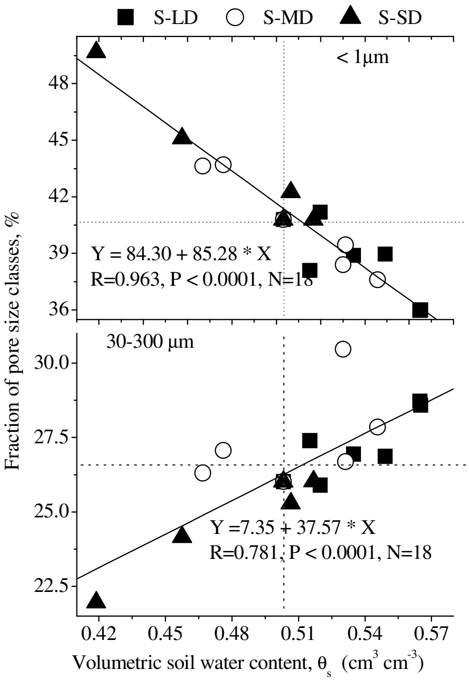

Figure 1. (Left). Percentage of different soil pore size classes (<1, 1-10, 30-300 and > 300 μm) in total porosity in relation to near saturated volumetric soil water content (-0.03 kPa), θs during incubation time and for the W/D treatments with low (S-LD, square), middle (S-MD, void circle) and strong (S-SD, triangle) drying intensity. The dot lines indicated the initial values θs and percentage of pore classes.

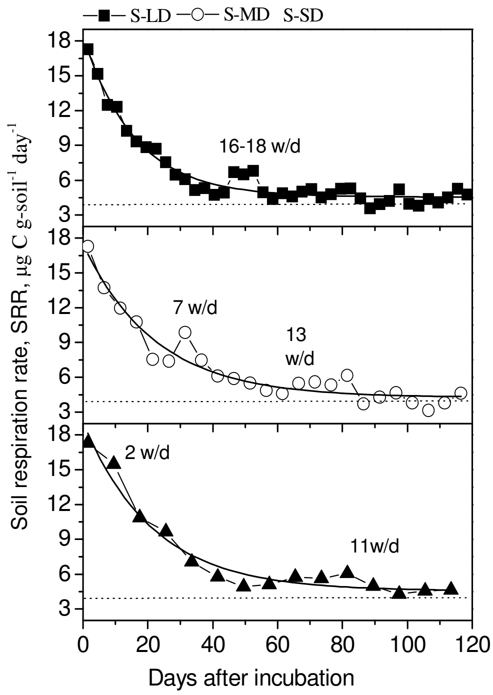

Figure 2. (Right). Soil respiration rate during the incubation period and the fitted line following first order exponential function in the W/D treatments with low (S-LD, upper, square), middle (S-MD, middle, void circle) and strong (S-SD, lower, triangle) drying intensity.

DOC content was constant during the incubation period. Both POC and SOC contents decreased over time and the dynamics were affected by drying intensity (Figure 4). The final POC content was greater in S-SD than in S-MD S-L. The final SOC content was greater in S-SD than in S-LD and S-MD.

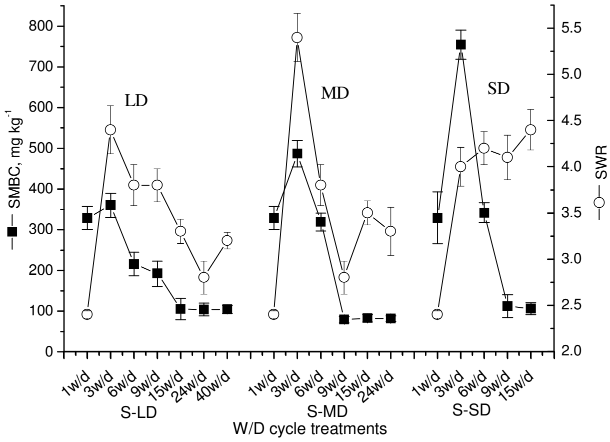

Figure 3. (left). Dynamics of soil microbial biomass carbon (SMBC) and soil water repellency (SWR) during the incubation period in the W/D cycle treatments with low (S-LD, left column), middle (S-MD, middle column) and strong (S-SD, right column) drying intensity.

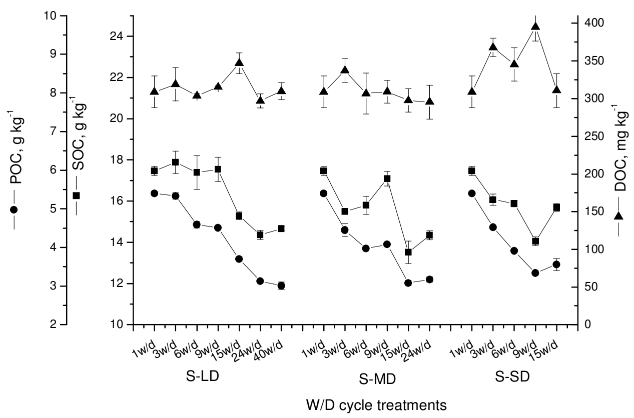

Figure 4. Dynamics of particulate organic carbon (POC), total soil organic carbon (SOC) and dissolved organic carbon (DOC) during the incubation period in the W/D cycle treatments with low (S-LD, left column), middle (S-MD, middle column) and strong (S-SD, right column) drying intensity.

SRR was significantly correlated to microbial biomass. SRR can be positively correlated to POC and negatively to SOC and DOC (SRR = 23.342-2.687 SOC-0.026 DOC+8.899POC, R2= 0.60. P = 0.003). In addition, SRR was also significantly affected by physical properties such as total porosity (R^2=0.86, P < 0.0001) and soil pore size distribution (Figure 5). In S-LD and S-MD, the decreases in SSR corresponded to the decreases in the fraction of < 1 μm pore class and the increases in the fraction of 30-300 μm pore class before the maximum θ_s (9th W/D cycles), while after the maximum θ_s, the reductions corresponded to the increases in the fraction of < 1 µm porosity and the decrease in 30-300 µm pore class.

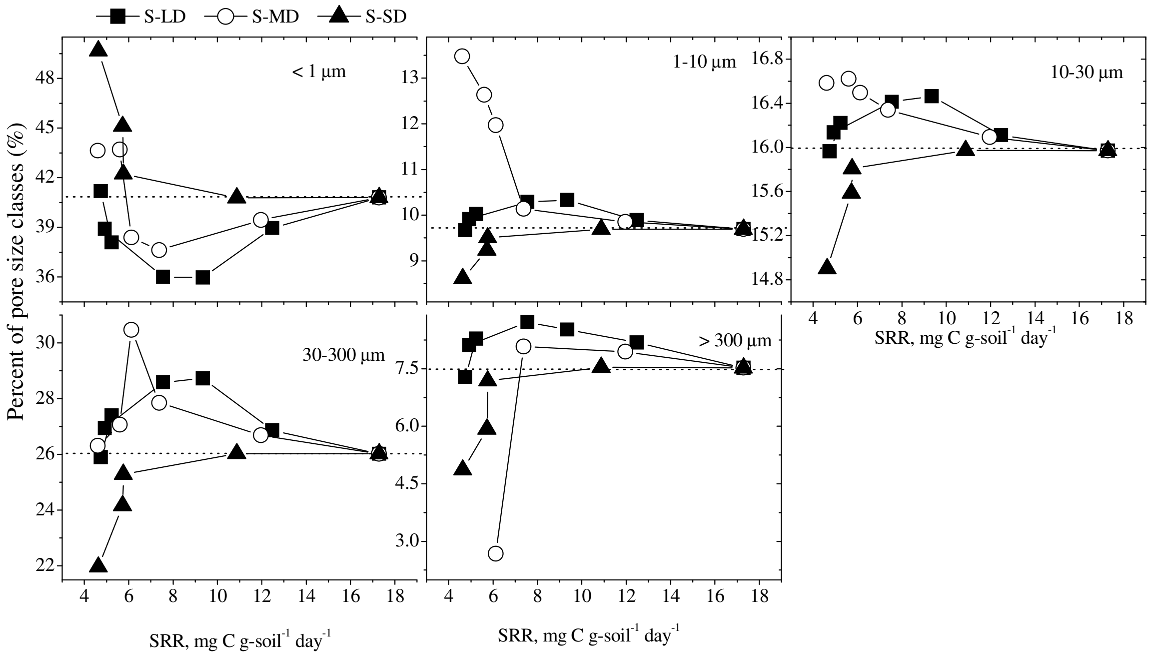

Figure 5. Fractions of the specified fractions of pore size class (<1, 1-10, 10-30, 30-300 and > 300 µm) in relation to soil decomposition rate (SRR) for the W/D treatments with low (S-LD, square), middle (S-MD, void circle) and strong (S-SD, triangle) drying intensity.

Conclusion

This study highlighted that the biophysical interaction during soil aggregation was affected by the number and intensity of W/D cycles. The increasing intensity of W/D enhanced the Birch effect at the early stage of incubation and physical protection of organic carbon after about two months due to increased micro-porosity (<1 µm). The results suggested that that the increasing intensity of W/D cycles would enhance carbon sequestration through soil aggregation in a long run although it stimulates the Birch effect for a short time.

References

Birch, HF (1958) The effect of soil drying on humus decomposition and nitrogen. *Plant and Soil* **10**, 9-31.

Borken W, Matzner E (2009) Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. *Global Change Biology* **15,** 808-824

IPCC (2007) Climate change 2007: impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergroverrnmental Panel on Climate Change. (Eds.P. Parry, C Osvaldo, J Palutikof, P van der Linden, C Handson). Fourth Assessment Report. Cambridge, UK. P. 976.

Lamparter A, Bachmann J, Goebel M-O, Woche SK (2009) Carbon mineralization in soil: impact of wetting-drying, aggregation and water repellency. *Geoderma* **150**, 324-333.

Orchard VA, Cook FJ (1983) Relationship between soil respiration and soil moisture. *Soil Biology and Biochemistry* **15**, 447-453.

Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil* **241**, 155-176.

Sohi SP, Mahieu N, Arah JRM, Powlson DS, Madari B, Gaunt JL (2001) A Procedure for Isolating Soil Organic Matter Fractions Suitable for Modeling. *Soil Science Society of American Journal* **65**, 1121-1128.

Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. *Journal of Soil Science* **33**, 141-163.

Xiang SR, Doyle A, Hoden PA, Schimel JP (2008) Drying and rewetting effects on C and N mineralization and microbial activity in surface and subsurface colifornia grassland soils. *Soil Biology and Biochemistry* **40**, 2281-2289.