Long-term tillage effects on the distribution patterns of microbial biomass and activities within soil aggregates

X. Jiang a,b,⁎, A.L. Wright b, J. Wang a, Z. Li a

Purpose:

The effects of tillage on the interaction between soil structure and microbial biomass vary spatially and temporally for different soil types and cropping systems. We assessed the relationship between soil structure induced by tillage and soil microbial activity at the level of soil aggregates. To this aim, organic C (OC), microbial biomass C (MBC) and soil respiration were measured in water-stable aggregates (WSA) of different sizes from a subtropical rice soil under two tillage systems: conventional tillage (CT) and a combination of ridge with no-tillage (RNT). Soil (0–20 cm) was fractionated into six different aggregate sizes (<0.053, 0.053–0.25, 0.25–0.25, 0.25–4.76, 4.76–2.0, 2.0–1.0, 1.0–0.25, 0.25–0.053, and <0.053 mm in diameter). Soil OC, MBC, respiration rate, and metabolic quotient were heterogeneously distributed among soil aggregates while the patterns of aggregate-size distribution were similar among properties, regardless of tillage system. The content of OC within WSA followed the sequence: medium-aggregates (1.0–0.25 mm and 1.0–2.0 mm) > macro-aggregates (4.76–2.0 mm) > micro-aggregates (0.25–0.053 mm) > large aggregates (>4.76 mm) > silt + clay fractions (<0.053 mm). The highest levels of MBC were associated with the 1.0–2.0 mm aggregate size class. Significant differences in respiration rates were also observed among different sizes of WSA, and the highest respiration rate was associated with 1.0–2.0 mm aggregates. The Cmic/Corg was greatest for the large-macroaggregates regardless of tillage regimes. This ratio decreased with aggregate size to 1.0–0.25 mm. Soil metabolic quotient (qCO2) ranged from 3.6 to 17.7 mg CO2 g−1 MBC h−1. The distribution pattern of soil microbial biomass and activity was governed by aggregate size, whereas the tillage effect was not significant at the aggregate scale. Tillage regimes that contribute to greater aggregation, such as RNT, also improved soil microbial activity. Soil OC, MBC and respiration rate were at their highest levels for 1.0–2.0 mm aggregates, suggesting a higher biological activity at this aggregate size for the present ecosystem.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Soil microorganisms live in an ecosystem dominated by soil particles which vary greatly in shape and size, and have complicated spatial arrangements and composition (Dexter, 1988). The spatial arrangement of solid particles results in a complex and discontinuous pattern of pore spaces of varying sizes and shapes filled with water or air (Chenu and Stotzky, 2002; Young and Ritz, 2000). Soil aggregates represent an ecological niche whose chemical and physical properties contribute to the heterogeneous distribution of microorganisms among aggregates of different sizes (Young et al., 2008). For example, microbial distribution patterns may be influenced by pore size associated with particular aggregates, or by differences in the clay and organic C content among aggregate-size classes (Van Gestel et al., 1996).

Agricultural land management is one of the most significant anthropogenic activities that alter soil characteristics, including physical, chemical, and biological properties and processes. Previous studies have shown that microbial biomass can be altered by changes in agricultural management practices (Angers et al., 1992; Elfstrand et al., 2007; Frey et al, 2007; Govaerts et al., 2008; Jackson et al., 2003; Liebig et al., 2006; Lauber et al., 2008; Schutter and Dick, 2002; Visser and Parkinson, 1992; Yao et al., 2006). Conservation tillage is a widely adopted practice to improve sustainability of agricultural ecosystems and reduce input costs. However, differences in soil structure and function often develop as a result of application of conventional tillage or reduce tillage regimes. Generally, microbial biomass is higher in soils under no tillage (NT) than conventional tillage (CT) management (Alvear et al., 2005; Bausenwein et al., 2008; Feng et al., 2003; Kandeler et al., 1999; Spedding et al., 2004; von Lutzow et al., 2002). However, tillage effects on the distribution pattern of microorganisms associated with soil structure are not widely reported (Bronick and Lal, 2005; Väisänen et al., 2005). Furthermore, results vary

⁎ Corresponding author at: College of Resources and Environment, Southwest University, 2 Tiansheng Road, Beibei, Chongqing, 400715, China.
E-mail address: jiangxj@swu.edu.cn (X. Jiang).

0341-8162/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.catena.2011.06.011
greatly due to changes in climate, soil type, especially texture and dominant mineralogy. The content and activity of microbial biomass can be higher in macroaggregates (Beauchamp and Seech, 1990; Franzluebbers and Arshad, 1997; Gupta and Gemruda, 1988; Lupsway et al., 2001; Miller and Dick, 1995; Singh and Singh, 1995), but also concentrated in microaggregates (Jocoteur et al., 1991; Kanazawa and Filip, 1986; Kandeler et al., 2000; Sessitsch et al., 2001; van Gestel et al., 1996).

Further research is needed, however, to determine how tillage-induced changes in the soil environment shape microbial biomass and activity in agro-ecosystems (Bronick and Lal, 2005). The aim of the present study was to evaluate soil microbial biomass and activities associated with soil aggregates under different tillage management in a sub-tropical purple rice soil to ascertain causative factors influencing the activity of soil microorganisms.

2. Materials and methods

2.1. Tillage systems and soil sampling

The experimental station is located in southwestern China (30° 26' N, 106° 26' E). Annual mean temperature ranges between 14 and 19 °C and mean rainfall between 1000 and 1400 mm. The field experiment was established in 1990 on a hydric Anthrosol (FAO/Unesco, 1988) at Chongqing, southwest China. Basic soil properties (0-20 cm) are: pH (H2O) = 7.1, organic C = 21.7 g kg\(^{-1}\), total N = 1.7 g kg\(^{-1}\), total P = 0.8 g kg\(^{-1}\), and total K = 22.7 g kg\(^{-1}\). The field was planted with rape (Brassica napus L) in winter and rice (Oryza sativa L) in summer, with crop residues returned to the soil.

Two tillage systems were compared: conventional tillage (CT) and a combination of ridge with no-tillage (RNT). Tillage treatments were described in detail by Jiang and Xie (2009). Briefly, for RNT, no tillage was imposed on soil that was ridge tilled before the rice was harvested and tilled again before rape planting. The size distribution of plots was 4 x 5 m\(^2\) and the experiment was organized in a randomized complete block design (RCBD) with four replications.

Five surface soil samples (0-20 cm) were collected from each plot on October, 2008 (4 weeks after rape planting). Fractionation of soil aggregates was achieved using a wet sieving procedure (Wright and Upadhyaya, 1998; Chiu et al., 2006) with a small adaption. Field-moist soil was immersed in water on a set of five nested sieves (4.76, 2, 1, 0.25, and 0.053 mm) and shaken vertically 3 cm for 50 times during a 2 min period. The aggregates retained on each sieve were collected. The silt + clay fraction (<0.053 mm) was collected after centrifugation.

2.3. Microbial and chemical analysis

Soil microbial biomass C was determined by fumigation extraction (Anderson and Ingram, 1993; Vance et al., 1987) and K values of 2.64 was used for calculation of MBC (Vance et al., 1987). Soil organic C was determined by acid dichromate wet oxidation as described by Nelson and Sommers (1996). Soil respiration rate was assessed by measuring CO\(_2\) production by trapping respired CO\(_2\) in NaOH (Dahlin et al., 1997). All assays were performed in triplicate. Soil metabolic quotient was calculated as the soil respiration rate divided by microbial biomass C (Anderson and Domsch, 1990; Killham and Firestone, 1984). Data were subjected to ANOVA and mean values separated using Fisher’s least significant difference test at p<0.05. All statistical analyses were performed by SPSS statistical package.

3. Results

3.1. Size distribution of water-stable aggregates

The proportion of silt + clay (<0.053 mm) represented the greatest fraction of whole soil for CT, while macro-aggregates of 4.76–2.00 mm represented the greatest fraction for RNT (Table 1). Approximately 13% of large aggregates are broken into smaller aggregates (from the class of 4.76–2 mm to the one <0.053 mm) by tillage. No significant difference between tillage regimes occurred for other sizes of aggregates, indicating that CT disrupted soil macroaggregates into microaggregates or individual particles.

3.2. Organic C of soil aggregates

The OC content within water-stable aggregates ranged from 7.5 to 32.2 g kg\(^{-1}\) (Fig. 1). The size distribution patterns of OC were similar between RNT with the highest values were associated with medium-aggregate (1.0–0.25 and 1.0–2.0 mm) fractions (32.2 and 21.9 g kg\(^{-1}\) for RNT and CT, respectively) and the lowest with the silt + clay fraction (9.0 and 7.5 g kg\(^{-1}\) for RNT and CT, respectively). For both tillage treatments, OC followed the sequence: medium-aggregates (1.0–0.25 and 1.0–2.0 mm) > macro-aggregates (4.76–2.00 mm) > micro-aggregates (0.25–0.053 mm) > large aggregates (>4.76 mm) > silt + clay fraction (<0.053 mm) (p<0.05).

Soil OC under RNT was significantly higher than under CT in most aggregates from 0.053 to 4.76 mm. However, no effect occurred in the smallest and largest aggregate sizes (Fig. 1). Organic C was ≈11 g kg\(^{-1}\) in >4.76 mm aggregates and 8–9 g kg\(^{-1}\) in <0.053 mm aggregates.

<table>
<thead>
<tr>
<th>Aggregate size (%) of soils under RNT and CT.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tillage</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>RNT</td>
</tr>
<tr>
<td>CT</td>
</tr>
</tbody>
</table>

* Values with different letters in columns indicates significant differences (p<0.05).

Fig. 1. Soil total organic C associated with different sizes of aggregate under RNT and CT (RNT, combines ridge with no-tillage; CT, conventional tillage).
3.3. Microbial biomass C within soil aggregates

The distribution patterns of MBC associated with different sizes of aggregates under RNT and CT showed similar trends (Fig. 2). The highest MBC was observed in the 1.0–2.0 mm fraction (1025 and 805 mg C kg\(^{-1}\) for RNT and CT, respectively) and the lowest in the <0.053 mm fraction (390 and 251 mg C kg\(^{-1}\) for RNT and CT respectively). It is interesting to note the sudden decrease of MBC values in 1–0.25 mm aggregates (511 and 353 mg C kg\(^{-1}\) for RNT and CT respectively). Statistical analysis showed that MBC was significantly higher for RNT than CT for all aggregate size fractions (p<0.05).

3.4. Respiration rate of soil aggregates

Soil respiration rate ranged from 2.5 to 12.1 mg CO\(_2\) kg\(^{-1}\) h\(^{-1}\) (Fig. 3). Although soil respiration rates were heterogeneously distributed within different sizes of WSA, similar trends in aggregate-size distribution were observed under RNT and CT. The highest respiration rate occurred for 1.0–2.0 mm aggregates (10.0 and 12.1 mg CO\(_2\) kg\(^{-1}\) h\(^{-1}\) for RNT and CT respectively), while the lowest respiration rates occurred for micro-aggregates of 0.25–0.053 mm (2.5 and 3.3 mg CO\(_2\) kg\(^{-1}\) h\(^{-1}\) for RNT and CT, respectively).

3.5. Ratio of soil MBC to soil OC within aggregates

Soil MBC represented 1.6–6.8% of total soil OC in the present study (Fig. 4). While significant differences of \(C_{\text{mic}}/C_{\text{org}}\) occurred among different sizes of WSA for both tillage treatments, the size distribution patterns were similar. The highest values corresponded to the largest aggregates, >4.76 mm, (8.8 and 5.4% for RNT and CT respectively) and the lowest to the aggregate size of 1.0–0.25 mm (1.6 and 1.7 for RNT and CT, respectively).

3.6. Microbial metabolic quotient (q\(\text{CO}_2\)) within soil aggregates

Fig. 5 shows that q\(\text{CO}_2\) within soil aggregates ranged from 3.6 to 17.7 mg CO\(_2\) g\(^{-1}\) MBC h\(^{-1}\). Similar distribution patterns of microbial quotient associated different sizes of aggregates were observed for RNT and CT. Higher levels of q\(\text{CO}_2\) were found for 1.0–0.25 mm, silt + clay fractions (<0.053 mm) and 2.0–1.0 mm aggregates, while
the lowest levels were associated with 0.25–0.053 mm and 4.76–2.0 mm aggregates under RNT and CT, respectively.

4. Discussion

This work reports data on soil OC, MBC and respiration rate associated with soil aggregates of different size under RNT and CT in a subtropical purple rice soil. While it was observed that OC, MBC, respiration rate and qCO₂ were heterogeneously distributed among soil aggregates of different sizes, their size-distribution patterns were similar between RNT and CT. The results indicated that the influence of the aggregate size on the soil properties considered was not affected by tillage.

The primary effect of tillage is to physically disturb the soil structure. Tillage usually disrupts soil aggregates and lowers TOC, CEC, nutrients that contribute to aggregation (Filho et al., 2002; Jiang and Xie, 2009; Jiang et al., 2011). The specific effect will depend largely on the disturbance that occurs at the spatial scale to which the microorganisms are most sensitive (Young and Ritz, 2000). Hernandez and Lopez (2002) reported that tillage had no significant effect on microbial biomass in soil microaggregates. Wright and Hons (2005) also reported that the tillage had no significant effects on the distribution of TOC in soil aggregates through 20 years of long-term management, and the distribution of microbial biomass in soil aggregates produced similar results (Elmholdt et al., 2008).

According to a hierarchical model proposed by Tisdall and Oades (1982), the formation of soil micro- and macroaggregates are different, yet interrelated processes. Free primary particles and silt-sized aggregates are bound together into micro-aggregates by persistent binding agents, oxides and highly disordered aluminosilicates. These stable micro-aggregates, in turn, are bound together into macro-aggregates (>0.25 mm) by temporary (i.e. fungal hyphae and roots) and transient (i.e., microbial- and plant-derived polysaccharides) binding agents. Because of this hierarchical order of aggregates and their binding agents, the quantity and quality of readily mineralizable organic matter may be different depending on the aggregate size. Secondly, the rate of O₂ diffusion is directly related to distance (aggregate radius), and O₂ concentrations are assumed different for different aggregate sizes (Kremen et al., 2005; Sexstone et al., 1985). This rate of diffusion and O₂ availability as affected by tillage influences the soil respiration rate. Other evidence may substantiate our speculation, such that similar patterns of soil pore-size distribution occurred under RNT and CT (Shi et al., 2008). The present results suggest that the size-distribution patterns of soil TOC, MBC, qCO₂ and respiration rate were governed by the size of aggregates, whereas tillage regimes that contribute to greater aggregation, such as RNT, affect soil microbial biomass and activity. Microbial biomass C in all aggregate sizes was significantly higher under RNT than CT, which may imply that RNT was the ideal enhancer of soil productivity for this subtropical rice ecosystem.

Heterogeneous distribution of microbial biomass has been reported (Beauchamp and Seech, 1990; Franzluebbers and Arshad, 1997; Gupta and Gemuda, 1988; Miller and Dick, 1995; Roy and Singh, 1994). However, great variability of microbial biomass associated with aggregates was observed. For example, several studies reported that microbial biomass was higher in macroaggregates than microaggregates (Elliott, 1986; Franzluebbers and Arshad, 1997; Jastrow et al., 1996; Lupwayi et al., 2001; Monreal and Kodama, 1997), while in other studies, higher microbial biomass levels and activities were observed in microaggregates (Kandeler et al., 2000; Mendes et al., 1999; Seech and Beauchamp, 1988; Sesitsch et al., 2001). These quantitative differences in MBC among different sizes of soil aggregates are thought to be related to soil organic matter (Alvear et al., 2005; Miller and Dick, 1995; Van Gestel et al., 1996;) and clay content (Alvear et al., 2005; Van Gestel et al., 1996). However, this seems unlikely in our study. The highest OC was observed in medium-aggregates including both 2.0–1.0 mm and 1.0–0.25 mm size fractions, and the highest levels of MBC were found for the 2.0–1.0 mm size fraction. However, MBC within 1.0–0.25 mm was at the second lowest levels under CT and RNT. Present results clearly demonstrated that Cmic/Cagg was at the lowest levels for 1.0–0.25 mm aggregates for both CT and RNT. Greater biomass in microaggregates has also been attributed to a larger percentage of clay in microaggregates (Van Gestel et al., 1996), but this seems unlikely in our study as MBC was quite low in the silt + clay fraction. Alternatively, it is possible that a substantial portion of the soil microbial biomass was disassociated from the surface of aggregates, especially when ultra-sonication or some chemicals were employed to disperse soil during the sieving process in some studies (Ashman et al., 2003; Kandeler et al., 1999; Van Gestel et al., 1996). A substantial portion of the soil microbial biomass is thought to live on or near the aggregate surface (Oades, 1984), which may explain the high MBC in microaggregates if they originated on macroaggregate surfaces.

Consistent with our results, higher soil OC associated with aggregates of 0.2–2.0 mm was observed earlier, and it was attributed to the non-active organic matter consisting mainly of plant residues (Kandeler et al., 1999; Schulten et al., 1993). However, when further separating this soil into 0.25–1.0 and 1.0–2.0 mm fractions, significant differences were observed. The highest levels of MBC occurred for the 2.0–1.0 fraction while MBC was the second lowest for the 0.25–1.0 mm size fraction. Furthermore, soil respiration rate was also significantly higher for the 1.0–2.0 than 0.25–1.0 mm size fraction under both tillage regimes. The basal respiration of the individual aggregate-size classes reflects the overall activity of the microbial community (Miller and Dick, 1995), which indicated there was a qualitative difference in microbial communities between the 1.0–2.0 and 0.25–1.0 mm size fractions. The lowest level of Cmic/Cagg was associated with 1.0–0.25 mm aggregates for both CT and RNT, which indicated the lowest substrate availability to microorganisms compared to other sizes of aggregates. The highly complicated spatial arrangement and composition of the solid particles results in heterogeneity of soil structure that may contribute to heterogeneous distribution of OC and microorganisms among aggregates of different sizes. Therefore, heterogeneous distribution of OC may lead to “hot-spots” of aggregation (Bronick and Lal, 2005). In the present study, soil OC, MBC and respiration rate were at their highest levels in 1.0–2.0 mm aggregates, suggesting that microorganisms inside of these aggregates are the most biologically active in the present ecosystem.

5. Conclusions

Soil OC, MBC, respiration rate, and metabolic quotient were heterogeneously distributed among soil aggregates while their size-distribution patterns were similar between the two tillage systems considered. The distribution pattern of soil microbial biomass associated with aggregates was likely governed by the size of aggregates, whereas the tillage effect was not significant at the aggregate-size scale. Tillage regimes, such as RNT, that contribute to greater soil aggregation also will improve soil microbial activity to aid in crop production. Heterogeneous distribution of OC and microbial biomass may lead to “hot-spots” of aggregation, and the present study suggests that microorganisms associated with 1.0–2.0 mm aggregates are the most biologically active in the present ecosystem.

Acknowledgements

We are grateful to the Natural Science Foundation of Chongqing, China (CSTC-2008BA1024) and Natural Science Foundation of China (No. 40501033). We wish to acknowledge useful suggestions by the reviewers and the editor.
References