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Changes in water stable aggregate and soil carbon accumulation in a no-tillage with weed mulch management site after conversion from conventional management practices☆

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ABSTRACT

Soil carbon (C) is crucial for maintaining soil functions, and it increases after conversion of an agricultural field from conventional tillage management to no-tillage management due to decreasing human-induced soil disturbance and the modification of soil structure through ecosystem engineers such as earthworms. To improve soils and prevent degradation, understanding the effects of no-tillage management over time in changing water stable aggregates (WSA) and soil C is important. We investigated the changes in WSA and soil C at a site in Akame, Mie, Japan, operating a no-tillage with weed mulch management (NWM) system over a chronosequence from 0 to 17 years after conversion from conventional tillage practices (NWM for 0, 5, 10, 15, and 17 years). We measured weed aboveground biomass, litter accumulation, and root and earthworm density and biomass, and analyzed the WSA and C of bulk soil and each WSA size fraction. Weed aboveground biomass increased with site age, while litter accumulation, root biomass (soil depth of 0–4 cm), and earthworm density and biomass did not appear to be related to site age. Endogeic earthworm density and biomass tended to increase at year 5 of NWM compared to year 0. The WSA >2 mm and soil C stock in WSA of >2 mm increased over time under NWM at a soil depth of 0–15 cm, while the soil C stock of 0.25–1-mm WSA decreased at soil depths of 0–5 cm. The total soil C accumulation rate was 60 g C m^{-2} yr^{-1} at a soil depth of 0–25 cm over the NWM chronosequence. Therefore, our results indicated that by adopting NWM, C inputs to the soil from weed aboveground biomass, as well as increases in the WSA of >2 mm, might be responsible for soil C sequestration.

1. Introduction

Soil organic matter (SOM) is important for the maintenance of soil functions, such as nutrient cycling, infiltration, and soil structure (Carter, 2002); however, carbon dioxide emissions from agricultural land have increased since the intensification of agriculture (Lal, 2004), and soil degradation has become a serious problem due to the decrease in soil carbon (C) (Bot and Benites, 2005; Lal, 2009). Soil C is decreasing rapidly due to anthropogenic soil disturbance from tillage and seeding (Luo et al., 2010). Therefore, increasing and maintaining the soil C content is necessary to ensure the sustainable use of croplands. Recently, conservation management practices, including no-tillage, mulching, cover crops, and fertilizer and manure application have attracted attention, as these management practices are known to increase levels of soil C and water stable aggregates (WSA) (Aoyama et al., 1999; Edmeades, 2003; Ludwig et al., 2011).

Soil aggregates are secondary particles bound to mineral particles with organic and inorganic substances (Bronick and Lal, 2005; Kemper and Rosenau, 1986). Soil aggregate formation is influenced by agricultural management, and a relationship exists between soil aggregate stability and certain soil functions, including nutrient supply and retention, and water permeability and retention (Carter, 2002; Holland, 2004). Soil aggregates are formed by the activities of soil animals, roots, and microorganisms, and exhibit varying degrees of water stability, as well as serving as indicators of the soil's structural stability. Tillage practices destroy soil aggregates, but WSA (>2 mm) increase when no-tillage management is adopted (Pinheiro et al., 2004; Shi et al., 2010). Pinheiro et al. (2004) studied the increases in WSA (>2 mm) and soil C under no-tillage management compared to conventional management. Shi et al. (2010) revealed that WSA (2–10 mm) decreased under tillage management compared to grassland due to repeated tillage. The WSA size distribution can be used to estimate the effects of land use changes on soil structure (Pinheiro et al., 2004). Agricultural management has been shown to alter the stability of macroaggregates (>0.25 mm) that affect soil C dynamics (Six et al., 2000). The maintenance of soil aggregate structure

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prevents the decomposition of soil C and thus contributes to an increase in soil C.

Changes in soil structure, as well as increases in soil C content and ecosystem engineers, in terms of soil animal abundance and biomass, occur after the conversion from conventional management to no-till management (Kladivko et al., 1997). “Natural farming” (Fukuoka, 1987) is a unique method based on four major principles: no cultivation, no fertilizer, no weeding, and no pesticides. This type of management is different from no-tillage, as it uses weeds for mulching after slashing the aboveground weeds and retains the roots intact in the soil. Luo et al. (2010) reported that the adoption of stubble retention or incorporation significantly increased soil C content for only 25 years. Herbicides have been used worldwide to restrict the growth of weeds under no-tillage management systems (Soane et al., 2012; Stockmann et al., 2013), but weed populations and density increase under no-tillage management compared with conventional management (Cardina et al., 1991; Spandl et al., 1999). Some studies on natural farming (i.e., no-tillage and weed mulch management: NWM) have shown that decreasing human-induced disturbance changed weed biomass and soil organism density and biomass (Arai et al., 2013; Miura et al., 2010). Additionally, changes in weed above- and belowground biomass in agricultural fields are known to influence soil C accumulation. Previous studies have found that soil C under fallow conditions increased or decreased due to variations in the weed above- and belowground input compared to conventional management (Luo et al., 2010; Shimoda and Koga, 2013). Therefore, studies to determine the effects of weed management without external inputs over time on soil C accumulation are necessary. NWM systems are beneficial for earthworms because the level of disturbance decreases and more food is provided as weed mulch than in conventional management systems. Many studies have indicated that earthworm density and biomass change under different agricultural practices (Chan, 2001; Fonte et al., 2009; Kladivko et al., 1997). However, few studies have investigated the effects of weeds on earthworm density and biomass under NWM.

NWM sites are usually covered by plant residue at the soil surface, and this soil condition is preferred by earthworms because it contributes to the formation of soil aggregates with fresh C inputs (Arai et al., 2013). Furthermore, above- and belowground biomass increases residue input and root activity, which enhance the formation of soil aggregates and the accumulation of soil C (Arai et al., 2013; Fonte et al., 2012; Luo et al., 2010; Six et al., 2004). The half-life of earthworm casts ranged from 2 to 11 months in pastures (trampled and protected, respectively; Decaëns, 2000); therefore, earthworm casts may affect the soil environment regardless of temporal changes in earthworm activity. Under NWM, the potential exists for an increase in biological factors involved in soil aggregate formation that may contribute to the accumulation of soil C compared to conventional management. Studies on soil aggregates in croplands under different management practices have been reported (Fonte et al., 2009; Riley et al., 2008), but no studies on the changes in soil aggregates, soil C, and biological factors over the NWM chronosequence have been reported. Earthworm biomass increased under no-tillage management in Japan, but earthworm recovery in agricultural fields was not easy after conversion from conventional management to no-tillage management (Arai et al., 2013; Miura et al., 2010). Therefore, studies are needed to determine the earthworm density and biomass under NWM.

Changes in soil aggregate formation, mediated by biological factors after conversion from conventional management to NWM, may contribute to improvements in soil C accumulation without external inputs. In this study, we focused on weed aboveground biomass, litter accumulation, and root biomass, as well as the density and biomass of earthworms following the adoption of NWM. We investigated 10 plots under NWM over a chronosequence from 0 to 17 years. We examined earthworm density, biomass, and species, weed aboveground biomass, litter accumulation, and root biomass; WSA size distribution and soil C at each WSA size; and changes in soil C abundance over the NWM chronosequence. We hypothesized that continuous NWM practice would increase above- and belowground weed biomass and then WSA size distribution and soil C accumulation would be influenced.

2. Materials and methods

2.1. Study site

The study site was a terraced field with an area of 2.7 ha located in Akame, Mie, Japan (34°35′N, 136°03′E). Monthly means of precipitation and daily temperature ranged from 38.5 to 273.1 mm and 1.9 °C to 24.4 °C, respectively. Annual averages in precipitation and temperature were 1581.4 mm and 15.9 °C, respectively, over the last 30 years (1981–2010). The soils were identified as gravelly yellow soils with mottling, which are classified as Alisols derived from sandy granite according to FAO/UNESCO. The soil physical and chemical parameters, such as pH (H_2O) that was determined by a 1:2.5 soil: H_2O suspension and soil texture, are shown in Table 1, and levels of exchangeable base cations (Ca, Mg, and K) were determined by Watanabe et al. (in preparation).

2.2. Land management and use

2.2.1. Natural farming (NWM)

The study sites are managed by Mr. Yoshikazu Kawaguchi, an expert on natural farming. Natural farming, which includes NWM, was first introduced by Fukuoka (1987) and later modified by several other farmers. Natural farming is a simple agricultural practice that involves minimal fertilizer application and weeding and relies on weed or mowed weed cover to prevent the exposure of a bare soil surface. The characteristics of the natural farming site in this study are as follows:

- No-tillage.
- No chemical fertilizer, only one application of rice bran or oil cake at the time of planting.
- No pesticide or herbicide.
- Weed control by mowing, with weeds used as living mulch.

We investigated the sites over a chronosequence of conversion from conventional cropping to natural farming (site age: 5, 10, 15, and 17 years), and sampling plots (0.9 m × 1.8 m) with two replications. Following conventional management, a site left fallow for a year was also investigated, and the site age was set as year 0. These sites had been paddy fields under conventional management prior to the commencement of natural farming management. For details on the management of conventional farming before the fallow period and NWM system was adopted, refer to the next Section. A variety of crops were grown with minimum weed control. The crops harvested in the summer were *Zea mays*, *Capsicum annuum* var. *angulosum*, *Zingiber officinale*, *Abelmoschus esculentus*, and *Solanum lycopersicum*, while those harvested in the winter included *Lactuca sativa*, *Allium fistulosum*,

Table 1
Soil pH (H_2O) and soil texture at each site (soil depth: 0–5 cm). S.D. of soil pH (H_2O) shows replication (n = 3) within each site.

Site age (years)	Replication	pH (H_2O)		Soil texture (%)		
		Mean	±S.D.	Clay	Silt	Sand
0	1	6.35	0.17	0.87	15	84
0	2	6.47	0.23	1.3	19	80
5	1	5.81	0.08	3.1	36	61
5	2	5.46	0.25	0.39	9	91
10	1	5.17	0.04	4.4	36	60
10	2	5.09	0.14	6.1	35	59
15	1	5.21	0.17	2.5	25	72
15	2	5.26	0.17	4.0	34	62
17	1	4.96	0.26	3.9	31	65
17	2	5.14	0.41	3.9	34	62