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Change in soil carbon in response to organic amendments in orchards and tea gardens in Japan

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ABSTRACT

Changes in total carbon (C) concentrations in topsoil were examined in response to organic amendments (OAs) in Japanese orchards and tea gardens at the farm level using 20 years of survey data. A rolling nationwide survey was conducted four times between 1979 and 1998. Each complete survey required approximately 5 years. In the tea gardens (n = 191), the proportion of strongly acidified soils (pH < 4) increased from 31% (1979–1983) to 69% (1994–1998). Large C inputs mainly resulted from trimmed branches in the spaces between the hedges. The concentration of C in the topsoils increased significantly, regardless of the initial soil C concentration, in the strongly acidic soils when mineral fertilizers containing nitrogen (N) were added at rates of 0.6 to 0.9 Mg ha^{-1} N. The soil C concentration increased by 2.0, 2.2, and 2.5 g kg^{-1} yr^{-1} at the non-Andosol sites with 'low pH' (soil pH was <4 over time), 'decreasing pH' (soils had a pH > 4 at the beginning of the survey but a pH < 4 at the end of the survey), and 'fluctuating pH' (soils had a pH that fluctuated above and below pH 4 over time), respectively. Soil C increased by 1.9 and 2.2 g kg^{-1} yr^{-1} at Andosol sites with 'decreasing pH' and 'fluctuating pH,' respectively. In contrast, in the orchards (n = 787) where the soil pH was adjusted to maximize plant growth, the long-term changes in soil C varied depending on the initial soil C concentrations. The initial topsoil C concentrations differed depending on the soil type and soil temperature. The soil C concentration increased by 0.2–0.3 g kg^{-1} yr^{-1} in the non-Andosol sites where the initial soil C level was low, but this increase was not significant. However, the soil C concentrations did not change at the Andosol sites where the initial soil C concentrations were high. The application of OAs did not differ significantly among the sites and did not vary significantly with time (with a few exceptions). Strongly acidic tea soils can potentially sequester large quantities of applied C, mainly from trimmed branches. Thus, tea soils are important for alleviating greenhouse gas emissions from tea gardens where large amounts of nitrous oxide have been emitted. Moreover, orchard soils with low initial soil C concentrations have the potential to increase soil C.

1. Introduction

Management practices that increase soil carbon (C) and enhance soil fertility while reducing erosion susceptibility include no-tillage, which is partly accomplished by the cultivation of perennial crops, the retention of crop residues and the application of organic amendments (OAs) (Eggleston et al., 2006; Freibauer et al., 2004; Lal, 1997; Reeves, 1997). In recent years, these management practices have received increasing interest because of their relevance in mitigating the effects of climate change (Lal, 2009).

Orchards and tea gardens are perennial crops that can be cultivated using a greater degree of no-till farming relative to annual crops. Intensive tillage and lower organic matter inputs reduce the content, quality, and function of organic matter in soils (Montanaro et al., 2010). Maintaining or enhancing soil fertility for sustainable food production is an important objective of agricultural policy (Canali et al., 2004; Dang, 2005; Glover et al., 2000; Montanaro et al., 2010; Neilsen et al., 2003). The pursuit of such an objective requires knowledge regarding whether and to what degree soil C changes are associated with a given cultivation method.

Many field experiments have been conducted to elucidate the long-term (4–7 years) effects of applying OAs on the soil C of orchards (Canali et al., 2004; Glover et al., 2000; Montanaro et al., 2010; Sekiya et al., 1983; Umemiya and Sekiya, 1985; Zhang et al., 2013). However, the results of these studies are inconclusive because orchard soil C is often related to the initial soil C levels (Glover et al., 2000; Umemiya and Sekiya, 1985). If the initial soil C level is close to reaching a new equilibrium, the soil C will not vary when OAs are applied (Powlson et al., 2012; Six et al., 2002; Stewart et al., 2008). Moreover, the

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responses of the soil to OA applications depend on the soil type (Sekiya et al., 1983), soil texture (Neilsen et al., 2003), moisture (Montanaro et al., 2012) and temperature (Batjes, 1999; Robert, 2001).

The soil C increases in tea gardens (Han et al., 2007; Pansombat et al., 1997) because large amounts of trimmed branches are applied to the spaces between hedges (Shiwa et al., 2012). The narrow spaces, which account for only one-sixth of the total area (Miura and Ae, 2005), result in more concentrated C application rates in tea gardens relative to those in orchards. Despite the high C inputs, the soil does not seem to be saturated, mainly as a result of the low soil pH. Large amounts of mineral fertilizer are applied to the spaces between the hedges to improve tea yields and quality (Han et al., 2007; Kosuge, 1982; Pansombat et al., 1997), which results in a decreasing soil pH (Han et al., 2007; Oh et al., 2006; Pansombat et al., 1997) that can reach values below the optimal conditions for tea growth (soil pH between 4 and 5.5). Due to excess nitrogen application, the ground water in tea gardens is contaminated with nitrate (Oh et al., 2006), and nitrous oxide (N_2O) emissions are increased. However, N_2O emissions have a global warming potential that is 298-fold higher than that of carbon dioxide over a 100-year time scale and are especially prevalent from strong acidic soils (Akiyama et al., 2006; Tokuda and Hayatsu, 2001). Therefore, information regarding soil C, especially in relation to soil pH, is important for better understanding the impacts of tea gardens on climate change and plant growth.

To date, knowledge of the relationship among long-term changes in soil C, the initial soil C concentrations and the application of OAs in orchards and between long-term changes in soil C and soil pH in tea gardens is limited at the farm level. It was hypothesized that the influences of applying OAs on soil C changes vary depending on the initial soil C concentrations in the orchards, where the soil pH values are adjusted for plant growth. However, in tea gardens, the soil C will increase regardless of the initial soil C level due to the low soil pH. Information regarding soil C changes in relation to management will be important for understanding carbon cycling and for establishing policies for soil management in farmlands.

This study examined changes in soil C in Japanese orchards and tea gardens between 1979 and 1998 using a national soil survey dataset. The national soil survey was initiated in 1979 by the Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF) to increase knowledge regarding soil properties (physical, chemical, etc.) and the long-term changes of these properties with the purpose of improving soil management (Nakai and Obara, 2003). In the survey, soil samples and questionnaires were collected from approximately 20,000 farmers using a rolling survey over 20 years. A new and complete set of data was produced approximately every 5 years, making it an extremely valuable dataset with respect to sample size and repetition over time.

2. Materials and methods

2.1. National soil survey dataset

A national soil survey was conducted by the Ministry of Agriculture, Forestry, and Fisheries of Japan (MAFF) in 1979. Between 1979 and 1998, soil samples and questionnaires were collected in four survey waves: Wave 1, 1979–1983, 19,425 sample points; Wave 2, 1984–1988, 19,021 points; Wave 3, 1989–1993, 18,875 points; and Wave 4, 1994–1998, 17,846 points.

From the survey dataset, we used data points for orchards (orange, peach, Japanese pear, apple, etc.) and tea gardens (2856 sample points in Wave 1, 2881 points in Wave 2, 2785 points in Wave 3, and 2601 points in Wave 4) and only selected growers who responded in each of the four consecutive surveys and provided soil C concentrations ($g\ kg^{-1}$). We eliminated data points that had surface layer depths that differed by ≥5 cm from those in the previous survey wave to reduce the influences of changing surface layer depth on soil C concentrations. However, an exception to this rule was made for the soils belonging to the Andosol group (IUSS Working Group WRB, 2006; Third Division of Soils, National Institute of Agricultural Science, 1982), in which the soil C concentrations changed little between the surface and subsurface soils. Consequently, we used 981 data points that were common to each wave. The average topsoil depths were 19.8, 18.4, 17.1, and 15.8 cm in Waves 1, 2, 3, and 4, respectively.

The survey was continued after 1999. However, the number of farmers that participated in the survey declined dramatically (e.g., in 1999–2004, there were only 295 growers who had participated in the survey in 1979). Moreover, the datasets did not always contain the same variables. For example, crop residue management surveys began after 1999 and data are missing for bulk density (in our study, bulk density data were available at 498 of the 981 data points). To obtain the largest possible number of samples, this study did not calculate the amount of C ($Mg\ C\ ha^{-1}$) by using bulk density values and did not analyze the data after 1999. Due to the lack of crop residue data, this study used data collected from the same farmlands that responded to this study between 1999 and 2004, except for tea gardens, where all available data were used due to the small sample sizes ($n = 91$). Because the data for this study were collected at different times (i.e., 1999–2004 rather than 1979–1998), we used conservative estimates when evaluating the influences of crop residue managements on soil C changes.

Soil samples were collected and analyzed from each farm by technicians at the MAFF agricultural experiment station of the prefecture in which the farm was located. At each point, three soil samples were collected, and equal weights of each sample were mixed thoroughly to obtain one composite sample. The total carbon concentration ($g\ kg^{-1}$) was obtained using the dry combustion method or the modified wet combustion method (Kosaka et al., 1959) which provides equivalence with the dry combustion method (Kosaka et al., 1959).

The application rates of the OAs and the mineral nitrogen fertilizer were obtained from the farmers that provided the soil samples. Because various types of OAs were applied throughout the survey waves, the application rates of the OAs were calculated by taking the sum of the livestock waste compost with/without sawdust or other OAs (e.g., rice straw compost, husks, sawdust or bark compost, green manure, rice or wheat straw residues, city refuse compost, sewage sludge compost, food processing industry waste, and industry waste).

2.2. Grouping data points according to soil type, soil pH, and soil temperature

Andosols typically contain high soil C concentrations (Batjes, 1999). Therefore, the data points were divided into two groups: Andosols and non-Andosols (other soil types).

The minimum soil pH for healthy mature trees is 4 (Matumoto et al., 2002). Soil pH values of <4 can be attributed to heavy mineral fertilizer application (Kosuge, 1982). Accordingly, the data points for tea gardens were divided into four ranges: 'high pH' with a pH of >4 for the duration of the wave, 'low pH' soils with a pH of <4 for the duration of the wave, 'decreasing pH' soils with a pH of >4 at the beginning of the wave and a pH of <4 at the end of the wave, and 'fluctuating pH' soils with a pH that fluctuated above and below 4 over time. The results are only shown for cases when the sample size was greater than 18.

Soil C is usually higher in cooler zones than in warmer zones (Batjes, 1999). The data points were divided according to the soil temperature regime. At the mesic sites, the mean annual soil temperature was greater than 8 °C but lower than 15 °C and a difference of more than 5 °C was observed between the mean summer and mean winter soil temperatures. At the thermic sites, the mean annual soil temperature was greater than 15 °C but lower than 22 °C, with a difference of more than 5 °C between the mean summer and mean winter soil temperatures. Because teas are mainly from thermic sites, the tea gardens were not divided in terms of soil temperature.