Soil Profile Alteration in a Brown Forest Soil under High-Input Tea Cultivation

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Soils in the tea (Camellia sinensis L.) gardens of Japan have distinctive properties as indicated by strongly acidic reaction, and high exchangeable acidity and high active-Al contents (Kawai and Morita, 1958a, b). Such uniqueness is primarily due to the long-term high-input farming systems (Kato et al., 2001). To enhance the quality and quantity of tea leaves, Farmers in Japan usually apply nitrogen fertilizers at a rate of more than 1.0 Mg N ha\(^{-1}\) yr\(^{-1}\), which results in severe soil acidification in the tea fields (Tachibana et al., 1995; Matsumoto et al., 2002). Heavy fertilizer application also causes chemical pollution in the agroecosystems and neighboring local environments through the leaching or erosion of applied nutrients (Kato et al., 2001). However, the high-input farming practice has been continued in spite of the environmental risks since tea plants prefer an acidic soil and are a source of dietary Al that is toxic for most of other plants (Yokota et al., 2005).

Lack of understanding of the process and magnitude of environmental deterioration under tea cultivation has made it difficult to explore alternative management practices. We, therefore, investigated the changes in physicochemical properties of soil profiles in a tea field using a chronosequence of cultivated soil series, which can provide useful information about alternative fertilization and soil management practices towards the sustainable tea farming in Japan.

Materials and Methods

The study site was at the Education and Research Center for Biological Resources of Shimane University (N35°30', E133°06') in Japan. Mean annual precipitation was about 1800 mm and mean daily temperature was 14.6°C (19.1/10.7°C of max./min. temp.) in the last 30 years. Geological components consisted of tertiary sedimentary rocks with some volcanic ash materials. The soil was classified into brown forest soils under the United Classification System of Japan and Ultisols according to the U.S. Soil Taxonomy. Soil texture was silty clay and the clay content gradually increased with depth (Hashi, 1999). Mineral constituents in the clay fraction consisted of kaolinite accompanied by illite, chlorite and smectite in addition to certain amounts of quartz (Abe et al., unpublished).

Soil samples were collected from 19- and 34-year tea fields (TF-19 and TF-34, respectively) in May 1998 and a neighboring native forest (NF-0) in 1997. Camellia sinensis L. cv. Yabukita, Asatsuyu and Yaeho were planted in 3000 m\(^2\) plots of TF-19 and TF-34. TF-19 and TF-34 received 0.7 t N ha\(^{-1}\) yr\(^{-1}\), 0.6 t P\(_2\)O\(_5\) ha\(^{-1}\) yr\(^{-1}\), 0.3 t K\(_2\)O ha\(^{-1}\) yr\(^{-1}\) and 0.1 t MgO ha\(^{-1}\) yr\(^{-1}\) in addition to dolomitic lime (1.0 t ha\(^{-1}\) yr\(^{-1}\)), oilcake (3.0 t ha\(^{-1}\) yr\(^{-1}\)), fish flour (1.9 t ha\(^{-1}\) yr\(^{-1}\)) and bone meal (1.0 t ha\(^{-1}\) yr\(^{-1}\)) during 1995-1997. Vegetation type in NF-0 was a broad-leaved semi-deciduous forest comprised of Lonicera japonica and Ilex integra, etc. Three soil pits were dug between hedgerows along the toposequence of each tea plot (average slope is 15.9% in TF-19 and 32.7% in TF-34), and a representative soil profile was made in NF-0 on the gently undulating hilltop for the field survey and soil sampling. The samples obtained were air-dried, gently ground and passed through a 2 mm
Soil pH was measured in deionized water and 1.0 M KCl, at a soil solution ratio of 1:2.5 with a glass electrode. The amount of total C (TC) and N (TN) were determined by dry combustion method using a NC analyzer (Sumigraph NC-80, Sumika Chem. Anal. Serv. Ltd.). The amount of available P (Av-P) was determined by means of the Bray No. 2 method followed by spectrophotometric measurement with molybdate. Exchangeable Ca, Mg and K (Ex-Ca, Ex-Mg and Ex-K, respectively) were leached with 1.0 M NH₄OAc at pH 7 and the amount was determined by
inductively coupled plasma spectroscopy (ICPS) (ICP Mass 2010, Shimazu Co.). Exchangeable Al (Ex-Al) was obtained by subtraction of exchangeable H from exchangeable acidity using IITA’s method (IITA, 1979). Selected micronutrients, i.e., Fe, Mn, Cu, Zn, Mo and B (Et-Fe, Et-Mn, Et-Cu, Et-Zn, Et-Mo and Et-B, respectively), were extracted with 0.1 M HCl as described by Viets and Boawn (1965) and subsequently examined on the ICPS.

The data obtained were statistically analyzed by ANOVA using StatView (SAS Inst. Inc.).

Results and Discussion

Fig. 1 shows the changes in physicochemical properties of soil profiles investigated, and Table 1 gives the correlation matrix between components examined.

Soil pH measured in H$_2$O ranged from 4.47 to 4.72 in the profile of NF-0, although TF-19 and TF-34 showed lower pH values (3.60-4.07) throughout the profile. As shown in many reports (Kawai and Morita, 1958a; Tachibana et al., 1995; Matsumoto et al., 2002), soil acidification occurred throughout the profiles under the tea cultivation. The pH values at the 0-10 and 10-30 cm layers were lower than the rests (deeper than 30 cm). The magnitude of acidification was more prominent in the topsoils to which fertilizer was applied. The pH value of the soils extracted with 1.0 M KCl was substantially lower than that with H$_2$O. On the other hand, there was no significant difference in pH values between TF-19 and TF-34 in both extractions (H$_2$O and KCl). This suggests that the soil reaction reached equilibrium within the 19 years of tea cultivation in the study site.

The TC contents in the surface layers (0-10 cm) increased significantly with the lapse of time under cultivation. Total C was considered to exist entirely in organic forms, because the result of the HCl test, which detects carbonates in the soils, was negative. The mean accumulation rate of organic C in the surface layers during the cultivation was calculated as 1.22 kg C m$^{-3}$ soil yr$^{-1}$. High litter production of tea plants and application of organic amendments could be responsible for rapid accumulation of organic matter. The beneficial effect of organic matter on soil structure is well known (Brady and Weil, 2001). However, there were no relevant differences in bulk density and three phase distribution of the surface layers among NF-0, TF-19 and TF-34 (Data not shown here). Foot compaction between hedgerows would diminish the positive influence of organic matter accumulation on soil structure.

Accumulation of Av-P was noticed only in the surface layers of TF-19 while considerable increase of Av-P was recognized in the 10-30 and 30-50 cm layers as well as in the surface layers in TF-34. Downward mobility of P through the profile is usually low especially in acid soils due to strong fixation of inorganic P by the active
forms of Al and Fe under acidic conditions in the topsoils to which the fertilizer was applied (Sanchez and Uchihara, 1980). The accumulation of Av-P in the subsoils of TF-34 implies that addition of fertilizer P has exceeded the P retention capacity of the surface layers. The amount of Av-P was well associated with that of Et-Fe ($R=0.77$), which suggested the significant role of Fe in P fixation. Phosphorus accumulated in the surface layers of TF-19 and TF-34 might make it susceptible to runoff and erosion because of the steep landscape in the study site.

Exchangeable base status was very low in NF-0 which would be due to the leaching under humid climate. The loss of NO$_3$-N in TF-19 and TF-34 suggested above might have been accompanied with the loss of counter bases. The high susceptibility of the bases to the leaching was indicated by the significant decrease in exchangeable Na contents of TF-19 and TF-34 in comparison with that of NF-0 (data not shown here). However, the amounts of Ex-Ca, Ex-Mg and Ex-K generally increased under cultivation. A similar trend was observed for distribution of Ex-Ca and Ex-Mg as indicated by their correlation coefficient ($R=0.84$) (Table 1). The contents of Ex-Ca and Ex-Mg in the surface layers differed in the order; TF-19 $>$ TF-34 $>$ NF-0. The contents of Ex-Ca were higher in TF-19 and TF-34 than in NF-0 throughout the profile while the Ex-Mg content in the subsurface layers (at depth below 10 cm) was not significantly different between NF-0 and TF-19. However, the content of Ex-Mg was lower in TF-19 and TF-34 than in NF-0 at the depth of 70-90 cm. The contents of Ex-K increased with the lapse of time under cultivation throughout the profile. These findings suggest that generally exchangeable bases are increased by fertilizer application in spite of soil acidification.

The contents of Ex-Al significantly increased by acidification under tea cultivation might have enhanced the Al activity. As suggested before, soil reaction may have reached the equilibrium during the 19-yr cultivation whereas Ex-Al seemed to be still increased after the 19-yr cultivation. Dong et al. (1999) reported that both the available Al in soils and the uptake of Al by tea leaves increased with decreasing soil pH. Therefore, it is necessary to keep soil reaction at an optimal level (Recommended range of soil pH is between 5.0 and 5.5 under the tea farming in Japan) so as to control Al content of tea leaves since the tea product is considered to be a potentially important source of dietary Al.

The distribution of Et-Fe was relatively erratic in the profiles (Fig. 1). This suggests that the Et-Fe contents were not well correlated to the period under cultivation in TF-19 and TF-34. On the other hand, Et-Fe was found to be highly correlated with TC ($R=0.79$) and TN ($R=0.80$) in addition to Av-P ($R=0.77$) (Table 1). Iron shows highly complex reactions with organic matter and makes stable compounds with P under acidic condition. The content of Et-Mn in NF-0 was highest in the surface layers and decreased with depth reflecting the soil profile development process under natural weathering. There was a small amount of Et-Mn throughout the profile in TF-19 and TF-34. This suggests that Et-Mn as well as exchangeable bases is susceptible to the leaching under strongly acidic conditions (Goto et al., 1994). The contents of Et-Cu markedly increased in the surface layers but not significantly in the subsurface layers during tea cultivation. Copper preferentially complex with organic matter (Yoshida and Nakao, 1971) as indicated by high correlation coefficients with TC ($R=0.83$) and TN ($R=0.82$) (Table 1). On the contrary, there was no significant difference in Et-Zn contents of the surface layers among the three plots. However, TF-34 had a significantly larger amount of Et-Zn in the subsurface layers (10-30, 30-50 and 50-70 cm) than NF-0 and TF-19. The Et-Mo content tended to increase with the lapse of time under tea cultivation while there was no significant difference in its contents in the layers at 0-10, 50-70 and 70-90 cm depth between TF-19 and TF-34. Increase in the contents of Et-Cu, Et-Zn and Et-Mo might have originated from organic amendments or agro-chemicals such as P fertilizers that usually include impurity of heavy metals. The Et-B content was greater in TF-19 and TF-34 than in NF-0 throughout the profile (Fig. 1) and highly correlated with pH extracted with H$_2$O ($R=-0.84$) and KCl ($R=-0.81$) (Table 1). This suggests that boron extractability with 0.1 N HCl was driven by soil reaction. There was no significant difference in Et-B distribution between TF-19 and TF-34 because of the similarity in soil reaction.

The findings of this study revealed that acidification and chemical contamination of soils under tea cultivation were caused by heavy application of fertilizers. Severe acidic reaction and excess amount of active Al in the soils prevents root elongation and its physiological function, which would eventually reduce quality and quantity of the tea leaves (Tachibana et al., 1995, 1996). Heavy fertilization also induces chemical pollution in local environments by leaching, runoff and/or erosion of applied nutrients, e.g., N, P, and bases. Soil contamination with heavy metals such as Cu, Zn and Mo is another aspect of environmental degradation in the tea fields. Soil pH adjustment may be the key to improve fertilizer efficiency and to reduce its application rate. Therefore, it is necessary to develop a simple soil testing system to allow the farmers to easily check their soil conditions, which could be helpful for appropriate use of fertilizers and limes.

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