Rates of soil acidification in tea plantations and possible causes

Shiyu Li[a], Haixia Li[b], Changliang Yang[a,*], Yandan Wang[a], Hui Xue[c], Yanfen Niu[d]

[a] School of Ecology and Environmental Science, Yunnan University, Kunming 650091, China
[b] Faculty of Land Resource Engineering, Kunming University of Science and Technology, Kunming 650093, China
[c] College of Tourism and Geographical Science, Qingdao University, Qingdao 266071, China
[d] School of Agriculture, Kunming University, Kunming 650214, China

ABSTRACT

Soil acidification has threatened the sustainability of agricultural systems. Organic manures have been reported to alleviate soil acidification in tea (*Camellia sinensis*) plantations. However, little is known about the pH status at different soil depths in these plantations. Whether the downward movement of acid contributes to subsurface soil acidification and the magnitude of the movement are unknown. We took soil samples from tea plantations that were 5, 10, 20, 33, and 56 years old at depths up to 120 cm in the soil profile. We examined the soil pH, Fe, Al, nitrate N (NO_3-N), ammonium N (NH_4-N), and organic carbon (OC) in every 20-cm soil layer, and observed the downward movement of H^+, NH_4-N, and OC using undisturbed soil column experiments. The results show that organic manures and plant residues increased the topsoil pH, but did not reduce soil acidification below 80 cm. At a planting density of 10,000 plants ha^{-1} and with the application of organic manures at 6000 kg ha^{-1} a^{-1}, the soil acidification rates (decrease in pH) were −0.0161 and −0.0245 per year at depths of 80–100 and 100–120 cm, respectively. The soil pH increased by 0.0158 and 0.0140 per year at depths of 0–20 and 20–40 cm, respectively. The downward movement of acid is one cause of topsoil alkalization and deeper soil acidification in cultivated tea plantations. No-till farming and increased vegetation coverage to reduce the downward movement of H^+, NH_4-N, and OC are effective measures to alleviate deep-soil acidification. Planting density also affects soil acidification; tea trees excrete less H^+ into the rhizosphere at a lower planting density than at a higher planting density. Tea plantation soil is not acidified at a lower planting density of 5000 plants ha^{-1}.

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1. Introduction

Soil pH is considered to be a critical factor in soil science (Brady and Weil, 2010; Simek and Cooper, 2002), as it directly affects plant growth (Brady and Weil, 2010). Similarly, soil pH is affected by various anthropogenic factors (Ok et al., 2007), including intense crop production, which tends to reduce soil pH. Soil acidification can negatively impact the sustainability of agricultural systems (Guo et al., 2010).

Tea (*Camellia sinensis*) originated from the Guizhou Plateau in southwest China and is a major commercial crop in China, India, and Sri Lanka (Han et al., 2007). The optimal soil pH for tea plants is 4.5–6.0, with 5.5 being the preferred pH (USEPA, 2008). The growth of tea plants is gradually arrested when the soil pH exceeds 6.5, and

they die when the pH is greater than 7.0 (Su, 2012). When the pH is lower than 4.0, tea plant growth is inhibited, affecting both the quality and quantity of tea production (Su, 2012), and jeopardizing human health (Aloway, 1995). Therefore, soil acidification not only results in soil nutrient loss, but also compromises tea consumption safety.

Cultivation of tea plants may cause soil acidification, which is increasingly serious in countries such as Japan (Oh et al., 2006), Sri Lanka, Rwanda (Mupenzi et al., 2011), and China (Ma et al., 2000; Alekseeva et al., 2011). Soil acidification has become a global issue in tea production, in terms of soil science, ecology, and tea science. Previous studies reported that soil pH generally decreases as tea plantations age (Han et al., 2007). The rate of soil acidification can be used to estimate lime quantities required to maintain a preferred soil pH (Helyar and Porter, 1989).

Usable published data on acidification rates of tea plantation soils are not available (Wang et al., 2010). Previous research has shown that the downward movement of H^+ and NH_4^+ may contribute to subsurface soil acidification (Hue and Licudine,

1999), but the magnitude of the movement was unknown (Tang et al., 2013). Although the lowest pH is generally present in the subsurface soil layer, there is no experimental evidence showing that this high concentration of acid moves deeper over time (Tang et al., 2013). Such movement of acid would be small, but additional studies are required to verify this view (Tang et al., 2013). Studies have focused on topsoil (Wang et al., 2010; Yi et al., 2011; Butterly et al., 2013; Martins et al., 2014), but the pH changes in deeper soil layers have not been characterized. Organic manure is frequently used to reduce soil acidification (Haynes and Mokolobate, 2001; Su, 2012; Jiang et al., 2013; Pérez-Esteban et al., 2014), but the impact on pH is generally restricted to topsoil. These reports paid limited attention to subsurface soil. Acidification rates are greater in the subsurface soil than in the topsoil in many soil profiles (Tang et al., 2013). Subsurface soil acidity is widespread; its amelioration is costly and often practically infeasible (Tang et al., 2013). Further study of pH changes below the plough layer in the soil profile is needed to identify measures to prevent subsurface soil acidification, which is more important than topsoil acidification in tea plantation.

Tea plantations in China cover an area of 1.64 million ha, which is approximately 50% of all tea cultivated globally (Li et al., 2011). Tea production in China has expanded 900% in the last six decades (Li et al., 2011). In this study, we focused on tea plantations in Pu'er, one of the largest tea cultivation zones in China. Our goals were to: 1) illustrate how the pH in each soil layer changes as tea plantations age, assuming the application of $6000 \, kg \, ha^{-1} \, a^{-1}$ organic manure and a high planting density ($d = 10,000$ plants ha^{-1}); 2) provide a case study of the downward movement of acid in soil; 3) compare the soil pH of low-plant-density tea plantations ($d = 5000$ plants ha^{-1}) with the pH of adjacent forests and high-plant-density tea plantations ($d = 10,000$ plants ha^{-1}) at all soil profile layers; and 4) compare the differences in pH in managed and abandoned (i.e., unmanaged) tea plantations at all soil profile layers and analyze the impact of management practices on soil pH. The results are expected to contribute to the optimization of tea plantation cultivation and management.

2. Materials and methods

2.1. Field sites

The study area was located in Yunnan province, in southwestern China (22°30′N, 101°12′E). The altitude was approximately 900 m, with an annual mean temperature of 18 °C and annual mean precipitation of 1200–1700 mm. The climate is mild and humid, with a hot and rainy season, which is suitable for tea growth. The soil type in Yunnan province is acid red soil.

The tea plants were arbor trees. Tea bushes were planted on contour terraces, previously occupied by evergreen and broad leaf forests. The tea plantations in existence for 5, 10, 20, and 33 years (yr) were planted in double rows at 10,000 plants ha^{-1}. The 56-year-old plantation was planted in single rows in 1958, at a planting density of 5000 plants ha^{-1}.

The tea plantations were pruned in December of every year. Branches were pruned to a length of about 30 cm and typically deposited onto the soil surface. Plowing was conducted annually in December at a depth of 20–30 cm. Organic manure was applied at a rate of about 6000 kg $ha^{-1} a^{-1}$. The pH value of the organic manure is 6.3 ± 0.5 (n = 10), which is slightly higher than that of local tea plantation soil. The abandoned tea plantations were those plantations without plowing, fertilizing, pruning, and harvesting for at least 5 yr after continuous cultivation for 15 yr. To demonstrate the effects of management practices on soil acidification in tea plantations, we studied managed and abandoned tea plantations established 20 yr ago

(1994) on the same mountain. The managed tea plantation had been plowed, fertilized, pruned and harvested as abovementioned annually.

2.2. Sample sites

Yunnan province is the largest tea producing area in China (Li et al., 2011). Five representative tea plantation sample plots with different cultivation ages (5, 10, 20, 33, and 56 years old respectively) were selected in this province, and samples were collected from adjacent forests as a control, due to the original land use type was forest before the planting of tea trees, local tea plantations were planted by deforestation, so soil pH and other parameters of forest were used as a reference value. 3–5 sampling subplots for each selected tea plantation and forest were investigated. All soil samples were taken on sunny days.

2.3. Soil sampling

We surveyed the basic conditions in each plot, including the history of land development and utilization, and management practices such as fertilization, pruning, and harvesting. A composite consisting of five soil cores at the same layer were collected randomly within each subplot (scattered, but not close to the edge of sample sites). Soil profiles were explored in increments of 20 cm and thin layers of soil were sampled vertically to the depth of the profile. Plant residues, roots, stones, and obvious macrofauna were removed manually.

The six profiles were 0–20, 20–40, 40–60, 60–80, 80–100, and 100–120 cm, identified as a–f, respectively. Soil samples were taken from five plots for each profile. Five samples from the same profile depth were mixed and excessive soil was removed, using the diagonal quartering method (Wang et al., 2014). These soil samples were stored in plastic bags. Labels were attached to the interior and exterior of each bag. All soil samples were sent to the laboratory for analysis.

A total of 36 undisturbed-soil columns (including 18 columns 20 cm in length × 7 cm in diameter, and another 18 columns 40 cm in length × 7 cm in diameter) in stainless steel tubes were extracted by hand in February 2014 using the method described by Landry et al. (2006). To retain soil and minimize losses during the experiment, glass wool and nylon mesh (105-mm opening) plugs were placed at the base of each column.

2.4. Leaching tests

The columns were set up in the laboratory and maintained at a temperature of 16–23 °C. They were saturated with distilled water, and then 1104 mL of distilled water was applied to the top of the columns in a dropwise manner so as to cover the entire column surface. The columns were leached with 1104 mL of distilled water, which is equivalent to 140.6 mm of rainfall, to simulate the maximum rainstorm intensity during the past five decades at that location. All leachates were collected, filtered through a filter membrane ($\Phi = 0.45 \, \mu m$), and the volumes were recorded. The leaching tests were repeated at intervals of 24 h until no H^+ (pH $\geqq$ 7), NH_4^+, and OC were detected in the leachate.

The pH values of the collected leachate samples were measured using an HI 8424 NEW Portable pH/mV/°C Meter (HANA Instruments, Italy). The concentrations of OC in the leachate samples were determined using a Sievers InnovOx Laboratory Total Organic Carbon Analyzer (Sievers InnovOx, GE, USA). The concentrations of NH_4^+ in the leachate samples were determined using ion chromatography (IC20, Dionex, USA) with three replicates per leachate.

2.5. Soil analysis

The soil samples were air-dried and ground to pass through a 2-mm sieve. A 10-g subsample was placed in a 50-mL high beaker and mixed with 25 mL of CO_2-free deionized water. The soil solutions were mixed thoroughly and stored for 30 min. The pH was evaluated using an HI 8424 NEW Portable pH/mV/°C Meter (HANA Instruments). Other soil subsamples taken from each composite were extracted by shaking in 2 M KCl at a soil/solution ratio of 1:5 for 30 min, filtered, and the soil nitrate N (NO_3-N) and ammonium N (NH_4-N) concentrations were determined colorimetrically using a Bran and Luebbe Auto Analyzer III (Germany) (Price et al., 2015).

An air-dried soil subsample of approximately 3 g was taken from each composite, soaked in 1 M HCl for 6 h to remove soil inorganic carbon, stirred once every hour, and the supernatant was drained after precipitation. The precipitate was washed with deionized water, stirred, and the supernatant was poured off after sedimentation. This wash process was repeated four times to sufficiently remove excess HCl, and then the sample was oven-dried at 60 °C for 48 h and ground to pass through a 0.25-mm sieve. Soil organic carbon (OC) concentrations were analyzed using an isotope ratio mass spectrometer (Thermo Scientific MAT 253, Germany) at the Third Institute of Oceanography, State Oceanic Administration, Xiamen, China. Al and Fe concentrations were determined in pressed powder pellet samples of soil using a ZSX Primus II X-ray fluorescence spectrometer (XRF) (ZSX Primus II, Japan) at the Northwest Geological Institute of Nonferrous Metals.

2.6. Statistical analysis

Data were analyzed using SPSS 20.0 software, at a significance level of $\alpha = 0.05$. One-way ANOVA was performed on soil pH data from different soil layers. If the difference was significant, we performed a comparison of means (least significant differences [LSD]) for the different profile layers from the same tea cultivation period. The differences between the different cultivation ages in the same soil layer were subjected to univariate analysis in a general linear model. Two-way ANOVAs were used to analyze the interaction between depth and age.

3. Results

3.1. Rates of soil acidification in high-planting-density ($d = 10,000$ plants ha^{-1}) tea plantations

With increasing cultivation age, the pH of the 0–20-cm and 20–40-cm soil layers tended to increase linearly (Fig. 1A, B). The pH of the 40–60-cm and 60–80-cm soil layers did not change significantly (Fig. 1C, D), while the pH of the 80–100-cm and 100–120-cm soil layers decreased significantly and in a linear fashion (Fig. 1E, F).

3.2. The vertical patterns of pH and other parameters

Soil pH first increased and then decreased with increasing soil depth in most tea plantations (Fig. 2). The interaction between depth and age was significant. The pH averages of forests adjacent to the tea plantations ranged from 3.7 to 4.3. Soil pH was the lowest (3.7) in the 0–20-cm layer and highest (4.3) in the l00–120-cm layer. Soil acidity increased gradually with increasing soil depth (Fig. 2A), but the differences were not statistically significant.

The average soil pH values of 5-year-old tea plantations ranged from 3.4 to 4.2. The minimum pH was 3.5 in the 0–20-cm layer, and the maximum pH (4.1) was in the 40–60-cm layer (Fig. 2B). Soil pH in the 0–20-cm layer was significantly lower than that in the 20–40-cm, 40–60-cm, 60–80-cm, 80–100-cm and 100–120-cm layers.
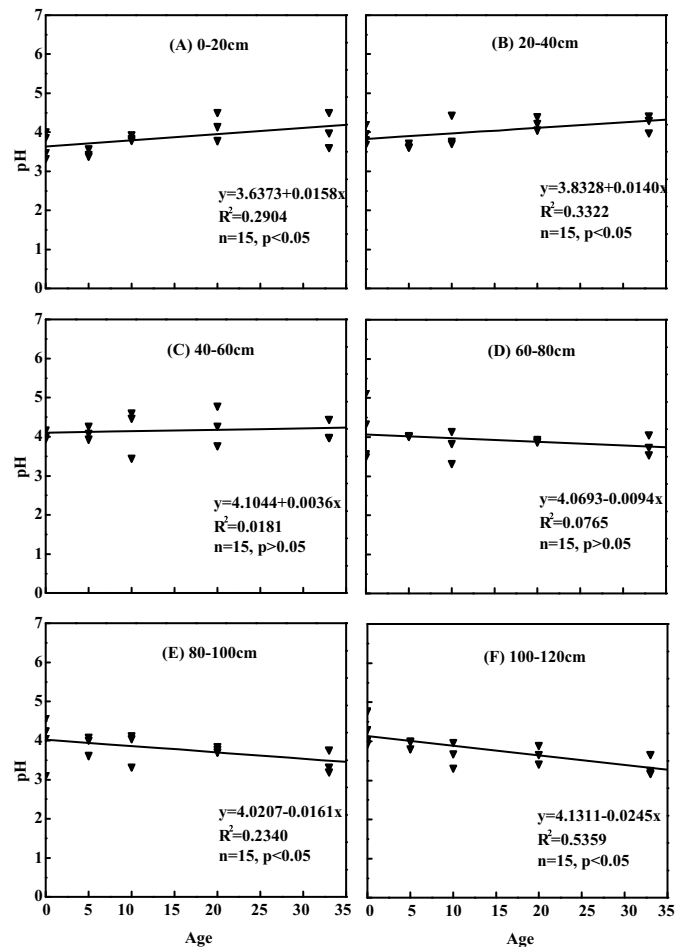

Fig. 1. Acidification rates in various soil layers of high-planting-density (10,000 plants ha^{-1}) tea plantations under the same management regimes.

Soil pH in the 20–40-cm layer was also significantly lower than that in the 40–80-cm and 100–120-cm layers.

The average pH values at the 10-year-old tea plantations ranged from 3.6 to 4.2. There were no significant differences between the soil layers (Fig. 2C). The average pH at the 20-year-old tea plantations ranged from 3.6 to 4.3. The pH of the 0–40-cm soil layers was significantly higher than the pH of the 80–120-cm layers (Fig. 2D).

The pH averages of the 33-year-old tea plantations ranged from 3.3 to 4.3. The maximum pH was 4.25 in the 20–40-cm layer and soil acidity gradually decreased below the 20–40-cm layer (Fig. 2E). The pH of the 0–60-cm layer was significantly higher than the pH of the 80–120-cm layer.

The pH averages of the 56-year-old tea plantations ranged from 3.6 to 4.2. The minimum pH was in the 0–20-cm layer and the maximum pH was in the 100–120-cm layer (Fig. 2F). The average pH in the 0–80-cm layers was lower than that in the 80–120-cm layers.

Al showed an increasing trend with the increase of soil depth (Fig. 3A), while there was no significant change of Fe (Fig. 3B), NO_3-N, NH_4-N, and SOC decreased with the soil depth increasing (Fig. 3C–E).

Variation in soil pH between adjacent forests and low-planting-density ($d = 5000$ plants ha^{-1}) tea plantations were investigated. The pH averages of 56-year-old tea plantations were slightly lower than those of adjacent forests in all layers, but not significantly ($p > 0.05$).
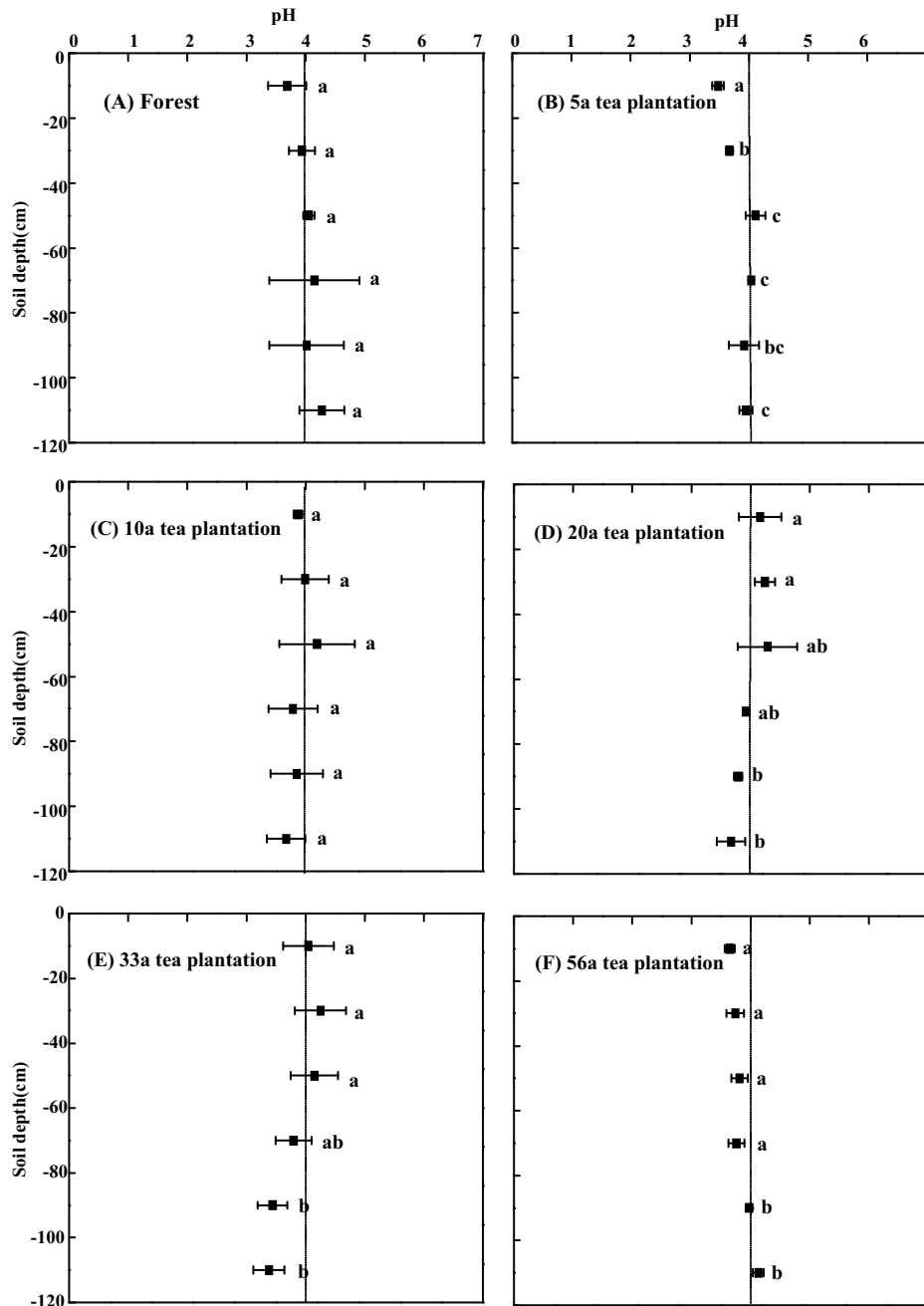
Fig. 2. Vertical distribution of soil pH in tea plantations of various cultivation ages. The auxiliary line at a pH value of 4.0 in the figure is a threshold value, below which the tea plant growth is inhibited, affecting both the quality and quantity of tea production (Wu and Lin, 1991; Su, 2012 Su, 2012) and jeopardizing human health (Aloway, 1995).

3.3. Effects of managed and abandoned conditions on soil pH

In the 0–60-cm layers, soil pH was not significantly different between the managed, abandoned tea plantations and adjacent forests (Fig. 4, p > 0.05). In the 60–120-cm layers, the soil pH of managed tea plantations was significantly lower than that of abandoned tea plantations and adjacent forests (Fig. 4, p < 0.05). Soil pH of the managed plantations decreased with increasing soil depth, while there was no trend with increasing soil depth for abandoned tea plantations and adjacent forests (Fig. 4, p > 0.05).

3.4. Downward movement flux of OC, NH^{4+} and H^+

The downward movement fluxes of OC and NH_4^+ in soil were showed in Fig. 5 and the downward movement flux of H^+ was showed in Fig. 6.

3.5. Relationships between pH and the contents of OC, Al, Fe, NO_3-N, and NH_4-N

We analyzed the relationships between pH and the contents of OC, Al, Fe, NO_3-N, and NH_4-N in each soil layer in tea plantations in
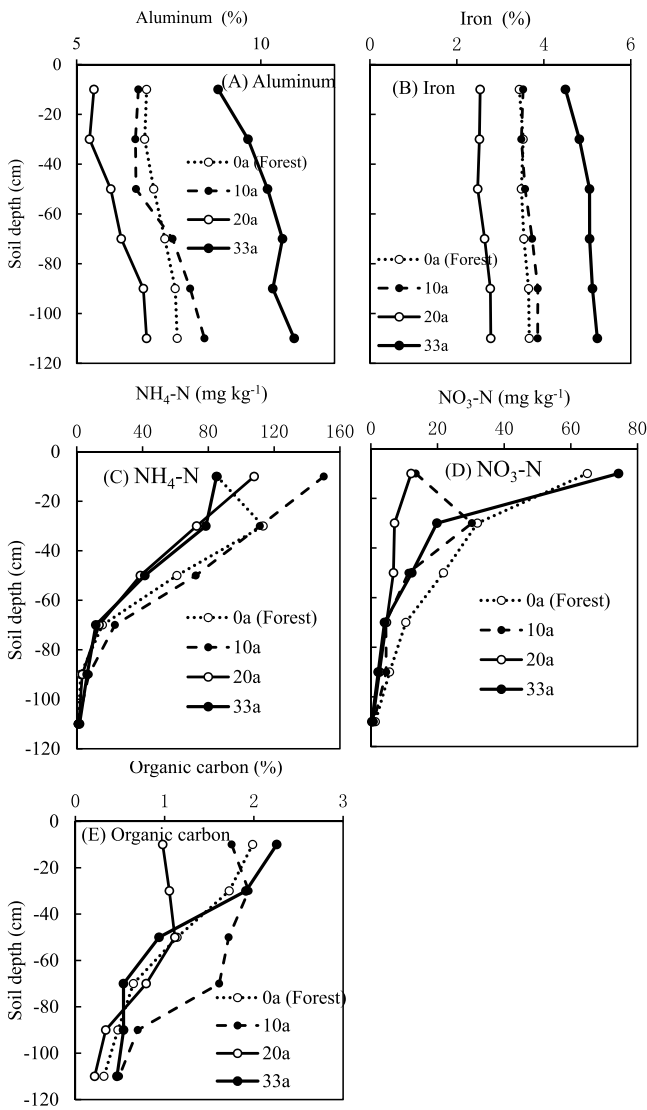
Fig. 3. The vertical patterns of Al, Fe, NO$_3$-N, NH$_4$-N, and SOC along plantation ages.
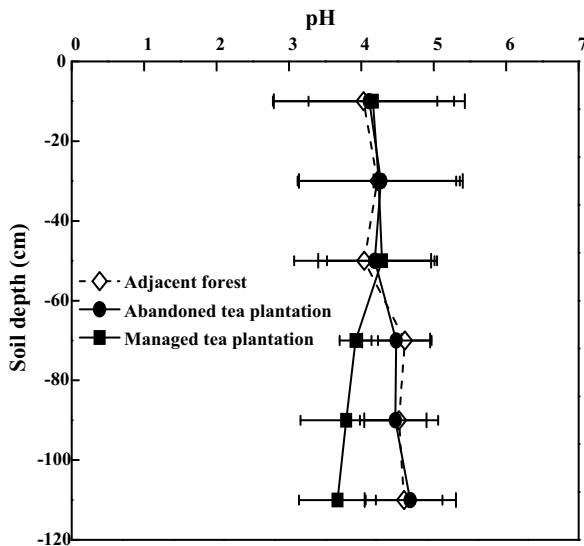

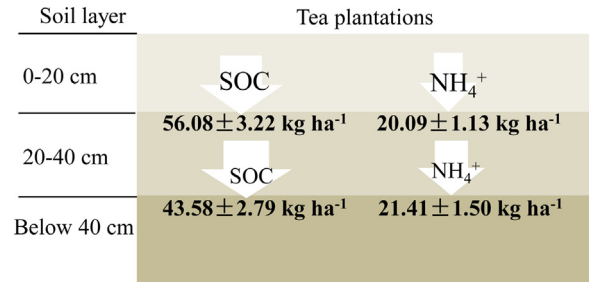Fig. 4. Vertical distribution of soil pH in managed, abandoned tea plantations and adjacent forests.

Fig. 5. The downward movement flux of SOC and NH$_4^+$ in soil.
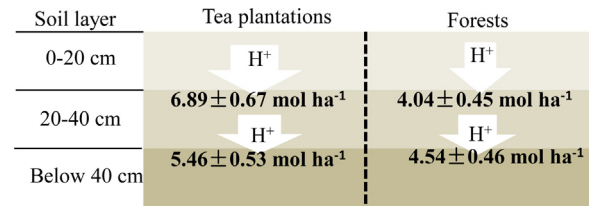

Fig. 6. The downward movement flux of H$^+$ in soil.

this study. The relationship between pH and the OC content in the 40–120-cm soil layer showed a significant negative correlation (Fig. 7A, p < 0.05), as did the relationship between pH and the NH$_4^+$ content in the 20–120-cm soil layer (Fig. 7B, p < 0.05), but the relationships between pH and the other parameters in each soil layer were not significantly correlated in this study (p > 0.05). The OC content in the 0–40-cm soil layer and the NH$_4^+$ content in the 0–20-cm soil layer did not correlate significantly with the pH in this study (p > 0.05).

4. Discussion

In tea plantations, the pH values of 270 soil samples ranged from 3.2 to 4.8, with an average of 3.9 ± 0.4. The average soil pH of adjacent forests was 4.0 ± 0.5. These results demonstrate that Yunnan red soil itself is acidic (Fig. 2A). Acidification, particularly in
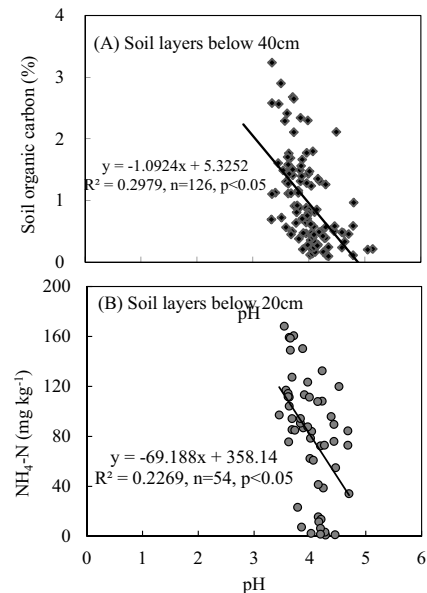

Fig. 7. Relationships between pH and the contents of soil organic carbon and NH$_4$-N.

the 60–120-cm layers, occurred as a result of tea cultivation (Fig. 2B–E). The pH values in this study were below the optimum (5.5; USEPA, 2008) for tea cultivation. Most of the pH values were < 4.0, which can inhibit tea growth (Su, 2012).

Subsurface soil acidification, which depends largely on acid production by plant roots due to excess cation uptake (Tang et al., 2013), but the relationships between pH and the contents of Al and Fe in each soil layer were not significant. Therefore, this is not the main cause of soil acidification in these tea plantations.

4.1. The role of organic manure and plant residues in soil pH changes

It is generally accepted that soil becomes acidified following tea planting (Tachibana et al., 1995; Wang et al., 2010), and soil acidity increases with increasing tea cultivation period (Pansombat et al., 1997; Han et al., 2007). However, we found that pH in the 0–40-cm layer actually increased with cultivation age (Fig. 1A, B). This could be attributed to the application of commercial organic manures at 6000 kg ha^{-1} a^{-1} and the addition of annual tea tree pruning shoot residues. Both the addition of organic manures and plant residues are believed to increase the soil organic matter (the major component is OC). The addition of organic matter to soil can increase, decrease, or have no effect on soil pH. The effect is dependent upon the organic matter composition, soil characteristics, and environmental conditions of decomposition (Tang et al., 2013). Organic matter reduces soil acidity (Magdoff and Bartlett, 1984) by neutralizing hydrogen ions (Brady and Weil, 2010). The application of organic manure to tea plantation soils exerts a buffer effect, preventing soil acidification (Su, 2012; Jiang et al., 2013; Pérez-Esteban et al., 2014). Pruned tree branches also contribute to the level of organic matter in the soil by promoting root growth and reducing the active Al content (Kretzschmar et al., 1991; Haynes and Mokolobate, 2001). The addition of plant residues to acidic soils generally increases the topsoil pH (Tang et al., 2013). The decomposition of shoot residues can neutralize the acid created during tea plant growth in the topsoil because the oxidation of organic anions during the decomposition process occurs mainly in this soil layer and is not incorporated into deeper layers. In contrast, root residue decomposition cannot fully neutralize the acidity created near the roots in subsurface soil layers because root residues usually have lower concentrations of excess cations than shoot residues (Tang et al., 2013). This mechanism not only partially explains why soil in the 0–20-cm and 20–40-cm layers became more alkaline with cultivation age (Fig. 1A, B), but also partially explains why soil in the 80–100-cm and 100–120-cm layers became more acidic in our study (Fig. 1E, F). In these sampling subplots, the average tea tree roots depth were 105 ± 11 cm.

4.2. Impact of the downward movement of OC, NH_4^+, and H^+ on deep-soil acidification

NH_4^+ nitrification (Kosuge, 1982; Pansombat et al., 1997; Ruan et al., 2004; Oh et al., 2006; Han et al., 2007) may cause soil acidification. Soil acidification after the planting of tea trees results from a gradual extension from the rhizosphere to surrounding soil, and from the soil surface to deeper soil layers (Wu, 2009). The downward movement of OC and NH_4^+ in soil (Fig. 5) may contribute to subsurface soil acidification based on a significant negative correlation (Fig. 7, p < 0.05) between pH and the contents of OC and NH_4^+ in subsurface soil layers. These results explain the gradual increase in soil acidification in the 80–120-cm layer detected in our study. Organic manures had no effect on alleviating soil acidification in this layer.

Moreover, previous research has shown that topsoil acidification is slower after 14 yr of cultivation, when H^+ moves to deeper soil layers, increasing acidification (Wang et al., 2010). In this study, our results show that the downward movement of H^+ occurs (Fig. 6) and that the magnitude of this movement is one of the causes of subsurface soil acidification in tea plantation systems.

4.3. Effect of planting density on soil acidification

The rhizosphere of tea plants, which can excrete organic acids, carbonic acid, and polyphenols, contributing to acidification (Yang, 2005). The organic acids, carbonic acid, and polyphenols excreted into the rhizosphere of tea plants are difficult to quantify. Here, we assumed that different planting densities represented different amounts of these secretions: the plantations that had a higher tea tree planting density were considered to secrete larger amounts of these compounds. Increased planting density, when land is limited, maximizes the use of soil resources and economic benefits. Tea planting in China ranges from low to high plant density, and from scattered clump planting to stripped clump planting. In our study, 56-year-old tea plantations were planted at a low density of 5000 plants ha^{-1} in 1958. The 5-, 10-, 20-, and 33-year-old tea plantations were planted in double rows at a density of 10,000 plants ha^{-1}. The planting density of the 56-year-old tea plantations was half that of the other plantations; otherwise, the management practices were uniform across plantations. We found that the pH distribution in 56-year-old tea plantations and adjacent forests was similar in all soil layers. A comparison of the acidification of the 80–120-cm soil layers in the high-density and the low-density tea plantations identified planting density as an important contributor to soil acidification. Acidification was ignorable at a tea planting density of 5000 plants ha^{-1} compared to that in high-plant-density plantations.

Plant density and cultivation age have been shown to influence microbial biomass, community structure, and activity (Han et al., 2007). Microbial activity can decompose organic compounds in humus. Soil buffer capacity is increased as a result of humus binding to a mineral colloid in soil to form an organic-inorganic compound colloid. Soil physical, chemical, and biological properties are improved due to increased activity of soil microbes. Therefore, we concluded that soil acidification in low-density tea plantations was reduced by limiting the production of hydrogen ions.

4.4. The influence of soil management on soil acidification

It is generally believed that soil pH change is influenced by fertilization levels, the amount and type of fertilizers, accumulation of pruning tea litter, soil management. We compared the soil pH of managed and abandoned tea plantations in this study. On the managed tea plantations, commercial organic manure (6000 kg ha^{-1} a^{-1}) was applied, and pruned branches and leaves were returned to the soil as a supplement to soil organic matter. Abandoned tea plantations did not accumulate organic matter, as described above, during an at least 5-year period.

These results reflect the content of tea plantation topsoil 5 yr before abandonment. The abandoned plantations did not receive supplementary organic matter, such as organic manures and pruning litter, resulting in no change in soil pH. Notably, there were no significant differences in soil pH in all soil profile layers between the abandoned tea plantations and adjacent forests, but was significantly higher than that of managed tea plantations in the 60–80-cm, 80–100-cm, and 100–120-cm layers (Fig. 4). Soil acidification at abandoned tea plantations was restored as a result of plantation management.

In addition, the soil in managed tea plantations was plowed every year to a depth of approximately 20 cm. Soil preparation (deep plowing) of managed tea plantations changes soil structure,

thus affecting the pH (Husson, 2013). In managed tea plantations, the soil is loose due to plowing and removal of weeds to decrease vegetation coverage, which favor the infiltration of organic acids excreted by the rhizosphere. This allows H^+ to diffuse into the deeper soil and increases the acidity. The lack of plowing in abandoned tea plantations resulted in decreased H^+ infiltration and reduced soil acidification. Thus, plowing likely explains the accelerated soil acidification in tea plantations, and no-till farming may partially alleviate the acidification of deeper soil layers.

As a result of natural selection and thinning natural branches, the plant density of abandoned tea plantations decreased with increased numbers of no-tillage years and soil acidification was reduced. Compared with the managed tea plantations, abandoned tea plantations had no tillage during the 5-year abandonment period. The soil pH of abandoned tea plantations was similar to that of managed tea plantations in the 0–20-cm, 20–40-cm, and 40–60-cm layers (Fig. 4). This similarity could be the result of the extensive use of organic manures during the 15 yr of management before abandonment.

5. Conclusions

Our investigation of the soil pH at plantations with different tea cultivation periods and in the 0–120-cm layer led to the following conclusions. Except for the 56-year-old tea plantations, there were significant positive linear correlations between tea cultivation age and soil pH in the 0–20-cm and 20–40-cm layers, with alkalization rates (increase in pH) of 0.0158 and 0.0140 per year, respectively. The soil pH in the 40–80-cm layer did not change significantly. There was a significant negative linear correlation in the 80–100-cm and 100–120-cm layers, with acidification rates of −0.0161 and −0.0245 per year, respectively. Planting density is an important factor in affecting soil acidification, and reduces the planting density can reduce the production of H^+ so that it reduces soil acidification. The tea plantation soils exhibited no acidification at a lower planting density of 5000 plants ha^{-1}. Organic manure cannot alleviate deep-soil acidification in acid soil tea plantations. Our results demonstrate that the downward movement of acid is one cause of topsoil alkalization and deeper soil acidification in cultivated tea plantations. No-till farming is an effective measure to alleviate deep soil acidification.

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