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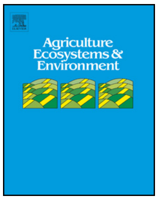

Rates of soil acidification in tea plantations and possible causes

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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}.

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,

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Abbreviations: NO_3-N, nitrate-N; NH_4-N, ammonium-N; OC, organic carbon.
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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.