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ORIGINAL ARTICLE

Changes of soil ecological stoichiometric ratios under different land uses in a small catchment of subtropical China

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The role of soil elemental ecological stoichiometry in evaluation of nutrient cycling and limitation was not clear in local spatial scale. Thus, characteristic of soil C, N and P stoichiometric ratios and their relationships to land-use and soil properties were analyzed in a small catchment of subtropical China. Results showed that there were constrained soil C:N ratios in a small catchment. Soil C:P and N:P ratios were also constrained at the beginning; but they became variable after 10 years of different land uses. Soil C:N ratios in the small catchment were similar to those at national scale, but soil C:P and N:P ratios were remarkably lower at the local scale. Soil C:P ratios in paddy fields were 5.1–76.9% and 16.0–80.4% higher than those for other land uses in 2000 and 2010, respectively; the corresponding soil N:P ratios were also 3.8–66.7% and 19.1–75.0% higher. Over time, soil C:N ratios increased approximately 19.7–29.6% for all land uses after 10 years of utilization. Soil C:P and N:P ratios also increased for most land uses. Clay content was an important factor influencing soil C:P and N:P ratios. Except for paddy fields, N was still the limiting nutrient in most land uses, evaluating by elemental stoichiometry. Future work should focus on determining direct evidence of C and N limitations and their relationships to elemental stoichiometry in a small catchment.

Keywords: soil C:N:P stoichiometric ratios; land use; utilization time; small catchment; nutrient cycling

Introduction

Redfield (1958) reported that there was a constrained carbon (C): nitrogen (N): phosphorus (P) ratio (106:16:1) in planktonic biomass and marine water. It was said that the high mobility, mixing and relative homogenizing in ocean ecosystems led to constrained elemental ratios (Redfield 1958). This 'Redfield Ratio' provided insights into the CO_2 exchange and biogeochemical cycling of nutrients in the world's aquatic ecosystems (Hecky & Kilham 1988; Cooper et al. 1996). Increasing numbers of studies have indicated that there are also 'Redfield-like' elemental ratios in terrestrial ecosystems (McGroddy et al. 2004; Cleveland & Liptzin 2007; Tian et al. 2010). Recently, the ecological stoichiometric theory and approach was introduced to soil ecosystem research (Cleveland & Liptzin 2007; Tian et al. 2010). It provides a new method for studying soil–plant interactions and gives alternative scope for better understanding nutrient cycling in soil ecosystems.

Different land uses and anthropogenic activities can affect a series of soil processes (Lepsch et al. 1994; Hontoria et al. 1999). It was reported that land-use changes and soil management influenced soil erosion, soil nutrients and soil moisture changes (Fu et al. 2000). The earlier-mentioned nutrients-related process can lead to transport and distribution of different nutrients (Wang et al. 2001). This can subsequently cause significant soil heterogeneity in local spatial scale. Nevertheless, it is unknown whether soil C, N and P elemental stoichiometric ratios are constrained in such situations. The relationships between elemental ratios, environmental factors and nutrient cycling are also unclear in local spatial scale. Small catchments of subtropical

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China, as the basic landscape and agro-ecological units, are suitable templates to discuss the above problems.

In total, 52 soil samples were collected from a small catchment of subtropical China in 2000 and 2010 in the present study. Patterns and variances of soil C:N:P ratios as well as their relationships to land-use and soil properties were analyzed. The goal of our study was to answer the following questions. First, what is the soil C:N:P stoichiometric ratio in this small catchment? Second, do different land uses, utilization times and environmental factors affect soil C:N:P ratios at this local spatial scale? Third, could soil elemental ratios reflect soil nutrient cycling and limitations in a small catchment?

Materials and methods

Study area

The Sunjia small catchment is located in Yingtan city, Jiangxi Province in subtropical China (116°55′E, 28° 15′N). This area has an annual precipitation of 1795 mm, annual evaporation of 1318 mm and mean annual temperature of 17.6°C. The catchment had an area of 46.2 ha, altitudes of 41–55 m and slopes of 3°–8°. The soil parent material was derived from Quaternary red clay. The four types of land use selected for soil sampling had remained unchanged for 10 years and were paddy field (planted with rice, *Oryza sativa*), dry cropland (planted with peanut, *Arachis hypogaea*), orchard land (planted with orange, *Citrus reticulata*) and waste land with sparse grass. Parent material, land use and geomorphology of the catchment were typical of the local area.

Soil sampling and measurement

A total of 26 sampling points – 9 in paddy fields, 11 in dry cropland, 3 in orchard land and 3 in waste land – were approximately evenly distributed throughout the small catchment. At each sampling point, 5–6 subsamples were randomly collected from the 0–15 cm surface soil layer in October of 2000 and 2010. After removing plant debris and small stones, soil samples were air-dried and sieved with 2 mm sieve for chemical measurement. Soil organic C was determined by Tyurin method, soil total N by Kjeldahl method and soil total P by Na_2CO_3 melting method (Lu 1999). Soil pH was determined by potentiometric method and clay content by pipette and sieve analysis (Lu 1999). Soil microbial biomass carbon (MBC) and nitrogen (MBN) were measured by fumigation–extraction method (Vance et al. 1987) in 2010.

Data analysis

Molar ratios of soil C:N, C:P and N:P were calculated. All statistical analysis were conducted using SPSS software (SPSS Inc., Chicago, USA). Relationships among soil organic C, total N, total P were determined by regression analysis. Relationships between soil elemental stoichiometric ratios and other soil properties were analyzed with bivariate correlation analysis. Significant differences in soil C, N and P concentrations and ratios and other properties for different land uses or utilization times were analyzed using one-way ANOVA with LSD post hoc test. Significant differences between soil elemental ratios at the small catchment and national scales were determined by one-sample *t*-tests.

Results

Patterns and variations of soil C:N:P ratios in a small catchment

The results suggested that there were well constrained relationships between soil total C and N (correlation coefficients of 0.976 and 0.933 in 2000 and 2010, respectively) in this small catchment (Figure 1). Soil total C and P (a correlation coefficient of 0.331) and total N and P (a correlation coefficient of 0.236) were also closely related at the local spatial scale in 2000. However, correlation of soil C and N and soil N and P became weak in 2010 (Figure 1). Results of frequency analysis showed soil C:N, C:P and N:P ratios followed log-normal distributions across the soil samples (Figure 2). The distribution also indicated the different constraint of soil elemental stoichiometric ratios. For example, compared to those of soil C:P and N:P ratios, the central tendency of soil C:N ratios was more obvious (Figure 2). In 2000, soil C:N, C:P and N:P ratios were 6.8–13.0, 17.8–121.5 and 1.6–10.4, respectively, but in 2010, were correspondingly 10.8–21.8, 25.8–137.4 and 1.8–9.8 (Table 1). Compared to the large scale, soil C, N and P elemental ratios in this small catchment were significantly different except for C:N ratios in 2010 (Table 1).

Factors affecting soil C:N:P elemental ratios

Soil C:N, C:P and N:P ratio changes were different for the different land uses (Table 2). Paddy soil C:P and N:P ratios were relatively higher than for other land uses: 5.1–76.9% and 16.0–80.4% higher in 2000 and 2010, respectively. The corresponding soil N:P ratios were also 3.8–66.7% and 19.1–

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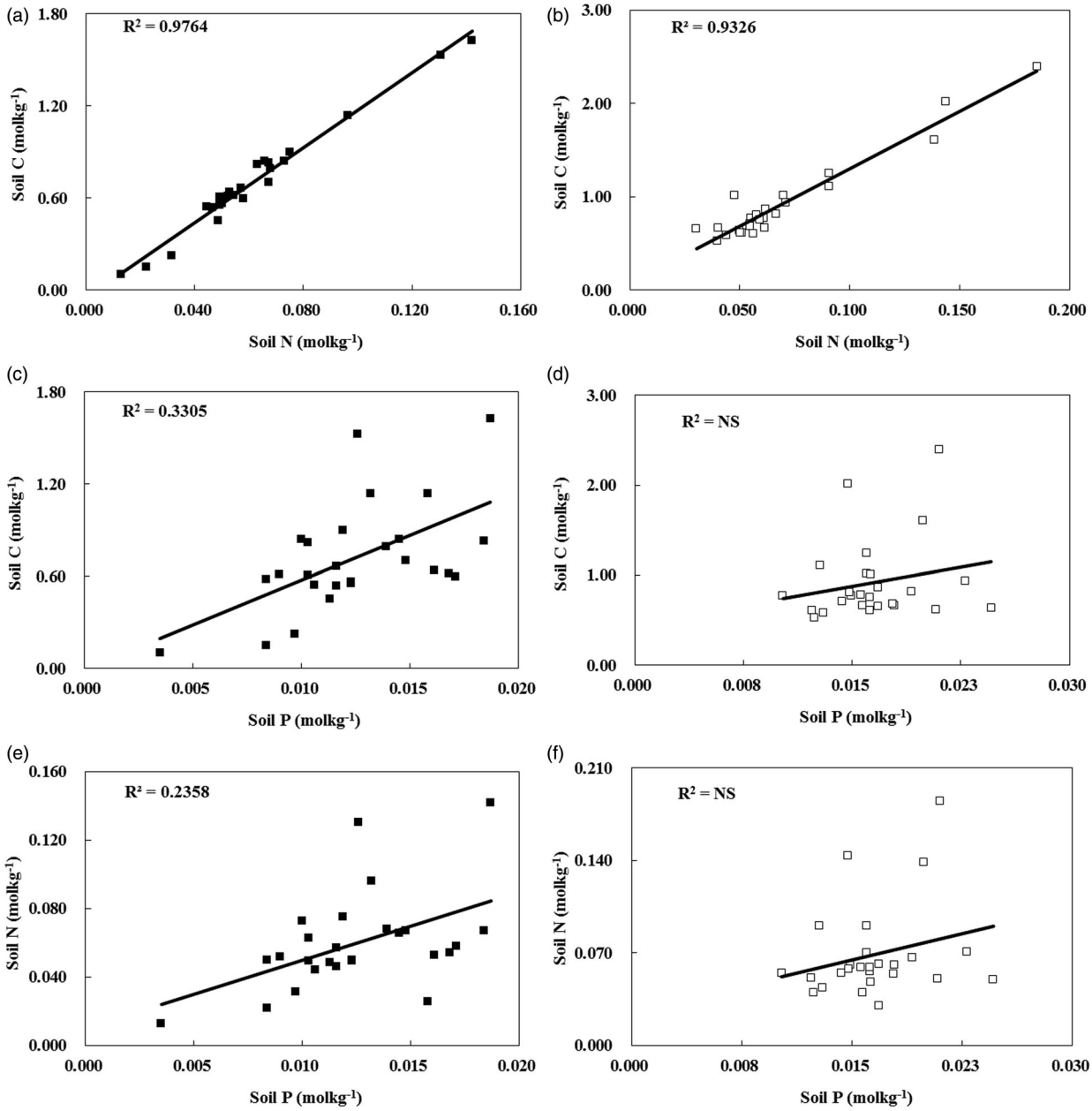

Figure 1. Relationships between soil C and N in 2000 (a) and 2010 (b), soil C and P in 2000 (c) and 2010 (d), and soil N and P in 2000 (e) and 2010 (f) in a small catchment.
NS, not significant; Solid squares represent variables of 2000 and hollow squares represent variables of 2010.

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75.0% higher than for other land uses. Utilization time also affected the changes in soil elemental ratios. Soil C:N ratios increased approximately 19.7–29.6% for all land uses after 10 years of utilization. Soil C:P and N:P ratios also increased for most land-use types, but declined approximately 22.9% and 40.6% in dry cropland in 2010, respectively. Correlation analysis also showed that clay content was significantly negatively correlated with soil C:P ($r = -0.393$, $P < .05$) or N:P ($r = -0.409$, $P < .05$) ratios in 2010.

Comparing of soil and microbial biomass C:N ratios

Extraordinary low soil C:P and N:P ratios indicated that C or N might be the potential limiting nutrients in this region. The relationship between microbial biomass and environmental elemental stoichiometry ratios could help clarify the nutrient cycling and limitations in ecosystems (Hall et al. 2011). Therefore, the C:N ratios in soil and microbial biomass were also compared in the present study. Soil and microbial biomass C:N ratios were influenced by different

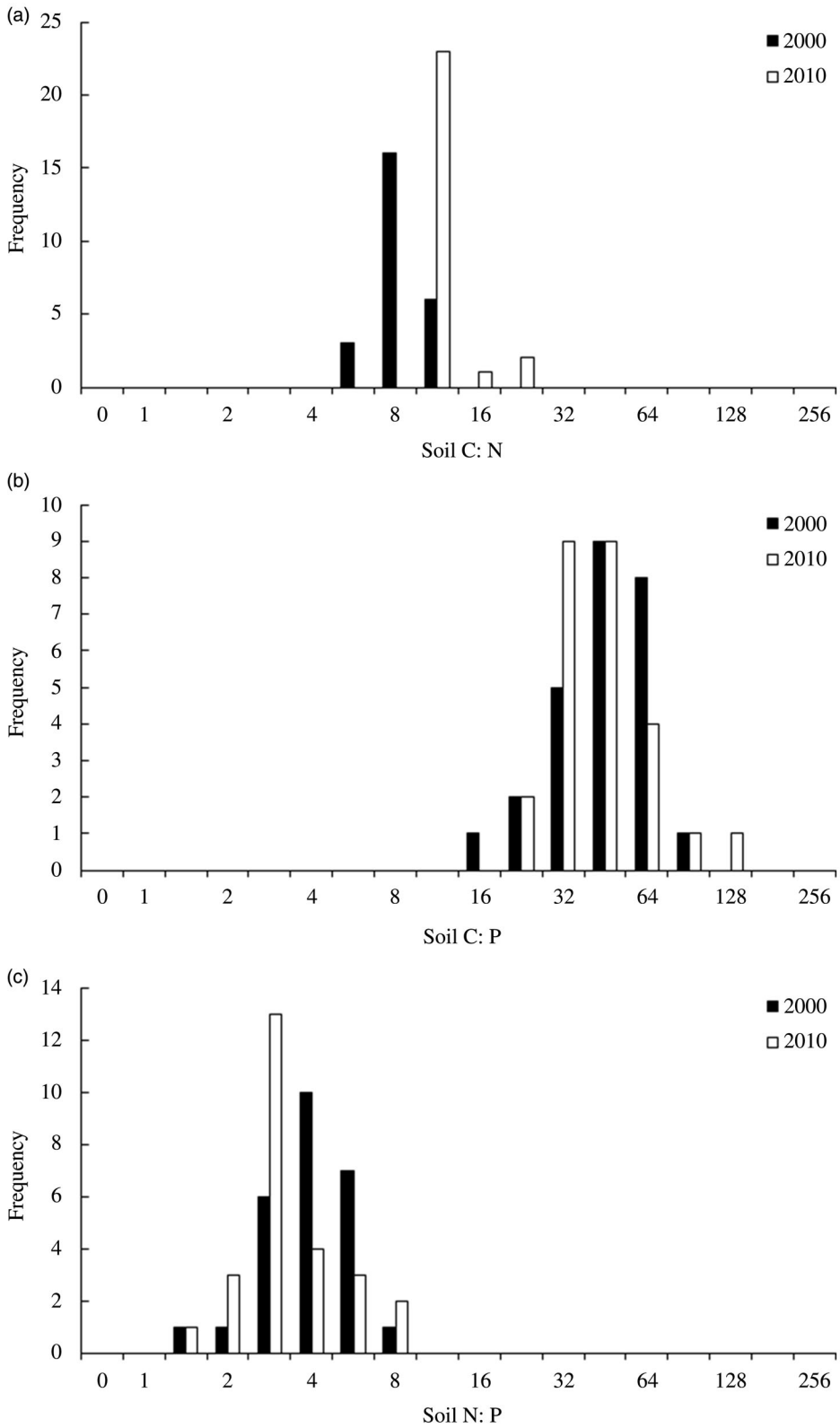

Figure 2. Frequency distribution of soil C:N (a), C:P (b) and N:P (c) ratios in a small catchment.
Bars in black and white represent ratios in 2000 and 2010, respectively. The x-axis of the histogram is transformed to log2 scale to highlight the log-normal distribution.

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Table 1. Soil C, N and P stoichiometric ratios in a small catchment, compared to ratios in China's soil.

		2000					2010				
	Ratios in China's soils	LL	Mean	UL	*t*	*P*	LL	Mean	UL	*t*	*P*
Soil C:N	14.4	6.8	11.1	13.0	−10.088	<.001	10.8	13.7	21.8	−1.431	NS
Soil C:P	136	17.8	56.8	121.5	−17.346	<.001	25.8	56.7	137.4	−15.726	<0.001
Soil N:P	9.3	1.6	4.8	10.4	−12.234	<.001	1.8	4.2	9.8	−13.114	<0.001
Soil C:N:P	134:9:1		59:5:1					54:4:1			

Note: LL and UL represent the lower and upper confidence limits, respectively, for the means of soil C:N, C:P and N:P ratios; *t* represents *t*-test statistic comparing soil C, N and P ratios in a small catchment to those in China's soils; *P* represents probability values for significant difference; NS indicates not significant.

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land uses (Figure 3). For instance, soil C:N ratios were relatively constrained among different land uses; however, microbial biomass C:N ratios in paddy fields were significantly higher than for other land uses (Figure 3). In paddy fields, C:N ratios were higher in microbial biomass than in soil, but the converse was true for the other land uses (Figure 3).

Discussion

Do well constrained soil C:N:P ratios exist on a small spatial scale?

Regression analysis (Figure 1) and frequency analysis (Figure 2) indicated soil C:N ratios in surface soil samples were well constrained in both 2000 and 2010 in this small catchment. Relatively constrained C:P and N:P ratios were also observed in 2000 (Figure 1). The strong correlations between soil total C, N and P in 2000 were consistent with previous reports (Melillo et al. 2003; Vitousek 2004; Cleveland & Liptzin 2007). For example, Cleveland and Liptzin (2007) found strong associations between soil total C, N and P on a global scale, although the correlation coefficients between soil C and P and between N and P were less than that between soil C and N. Constrained C:N:P ratios across a large spatial scale indicated that total soil C, N and P in terrestrial ecosystems were mainly influenced directly or indirectly by plant productivity (Cleveland & Liptzin 2007). In the present study, nevertheless, soil C:P and N:P ratios became variable after 10 years of different utilization (Figure 1). This indicated that agricultural practice might dramatically affect soil C:N:P ratios in a small catchment. For example, about 138–345 kg ha^{-1} y^{-1} of N and 50–100 kg ha^{-1} y^{-1} of P were the inputs in dry cropland and paddy field in this small catchment, but fertilizer was rarely used on waste land. The different fertilizer use might lead to chronic changes in soil elemental stoichiometric ratios.

Soil C:N:P ratios at small versus large spatial scale

Soil C:N ratios on a global or national scale were discussed in previous studies (Post et al. 1985; Batjes 1996; Cleveland & Liptzin 2007; Tian et al. 2010). For example, in analysis of soil and microbial biomass C:N:P ratios, Cleveland and Liptzin (2007) observed that soil C:N ratio was about 14.3 at the global scale. At a national scale, Tian et al. (2010) found a relatively constrained C:N ratio (14.4) in surface soil of China. Compared to these previous results, soil C:N ratios were significantly lower in 2000 in the present study, but were similar to China's soil C:N ratios after 10 years of utilization (Table 1). C:P and N:P ratios of surface soil were 186 and 13.1 at the global scale, respectively, (Cleveland & Liptzin 2007), but correspondingly were 136 and 9.3 at the national scale (Tian et al. 2010). Our results showed remarkably lower soil C:P (56.8 in 2000 and 56.7 in 2010) and N:P (4.8 in 2000 and 4.2 in 2010) ratios in surface soil layer in this small catchment (Table 1). As Cleveland and Liptzin (2007) explained, high soil C:N ratios might be because most soil samples were taken from forest and grass land, which usually has a humified litter layer or root felt with a high C:N ratio. However, in the red soil region of subtropical China, acidic soils are rich in Fe and Al oxides and lead to strong fixation of P (Jin et al. 2008). Additionally, total C and N contents are relatively low due to high mineralization of soil organic matter. These partly explained the low soil C:P and N:P ratios in the small catchment of the present study.

Factors affecting soil C:N:P ratios at the small spatial scale

At the local scale, different land uses and human practices could affect a series of soil processes (Lepsch et al. 1994; Hontoria et al. 1999) and lead to nutrient transport and distribution (Wang et al.

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Table 2. Soil C, N and P contents and ratios among different land use and utilization time in a small catchment.

Year	Land use	Soil C:N	Soil C:P	Soil N:P	SOC (mol kg^{-1})	TN (mol kg^{-1})	TP (mol kg^{-1})	pH	Clay (%)
2000	Paddy field	10.8 ± 0.4 a	65.8 ± 9.1 a	5.5 ± 0.8 a	0.86 ± 0.15 a	0.069 ± 0.013 a	0.012 ± 0.001 a	5.43 ± 0.09 a	33.3 ± 2.5 abc
	Dry cropland	11.2 ± 0.6 a	51.5 ± 5.5 a	4.5 ± 0.3 a	0.61 ± 0.07 a	0.052 ± 0.004 a	0.012 ± 0.001 a	5.12 ± 0.06 b	33.4 ± 1.8 abc
	Orchard land	11.7 ± 0.0 a	62.6 ± 5.4 a	5.3 ± 0.4 a	0.70 ± 0.09 a	0.060 ± 0.008 a	0.011 ± 0.002 a	4.93 ± 0.27 bc	28.4 ± 4.5 c
	Waste land	11.2 ± 0.9 a	37.2 ± 2.5 a	3.3 ± 0.1 a	0.62 ± 0.02 a	0.055 ± 0.003 a	0.017 ± 0.000 a	4.94 ± 0.11 bc	42.5 ± 1.9 a
2010	Paddy field	14.0 ± 0.8 a	75.6 ± 9.9 a	5.6 ± 0.8 a	1.26 ± 0.18 a	0.093 ± 0.015 a	0.017 ± 0.001 a	4.86 ± 0.03 bc	30.6 ± 1.9 bc
	Dry cropland	13.5 ± 0.9 a	41.9 ± 2.5 a	3.2 ± 0.2 a	0.69 ± 0.03 a	0.053 ± 0.003 a	0.017 ± 0.001 a	4.71 ± 0.03 c	36.2 ± 1.6 abc
	Orchard land	14.0 ± 0.0 a	65.2 ± 10.5 a	4.7 ± 0.7 a	0.79 ± 0.02 a	0.056 ± 0.001 a	0.013 ± 0.002 a	4.77 ± 0.13 c	26.2 ± 7.2 c
	Waste land	12.6 ± 0.1 a	42.5 ± 4.0 a	3.4 ± 0.3 a	0.72 ± 0.03 a	0.057 ± 0.002 a	0.017 ± 0.001 a	4.70 ± 0.06 c	40.4 ± 1.2 ab

Note: SOC indicates soil organic C, TN indicates total N, TP indicates total P, different letters in columns indicate significant difference at $P < .05$.

2001). Different land uses and utilization times affected soil elemental ratios, particularly soil C:P and N:P in the present study. Generally, soil C:N, C:P and N:P ratios in paddy and orchard land soils were higher than those for other land uses (Table 2). After 10 years of utilization, soil C, N and P contents and their elemental ratios also increased for all land uses (Table 2). Differences in nutrient accumulation might be one factor affecting soil elemental stoichiometry. For example, it was reported that input of organic matter in paddy soils was two to three times higher than that in waste land soils in this region (Li et al. 2003). This could explain the discrepancy in C:P and N:P ratios between paddy and waste land soils. Moreover, clay content was an important environmental factor influencing soil elemental stoichiometric ratios in this small catchment of subtropical China. Negative relationships between clay content and soil elemental ratios showed that decreased clay content was associated with high soil elemental stoichiometric ratios. As far as effects of land use were concerned, paddy and orchard land soils were usually of lower clay content. Long periods of utilization also decreased the clay content. The low clay content caused high soil C:P and N:P ratios because leaching of soil clay commonly accompanied the increase of soil organic matter synchronously in this region (Li et al. 2003). For instance, soil organic C increased faster and reached a constant value more quickly in soils with a low rather than a high clay content (Li et al. 2003).

Were soil elemental ratios an indicator of nutrient limitations in a small catchment?

The concept of constrained stoichiometric relationships of C, N and P in ocean water and plankton could provide insights into the status of nutrient cycling and limitation in aquatic ecosystems (Hecky & Kilham 1988). In terrestrial ecosystems, several studies have indicated that plant foliar N:P ratios were reliable indices of nutrient limitation (Koerselman & Meuleman 1996). It was also suggested that the relationship between microbial biomass and environmental elemental ratios could indirectly reflect nutrient recycling in ecosystems (Hall et al. 2011). For example, it was reported, when environmental N:P was less than microbial biomass N:P, that N was the limiting element and microorganisms would retain more N. In contrast, when environmental N:P was greater than biomass N:P, P was the limiting element and microorganisms would recycle more N (Hall et al. 2011). Very low C:P and N:P ratios indicated a potential C or N limitation in soil ecosystems in the present study. Furthermore, soil C:N ratios were lower than microbial biomass C:

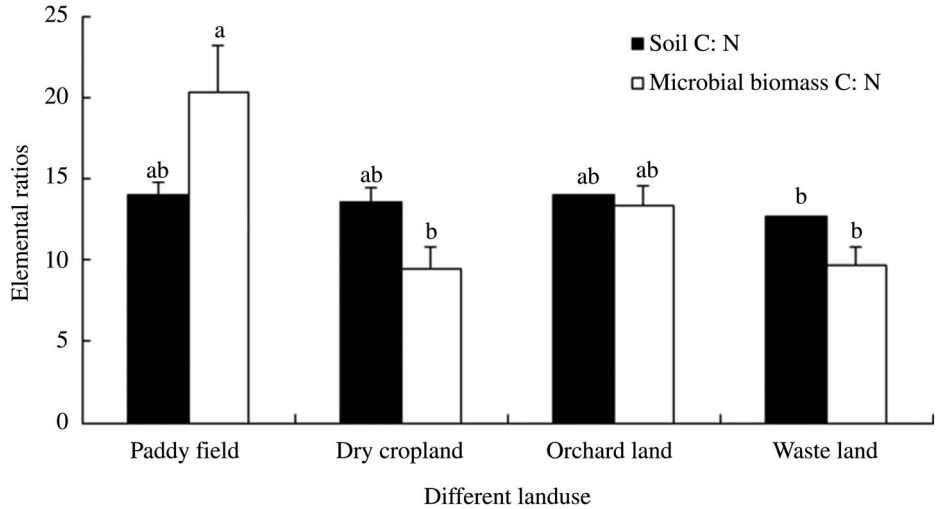

Figure 3. Soil C:N and microbial C:N ratios among different land use in 2010 in a small catchment. Different letters on bars indicate significant difference at $P < .05$.

N ratios in paddy fields, but was opposite for the other land uses (Figure 3). It was assumed that N was not the potential limiting nutrient in paddy fields due to their higher N fertilizer input. However, N was still a limiting element for other land uses because of the low level of N input. Future work should be carried out to determine relationships between soil elemental stoichiometric ratios and for direct evidence of C or N limitations in ecosystems.

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Disclosure statement

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