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RESEARCH ARTICLE

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Spatial variation in organic carbon, nutrients and microbial biomass contents of paddy soils in a hilly red soil region

Abstract The contents of soil organic C (SOC), total N (TN), total P (TP), dissolved N (D_N), Olsen-P, and microbial biomass C, N, P (B_C, B_N, B_P) of 254 paddy soils (0–18 cm in depth) in a hilly red soil region of subtropical zone of China were studied. The results showed that the contents of SOC, TN, B_C, B_N and D_N of paddy soils at the bottom of hills were 14.6%, 13.6%, 24.6%, 20.4% and 95.8% higher than those at the foothill, respectively. The Olsen-P content of paddy soils at the foothill was 33.3% higher than that at the bottom of hills. However, the differences in TP, B_P and available P (the sum of B_P and Olsen-P) contents were not significant between the two positions. In addition, the ratios of soil C/P, B_C/B_P and B_C/SOC of paddy soils at the bottom of hills were 12.7%, 28.5% and 8.2% higher than those at the foothill, respectively, but the differences in ratios of soil C/N, B_C/B_N, B_N/TN and B_P/TP were not statistically significant between various positions.

Keywords hilly red soil region, paddy soil, soil nutrients, microbial biomass, topographic position

1 Introduction

The subtropical hilly red soil regions of China play a key role in the agricultural sustainable development strategies in the whole state because of seasonable heat and water resources, rapid nutrient cycling as well as great potential of agricultural production (CAAS, 2001). However, the severe degradation of soil fertility and ecological environment caused by long-term inappropriate utilization of land resources has been considered as the leading factor to block the grain production and the sustainable development of agricultural ecosystems in these regions (CAAS, 2001). To meet the need of maintaining or improving soil fertility and grain production with the conservation of ecological environment, economical fertilization has become the frontier field in the study of agricultural sustainable development in China. Understanding the present status of soil fertility and availability of soil nutrients is requested for economical fertilizer application. Hu et al. (1997) explored the variation of soil nutrients and soil fertility at a hilly brown red soil region in the subtropical region and found that the content of soil organic matter, total nitrogen, and alkali-hydrolyzable-N in paddy soils at low terrain with lower available P and K was higher than that in upland soils at the middle of hills, and that soil fertility in woodland on the top of hills was higher than that in fallow land. Sariyildiz et al. (2005) suggested that soil organic carbon contents were not significantly different among various topographical positions, but total N showed a trend of higher content at the bottom of mountains and lower content at the top of mountains in the northwest of Turkey. Liu et al. (2006) discussed soil organic C (SOC) distribution on a county scale in China and suggested that the SOC spatial pattern was approximately consistent with the spatial structure of topography. Research has focused on the soil fertility and nutrient availability in the subtropical hilly regions (Hu et al., 1997; Li et al., 1998; Liu et al., 2003; Huang et al., 2004; Sariyildiz et al., 2005; Tang et al., 2006a), but few researchers concerned the impact of micro-topography on soil nutrients and microbial biomass in paddy soils, which widely spread in the subtropical region of China. In view of that, paddy soils were intensively sampled and investigated from an integrated hilly red soil landscape. The objectives of this paper were to explore the characteristics of soil organic carbon, soil nutrients and microbial biomass in paddy soils at various topographical positions, and to further provide suggestions for economical fertilizer application and agricultural sustainable development in paddy fields of the subtropical hilly red soil regions in China.

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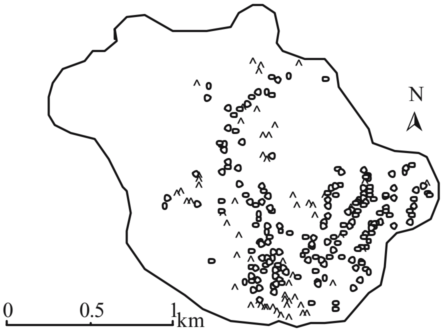
2 Materials and methods

2.1 Study site

The study site is located at Pantang Town, Taoyuan County of Hunan Province, where is located at one of the demonstration plots for integrated control red and yellow soils in the south of China founded at 1990. This site has a subtropical humid monsoon climate with an annual average temperature of 16.8°C and annual precipitation of 1 330 mm. Agricultural lands in this area mainly consist of paddy fields distributed at low terrain of hills, upland and orchard located on the hillsides, and woodland on the tops.

2.2 Sample collection

An integrated hilly red soil landscape in this demonstration plot with the area of 355.2 hm^2 was selected. The relative elevation was about 15–30 m and slope gradient was 8°–12°. The terrain at east, north and west of this site was relatively higher than that at the south. In 2003, 193 surface (0–18 cm) paddy soil samples at the bottom of hills (BH) and 61 paddy soil samples at foothill (FH) with a sampling density of three to four samples per hectare were collected (Fig. 1). The basic information about paddy samples at the various topographical positions is shown in Table 1.



○ represents bottom samples; ^ represents foothill samples

Fig. 1 Spatial distribution of soil samples

2.3 Soil treatment and analysis

All soil samples were hand-picked, with the plant debris and roots removed, then they passed through a sieve (<2 mm), followed by adjusting the sieved moist soils to 40% water holding capacity (WHC) by gently spraying them with distilled water. The adjusted soil was pre-conditioned for seven days at 25°C in a 150 L air-tight bin containing free water to maintain high humidity, and a breaker of 10 mol NaOH (250 mL) was used to trap CO_2 evolved. The pre-conditioned soil samples were used to determine soil microbial biomass C (B_C), N (B_N) and P (B_P). As for the determination of SOC, total N (T_N) and total P (T_P), a separate portion of the sieved soil samples were air-dried and milled to pass through a 0.25 mm sieve.

Soil B_C and B_N were measured by a fumigation and extraction procedure (Brookes et al., 1982a, 1985; Wu et al., 1990, 2003). Briefly, a portion of unfumigated soil (25 g on an oven-dry basis) was extracted with 40 mL 0.5 mol K_2SO_4 by shaking at 250 r/min for 30 min. The suspension was filtered using a Whatman No. 42 filter paper. A separate portion was fumigated by exposing soil to alcohol-free $CHCl_3$ vapor for 24 h in a vacuum desiccator (Brookes et al., 1985). After $CHCl_3$ was removed by vacuum extraction, the fumigated portion was extracted with K_2SO_4, as the above mentioned. Organic C in the extract was analyzed by an automated procedure using a total organic C (TOC) analyzer (Phoenix–8000). After digestion, N in the extract was analyzed by Flustar–5000. The amount of B_C and B_N was calculated from the amount of organic C and total N extracted from the fumigated soil minus that extracted from the non-fumigated soil, using a conversion factor of 0.45 (Wu et al., 1990) and a conversion factor of 0.45 (Brookes et al., 1985), respectively. Dissolved N (D_N) was considered as the N content extracted by 0.5 mol K_2SO_4 at unfumigated soil.

Soil B_P was measured by a fumigation and extraction method (Brookes et al., 1982b). Fumigated and non-fumigated portions (5.0 g on an oven-dried basis) of soil were extracted with 80 mL Olsen reagent (0.5 mol $NaHCO_3$ at pH 8.5). The inorganic P extracted was analyzed by a spectrophotometer (Murphy and Riley, 1962). To minimize the errors caused by using a fixed conversion factor (Morel et al., 1996; Wu et al., 2000; Oberson et al., 2001), the amount of soil B_P was calculated from the amount of extractable P in fumigated soil minus that in non-fumigated soil, using a recovery efficiency of B_P as the conversion factor (Wu et al., 2000). The recovery efficiency of B_P was 0.29, determined by spiking a suspension of cultivated microorganisms produced according to Wu et al. (2003). The suspension provided 25 mg biomass-P per kg soil, and this was fumigated with the soil. The Olsen-P was considered as the P content extracted by 0.5 mol $NaHCO_3$ in the unfumigated soil. The sum of B_P and Olsen-P was viewed as available P (A_P).

Table 1 Basic information about soil samples

Topography	n	Soil type	pH	Water condition	Irrigation	Cultivation system	Crop yield /(kg·hm^{-2})
Bottom	193	Gleyed paddy soil	5.05	Gleyed	Artesian water	Rice–rice–fallow (95%)$^{a)}$	Rice: 11 000
Foothill	61	Submergenic paddy soil, waterloggogenic paddy soil	4.92	Submergenic, waterloggogenic	Precipitation, irrigation	Rice–oilseed-rape (65%), rice–fallow (30%)	Oilseed-rape:1 350, rice: 6 450

Note: $^{a)}$ means values in parentheses are the percentages of the cultivation system areas to total cultivation areas.

Soil organic C and total N were measured by C/N analyzer (Vario MAX) as dry combustion. TP was determined by the NaOH fusion method (Olsen and Somers, 1982).

2.4 Data treatments

Data were processed using Statistics Package for Social Science (SPSS) 10.0 for the means and the significance of the differences between the means analyzed by the *t*-test at 5% probability.

3 Results and discussion

3.1 Variation in soil organic C and microbial biomass C

Soil organic matter, as a material foundation of soil fertility and providers for nutrients such as N and P for plants, can be calculated based on SOC. As an important available nutrient pool (Parffit et al., 2005), soil microbial biomass can be calculated by B_C, and the biomass change can sensitively indicate the dynamics of SOC (Tang et al., 2006a).

In our study, the paddy SOC at BH predominately distributed at 13–22 g/kg with 86.0% probability, and the average SOC was 16.5 g/kg. The main distribution range of the paddy SOC at FH was 10–19 g/kg with 98.4% probability, and the average content was 14.4 g/kg, with a value about 85% of SOC at BH and statistically significant differences ($P<0.01$) (Table 2, Fig. 2). The paddy soil B_C content at BH mainly scattered at 400–1,300 mg/kg with 87.0% probability, and the average content was 866 mg/kg. The main distribution range of the paddy B_C at FH was 400–1,000 mg/kg with 82.0% probability, and the average content at FH (695 mg/kg) was approximate 80% of the value at BH, with a statistically significant difference ($P<0.01$). In general, the ratios of B_C to SOC (B_C/SOC) were about 1%–5% (Jenkinson and Ladd, 1981; Liu et al., 2003). Table 2 showed that the B_C/SOC at paddy fields was significantly ($P<0.05$) higher at BH (5.14%) than at FH (4.75%).

Table 2 Comparison of soil organic C, microbial biomass C in paddy soils at the bottom of hills and foothill

Topography	SOC /(g·kg^{-1})	B_C/(mg·kg^{-1})	B_C/SOC /%
Bottom	16.5A[a)]	866A	5.14a
	(2.68)[b)]	(308)	(1.35)
Foothill	14.4B	695B	4.75b
	(2.02)	(213)	(0.99)

Note: [a)] means that different capital and small letters in the same column indicate significant difference at the 1% and 5% levels, respectively; [b)] means data in parentheses are standard deviations (the same in the following tables).

The variation in the paddy SOC at various topographical positions might be related to the differences in cultivation systems, soil erosions and hydrographic status. By taking advantages of the low terrain and high water table, the retention of high soil water content in paddy field at BH could benefit the decomposition of the paddy SOC at a low rate, and an increase in the accumulation of soil organic matter. Air drying-rewetting cycles of paddy soils at FH occurred frequently due to the relative low water table, causing an increase in the mineralization rate of soil organic matter. Cultivation systems at BH mainly were rice–rice–fallow (at submerged status), and the crop production was higher than that at FH where the cultivation systems were rice–oilseed rape rotation or rice–fallow (at drained status) (Table 1). Therefore, it can be deduced that plant root stubble and root exudates biomass at BH may be also higher than those at FH. Additionally, the root stubble is easily transformed to soil organic matter, so the exogenous input amount of stubble may determine organic carbon contents in soils (Li et al., 1998; CAAS, 2001; Tang et al., 2006a, b) while the root exudates tend to stimulate soil microorganism growth and then improve microbial biomass (Manjaiah et al., 2000; Dignac et al., 2002; Tang et al., 2006a). Submerged condition is in favor of maintaining microbial biomass (Liu et al., 2003), but air drying-rewetting cycles tend to reduce soil microbial biomass (Wu and Brookes, 2005). Moreover, paddy fields at BH can receive more organic carbon brought by soil and water at adjacent lands than at FH (CAAS, 2001).

3.2 Variation in total N, microbial biomass N and dissolved N

Nitrogen is not only one of the essential macronutrients that plants require, but also an element to bring agricultural environment risk, such as water body eutrophication (Tang et al., 2005). Soil B_N is an important component of soil available N pool, and plays a key role in soil N transformation and

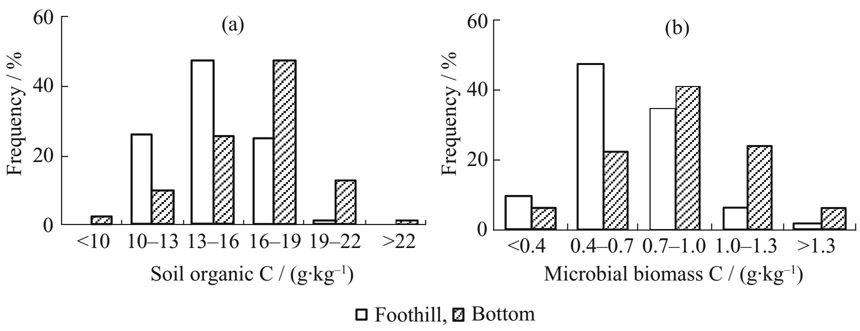


Fig. 2 Frequency of soil organic C (a) and microbial biomass C (b) content in paddy soils at the bottom of hills and foothill

cycling (Wang et al., 2003; Parffit et al., 2005; Tang et al., 2005). The main components of soil D_N extracted by 0.5 mol K_2SO_4 are mainly composed of mineral N, amino acid-N, and easily mineralized low molecular-N. Research has proved that D_N is the direct source of available N, and the availability is higher than B_N (Richard et al., 2002). However, D_N easily loses with water and brings environmental risks (Karsten and Stefan, 2002).

Table 3 and Fig. 3 showed that the paddy soil TN, B_N and D_N at BH mainly distributed at 1.5–2.5 g/kg, 30–120 and 10–70 mg/kg, respectively, with their probabilities being 88.1%, 93.6% and 87.0%, and their average contents being 2.00 g/kg, 58.4 and 19.3 mg/kg, respectively. But the main distribution of TN and B_N at FH ranged from 1.0–2.0 g/kg with 83.6% probability, 30–90 mg/kg with 85.2% probability, respectively, and that of D_N was lower than 50 mg/kg with the average content at 19.3 mg/kg, which was about half of content at BH. A statistical analysis indicated that there existed a significant difference in the TN contents at FH, which was 13.6% lower than that at BH ($P < 0.01$), the mean value of B_N content at FH was 58.4 mg/kg, significantly lower than that at BH ($P < 0.01$), and the difference in D_N contents was significant between the two topographical positions ($P < 0.01$). However, there existed no significant difference in the ratios of B_N and TN (B_N/TN) in the paddy field at both BH (3.53%) and FH (3.27%) statistically.

Table 3 Comparison of TN, microbial biomass N (B_N) and dissolved N (D_N) contents in paddy soils at the bottom and foothill

Topography	TN /($g \cdot kg^{-1}$)	B_N/($mg \cdot kg^{-1}$)	D_N/($mg \cdot kg^{-1}$)	B_N/TN /%
Bottom	2.00A	70.3A	37.79A	3.53a
	(0.30)	(26.65)	(23.18)	(1.26)
Foothill	1.76B	58.4B	19.33A	3.27a
	(0.23)	(21.42)	(14.18)	(0.97)

N in soil organic matter accounts for 90% of total N in soil, and the soil TN content was primarily determined by the soil organic matter content. As discussed above, the paddy soil SOC content at BH was significantly higher than that at FH. The B_N and D_N at BH were both significantly higher than those at FH, which may be related to the relatively higher contents of SOC, TN and B_C at BH (Karsten and Stefan, 2002; Richard et al., 2002; Liu et al., 2003; Wang et al., 2003; Parffit et al., 2005). In addition, the soil and water loss at FH in hilly red soil regions was relatively severe, consequently, more N lost with soil and water (CAAS, 2001). Whereas the bottom paddy field, located in the low terrain, held more N brought by soil and water from the adjacent upland. As B_N and D_N both are direct sources of available N, so it can be suggested that the availability of soil N at the bottom paddy soils may be higher than that at FH.

3.3 Variation in total P, microbial biomass P, Olsen-P and available P pool

Phosphorus is another essential macronutrient requested by plants. Due to the strong adsorption and fixation of soil mineral matter and organic matter to P, the availability of soil P for plants is rather low, especially in the subtropical red soil region (Guo et al., 2005). However, a large number of soil microorganisms have a capacity to transform the insoluble P to the available P (Brookes et al., 1982b). The rapid turnover of P in the microbial pool can contribute a major source to the available P pool (A_P), as P released from the microbial biomass is highly available to plant uptake, and also the microbial immobilization of inorganic P may protect the P from physico-chemical fixation (Brookes et al., 1982a, b; Oberson et al., 2001; Huang et al., 2004). Olsen-P is considered as rapidly available P both for microorganism and plant uptake (Huang et al., 2004; Parffit et al., 2005).

The differences in TP, B_P, A_P, and ratios of B_P and TP (B_P/TP) were not significant between at BH and at FH (Table 4, Fig. 4). But Olsen-P contents at the two positions were significantly different ($P < 0.01$), and the average content at BH (6.93 mg/kg) was 33% higher than that at FH (5.20 mg/kg).

Table 4 Comparison of TP, microbial biomass P (B_P), Olsen-P and available P pool (A_P) in paddy soils at the bottom of hills and foothills

Topography	TP /($g \cdot kg^{-1}$)	B_P /($mg \cdot kg^{-1}$)	Olsen-P /($mg \cdot kg^{-1}$)	A_P /($mg \cdot kg^{-1}$)	B_P/TP /%
Bottom	0.457a	32.1a	5.20A	37.3a	6.98a
	(0.054)	(12.35)	(2.83)	(13.52)	(2.55)
Foothill	0.456a	33.3a	6.93B	40.2a	7.39a
	(0.072)	(11.24)	(4.89)	(13.90)	(2.47)

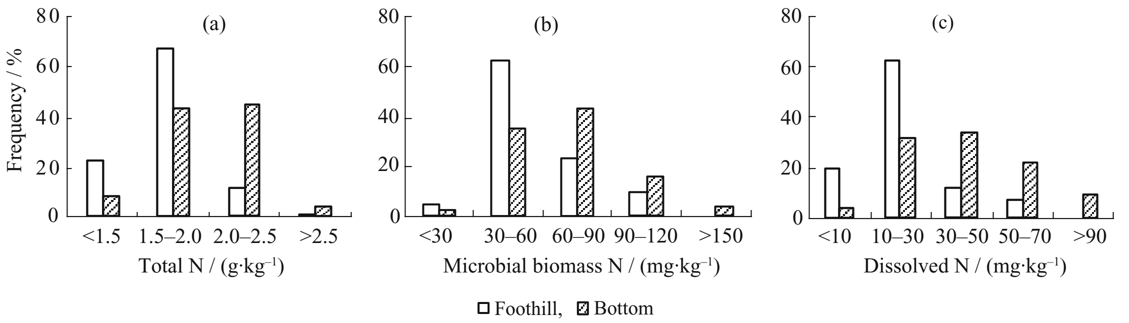


Fig. 3 Frequency of soil total N (a), microbial biomass N (b) and dissolved N (c) content in paddy soils at bottom of hills and foothill

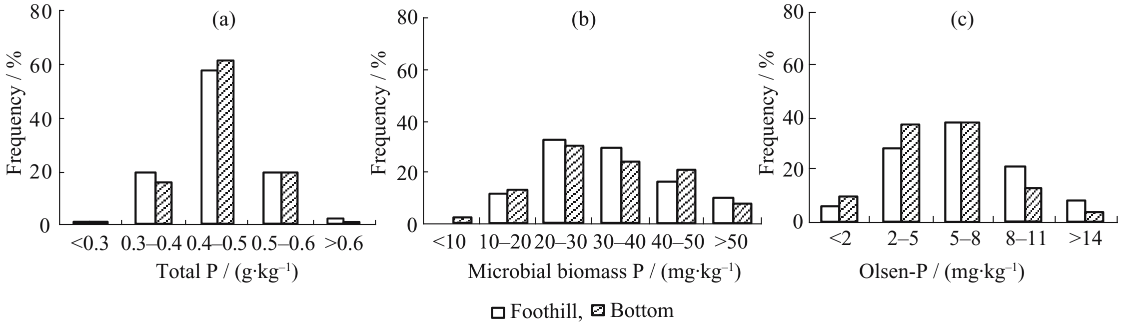


Fig. 4 Frequency of soil total P (a), microbial biomass P (b) and Olsen-P (c) content in paddy soils at bottom of hills and foothills

It is not surprising that there was no significant difference in TP content at the two positions in our study, because the TP content was related to soil mother materials and P fertilizer application. The paddy soil mother material was the Quaternary red soil throughout this site. And there were no differences in the amount and method of P fertilizer application between at BH and at TH. The homogeneity of B_P, A_P and B_P/TP in paddy fields at the two positions in our study indicated a weak impact of topographical positions on the soil P content and its availability in paddy soils in this region. The significant higher content of Olsen-P at FH may result from the planting of oilseed rape in the most paddy fields (65%) at FH.

3.4 Soil C/N, C/P and microbial biomass C/N, C/P

Soil C/N and C/P are important indexes to evaluate soil fertility status and can reflect to a large extent the constitutions and chemical properties of soil organic matter (Dignac et al., 2002). The ratios of B_C to B_N (B_C/B_N) showed the structures of microbial communities, whereas the ratios of B_C to B_P (B_C/B_P) revealed the regulation of soil microorganisms to P availability (He et al., 1997). Soil microorganisms always have a potential to release P and then supply Olsen-P to plant uptake under the low soil B_C /B_P condition. However, soil microorganisms tend to utilize Olsen-P under the high soil B_C/B_P condition (He et al., 1997).

In this study, there were not significant differences of paddy soil C/N and B_C /B_N between at BH and at FH (Table 5), which illustrated the homogeneity of constitutes and chemical properties of soil organic matters in paddy soils at the two positions, and less variation in structures of soil microorganism communities. The paddy soil C/P and B_C/B_P at BH were higher than at FH by 12.7% and 28.5%, respectively, and the differences were both statistically significant ($P <$ 0.01). The lower B_C/B_P at FH suggested a relatively high capacity of releasing P by soil microorganisms, which is consistent with the above result that the paddy soils at FH have a high Olsen-P content. And the paddy soils at BH with high B_C/B_P may have a relatively strong fixation of soil available P, which revealed that the balanced fertilization of organic and chemical P fertilizer may avoid the potential debate for available P of microorganisms and crops.

Table 5 Comparison of soil C/N, C/P and microbial biomass C/N, C/P in paddy soils at the bottom of hills and foothills

Topography	Soil C/N	Soil C/P	B_C/B_N	B_C/B_P
Bottom	8.3a (0.028)	36.4A (0.45)	12.9a (4.37)	29.3A (12.05)
Foothill	8.2a (0.047)	32.3B (0.81)	12.5a (3.33)	22.8B (8.66)

4 Conclusion

Soil organic C, TN, B_C, B_N and D_N contents at the bottom paddy field of hills were significantly higher than those at the foothill. Olsen-P content at the bottom was significantly lower than that at the foothill. There were no significant differences in TP, B_P and A_P contents at both the bottom of hills and foothills of paddy field. Soil C/N and B_C/B_N were not significant at the two positions. Soil C/P and BC/BP at the bottom paddy field were significantly higher than those at the foothill.

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