

## FERTILITY DYNAMICS OF THREE TYPES OF TEA GARDEN SOILS IN WESTERN SICHUAN, CHINA

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Understanding the seasonal dynamics of soil fertility is a key to providing decision support for rational use of fertilizers in tea gardens. In this study, seasonal variation in fertility parameters and the comprehensive fertility of 3 types of tea garden soils in western Sichuan, China, were investigated using a field survey and laboratory analysis. The results showed that pH, available phosphorus (AP), and available potassium (AK) in yellow earth remained low regardless of season; the lowest levels (among all soils) of total organic carbon (TOC) and total nitrogen (TN) occurred in yellow earth during spring and summer. Higher TOC, TN, and AP content occurred in spring due to basal fertilizer application; TOC was lower in summer due to higher decomposition rates and extensive soil erosion; lower TN and AP contents in summer were attributed to absorption by tea plants and to soil erosion; higher TOC and TN in autumn occurred as litter returned to the soil. Seasonal variation in AK was less obvious than that of the other fertility parameters. The comprehensive fertility of tea garden soils, ranked in order from higher to lower by season and soil type, was as follows: spring > autumn > summer for bleached paddy soil and yellow earth; but spring > summer > autumn for acid purple soil. Among the 3 tea garden soils, the fertility of acid purple soil was highest, and that of yellow earth was lowest in every season. Fertility was highest in spring for all soils. These results can provide a theoretical basis for scientific management of tea plantations in western Sichuan and similar regions.

**Key words:** tea plantation, soil fertility, seasonal dynamics, principal component analysis

### INTRODUCTION

Soil fertility is the capacity of a soil to provide and coordinate nutrients and environmental conditions for plant growth (Zhu, 1983). Soil fertility varies with seasonal changes in hydrothermal conditions, plant growth and development, and soil management practices. Research has shown that the lowest levels of total phosphorus in soils among various saline-alkaline grasslands occurred in September (Wang *et al.*, 2009). Soil N, P, K, Ca, and Mg in *Alnus cremastogyne* Burk plantations was found to be higher in summer and autumn than in winter and spring (He *et al.*, 2008). In contrast, nutrient content of forest soils in Dinghushan Nature Reserve was generally higher in winter, but organic matter in these soils showed little seasonal variation (Xia *et al.*, 1997).

Soil fertility directly affects the growth of tea plants, and the yield and quality of tea. Fully understanding soil fertility dynamics in tea gardens could provide decision support for the rational use of fertilizer to improve the yield and quality of tea. Researches addressing seasonal dynamics in fertility parameters of tea garden soils have been conducted in some regions. Soil pH value was found to vary among seasons, and was generally low in May, in the Meitan region (Sun

and Wu, 1980). Peak values of available K occurred in February, July, and August, while available K was low in May and reached a minimum in October; a similar annual trend was found among different soil types in Sichuan (Wu *et al.*, 1996). In Anhui, seasonal nutrient concentrations were as follows, in decreasing order of concentration: ammonium-N, July > September > April > November; nitrate-N, November > September > April > July; available P, April > July > November > September; and available K, April > November > September > July (Liao, 1996). Seasonal nutrient trends in Guizhou were as follows: soil organic matter, autumn > spring > summer; total N and alkali-hydrolyzable N, summer > spring > autumn; available P, summer > autumn > spring; and available K, autumn > summer > spring (Tian, 2001). Research conducted in Shandong found soil organic matter in autumn > spring > summer; alkali-hydrolyzable N in spring > autumn > summer; and available P in summer > autumn > spring (Li *et al.*, 2009). The above researches demonstrate that soil nutrient dynamics vary among different geographical research regions. Comprehensive seasonal fertility dynamics have not been reported for tea garden soils. To address this research gap, 3 types of tea garden soils (bleached paddy soil, yellow earth, and acid purple soil) in Mingshan County,

the home of tea culture in western Sichuan, China, were selected for study. Seasonal dynamics of pH, total organic carbon (TOC), total nitrogen (TN), available phosphorus (AP), and available potassium (AK) of surface soil during each tea-picking period were analyzed. Comprehensive evaluation of soil fertility according to picking season and soil type was carried out using principal component analysis to provide decision support for rational use of fertilizers to improve the yield and quality of tea.

## MATERIALS AND METHODS

**Study area:** The study was conducted in Mingshan County, Sichuan, China. The study area is characterized by a subtropical humid monsoon climate with mean annual air temperature of 15.4°C; mean annual precipitation of 1500 mm, the majority of which occurs in summer (June to September); mean annual sunshine of 953 h; and an annual frost-free period of 296 d. The zonal vegetation of the area is subtropical evergreen broad-leaved forest. The landform in the study area consists primarily of table-shaped hills with flat terraces (altitude 680–780 m a.m.s.l.). Three typical soil types occur in the study area: bleached paddy soil (Yuan *et al.*, 2012) on flat terraces; yellow earth on gentle slopes, developed from Pleistocene alluvium; and acid purple soil on steep slopes, developed from purple Cretaceous sandstone.

**Soil sampling:** The 3 typical soil types (bleached paddy soil, yellow earth, and acid purple soil), all of which support tea cultivation ("tea gardens"), were sampled from tea gardens of equal age during 3 tea-picking seasons: spring (early March), summer (mid-July), and autumn (late October), 2009. Surface soils (0–20 cm) were collected from 5 locations at each of the 3 sites by an "S" route at every sampling period, and were combined into one sample per site. In total, 27 samples were analyzed from the 3 seasons for the 3 soil types. The soil samples were air-dried, ground, and passed through nylon sieves with pore diameters of 2 mm, 0.25 mm, and 0.15 mm.

**Soil testing:** Soil pH was determined by potentiometer from slurries with a soil:water ratio of 1:2.5 (ISSCAS, 1978). TOC was determined using the potassium dichromate–sulfuric acid oxidation procedure (ISSCAS, 1978); TN was determined using the Kjeldahl method (Lao, 1980); AP was determined by molybdenum–antimony colorimetry (ISSCAS, 1978); and AK was determined by the flame photometric method (ISSCAS, 1978).

**Data analysis:** Descriptive statistics, including means, standard deviations (SD), and coefficients of variation (CV), were calculated using Excel 2003 software. Analysis of variance (ANOVA), multiple comparisons, and principal component analysis (PCA) were performed using SPSS 19.0 software. The means of each parameter were evaluated as primary estimates of the central tendency. The SD and CV

described the degree of variability in the measured soil attributes. ANOVA was used to determine whether there were significant differences between mean values for the 3 soil types or 3 seasons. Multiple-range tests with least significant differences (LSD) were performed to examine the difference between each pair of means when the results of ANOVA were significant at  $p < 0.05$ . PCA of the measured soil attributes was used to derive linear combinations of a set of variables that retained most of the information contained in these variables (Lu, 2004).

## RESULTS

**Seasonal variation in soil pH:** Soil pH ranged from 3.46 to 4.95, with a low coefficient of variation. The mean pH values by soil type, in decreasing order, were acid purple soil > bleached paddy soil > yellow earth. The mean pH of yellow earth (3.79) was significantly lower than that of the acid purple and bleached paddy soils. The mean pH of acid purple soil was 4.45 (Table 1).

Soil pH varied seasonally, but none of the seasonal variability was significant. The mean pH values of bleached paddy soil were 4.36 in spring, 4.20 in summer, and 4.14 in autumn. In yellow earth, mean soil pH was similar among seasons: 3.86 in summer, 3.78 in spring, and 3.72 in autumn. Acid purple soil had a mean pH of 4.62 in summer, 4.40 in autumn, and 4.33 in spring (Fig.1).

**Seasonal variation in TOC:** The mean TOC content of the 3 soil types was as follows: bleached paddy soil, 15.68 g/kg; acid purple soil, 12.99 g/kg; and yellow earth, 12.34 g/kg. There was no significant difference in TOC content among soils (Table 1).

Varying seasonal dynamics in TOC content were observed among the soils. The TOC in bleached paddy soil was 18.36 g/kg in spring, 13.31 g/kg in summer, and 15.38 g/kg in autumn. In yellow earth, TOC was 11.05, 11.86, and 14.11 g/kg in spring, summer, and autumn, respectively; in acid purple soil, TOC values were 14.87, 12.74, and 11.37 g/kg in spring, summer, and autumn, respectively. The largest difference in TOC content among the 3 tea garden soils occurred in spring, whereas the smallest difference occurred in summer (Fig.2).

**Seasonal variation in TN:** The mean TN contents were 1.23, 1.06, and 0.97 g/kg, respectively, in bleached paddy soil, acid purple soil, and yellow earth. However, these differences were not significant (Table 1). Seasonal trends in TN content were inconsistent. Bleached paddy soil contained average TN values of 1.31, 0.95, and 1.43 g/kg in spring, summer, and autumn, respectively. TN values of 0.98, 0.85, and 1.08 g/kg were observed in yellow earth in spring, summer, and autumn, respectively. In acid purple soil, measured TN contents were 1.36, 1.02, and 0.79 g/kg in spring, summer, and autumn, respectively. The largest difference in TN content among the soils was observed in

autumn, and the smallest difference was observed in summer (Fig.2).

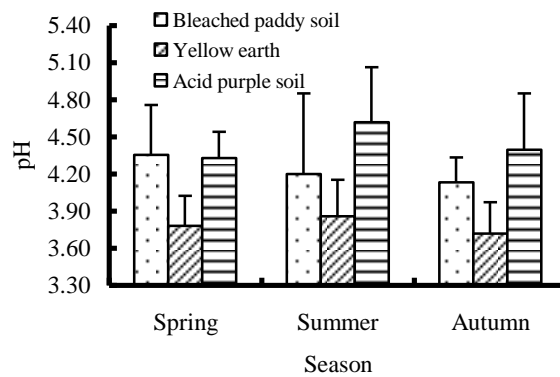
**Seasonal variation in AP:** Available P differed among soil types (Table 1). Mean AP in bleached paddy soil, acid purple soil, and yellow earth was 23.7, 23.2, and 10.2 mg/kg, respectively; none of these values differed significantly. The CVs for AP content were much higher than those of the other soil fertility parameters. Seasonal variation in AP content in bleached paddy soil was 123.8%, with contents of 42.4, 11.4, and 17.2 mg/kg in spring, summer, and autumn,

respectively. In acid purple soil, the mean AP content was 36.1, 15.4, and 18.0 mg/kg in spring, summer, and autumn, respectively. The mean AP content in yellow earth was 13.6, 9.5, and 7.4 mg/kg in spring, summer, and autumn, respectively. The largest difference in AP content among soils occurred in spring, and the smallest difference occurred in summer. The highest AP contents were observed in spring, and the lowest generally occurred in summer, although soil AP content was similar during summer and autumn in all soils (Fig.2).

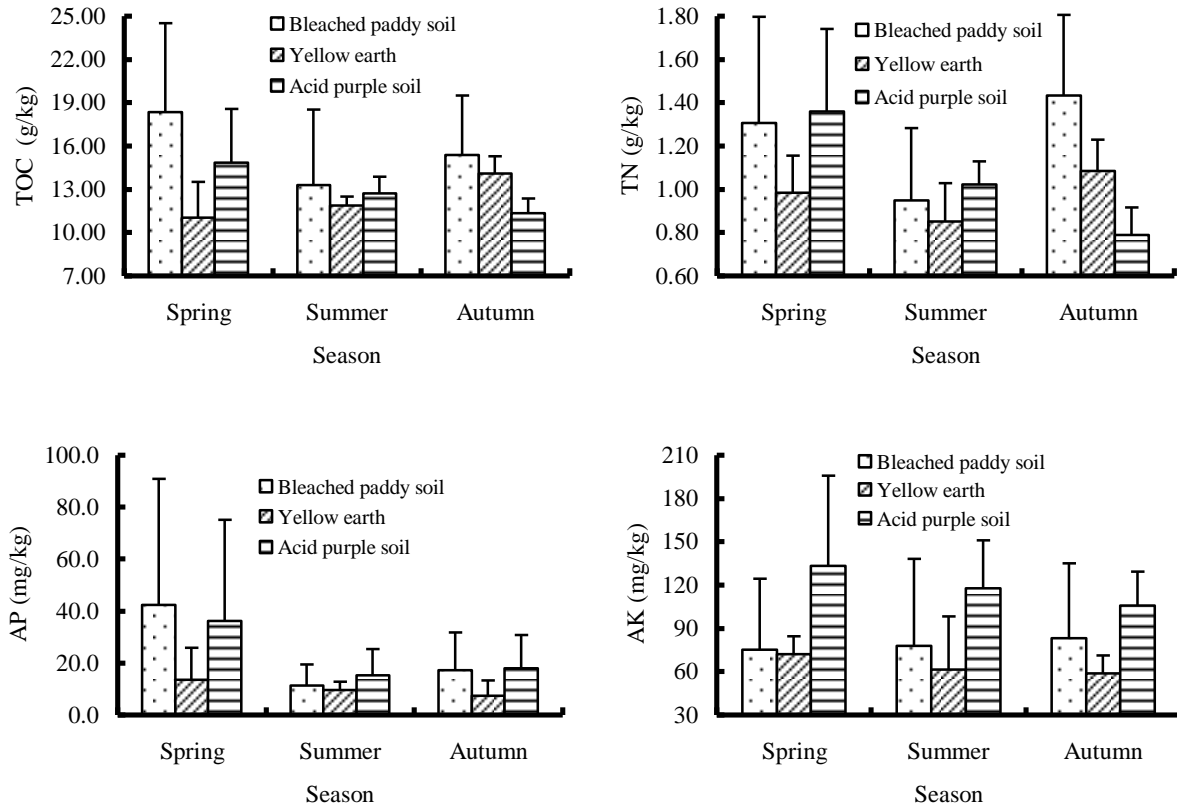
**Table 1. The mean values, standard deviations (SD), and coefficients of variation (CV), of the tested soil fertility parameters for each soil type. N = 9 samples per soil type.**

Soil type	Statistics	pH	Total organic carbon/(g/kg)	Total nitrogen/(g/kg)	Available phosphorus/(mg/kg)	Available potassium/(mg/kg)
<b>Bleached paddy soil</b>	Minimum	3.79	9.60	0.57	3.1	34
	Maximum	4.95	24.05	1.87	97.5	146
	Mean	4.23 a	15.68 a	1.23 a	23.7 a	79 b
	SD	0.41	5.03	0.41	29.3	47
	CV (%)	9.64	32.07	33.35	123.8	60
<b>Yellow earth</b>	Minimum	3.46	8.21	0.67	1.4	38
	Maximum	4.19	15.45	1.22	25.8	104
	Mean	3.79 b	12.34 a	0.97 a	10.2 a	64 b
	SD	0.23	1.98	0.18	7.5	21
	CV	6.20	16.01	18.14	73.9	33
<b>Acid purple soil</b>	Minimum	3.91	10.43	0.67	6.9	80
	Maximum	4.91	19.13	1.79	80.3	205
	Mean	4.45 a	12.99 a	1.06 a	23.2 a	119 a
	SD	0.36	2.52	0.32	23.2	39
	CV	8.06	19.39	30.47	100.3	33

**Note:** Values followed by different letters within columns are significantly different at the  $p < 0.05$  level.



**Figure 1. Variation in soil pH in tea gardens according to tea-picking season**



**Figure 2. Variation in total organic carbon (TOC), total nitrogen (TN), available phosphorus (AP), and available potassium (AK) in the 3 types of tea garden soils during the tea-picking period (spring through autumn). Values shown are means  $\pm$  standard deviation.**

**Seasonal variation in AK:** The AK content in the soils ranged from 34 to 205 mg/kg (Table 1), and the difference in AK content among soil types was significant. The mean AK contents for the 3 soils were 119, 79, and 64 mg/kg for acid purple soil, bleached paddy soil, and yellow earth, respectively, and the AK content of acid purple soil was significantly higher than that of the other 2 soil types. Seasonal concentrations of AK in acid purple soil were 133, 118, and 106 mg/kg in spring, summer, and autumn, respectively. In yellow earth, measured AK also decreased from spring to autumn. However, in bleached paddy soil, there was a slight increase in AK content from spring to summer to autumn (75, 77, and 83 mg/kg, respectively) (Fig.2).

**PCA:** Principal component analysis is a multivariate statistical analysis that can select a number of important variables (less than or equal to the original number of variables) from several attributes by linear transformation. PCA is useful in the evaluation of soil quality (Chen *et al.*, 2010). In the present study, 5 principal components (PC1 – PC5) were extracted through PCA (Table 2). The eigenvalues and variance of the 5 principal components are

presented in Table 2. PC1 and PC2 accounted for >85% of the total variance; these components can indicate soil fertility levels in the study area (Chen *et al.*, 2010). Therefore, soil fertility levels of tea gardens in different seasons were evaluated using the composite scores of the first 2 principal components.

The scores of the first 2 principal components can be presented using the eigenvectors of the principal components presented in Table 2, and the standardized values of the soil fertility variables were transformed in SPSS using the following equations (Equations 1 and 2).

$$Z_1 = 0.238pH_s + 0.278TOC_s + 0.275TN_s + 0.318AP_s + 0.205AK_s \quad \dots\dots\dots (1)$$

$$Z_2 = 0.427pH_s - 0.370TOC_s - 0.313TN_s - 0.045AP_s + 0.497AK_s \quad \dots\dots\dots (2)$$

Where  $Z_1$  and  $Z_2$  are the scores of PC1 and PC2, respectively, as calculated by the software;  $pH_s$ ,  $TOC_s$ ,  $TN_s$ ,  $AP_s$ , and  $AK_s$  are the standardized data values, transformed from the original data by the software.

After the scores of the principal components were obtained, the composite score of PC1 and PC2 was determined by the proportion of variance presented in Table 2 (Equation 3,

Table 2. Eigenvalues and eigenvectors

Principal component	Eigenvalues			Fertility parameters	Eigenvectors				
	Eigenvalue	Proportion (%)	Cumulative (%)		PC1	PC2	PC3	PC4	PC5
PC 1	2.835	56.698	56.698	pH <sub>s</sub>	0.238	0.427	-0.652	1.035	-2.116
PC 2	1.503	30.052	86.749	TOC <sub>s</sub>	0.278	-0.370	-0.483	0.604	3.651
PC 3	0.379	7.573	94.322	TN <sub>s</sub>	0.275	-0.313	1.036	0.439	-2.491
PC 4	0.254	5.087	99.409	AP <sub>s</sub>	0.318	-0.045	-0.505	-1.488	-1.295
PC 5	0.030	0.591	100.000	AK <sub>s</sub>	0.205	0.497	0.809	-0.298	2.853

Abbreviations: TOC = total organic carbon; TN = total nitrogen; AP= available phosphorus; AK= available potassium. Subscript "s" indicates the standardized value of a given variable.

Chen *et al.*, 2010):

$$F = 0.56698 Z_1 + 0.30052 Z_2 \dots\dots\dots (3)$$

Where F is the composite score of PC1 and PC2; and Z<sub>1</sub> and Z<sub>2</sub> are the scores of the first 2 principal components, respectively. For example, the composite score of the bleached soil in spring was obtained as follows:

$$F_{BS} = 0.56698 \times 1.5059 - 0.30052 \times 1.0982 = 0.5238$$

Fig.3 presents the composite scores of the 3 types of tea garden soils in spring, summer, and autumn, calculated using Excel 2003 software. The fertility of acid purple soil was highest among the 3 soils in every season, and that of yellow earth was lowest. Soil fertility was highest in spring for every soil type.

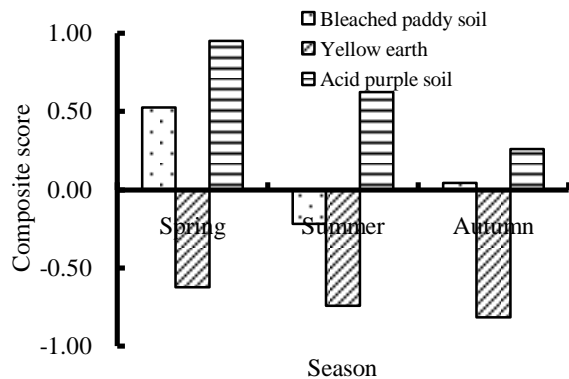


Figure 3. Variation in composite PC1 and PC2 scores of tea garden soils in spring, summer, and autumn.

## DISCUSSION

**Dynamic characteristics of soil pH:** Soil pH is an indicator of soil acidity, which plays an important role in soil physical and chemical properties, soil fertility, and plant growth. The significantly lower pH of yellow earth, in comparison to bleached paddy and acid purple soils, might be due to a large number of base cations leaching from yellow earth. However, base cations of bleached paddy soil could be

added to soil through irrigation and fertilization in the long-term paddy-upland rotation. Base cations in acid purple soil originate from the weathering of parent material and slowly continue to be added to soil. Overall, soil pH in the study sites was in the grade I - II based on the reference to soil survey standard (NSSO, 1992), confirming that each of the soils was strongly acidic. The soil pH values were significantly lower than those required for pollution-free tea-growing areas according to the *Agricultural Industry-Standard of People's Republic of China* (MOA, 2001). These soils could be amended with lime, organic fertilizer, and other measures to adjust the pH as part of the management process. In regards to seasonal variation in soil pH, yellow earth and acid purple soils are found in steep topographic localities, leading to severe erosion of topsoil and subsequent acidification under conditions of abundant precipitation in summer. In contrast, the topography of bleached paddy soil is flat; consequently, soil erosion does not occur and these soils accumulate organic acids (Sun and Wu, 1980) and exchangeable Al (Ding and Huang, 1991).

**Dynamic characteristics of soil TOC:** Organic matter is an important component of soil fertility, and the role of organic matter in soil fertility is determined primarily by the quantity and quality (composition) of its organic carbon (Lao, 1980). The large range of TOC contents in the tea garden soils may be closely related to soil hydrothermal conditions and human activity. Changes in soil hydrothermal conditions could affect the decomposition and transformation of soil organic matter carried out by microorganisms. In addition, management practices, including fertilizer application, pruning of tea trees, and soil tillage, might also have a substantial impact on TOC content (Zhu, 1983). The highest TOC content was found in bleached paddy soil, due to accumulation of organic matter during rice planting that takes place prior to planting tea in these soils. The higher TOC content observed in spring in bleached paddy and acid purple soils might be a result of the application of organic basal fertilizers, which takes place frequently during winter and spring. Conversely, the lower TOC content of yellow earth in spring might be due to low rates of fertilizer

application in these soils. On the other hand, the higher TOC content of bleached paddy soil and yellow earth in autumn may result from accumulation of organic matter from tea plant litter produced from pruning and natural shedding of leaves and stems (Li, 1997; Tian, 2001); and the lower TOC content of acid purple soil in autumn might be due to more-intensive soil erosion. In summer, greater decomposition rates in the 3 soils due to higher temperature and humidity (Zhu, 1983; Tian, 2001; Li *et al.*, 2009), and a greater degree of erosion in yellow earth and acid purple soils because of heavy rainfall could explain the similar lower TOC contents in the 3 tea garden soils, results that are consistent with those of Li *et al.* (2009).

**Dynamic characteristics of soil TN:** Total nitrogen is an important indicator of soil fertility, and can reflect recent conditions of nitrogen supply. According to the Ministry of Agriculture standards (MOA, 2005), the TN content of bleached paddy soil and acid purple soil was high (grade I), and TN of yellow earth was medium (grade II). In *Tea cultivation physiology* (Shi, 1982), a soil-fertility gradation is presented; according to this system, the TN content of bleached paddy and acid purple soils corresponded to a medium level, and TN of yellow earth corresponded to a lower level of fertility. The higher TN content of all soils in spring was consistent with the findings of Li *et al.* (2009), but not with those of Tian (2001) who found higher TN content in tea garden soils during summer. Li *et al.* (2009) also suggested that more inorganic N fertilizer was applied in spring. The higher TN content of bleach paddy soil and yellow earth in autumn might be due to the contribution of organic matter derived from tea plant litter (Li, 1997), and the lower TN content of acid purple soil in autumn might be due to more intensive soil leaching. However, the lower TN content in summer may also be caused by vigorous growth of tea trees, which consume a large amount of soil N during this season. At the same time, soil erosion led to decreases in TN content.

**Dynamic characteristics of soil AP:** The MOA (2005) classification of soil AP content places the 3 soils into grade I (excellent). The higher AP content of all of the soils in spring was consistent with the findings of Liao (1996), but not with those of Tian (2001) and Li *et al.* (2009), who found higher AP contents in tea garden soils during summer because of topdressing with P fertilizer. We believe that the higher AP content in spring was a result of large quantities of basal fertilizer applied in winter or spring. The lower AP content in summer can be attributed to reduced topdressing with P fertilizers and substantial absorption of P by tea trees (Shi, 1992; Liao, 1996; Li *et al.*, 2009), in addition to intensive soil erosion.

**Dynamic characteristics of soil AK:** Available potassium is easily absorbed and utilized by crops, and its content is an important index of nutrient abundance or deficiency. The MOA (2005) classification of soil fertility would place

bleached paddy soil and yellow earth into grade III (poor), and acid purple soil into grade II (ordinary), consistent with the classification presented in Shi (1982). The significantly higher AK content of acid purple soil compared to that of bleached paddy soil and yellow earth might be interpreted by the higher K level of the parent material from which acid purple soil is derived. Although the seasonal variation of AK content was minimal in all 3 soils, the higher AK content of bleached paddy soil in autumn was consistent with findings of Tian (2001), and the higher AK content of yellow earth and acid purple soil in spring was consistent with results presented in Liao (1996) and Wu *et al.* (1996). Potassium is not a major component of fertilizer in tea production, and the variation in this nutrient is controlled mainly by release from the parent material and absorption by tea plant.

**Comprehensive comparison of soil fertility:** In terms of overall fertility, acid purple soils were the most fertile, yellow earth was the least fertile, and bleached paddy soil was of medium fertility in all seasons. Some of these differences were probably due to the soil parent material, which is an important factor in soil nutrient status (Tang *et al.*, 2005). The parent material of acid purple soil is cretaceous purple sandstone and shale, which had a rapid rate of soil formation and represented a younger stage of development. This parent material contains more exchangeable cations, including K, and has higher pH, resulting in the highest fertility of the soils examined in this study. Yellow earth was developed from Pleistocene alluvium with strong acidification and nutrient leaching, resulting in low fertility. In addition to parent material, soil management—particularly fertilizer application—is important to improving soil fertility. Bleached paddy soil also developed on Quaternary older alluvium; however, long-term rice cultivation and abundant humus and nutrients led to a higher fertility level in this soil compared to yellow earth.

Of all the seasons examined, soil fertility was highest in spring. Spring is the season in which tea quality is highest, and the largest economic benefit can be realized from the sale of tea harvested in spring. This economic interest drove farmers to apply large quantities of fertilizer in spring, resulting in the highest seasonal fertility levels in all soil types. The high fertility of acid purple soil was probably due to the greater nutrient (particularly K) content of its parent material, and to the large amounts of organic basal fertilizer and topdressing of N fertilizer that were applied in spring. On the other hand, tea plants grow rapidly, and tea is picked frequently, during summer in Mingshan County. Large quantities of nutrients absorbed by the plants are removed from the soil when tea leaves are picked. In addition, higher temperatures and abundant rainfall during summer cause greater losses of soil nutrients through decomposition and leaching. Therefore, the soil fertility of yellow earth was at its lowest level in autumn.

## CONCLUSIONS

This study has demonstrated that, on the whole, pH values are highest in summer in tea garden soils; TOC, TN, and AP are highest in spring due to basal fertilizer application in winter or spring; TOC content is lower in summer due to higher decomposition rates and extensive soil erosion; TN and AP are lower in summer because of soil erosion and absorption by tea plants; and TOC and TN are higher in autumn as a result of litterfall and some reincorporation into soil. Seasonal variation in soil available K in tea garden soils is less obvious than that of other fertility parameters.

The comprehensive fertility of tea garden soils, ranked in order from higher to lower by season and soil type, was as follows: spring > autumn > summer for bleached paddy soil and yellow earth; but spring > summer > autumn for acid purple soil. Among the 3 tea garden soils, the fertility of acid purple soil was highest, and that of yellow earth was lowest in every season. All soils were found to have the highest comprehensive fertility levels in spring.

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