

# Soil quality assessment under different *Paulownia fortunei* plantations in mid-subtropical China

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## Abstract

**Purpose** *Paulownia*, one of the fastest growing broad-leaved tree species in the world, is widely distributed in the warm temperate regions of China. However, there are few commercial-scale *Paulownia* plantations, and there is only limited information available about the most suitable soil quality for *Paulownia fortunei* growth in mid-subtropical, Hunan Province, China.

**Materials and methods** To understand the effect of the growth of *P. fortunei* on soil conditions, 25 soil property parameters under *Paulownia* plantations were studied in Hunan Province, China. Seventy-two standard plots of eight different stand types were analyzed by three statistical approaches to assess soil quality (SQ) in the different *P. fortunei* plantations.

**Results and discussion** The results revealed that a majority of the soil characteristics when intercropping with oilseed rape and the pure *P. fortunei* (plantation III) were better than intercropping with *Camellia oleifera*, orange trees, and *Cunninghamia lanceolata* (Lamb.). Available calcium,

available magnesium, available potassium, available phosphorus, soil thickness, slope, soil organic matter, available sulfur, available copper, dehydrogenase, and available zinc were selected as the minimum data set (MDS). The SQ index (SQI) showed that three classes for soil quality among the eight *P. fortunei* plantations ranged from 0.48 to 0.88 and these were correlated with standing volume ( $p < 0.05$ ).

**Conclusions** From the results, we concluded that selected MDS indicators can describe the soil fertility quality of *P. fortunei* plantations, and that the relationship between SQI and standing volume has a biological significance. *P. fortunei* plantations intercropped with *Camellia oleifera*, orange trees, and *Cunninghamia lanceolata* (Lamb.) caused a deterioration in SQ, but intercropping oilseed rape and pure *P. fortunei* plantations produced an improvement in SQ.

**Keywords** Factor analysis · Forest strands · Gray cluster relation analysis · *Paulownia fortunei* · Soil quality assessment · Soil quality index

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## 1 Introduction

*Paulownia* sp. are indigenous to China and are among the fastest growing broad-leaved trees in the world. They have a large distribution area in subtropical and warm temperate regions, and are used to produce fast-growing and high-yield plantations (Caparrós et al. 2008). The timber volume of a 10-year-old tree can reach 0.5 m<sup>3</sup> and even 1 m<sup>3</sup> per year, under general growing conditions. In addition, the trees can be used to create plain protection forests, wind-breaks, and sand-fixation forests because they can tolerate a broad range of soil and climate conditions (Lucas-Borja et al. 2011; Wang and Shogren 1992). *Paulownia* are also suitable for intercropping because 80 % of the absorbing roots are distributed 40 cm below the surface, and *Paulownia* has an early defoliation and late foliation growth pattern (Waskiewicz 2015).

Forest farmers have developed different kinds of fast-growing trees that can quickly supply large amounts of wood, and *Paulownia* is an example of a new, fast-growing species. *Poplar* (Chen and Cao 2015), *Eucalyptus* (Morris et al. 2004), *Pinus massoniana* (Ge et al. 2012), and *Cunninghamia lanceolata* (Lamb.) (Huang et al. 2013) are currently the main fast-growing economic timber species in China. At present, the distribution of natural forest and planted *Paulownia* forest covers 23 provinces/municipalities/autonomous regions (Waskiewicz 2015), whereas commercial cultivation of *Paulownia* for timber production, or for improving the microclimate in intercropping systems (Wu et al. 2014), is restricted to warm, temperate regions. *Paulownia* is mainly used for promoting the “four sides” plan for green species that have not yet been grown on a commercial cultivation scale in subtropical zones (Hunan Province and Hubei Province). *Paulownia* is suitable for commercial cultivation in subtropical zones due to its rapid growth, broadleaf deciduous features, and unique wood properties, and it can be grown in mountain and hill areas that cannot support *Populus* growth. However, the optimum soil fertility conditions and the most suitable stand types have not been clarified, and currently there is no best practice guidance for forest farmers who want to plant *Paulownia* in this region. Ascertaining the soil quality (SQ) under existing *Paulownia fortunei* stands in Hunan is important because it could improve forest management of SQ (such as fertilizer use) and sustainable timber production (Fox 2000).

Our previous study on *P. fortunei* plantation SQ focused on three major indicators: total nitrogen, available phosphorus, and soil organic matter (SOM), which are not sufficient to evaluate the different land use and management practices that sustain or degrade soil attributes (Tu et al. 2013).

The SQ concept “the capacity of a soil to function within ecosystem boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health” (Sparling and Schipper 2002) has distinct

chemical, physical, and biological components, which should be sensitive to management practices and be related to the primary purposes of the SQ evaluation. There are numerous SQ evaluation methods, such as soil card design and test kits (Ditzler and Tugel 2002), SQ index (SQI) methods (Ngo-Mbogba et al. 2015), fuzzy association rules (Xue et al. 2010), and the “conceptual framework” model (Andrews et al. 2002). The SQI method is the most commonly used today (Andrews et al. 2002) and can be used to monitor trends in soil properties and functions over time.

In this study, eight different stands of *P. fortunei* growing in Hunan Province were selected and their SQ was assessed using 4 soil physical properties, 17 soil chemical properties, and 4 soil biological properties. The aim was to help foresters and researchers to ascertain whether the SQ was suitable for *P. fortunei* growth. The objectives of this study were as follows: (i) identify a minimum data set (MDS) for SQ assessment in *P. fortunei* plantations; (ii) compute a SQI parameter, and a suitable way of classifying and grading each plantation; and (iii) investigate the effect of different stand types on potential SQ.

## 2 Materials and methods

### 2.1 Study area

The sampling sites were located in central south Hunan Province, China, latitude 26°52'22"–28°32'39" N and longitude 111°23'06"–113°51'59" E, in areas characterized by a humid, continental and subtropical monsoon climate with an average annual sunshine of 1300–1800 h, an annual average temperature of 15–18 °C, a frost-free period range between 260 and 310 days, and an average annual rainfall of 1200–1700 mm. The dominant soil forms are Alliti-Udic Ferrosols. There are distinct seasonal climate changes, with a cold winter and a hot summer.

### 2.2 Plot design and soil sampling

The eight *P. fortunei* plantations in Hunan Province selected as sampling sites were identified in the five counties by recording their geographical positions via a handheld GPS. These eight different stand types, which consisted of two plantations intercropped with oilseed rape (stands I and II), three pure plantations, which were located in different places (III, IV, and V), a plantation intercropped with *Camellia oleifera* (VI), a plantation intercropped with orange trees (VII), and a plantation intercropped with *Cunninghamia lanceolata* (Lamb.) (VIII) are described in Table 1.

Each sampling site was laid out with nine replications per *P. fortunei* plantation type in 20 × 20 m plots, which were randomly orientated. The uniformity of the soil and land cover

**Table 1** Description of the eight different types of *P. fortunei* plantations in Hunan Province ( $n = 9$ )

Name	Age (years)	Area (ha)	Stem density	DBH (cm)	Tree height(m)	Site	Country	Strands
I	10	13.3	4 m × 4 m	26	15	N28°41'41", E112°56'49"	Xiangyin	Intercropped with oilseed rape
II	7	10	4 m × 4 m	21	14	N28°32'39", E112°58'44"	Xiangyin	Intercropped with oilseed rape
III	9	13.3	5 m × 6 m	21	15	N26°89'66", E113°38'51"	Youxian	Pure plantation
IV	8	1.3	3 m × 4 m	18	14	N27°10'00", E111°22'44"	Shaoyang	Pure plantation
V	7	1.3	4 m × 4 m	19	10	N26°53'42", E113°21'54"	Chaling	Pure plantation
VI	8	2.7	3 m × 4 m	16	13	N26°54'40", E113°23'33"	Chaling	Intercropped with <i>Camellia oleifera</i>
VII	9	10	6 m × 6 m	10	9	N26°52'10", E113°22'22"	Youxian	Intercropped with orange trees
VII	9	10	4 m × 5 m	5	7	N28°26'43", E113°51'19"	Liuyang	Intercropped with <i>Cunninghamia lanceolata</i> Lamb

$n$  number of standard plots, *DBH* diameter at breast height

was based on visual examination on arrival at the plantation. In each plot, ten sub-plots were selected based on walking a “W” between the end points of the main sampling plots and the field measurements. Unusually dry or wet areas and highly compacted areas were avoided. Composite surface (0–20 cm depth) soil samples ( $n = 72$ ) were collected from each plot where the tillage depth was more than 50 cm, which is the standard silvicultural practice in the eight *P. fortunei* plantations. Each sample was air-dried in the shade. Then it was ground to pass through a 2-mm sieve, a 1-mm sieve, and a 0.149-mm sieve, after which the sieved samples were mixed thoroughly and stored in a glass jar until needed.

### 2.3 Soil physicochemical properties analyses

To assess the physical components of soil quality, we measured bulk density (Gonzalez-Delgado et al. 2015), total capillary porosity (Peng et al. 2013), soil thickness (ST), and slope.

The chemical components of soil quality were assessed by measuring the pH of the water (Kader et al. 2015), total nitrogen by the Kjeldahl method (Tsiknia et al. 2014), nitrate-N according to Liu et al. (2005), and total phosphorus by a digestion method (Ojekanmi and Chang 2014; Ouyang et al. 2013), which was measured by a Smartchem 200 Discrete Chemistry Analyzer (WestCo Scientific Instruments, Brookfield, CT, USA). Total potassium (TK) was measured by a digestion method used by (Yanu and Jakmune 2015) and available potassium (AK) by the Mehlich 3 method (Bond et al. 2006) and flame photometry detection. SOM was assessed using the dichromate wet combustion method and a visible spectrophotometer (van Gaans et al. 1995), and the cation exchange capacity (CEC) was measured by the sodium

saturation method (Sparling and Schipper 2002). Soil available iron, available manganese (AMn), available copper (ACu), available zinc (AZn), available calcium (ACa), and available magnesium (AMg) were measured using the Mehlich 3 method (Bond et al. 2006) and a Smartchem 200 Discrete Chemistry Analyzer. Available boron (AB), available sulfur (AS), and available phosphorus (AP) were measured using the hot water extraction method, the calcium phosphate solution method, and the Mehlich 3 method and a Smartchem 200 Discrete Chemistry Analyzer (Daniels et al. 2001), respectively.

### 2.4 Soil biological properties analyses

The biological components of SQ were assessed by measuring urease using the ammonia release method (Kandeler and Gerber 1988), acid phosphatase (ACP) by *p*-nitrophenyl phosphate release (Lee et al. 2002),  $\beta$ -glucosidase (BG) by *p*-nitrophenyl glucoside release (Lee et al. 2002), and dehydrogenase (DH) activity according to Reichmann and Pette (1982).

### 2.5 Selection of the minimum data set

The development of the MDS should follow a logical path: (1) Factor analysis (FA) was used as a data reduction tool and Pearson correlation analysis was used to identify SQ factors. (2) The Delphi method used to select quality indicators.

FA was first used to standardize the data. Only the principle components (PCs) with eigenvalues  $\geq 1$  were considered as representative indicators (Andrews et al. 2002). The selected PCs were subjected to varimax rotation to maximize the correlation between PCs and the measured variable. With each PC, highly weighted indicators were defined as those with an absolute value

within 10 % of the highest PC, and the correlation among the indicators was examined to determine if any variable was redundant. When more than one variable was retained within a factor, the Delphi method was used and Pearson correlation values were determined to decide whether the variables were redundant. Among well-correlated variables, those with the highest sum of correlation coefficients (absolute values) were chosen as the MDS (Andrews et al. 2002).

## 2.6 SQI

The scheme used to assess the SQIs of the eight *P. fortunei* plantations is shown in Fig. 1. Weightings for the MDS were assigned by an analytical hierarchy process proposed by Saaty (1994), which provided a series of pair-wise comparisons of the relative importance of factors. Figure 2 shows the hierarchical structure for soil fertility. The use of colloquial terms, such as “very important,” “moderately important,” and “equal,” to describe the relationships between MDSs makes the model more understandable to other researchers. The consistency test was calculated by the average random consistency index. The results indicated that all random consistency indices for single and general hierarchy storage were lower than 0.1, which means that all the matrices had a satisfactory consistency.

We established the indicator scoring for SQ evaluation using a standard scoring function (SSF). The SSF considered the relationship between the evaluation index and the growth of *P. fortunei*. From a mathematical standpoint, SQ indicators can be divided into two types: the continuity indicator and the discrete index. In the continuity indicator, four types of soil indicators were divided, according to their function on SQ, into upper limit, lower limit, peak limit, and descriptive limit (Ojekanmi and Chang 2014). After establishing the SSF, the MDS indicators were standardized and normalized to a value between 0.1 and 1, where one represents

optimal conditions and 0.1 the worst conditions. The variables without certain threshold values were transformed using the scoring function described in Liebig et al. (2001). Detailed SSF equations for soil indicators are given in Hussain et al. (1999).

The equations for the score curves were as follows:

(i) Soil nutrient SSF:

$$f(x) = \begin{cases} 1.0 & x \geq x_1 \\ 0.1 + 0.9 \times (x-x_0) / (x_1-x_0) & x_0 < x < x_1 \\ 0.1 & x < x_0 \end{cases} \quad (1)$$

(ii) ST SSF

$$f(x) = \begin{cases} 1 & x \geq 20 \\ 0.9 & 80 \leq x < 120 \\ 0.7 & 40 \leq x < 80 \\ 0.5 & 20 \leq x < 40 \\ 0.3 & 0 < x < 20 \end{cases} \quad (2)$$

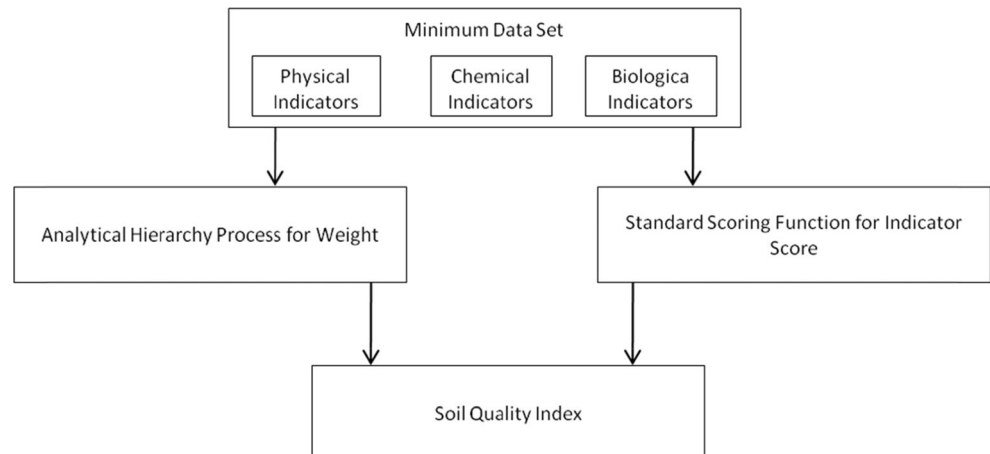
(iii) Soil slope SSF

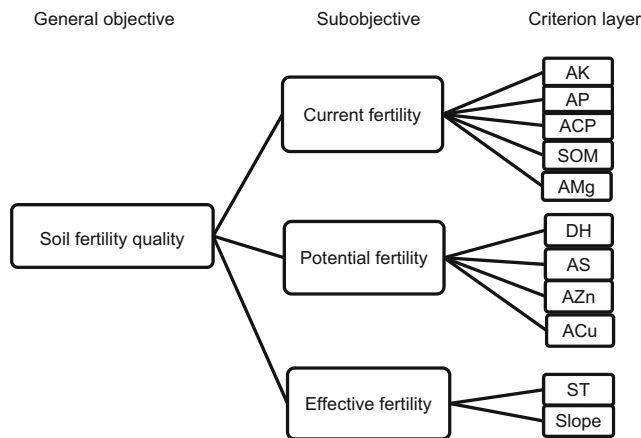
$$f(x) = \begin{cases} 1 & x \leq 3^\circ \\ 0.5 & 3^\circ < x < 30^\circ \\ 0.3 & x \geq 30^\circ \end{cases} \quad (3)$$

where  $f(x)$  is soil nutrient SSF;  $x$  is the soil variable value;  $x_0$  is the minimum value; and  $x_1$  is the maximum value of the soil variable (Masto et al. 2008).

After all MDS indicators had been scored and weighted, the SQI was calculated using the SQI equation described by Arun Jyoti et al. (2015). SQ is a comprehensive reflection of the various functions of the soil, so the actual function of the *Paulownia* soil must be evaluated. It is difficult to establish all the equations for soil function because soil has a large

**Fig. 1** The scheme for assessing the soil quality index of eight *P. fortunei* plantations





**Fig. 2** Hierarchical structure diagram of soil fertility quality assessment for the MDS weight assignment. AS, available sulfur; AZn, available zinc; ACu, available copper; ST, soil thickness; DH, dehydrogenase; SOM, soil organic matter; AP, available phosphorus; AK, available potassium; AMg, available magnesium; ACa, available calcium

number of ecological functions. Therefore, in this study, we established the MDS which provides a relatively complete system evaluation framework.

$$SQI = \sum_{i=1}^n W_i \times S_i \tag{4}$$

where  $W_i$  is the assigned weight of each indicator,  $S_i$  is the indicator score, and  $n$  is the number of variables in the defined MDS.

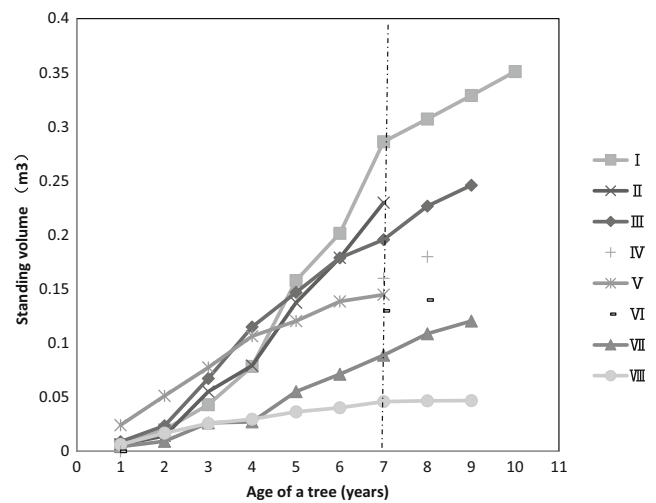
### 2.7 Standardization of tree age

The growth of the eight differently aged *P. fortunei* plantations was compared by measuring the standing volume (SV) of every tree in the seventh year. Xu and Zhao (1997) studied *P. fortunei* plantations in Heze and measured diameter at breast height (DBH), tree height, and the SV of 442 *P. fortunei* trees. The best return equation Eq. (5) with a correlation coefficient ( $R = 0.973$ ) was calculated using the return analysis. After comparing the theoretical result for SV with Eq. (5), the relative error for the observed SV was less than 0.5 %. Therefore, we calculated SV using Eq. (5).

$$V = 1.367857 \times 10^{-4} \times D^{1.666776} \times H^{0.893626} \tag{5}$$

where  $V$  is the SV ( $m^3$ ) of one tree,  $D$  represents DBH (cm), and  $H$  is tree height (m).

The DBH and tree height data for every year since the trees were introduced into the *P. fortunei* plantations were collected, except in plantations IV and VI because only the seventh and the eighth year data were available and were based on the individual measurements of 72 standard plots. The yearly SVs for the eight plantations were calculated using Eq. (5), as shown in Fig. 3.



**Fig. 3** Current annual increment curves for six of the *P. fortunei* plantations that data of current annual increment in standing volume in Hunan Province I–VIII are the names of plantations

### 2.8 Gray cluster relation analysis (GCRA)

The GCRA requires limited data to estimate the behavior of an uncertain system (Nielsen et al. 2004). The gray association degree between the samples was calculated and hierarchical clustering analysis used to classify all samples into different groups.

### 2.9 Statistical analysis

All statistical analyses were conducted using SPSS (version 15.0, SPSS Inc. 2006) and Microsoft Excel (version 2007, Microsoft Inc. 2006). All indicators were subjected to standard descriptive statistics. Means were compared by Duncan’s multiple comparison test. Data redundancy analysis was by principal component analysis and correlation matrix analysis. Correlation analysis was conducted to identify relationships between the measured parameters. The tests were performed at the 0.05 or 0.01 significance levels. SPSS and Excel were used to classify the *P. fortunei* plantations using GCRA.

## 3 Results

### 3.1 Characteristics of the different stands of *P. fortunei*

Significant differences were found in all physical characteristics (Table 2). The mean bulk density of the IV, I, and II plantations ranged between 1.24 and 1.33  $g\ cm^{-3}$ . They were significantly lower ( $p < 0.01$ ) than the other plantations, which ranged from 1.38 to 1.48  $g\ cm^{-3}$ . Plantations I and II had higher total capillary porosity (60.39–62.45 v/v%) and ST (112.11–122.67 cm) values than the VIII plantation

**Table 2** Descriptive statistics for the physical characteristics of the eight *P. fortunei* plantations in Hunan Province ( $n = 9$ )

Indicator	I	II	III	IV	V	VI	VII	VIII	ANOVA	
									F	p value
BD ( $\text{g cm}^{-3}$ )	1.33 ± 0.02cd	1.33 ± 0.05d	1.38 ± 0.05bc	1.24 ± 0.09e	1.42 ± 0.03b	1.38 ± 0.04bc	1.48 ± 0.08a	1.38 ± 0.04bc	15.54	0.00
TCP(v/v%)	60.39 ± 7.07ab	62.45 ± 6.09a	55.75 ± 3.79bc	49.50 ± 5.47cd	50.42 ± 8.86ab	49.83 ± 5.53d	58.92 ± 5.73cd	44.71 ± 4.42d	9.74	0.00
ST (cm)	122.67 ± 8.41a	112.11 ± 8.19b	84.22 ± 3.07c	83.56 ± 2.70d	85.89 ± 3.14d	86.89 ± 3.18d	93.78 ± 3.19d	70.56 ± 2.70e	107.21	0.00
Slope (deg)	3.00 ± 1.41c	8.11 ± 2.62c	3.22 ± 0.97c	2.89 ± 1.36c	10.89 ± 1.90b	2.44 ± 1.24c	12.22 ± 1.86b	27.00 ± 2.54a	187.58	0.00

Values followed by different letters show significant differences ( $p < 0.05$ ) after Duncan's multiple range text analysis.  $n$  is the number of representative sampling points  
*BD* bulk density, *TCP* total capillary porosity, *ST* soil thickness

(44.71 v/v%, 70.56 cm,  $p < 0.01$ ). In addition, plantation VIII had the steepest slope ( $27^\circ$ ).

Most of the chemical indicators for plantations I, II, and III (except pH, TK, AMn, and AZn) were higher than for plantations VI, VII, and VIII (Table 3). Plantation I produced significantly higher ( $p < 0.05$ ) soil chemical characteristic values (pH, nitrate-N, AP, AK, CEC, available iron, AB, ACa, and AMg) than the other plantations (Table 3). The exception was plantation VIII, which showed significant decreases ( $p < 0.05$ ) in ACu, TK, AP, and AK. The mean values for AP and AK in plantation I were 90.32 and 82.27 % higher than in plantation VIII, respectively. Plantation VII showed significant decreases ( $p < 0.05$ ) in AMn, AB, and ACa, and plantation VI showed significant decreases ( $p < 0.05$ ) in CEC, AZn, and AMg (Table 3). TN and SOM content was significantly higher ( $p < 0.05$ ) in plantations I, II, and III as compared to the soils taken from plantations VI, VII, and VIII (Table 3). The mean values for the nutrient elements ACa, AMg, AP, AK, and AS were significantly higher in plantations I and II than in VI, VII, and VIII, which had the lowest levels of soil element nutrients. ACu and CEC, an indicator of soil buffering power, showed similar tendencies to the nutrient elements, in that the values for the soil in plantation II were higher than in the soils from plantations VI, VII, and VIII.

Soil biochemical characteristics were significantly different ( $p < 0.05$ , Table 4) between the different plantation types. Plantation I had the highest mean urease value ( $82.30 \text{ mg g}^{-1}$ ) and III had the lowest urease value ( $44.42 \text{ mg g}^{-1}$ ). Plantation V had the highest mean BG and ACPs values of 0.93 and  $10.01 \text{ mg g}^{-1}$ , respectively, plantation III had the lowest BG value ( $0.11 \text{ mg g}^{-1}$ ), and IV had the lowest ACP value ( $6.23 \text{ mg g}^{-1}$ ). DH was highest under III with a mean value of  $2.64 \text{ mg g}^{-1}$  and was lowest under VII ( $0.66 \text{ mg kg}^{-1}$ ).

### 3.2 Grouping of measured variables

FA, Pearson correlation analysis, and the Delphi method were used to select 11 MDSs to measure soil fertility and function from a plot to the regional scale. These were ACa, AMg, AK, AP, ST, slope, SOM, AS, ACu, DH, and AZn.

Twenty-five variables were grouped into components for the principal component analysis, which was used to select the SQIs. The results showed that seven principal components had eigenvalues  $\geq 1$ , with values ranging from 1.09 to 6.27 (Table 5). They explained more than 75.31 % of the variation in the soil attributes.

The commonalities for the soil properties indicated that the AMn, AMg, TK, AP, slope, and ST explained more than 80 % of the variance, which showed that these indicators had large commonalities with other indicators (Table 5). The top 10 % of the highest weighted variables for the first principle component (PC1) included ACa, AMg, AK, AP, and ST, which

**Table 3** Descriptive statistics for the chemical characteristics of the eight *P. fortunei* plantations in Hunan Province (*n* = 9)

Indicator	I	II	III	IV	V	VI	VII	VIII	ANOVA	
									<i>F</i>	<i>p</i> value
pH water	4.92 ± 0.13a	4.63 ± 0.23b	4.60 ± 0.10b	4.83 ± 0.04a	4.40 ± 0.09c	4.66 ± 0.12b	4.60 ± 0.04b	4.58 ± 0.10b	16.39	0.04
TN (mg g <sup>-1</sup> )	1.53 ± 0.23b	1.24 ± 0.14c	1.89 ± 0.19a	1.10 ± 0.13cd	0.51 ± 0.22f	0.10 ± 0.21d	0.96 ± 0.22d	0.74 ± 0.29e	39.40	0.00
TP (mg g <sup>-1</sup> )	1.07 ± 0.24bc	1.43 ± 0.32ab	0.72 ± 0.36c	0.99 ± 0.43c	1.74 ± 0.46a	1.48 ± 0.65a	1.06 ± 0.19bc	0.79 ± 0.26c	7.57	0.04
AMn (mg g <sup>-1</sup> )	95.19 ± 14.02c	92.31 ± 23.97c	15.55 ± 4.12d	142.30 ± 33.62a	135.64 ± 12.43a	2.53 ± 1.84d	2.22 ± 1.06d	117.30 ± 17.77b	106.55	0.01
ACu (mg g <sup>-1</sup> )	1.19 ± 0.26bc	2.12 ± 0.81a	0.91 ± 0.16cd	0.70 ± 0.59de	1.47 ± 0.75b	0.59 ± 0.024de	0.54 ± 0.12de	0.27 ± 0.14e	14.70	0.00
TK (mg g <sup>-1</sup> )	18.11 ± 1.90b	13.26 ± 1.18cd	13.41 ± 3.01cd	12.56 ± 1.99cd	14.03 ± 2.89cd	29.07 ± 8.13a	15.55 ± 2.54bc	11.40 ± 0.99d	22.73	0.04
Nitrate-N (mg kg <sup>-1</sup> )	5.46 ± 1.18bc	4.83 ± 1.30ab	1.40 ± 0.64a	3.14 ± 1.52bc	0.31 ± 0.15c	5.56 ± 2.23bc	1.62 ± 0.61c	2.13 ± 0.78bc	24.74	0.00
AP (mg kg <sup>-1</sup> )	32.34 ± 1.78a	32.17 ± 1.33a	17.89 ± 5.36b	12.99 ± 3.97cd	15.43 ± 2.98bc	10.68 ± 3.37d	4.36 ± 1.04e	3.13 ± 1.19e	124.05	0.00
AK (mg kg <sup>-1</sup> )	265.11 ± 112.56a	243.78 ± 77.44a	175.23 ± 56.12b	97.05 ± 30.21b	155.95 ± 24.03c	93.33 ± 35.14c	58.20 ± 19.76c	47.00 ± 11.87c	19.37	0.00
SOM (mg g <sup>-1</sup> )	17.36 ± 1.70bc	19.3 ± 2.26ab	21.71 ± 0.34a	17.73 ± 0.38bc	15.52 ± 2.24d	16.69 ± 0.54bc	15.46 ± 0.30c	16.53 ± 0.33bc	7.12	0.01
CEC (cmol kg <sup>-1</sup> )	14.48 ± 2.38a	11.63 ± 1.72a	11.97 ± 2.29a	11.82 ± 3.49a	12.68 ± 3.85a	7.82 ± 4.13b	13.12 ± 2.95a	12.41 ± 1.03a	3.90	0.00
AFe (mg kg <sup>-1</sup> )	32.77 ± 10.98d	60.57 ± 13.74bc	56.75 ± 17.08c	77.20 ± 19.70ab	79.81 ± 22.28a	58.19 ± 18.63c	67.36 ± 18.93abc	82.05 ± 14.82a	7.81	0.04
AZn (mg kg <sup>-1</sup> )	1.90 ± 0.51cd	1.41 ± 0.23d	2.67 ± 1.60bc	3.11 ± 1.01b	4.39 ± 1.83a	1.03 ± 0.23d	1.26 ± 0.39d	1.25 ± 0.33d	13.07	0.00
AB (mg kg <sup>-1</sup> )	1.18 ± 0.12bc	1.12 ± 0.13c	1.34 ± 0.31bc	1.24 ± 0.23bc	1.17 ± 0.29a	1.55 ± 0.15a	1.17 ± 0.12bc	1.19 ± 0.05bc	4.34	0.00
AS (mg kg <sup>-1</sup> )	13.42 ± 2.57b	12.82 ± 2.87b	23.79 ± 6.45a	12.43 ± 4.18b	16.90 ± 4.79b	16.07 ± 5.36b	22.56 ± 7.41a	14.98 ± 3.60b	7.01	0.00
ACa (mg kg <sup>-1</sup> )	568.82 ± 156.15a	449.02 ± 162.46b	342.87 ± 128.49c	269.31 ± 131.23cd	134.88 ± 28.21e	215.54 ± 65.60de	115.27 ± 14.98e	147.14 ± 35.97e	21.00	0.01
AMg (mg kg <sup>-1</sup> )	135.23 ± 26.73a	74.10 ± 17.47b	71.10 ± 15.30b	62.11 ± 13.75b	31.05 ± 23.52c	18.43 ± 4.25c	20.87 ± 7.82c	34.74 ± 1.00c	50.08	0.00

Values followed by different letters show significant differences (*p* < 0.05) after Duncan's multiple range test analysis. *n* is the number of representative sampling points

TP total nitrogen, TN total phosphorus, TK total potassium, AP available phosphorus, AK available potassium, SOM soil organic matter, CEC cation exchange capacity, AFe available iron, AZn available zinc, AMn available manganese, ACu available copper, AB available boron, AS available sulfur, ACa available calcium, AMg available magnesium

**Table 4** Descriptive statistics for the biochemical characteristics of the eight *P. fortunei* plantations in Hunan Province ( $n = 9$ )

Indicator	I	II	III	IV	V	VI	VII	VIII	ANOVA	
									F	p value
Urease (mg g <sup>-1</sup> )	82.30 ± 20.28a	75.45 ± 35.68ab	44.42 ± 20.79c	65.15 ± 12.55abc	54.53 ± 23.59bc	47.53 ± 27.16c	49.24 ± 18.79c	56.03 ± 21.34bc	3.16	0.01
BG (mg g <sup>-1</sup> )	0.41 ± 0.21b	0.28 ± 0.12bc	0.11 ± 0.04d	0.30 ± 0.09bc	0.93 ± 0.28a	0.19 ± 0.09cd	0.31 ± 0.21bc	0.16 ± 0.02cd	23.83	0.00
ACP (mg g <sup>-1</sup> )	9.09 ± 1.28b	6.38 ± 1.41cd	9.18 ± 2.14b	6.23 ± 1.88a	10.01 ± 1.24d	8.17 ± 2.63bc	8.43 ± 1.17b	8.43 ± 1.17a	7.63	0.02
DH (mg kg <sup>-1</sup> )	1.75 ± 0.26b	1.45 ± 0.23b	2.64 ± 1.00a	0.84 ± 0.35c	1.57 ± 0.28b	1.57 ± 0.42b	0.66 ± 0.22c	1.76 ± 0.44b	15.16	0.00

Values followed by different letters show significant differences ( $p < 0.05$ ) after Duncan's multiple range text analysis.  $n$  is the number of representative sampling points  
ACP acid phosphatase, BG  $\beta$ -glucosidase, DH dehydrogenase

were subsequently identified as “effective fertility factors” since they mainly explained variations in characters related to the effective fertility of a soil. The Delphi method showed that after two rounds, the consultation response rates were higher than 80 %. The harmonious coefficient was 0.24 and was statistically significant ( $p = 0.03$ ). ACa, AMg, AK, AP, ST, SOM, AMn, and DH were then selected as indicators based on the statistical analysis and the panelists discussion. Therefore, all the indicators classified into PC1 were key factors in the growth of *P. fortunei*, and the first PC explained 20.84 % of the variation. Therefore, ACa, AMg, AK, AP, and ST were all selected for the MDS.

In PC2, TK and slope were highly weighted and were named as “potential fertility factors.” Slope was significantly correlated ( $r = 0.718$ ,  $p < 0.01$ ) with TK, so TK was rejected because it requires a complex and expensive test to acquire the TK data. PC3 was associated with two highly loaded factors: SOM and BG, and was defined as the “organic matter factor.” The SOM parameter was considered “important” by the Delphi method and was retained in the MDS due to its higher factor loading and correlation with BG ( $r = 0.484$ ,  $p < 0.01$ ). PC4 was defined as the “micronutrient factor” and was associated with two highly loaded factors: AMn and AS. AMn was considered important by the Delphi method and correlated with AS ( $r = 0.426$ ,  $p < 0.01$ ), so it was retained in the MDS. PC6 was named the “soil enzyme factor” and was associated with two highly loaded factors: DH and ACP. DH was considered important by the Delphi method and correlated with ACP ( $r = 0.389$ ,  $p < 0.01$ ), so it was retained in the MDS. PC5 was named the “Cu factor” and PC7 was named the “Zn factor.” ACu and AZn were the only elemental parameters selected for the MSD due to their higher factor loading.

### 3.3 Developing the SQI

The MDS indicator scores were calculated by the SSFs (Eqs. 1–3) used for normalizing the indicators. The “more is better curve” Eq. (1) was used for AP, AK, AMg, ACa, AZn, ACu, AS, and SOM, Eq. (2) was used for ST, Eq. (3) was used for slope, and DH was transformed by SSF as it did not have certain threshold values. All MDS variables were subjected to analytical hierarchy process and the weightings are shown in Table 6. The highest MDS weighting was SOM, which suggested that SOM played a more important role in soil quality evaluation than the other indicators.

After the MDSs were scored and weighted, the SOIs were calculated using the Integrated Quality Index equation (Eq. 4). The SQI values were calculated by the MDS method and ranged from 0.48 to 0.88, which showed that the values were significantly higher in I, II, and III (intercropping with oilseed rape and two pure plantations) than in the other plantation soils. The eight



**Table 5** Rotated loadings based on the principal components data

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	Communality
AB	-0.08	0.63	-0.21	-0.06	-0.07	0.32	-0.05	0.56
AF <sub>e</sub>	-0.72	-0.21	0.11	0.08	0.10	-0.00	-0.02	0.60
AM <sub>n</sub>	-0.02	-0.44	0.29	0.71	0.16	0.03	-0.26	0.87
AS	-0.15	-0.08	-0.14	-0.69	0.01	0.13	-0.09	0.55
AC <sub>u</sub>	0.25	-0.01	0.07	0.11	0.82	0.04	-0.15	0.77
AZ <sub>n</sub>	-0.02	-0.23	0.22	0.03	0.14	0.06	-0.78	0.73
AC <sub>a</sub>	0.82	-0.09	-0.18	0.20	0.15	-0.02	0.00	0.77
AM <sub>g</sub>	0.84	-0.30	-0.13	0.23	0.057	0.02	-0.02	0.86
TP	-0.05	0.41	0.47	0.08	0.37	-0.34	-0.17	0.69
TK	0.14	0.87	0.06	-0.04	-0.14	-0.06	0.16	0.83
TN	0.60	-0.04	-0.56	-0.28	0.04	0.03	-0.06	0.76
AK	0.76	-0.01	0.08	0.02	0.39	0.06	-0.16	0.77
AP	0.76	-0.01	-0.03	0.21	0.51	-0.07	-0.03	0.89
pH	0.60	-0.04	-0.19	0.39	-0.38	-0.13	0.24	0.77
Nitrate-N	0.51	0.49	-0.12	0.38	0.00	-0.16	0.35	0.80
SOM	0.19	0.035	-0.79	-0.02	0.14	-0.00	0.03	0.68
CEC	0.28	-0.58	0.36	-0.09	-0.18	0.16	0.16	0.63
Urease	0.18	-0.18	-0.10	0.49	0.33	0.26	0.38	0.64
DH	0.23	0.06	-0.31	-0.16	0.14	0.72	-0.28	0.79
BG	-0.02	-0.11	0.76	0.05	0.30	-0.00	-0.32	0.78
ACP	-0.18	-0.10	0.16	-0.05	-0.10	0.83	0.10	0.78
BD	-0.29	0.03	0.33	-0.59	0.08	0.26	0.37	0.75
TCP	0.39	-0.12	-0.15	-0.33	0.56	-0.25	0.34	0.79
Slope	-0.21	0.86	0.19	-0.12	0.07	-0.13	0.15	0.87
ST	0.76	-0.33	0.11	0.11	0.28	-0.05	0.34	0.89
Eigenvalue	6.27	3.61	2.74	2.14	1.59	1.39	1.09	
Percent%	20.84	12.84	10.03	9.16	8.58	6.99	6.86	
	20.84	33.68	43.71	52.87	61.45	68.44	75.31	

Extraction method, principal component analysis. Rotation method, varimax with Kaiser normalization

*BD* bulk density, *TCP* total capillary porosity, *ST* soil thickness, *TN* total nitrogen, *TP* total phosphorus, *TK* total potassium, *AP* available phosphorus, *AK* available potassium, *SOM* soil organic matter, *CEC* cation exchange capacity, *AFe* available iron, *AZn* available zinc, *AMn* available manganese, *ACu* available copper, *AB* available boron, *AS* available sulfur, *ACa* available calcium, *AMg* available magnesium, *ACP* acid phosphatase, *BG* β-glucosidase, *DH* dehydrogenase

*P. fortunei* plantations SQI values were I (0.88 ± 0.03), III (0.86 ± 0.03), II (0.83 ± 0.02), IV (0.69 ± 0.06), V (0.65 ± 0.04), VI (0.55 ± 0.09), VII (0.48 ± 0.07), and VIII (0.51 ± 0.06).

The relative contribution of each indicator to the SQI is shown in Fig. 4. A significant correlation was observed between the SQI and standing volume according to the correlation analysis results (Fig. 5), which can be described by the following regression equation:

$$y = 0.367x - 0.090 \quad (n = 72, r^2 = 0.699, p < 0.05)$$

where  $y$  represents the standing volume (m<sup>3</sup>) and  $x$  represents the SQI.

### 3.4 Verification of the SQIs

The degrees of the gray equation coefficient matrix are shown in Table 7. Based on the degree of the gray equation coefficient, hierarchical clustering analysis graded and classified the eight *P. fortunei* plantations into three main clusters (Fig. 6) which, along with the SQI, showed that plantations I and II were clustered into group one, the second group contained plantations III, IV, V, VI, and VIII, and the third group contained plantation VII.

The SQI and GCRA results for soils suggested that three soil quality classes could be defined: first class (SQI ≥ 0.83), second class (0.55 < SQI < 0.83), and third class (SQI ≤ 0.55).

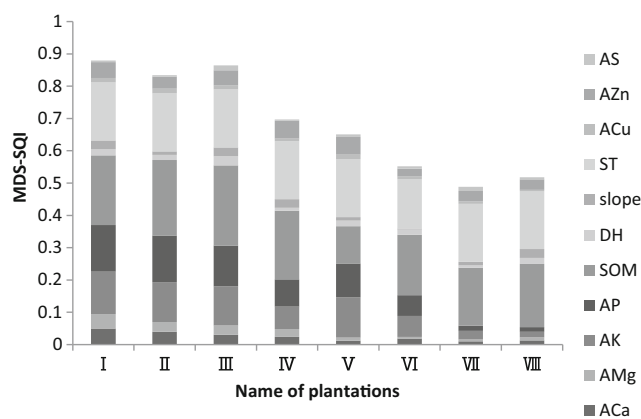
**Table 6** Minimum data set weightings calculated by the analytical hierarchy process

Indicator	Weight
SOM	0.25
ST	0.18
AP	0.14
AK	0.13
ACa	0.09
AZn	0.06
AMg	0.05
DH	0.04
Slope	0.03
AS	0.02
ACu	0.015

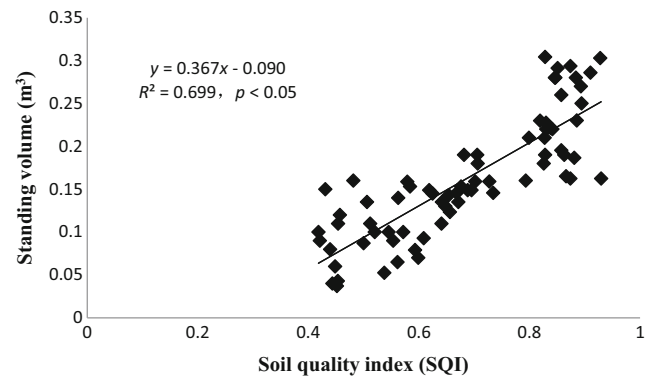
SOM soil organic matter, ST soil thickness, AP available phosphorus, AK available potassium, ACa available calcium, AZn available zinc, AMg available magnesium, DH dehydrogenase, AS available sulfur, ACu available copper

#### 4 Discussion

We found that SQ in the *Paulownia* plantations is measured in terms of soil productivity and fertility. When soil fertility quality is evaluated, the selection of indicators should reflect all soil properties, which include physical indicators, chemical indicators, and microbiological indicators (Karlen et al. 1997). In this study, the MDS of the soil indicators included physical (ST and slope), chemical (ACa, AMg, AK, AP, SOM, AS, ACu, and AZn), and biological (DH) properties. Our study showed that *Paulownia* grew well in the deeper soil and moderate slopes characteristic of first class soils. *Paulownia* are a deep-rooted tree species where 80 % of the



**Fig. 4** Soil quality index (SQI) results for the eight *P. fortunei* plantation types. Stacked bars show the SQI means added to the MDS index values. Significant differences between the plantations are denoted by different letters ( $p < 0.05$ ). AS, available sulfur; AZn, available zinc; ACu, available copper; ST, soil thickness; DH, dehydrogenase; SOM, soil organic matter; AP, available phosphorus; AK, available potassium; AMg, available magnesium; ACa, available calcium



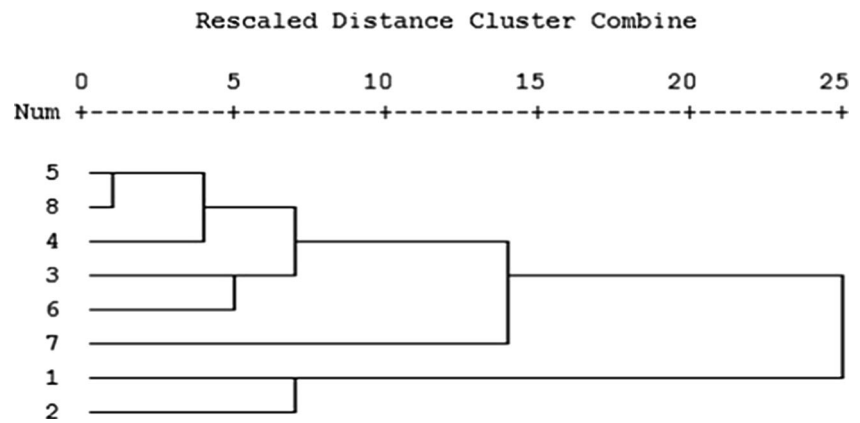
**Fig. 5** Relationship between the soil quality index and the binary standing volume

absorbing roots are distributed 40 cm below the ground (Waskiewicz 2015) and can grow well when the soil layer thickness is more than 70 cm (Caparrós et al. 2008); *Paulownia* can also grow on mountain sides, but do not grow well on mountains with steep gradients because ST, soil nutrient content, and soil moisture content decrease as the slope increases (Franzmeier et al. 1969; Sharpley 1985). The SOM, AP, and AK concentration results for the first class soils were higher than for the second and the third class soils, which may be partly attributed to oilseed rape because more than 80 % of the nutrients are returned to the forest in the form of fallen flowers, leaves, and seed meal, and to the fertilizer applied before planting (Madejon et al. 2016). SOM, a key component of soils, affects many reactions that occur in soil systems (Ownley et al. 2003). AP and AK are the best indicators of soil P and K supply and are used in soil diagnosis and fertility assessments (Barbosa et al. 2014). Therefore SOM, AP, and AK can reflect the soil fertility quality of the different *P. fortunei* plantations. ACa and AMg were significantly higher in the first class soils than in the others. This is because *Paulownia* prefers fertile soils, especially those containing high levels of Ca and Mg. Micronutrient assessment would give farmers and scientists a more balanced view of soil nutrition, whereas most soil assessments are solely focused on N, P, and K. Micronutrients, such as AS, ACu, and AZn, were

**Table 7** Degree of the gray equation coefficient matrix for the eight *P. fortunei* plantations in Hunan Province

	I	II	III	IV	V	VI	VII	VIII
I	1.00	0.84	0.78	0.70	0.68	0.77	0.72	0.76
II	0.84	1.00	0.77	0.73	0.75	0.76	0.78	0.74
III	0.78	0.77	1.00	0.75	0.75	0.86	0.78	0.79
IV	0.70	0.73	0.75	1.00	0.84	0.82	0.80	0.85
V	0.68	0.75	0.75	0.84	1.00	0.81	0.81	0.88
VI	0.77	0.76	0.86	0.82	0.81	1.00	0.80	0.85
VII	0.72	0.78	0.78	0.80	0.81	0.80	1.00	0.80
VIII	0.76	0.74	0.79	0.85	0.88	0.85	0.80	1.00

**Fig. 6** Cluster analysis results of the eight *P. fortunei* plantation types. 1 is plantation I; 2 is plantation II; 3 is plantation III; 4 is plantation IV; 5 is plantation V; 6 is plantation VI; 7 is plantation VII; 8 is plantation VIII



included in the MDS values because they could affect the growth of *P. fortunei*. The DH biological function is the catalytic decomposition of hydrogen peroxide in cells, which prevents the build-up of harmful peroxide. In conclusion, the MDS values produced by our study could be used to assess soil fertility quality in the different *P. fortunei* plantations.

The SQI results produced a more comprehensive outcome when calculated using weight and indicator score of MDS. It also has biological significance because it involves the analysis of the relationship between the SQI and SV. In this study, the relationship was analyzed and a significant correlation was observed between SQI and SV. Therefore, evaluating SQI could be a useful tool for assessing soil in *P. fortunei* plantations.

The results of the GCRA were fairly similar to the SQI results and could be used to reflect the effects of the different plantation types on SQ. GCRA is used to classify sites with high, medium, and low SQ. The results showed that the SQI in the plantations where there had been intercropping with oilseed rape (plantations I and II) and in the pure *P. fortunei* plantation (III) was higher ( $SQI \geq 0.83$ ) than in the plantations ( $SQI \leq 0.55$ ) where there had been intercropping with *Camellia oleifera* (plantation VI), orange trees (plantation VII), and *Cunninghamia lanceolata* (Lamb.) (plantation VIII). *Paulownia* sp. are suitable for intercropping because they have deep rooting systems, a sparse canopy, and defoliation occurs earlier and foliation occurs later. *P. fortunei* plantations intercropped with oilseed rape, which has a shallow root system and a spring growth period, had a generally positive impact on SQ (Caparrós et al. 2008). *Camellia oleifera*, orange trees, and *Cunninghamia lanceolata* (Lamb.) are perennial plants that have large nutritional requirements. If a mixed forest was not fertilized in spring, then the intercropping plants would compete for nutrients, which would reduce the productivity of *P. fortunei*, especially in the spring and summer. The SQ of pure *P. fortunei* plantations (IV and V) also showed significant, positive reactions to fertilizer application, so proper fertilization will also increase timber yields.

## 5 Conclusions

Different types of *P. fortunei* plantations were evaluated by measuring 25 soil properties using three synthetic approaches, i.e., FA, SQI, and GCRA. Selected MDS indicators can describe the soil fertility quality in *P. fortunei* plantations. SQI and GCRA divided the SQ into three classes, which could provide the basis for soil fertility management. SQI was found to be correlated with SV which meant it had a biological significance. Intercropping *P. fortunei* plantations with *Camellia oleifera*, orange trees, and *Cunninghamia lanceolata* (Lamb.) caused a deterioration in SQ, compared to other soil management regimes. In contrast, the *P. fortunei* plantations intercropped with oilseed rape and the pure *P. fortunei* plantations produced an improvement in SQ.

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