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Effects of rubber plantations on soil physicochemical properties on Hainan Island, China

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Abstract

Recent and rapid expansion of rubber [*Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg.] plantations requires understanding their effects on soil physicochemical properties and soil quality. An ideal testbed for analyzing such land-use change and its impacts is Hainan Island, the largest tropical island in China, which in recent decades has seen a dramatic expansion in the rubber industry. Based on 14 soil physicochemical properties at two soil depths (0–20 and 20–40 cm), a comprehensive assessment index was established using principal component analysis to assess soil qualities under rubber plantations (RPs; monoculture and intercropping) and five additional land-use types (areca palm [*Areca* L.], eucalyptus [*Eucalyptus loxophleba* Benth.] and banana [*Musa* L.] plantations, secondary forest, and tropical rainforest [TR]). The following results were obtained: (a) total porosity, ammoniacal N, total P, available P, and soil organic matter were vital soil physicochemical properties contributing to the comprehensive assessment index; (b) the comprehensive assessment indices of RPs were significantly lower than those of TR and areca palm plantation; (c) intercropping improves most soil physicochemical properties in RPs comparing monoculture and intercropped RPs; and (d) redundancy analysis demonstrated that land-use type interacted with climatic, geographical, and edaphic factors and collectively explained about half of the variation in the soil physicochemical properties across the study area. Deteriorating soil quality by converting TR to RPs and other land-use types provides another reason to protect TRs, especially on area-limited islands like Hainan.

1 | INTRODUCTION

Rubber [*Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg.] is an economically valuable tree species grown in different types of plantations in more than 40 tropical countries throughout the world (Warren-Thomas et al., 2015). Tropical Asia is currently the world's most important region for rubber production (FAO, 2017), where the area of rubber plantation (RP) has expanded rapidly over the last 20 yr due to unprecedented economic growth (Ahrends et al., 2015; Lang et al.,

Abbreviations: AK, available potassium; AN, ammonium nitrogen; AP, available phosphorus; APP, areca palm plantation; BD, bulk density; BP, banana plantation; CAISPP, Comprehensive Assessment Index of Soil Physiochemical Properties; CP, capillary porosity; EP, eucalyptus plantation; NCP, non-capillary porosity; NN, nitrate nitrogen; PC, principal component; PCA, principal component analysis; RP, rubber plantation; SF, secondary forest; SMC, soil moisture content; SOM, soil organic matter; TK, total potassium; TN, total nitrogen; TOP, total porosity; TP, total phosphorus; TR, tropical rainforest.

2017; Li et al., 2015; Warren-Thomas et al., 2015). The continuously rising need of RPs is accompanied by the conversion of tropical forests into RPs in tropical Asia (Allen et al., 2015; De Blécourt et al., 2014; Guillaume et al., 2018; Hassler et al., 2017). Generally, this conversion has negative impacts on soils and ecosystem services, threatening biodiversity and human livelihoods (Liu, Nie, et al., 2018; Liu et al., 2019; Qiu, 2009; Tan et al., 2011; Zhai et al., 2012, 2014).

Soil quality has been defined in previous studies as "the capacity of the soil to sustain biological productivity, maintain environmental quality and promote plant and animal health within ecosystem boundaries" (Doran & Parkin, 1994; Li et al., 2020; Shao et al., 2020). Development and applying soil quality indices (Doran & Parkin, 1994; Rahmanipour et al., 2014) support the evaluation of soil quality (Hemati et al., 2020), which involves three main steps: definition and selection of soil indicators, their scoring, and soil quality index calculation (Chen et al., 2013). Soil physicochemical properties have been widely used as soil indicators to assess soil quality and its response to land-use changes (Aon & Colaneri, 2001; Arévalo-Gardini et al., 2015; Deng et al., 2016; Liu, Huang, et al., 2018; Qiu et al., 2019; Wang et al., 2019). It has been reported that they were affected by tropical forest conversion to RP (Allen et al., 2015; De Blécourt et al., 2014; Guillaume et al., 2018; Hassler et al., 2017) and that, within RPs, they have been strongly influenced by the age of rubber trees (Yasin et al., 2010). However, a comprehensive assessment of the effects of RP, after being converted from tropical forest on soil physicochemical properties and soil quality, has rarely been reported.

Hainan Island is the largest tropical island in China and is a major producer of natural rubber, with the output of 350.68 million kg from an area of 5,283.51 km^2 under rubber cultivation in 2018 (Statistical Bureau of Hainan Province, 2019). During the past few decades, the area of RPs has been expanding rapidly on the island and mostly at the expense of forested land and agricultural land (Sun et al., 2020), leading to a strong decrease of tropical forest area. Analyzing the responses of RP expansion on the environment—especially on soil quality—has recently become a research focus. Most of the previous studies of RPs on Hainan Island focused on soil physicochemical properties analysis, such as soil nutrients and fertility (Cheng et al., 2007; Wei et al., 2014; Zhao et al., 2009), organic carbon storage (Wang et al., 2016), and water conservation (Wen et al., 2017). However, few studies have focused on a comprehensive assessment of soil physicochemical properties changes affected by the land-use changes, such as the conversion of forested land and agricultural land to RPs. Therefore, a Comprehensive Assessment Index of Soil Physiochemical Properties (CAISPP) based on a weighted summation of soil properties was established in this study, aiming (a) to comprehensively assess the soil physicochemical properties of RPs influenced by the age of rubber tree and intercropping and (b) to quantify soil physicochemical properties changes affected by the conversion of forested land and agricultural land to RPs on Hainan Island. Thereby, tests of the following hypotheses are required: (a) soil physicochemical properties, which are affected by the age of rubber tree; (b) intercropping, which improves the soil physicochemical properties of RPs; and (c) soil physicochemical properties, which deteriorated by the conversion of tropical forests to RPs.

Core Ideas

- Total porosity, ammonium N, total P, available P, and SOM were important properties for soil quality assessment.
- Intercropping improved soil physicochemical properties in rubber plantations.
- The soil comprehensive assessment index of rubber plantations lower than tropical rainforest.

2 | STUDY AREA AND METHODS

2.1 | Study area

Hainan Island (18°09′−20°10′ N, 108°37′−111°03′ E; Figure 1) is the largest island in southern China, with a geographical area of 33,920 km^2. It is characterized by a tropical monsoon climate with a rainy season lasting from May to October and a dry season from November to April (Sun, Wu, et al., 2017; Wu, 2008). Its topography is complex and is characterized by hilly regions in the center surrounded by coastal lowlands. The vegetation type is highly correlated with the topography of the island: natural forests occur mainly in the central and southern parts of the island, planted forests occupy the plains surrounding the mountains, and crops occupy the coastal flatlands (Sun, Chen, et al., 2017; Sun et al., 2020).

The study area was situated in the central part of Hainan Island (Figure 1). Two soil types were identified at the study sites according to the soil classification system of China: Ferralsols (subtypes: lateritic red soil, red soil, and yellow soil) and primitive soil (subtype: purplish soil), which corresponded to Ultisols and Inceptisols, respectively, in the USDA soil taxonomy (Shi et al., 2004). Soil data with a resolution of 1:1,000,000 were obtained from a soil survey (completed in 1995 by the National Soil Survey Office of China) and from the Resources and Environment Data Cloud Platform (http://www.resdc.cn/data.aspx?DATAID=145).

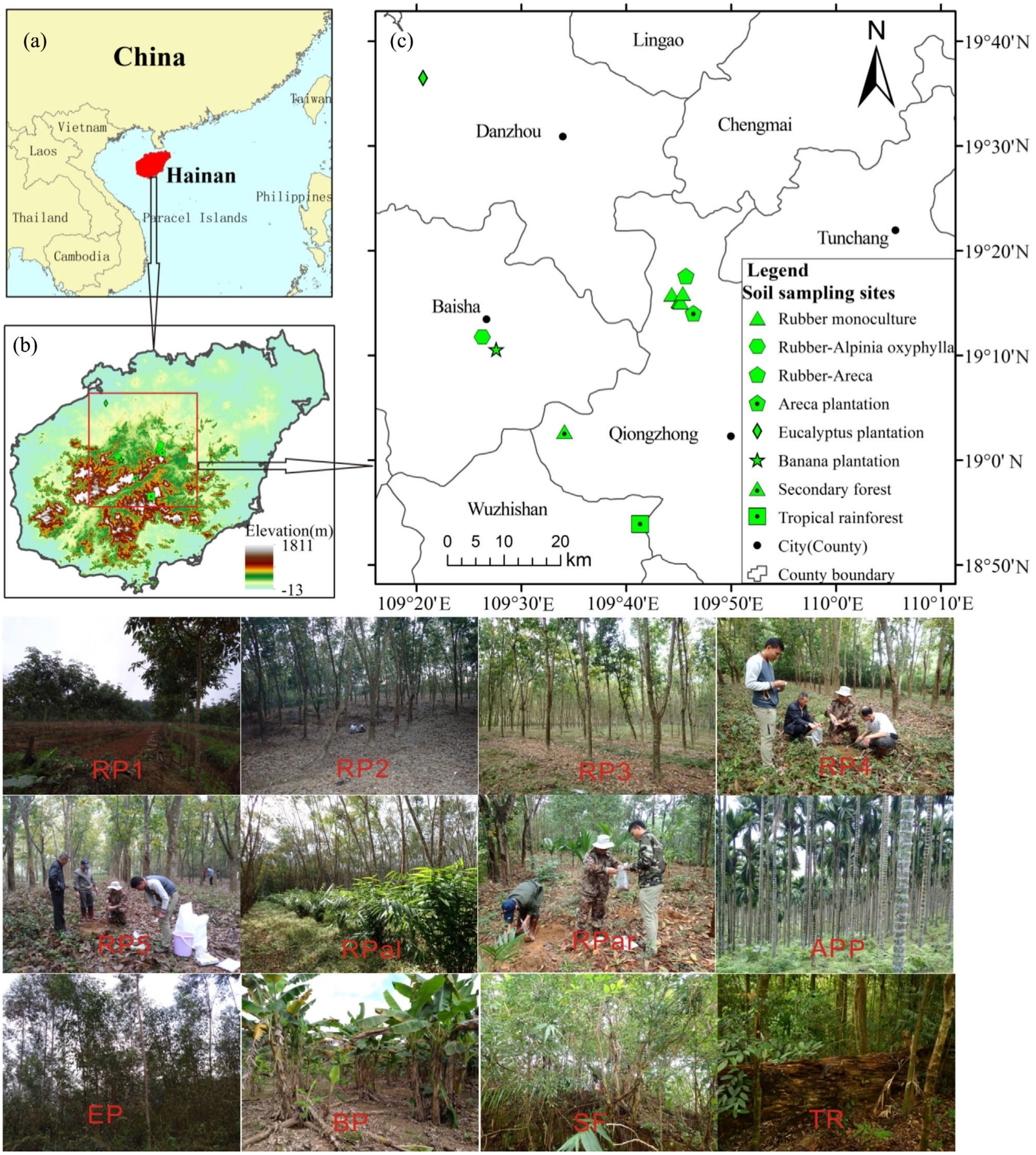

FIGURE 1 Maps of the geographic position, topography, and soil sampling sites of Hainan Island, China: (a) the location of Hainan Island is indicated in red; (b) topography of Hainan Island; (c) the spatial distribution of soil sampling sites for different land-use types; (d) photographs of the sampling sites (RP1, RP2, RP3, RP4, and RP5: monoculture rubber plantations at the age of 4, 13, 20, 28, and 33 yr, respectively). APP, areca palm plantation; BP, banana plantation; EP, eucalyptus plantation; RPal, RPar-rubber plantations intercropped with *Alpinia oxyphylla* and areca palm; SF, secondary forest; TR, tropical rainforest.

TABLE 1 General geographical, climatic, edaphic, and vegetative characteristics of the investigated sites

	Geographical location and topography						Vegetation				Climate	
Site	E°	N°	Altitude	Slope	Slope orientation	Soil type	Land-use type	Tree age	CD	UVC	T	P
			m asl	degrees				yr	——%——		°C	mm
1	109.76	19.27	178	<2	flat	Ferralsols (Lateritic red soil)	RP1: rubber plantation	4	30	60	23.4	2,085.3
2	109.75	19.25	187	<5	flat	Ferralsols (Lateritic red soil)	RP2: rubber plantation	13	90	20	23.4	2,105.3
3	109.75	19.25	202	<5	flat	Ferralsols (Lateritic red soil)	RP3: rubber plantation	20	90	30	23.4	2,092.3
4	109.75	19.25	176	<2	flat	Ferralsols (Lateritic red soil)	RP4: rubber plantation	28	90	35	23.4	2,086.2
5	109.74	19.26	165	<2	flat	Ferralsols (Lateritic red soil)	RP5: rubber plantation	33	90	40	23.4	2,067.3
6	109.44	19.2	224	<5	flat	Primitive soil (Purplish soil)	RPal: rubber × *alpinia oxyphylla*	30	40	55	23.7	1,898.6
7	109.76	19.29	160	<2	flat	Ferralsols (Lateritic red soil)	RPar: rubber × areca palm	25	95	98	23.5	1,924.6
8	109.77	19.23	310	56	northwest	Ferralsols (Lateritic red soil)	APP: areca palm plantation	15	70	100	23.3	2,148.7
9	109.46	19.18	216	<2	flat	Primitive soil (Purplish soil)	EP: eucalyptus plantation	3	45	100	23.8	1,811.3
10	109.34	19.61	46	<2	flat	Primitive soil (Purplish soil)	BP: banana plantation	3	50	30	23.7	1,924.6
11	109.57	19.05	559	12	southwest	Ferralsols (Red soil)	SF: secondary forest	30	96	100	23.5	2,078.6
12	109.69	18.9	1,064	15	northeast	Ferralsols (Yellow soil)	TR: tropical rainforest	>100	98	100	23.4	2,164.0

Notes: Climate data of each site were obtained from Sun et al. (2016). CD, crown density, P, annual precipitation; T, annual mean temperature; UVC, undergrowth vegetation cover.

2.2 | Sampling and measuring methods

Characteristic land-use types on Hainan Island were selected for this study: (a) RP, (b) eucalyptus (*Eucalyptus loxophleba* Benth.) plantation (EP), (c) areca palm (*Areca* L.) plantation (APP), (d) banana (*Musa* L.) plantation (BP), (e) secondary forest (SF; a forest area that has regrown after a major disturbance such as timber harvest), and (e) tropical rainforest (TR; primary forest). Soil quality under RP is the focus in this study; hence, rubber tree monocultures of different age for 4, 13, 20, 28, and 33 yr since their establishment and RPs intercropped with *Alpinia oxyphylla* (RPal) and areca palms (RPar) were investigated.

For each of the land-use types, a 100 m by 100 m area was selected for soil sampling. The general geographical, climatic, edaphic, and vegetative characteristics of the sites are given in Table 1.

For each sampling site, five replicate plots were selected following an S-shaped layout, and samples were obtained at two soil depths of 0–20 and 20–40 cm. A total of 120 undisturbed soil samples were collected almost simultaneously at all plots in a timely manner during January 2018 using an aluminum specimen box (inner diameter, 55.00 mm; height, 35.00 mm), cutting cylinders (inner diameter, 40.00 mm; height, 39.90 mm; volume, 100 cm^3), and transparent airtight bags. The weights of the aluminum specimen box and cutting cylinder (both hollow and containing wet soil) were recorded, and then the soil samples were transported to the laboratory.

A total of 14 soil physiochemical properties (bulk density [BD], total porosity [TOP], capillary porosity [CP], noncapillary porosity [NCP], soil moisture content [SMC], pH, soil organic matter [SOM], total nitrogen [TN], nitrate nitrogen [NN], ammonium nitrogen [AN], total phosphorus [TP], available phosphorus [AP], total potassium [TK], and available potassium [AK]) were determined as soil indicators for soil quality assessment.

Soil physical properties, including BD, TOP, CP, NCP, and SMC, were quantified using standard techniques following the recommendation by a guide for soil physical and chemical analysis (Institute of Soil Science, Chinese Academy of

Sciences, 1978). Detailed protocols for the measurement of each soil physical property are available (Chen et al., 2019; Deng et al., 2016; Zhang et al., 2019).

Soil chemical properties, including SOM, pH, TN, NN, AN, TP, AP, TK, and AK, were measured using 500-g soil samples collected in transparent airtight bags. Each sample was sieved (<2 mm mesh) to remove discernible roots, stones, and macrofauna and air dried. Each of the soil properties was measured three times for all soil samples in laboratory. Soil pH was measured in a 1:1 soil-water suspension with a pH meter (pHS-2, Leici). Soil organic matter was determined by the potassium dichromate oxidation method (Institute of Soil Science, Chinese Academy of Sciences, 1978). Total N was determined using a micro-Kjeldahl digestion followed by steam distillation; NN and AN were determined by steam distillation and indophenol-blue colorimetry, respectively; TP and AP were quantified using the molybdenum-antimony anti-spectrophotometric method; and TK and AK were measured by flame photometry (Soil Science Society of China, 2000).

2.3 | Comprehensive Assessment Index of Soil Physiochemical Properties

To compare soil quality between RPs and other land-use types, the Comprehensive Assessment Index of Soil Physiochemical Properties (CAISPP) is introduced based on a weighted summation of soil properties:

$$\text{CAISPP} = \sum_{i=1}^{n} W_i P_i \tag{1}$$

where W_i is the weight of each soil physiochemical property; P_i is the score of each of the properties (defined below); and $i = 1, \ldots, n = 14$ is their number.

The scores of soil physiochemical properties were normalized to values between 0 and 1 due to their different units of properties and calculated by two types of scoring functions: "more is better" and "less is better" (Andrews et al., 2002; Shao et al., 2020). The scoring functions "more is better" (Equation 2) and "less is better" (Equation 3) are defined as follows:

$$f(x) = \begin{cases} 0.1, & x \leq L \\ 0.9 \times \frac{x-L}{U-L} & L<x<U \\ 1, & x \geq U \end{cases} \tag{2}$$

$$f(x) = \begin{cases} 1, & x \leq L \\ 1 - 0.9 \times \frac{x-L}{U-L} & L<x<U \\ 0.1, & x \geq U \end{cases} \tag{3}$$

where $f(x)$ is the linear score of soil physiochemical properties, x is the value of soil properties, and L and U are the maximum and minimum values of each soil physiochemical property, respectively. In this study, the function "more is better" was applied to most of the soil properties (TOP, CP, NCP, SMC, pH, SOM, TN, NN, AN, TP, AP, TK, and AK) due to their positive effects on plant growth (Chen et al., 2013; Yu et al., 2018). The scoring function "less is better" was used for BD due to its inhibitory effect on root growth and soil porosity (Andrews et al., 2003).

The contributions (weights) of soil physiochemical properties characterize the significance of each property to the CAISPP. They were determined by principal component analysis (PCA) (Armenise et al., 2013; Masto et al., 2008; Wang et al., 2019) using SPSS 13.0 for Windows (SPSS Inc.). The weight of a given soil physiochemical property was defined by the ratio of the soil physiochemical property's communality to the sum of the communalities for all 14 soil physiochemical properties (Wang et al., 2019):

$$W_i = \frac{C_i}{\sum_{i=1}^{n} C_i} \tag{4}$$

where W_i is the weight of the selected soil physiochemical properties, C_i is the communality value of the property obtained from the PCA results, and n is the number of the properties.

The same PCA was used to diagnose important soil properties for the comprehensive CAISPP under different land-use types. The important soil physiochemical properties were determined based on the principal components (PCs) and norm values.

$$N_{ik} = \sqrt{\sum_{i}^{k} \left(U_{ik}^2 \lambda_{ik}\right)} \tag{5}$$

where N_{ik} is comprehensive loading of ith soil variable on the first k PCs, λ_{ik} is the eigenvalue of the PC, and U_{ik} is the loading of ith soil variable on PC$_k$. That is, the higher the norm value, the stronger its ability to interpret overall soil physiochemical properties information (Shao et al., 2020). To test the accuracy of selection results, a new CAISPP including important soil physicochemical properties was established, and its relationship with the CAISPP based on the total 14 properties data set was evaluated.

2.4 | Statistical analyses

One-way ANOVA and Tukey's honest significant difference post hoc tests (P < .05) were used to determine the significance of differences between the average soil physicochemical properties for different land-use types. A general linear model was implemented to examine the effects of land-use types, soil depths, and their interaction on soil physicochemical properties. Pearson's correlation coefficients were calculated to determine the relationships among soil physicochemical properties. Significance was determined at $P < .05$ and $P < .01$. All statistical analyses were performed using SPSS 13.0 for Windows (SPSS Inc.).

Redundancy analysis was performed to identify the contributions of influential factors to variation in total soil physicochemical properties (using the 'vegan' package in R; http://cran.r-project.org/web/packages/vegan). The influential factors that may drive variation in soil physicochemical properties are related to climate (average annual temperature and precipitation), geographical location (latitude, longitude, altitude, slope degree, and slope orientation), vegetation cover (land-use type, tree age, crown density, and undergrowth percent cover), and soil condition (soil depth and soil type).

3 | RESULTS

3.1 | Soil physicochemical characteristics

The analysis of the 14 soil physicochemical properties affected by RPs and their relation to additional five land-use types, presented in Table 2.9.9, reveals the following results: (a) Land-use types had a significant effect on all measured soil physicochemical properties; soil depth influenced most of the soil properties (except NCP, pH, and TK); and SOM, AK, and NN were significantly affected by their interaction. (b) The mean values of BD at both soil depths (0–20 and 20–40 cm) under RPs were significantly higher than TR, which was opposite to the TOP, CP, and NCP values. The SMC values of the two soil depths under RPs ranged from 16.94 to 26.76%, which were significantly lower than TR (42.30 and 36.53%) but higher than EP (8.62 and 9.10%). Rubber plantations with similar geographical and climatic conditions but different tree age showed little differences regarding soil physical properties, indicating that soil physical properties were not correlated with plantation age. (c) Soil pH was acidic (range, 3.75–4.75) in the all investigated land-use types. The SOM values of RPs were significantly lower than those of TR at both soil depths. The mean values of TN under RPs ranged from 0.07 to 0.12%, which were significantly lower than APP and a bit lower than TR. The TP of monoculture RPs were significantly lower than RPs intercropped with *Alpinia oxyphylla* and APP and slightly lower than BP and TR. The AK of monoculture RPs was significantly lower than APP and TR.

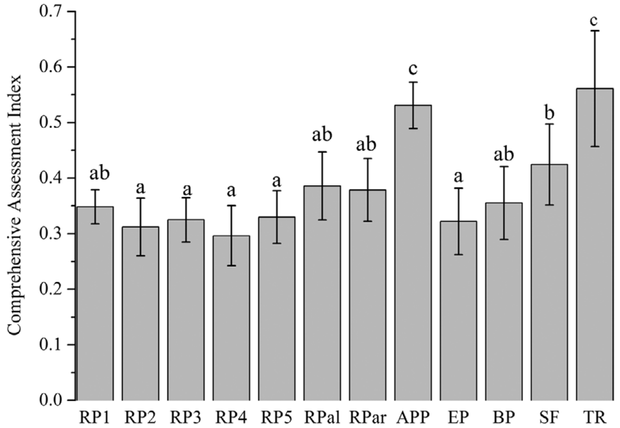

FIGURE 2 The mean values of the Comprehensive Assessment Index of Soil Physiochemical Property (CAISPP) in different land-use types (0–40 cm layer, $n = 10$). Error bars denote SD of the overall index value. Different lowercase letters represent significant differences at $P < .05$. APP, areca palm plantation; BP, banana plantation; EP, eucalyptus plantation; RP1, RP2, RP3, RP4, and RP5: monoculture rubber plantations at the age of 4, 13, 20, 28, and 33 yr, respectively; RPal, RPar-rubber plantations intercropped with *Alpinia oxyphylla* and areca palm; SF, secondary forest; TR, tropical rainforest.

3.2 | CAISPP

3.2.1 | Weights for CAISPP

The weights of soil properties were calculated using Equation 4 based on the values of their communalities calculated by PCA and are presented in Table 3. The first five PCs were used for the CAISPP because each explained at least 6% of the data variation and accounted for 85.794% of the total variance. The eigenvalues of first five components ranged from 0.921 to 6.328 (Table 3). The proportion of explained variance was 45.199% for the first PC and 15.006, 12.296, 6.718, and 6.575% for the other four PCs, respectively. Communalities for the soil properties indicated that the five components explained >90% of the variance in BD, TOP, CP, pH, and AP; >80% of the variance in SMC, SOM, TN, AN, NN, TP, and TK; and >69% of the variance in NCP and AK.

3.2.2 | CAISPP values

The CAISPP values were calculated using Equation 1 based on the score and weights, which ranged from 0.296 to 0.561 (Figure 2). The mean CAISPP values for all the land-use types were in the following order: TR (0.561) > APP (0.531) > SF (0.425) > RPal (0.386) > RPar (0.379) > BP (0.355) > RP1 (0.348) > RP5 (0.330) > RP3 (0.325) > EP (0.322) > RP2 (0.312) > RP4 (0.296). The results of CAISPP indicated that (a) TR had the highest soil quality and RP4 had the lowest soil

TABLE 2 Soil physicochemical properties of different land-use types at two soil depths (0–20 and 20–40 cm) and the effects of land-use type and soil depth on soil physicochemical properties tested by a general linear model

Site/ property[a]	Soil variables[b] Depth	BD	TOP	CP	NCP	SMC	pH	SOM	TN	AN	NN	TP	AP	TK	AK
	cm	g cm^{-3}	%					%		mg kg^{-1}		%	mg kg^{-1}	%	mg kg^{-1}
RP1	0–20	1.42 ± 0.08b	26.37 ± 3.98a	24.13 ± 3.50a	2.24 ± 0.55a	20.25 ± 1.25bc	4.37 ± 0.36bcde	1.29 ± 0.15a	0.07 ± 0.01ab	12.83 ± 1.82abc	6.57 ± 1.11abc	0.04 ± 0.01ab	3.72 ± 0.00cde	1.87 ± 0.36bc	34.62 ± 17.44a
	20–40	1.48 ± 0.06BC	23.26 ± 2.79AB	21.00 ± 2.86AB	2.25 ± 0.64A	16.94 ± 0.63AB	4.13 ± 0.28ABC	1.15 ± 0.19AB	0.07 ± 0.01AB	11.95 ± 0.96ABC	8.05 ± 2.56BCD	0.04 ± 0.01AB	3.02 ± 0.00BC	1.93 ± 0.31BCD	17.97 ± 5.50A
RP2	0–20	1.41 ± 0.09b	28.39 ± 3.76a	26.53 ± 3.56a	1.85 ± 0.20a	21.67 ± 3.89bc	3.79 ± 0.08a	1.39 ± 0.25a	0.09 ± 0.01ab	9.91 ± 1.23a	8.40 ± 1.38bc	0.04 ± 0.00ab	2.79 ± 0.69abcd	1.48 ± 0.58ab	25.23 ± 8.90a
	20–40	1.50 ± 0.05C	23.01 ± 2.79A	21.38 ± 2.64AB	1.62 ± 0.22A	20.77 ± 2.83BC	3.82 ± 0.13AB	1.24 ± 0.24ABC	0.07 ± 0.01AB	10.53 ± 1.43AB	5.68 ± 0.53ABCD	0.04 ± 0.01AB	1.69 ± 0.49AB	1.60 ± 0.63ABC	16.44 ± 3.64A
RP3	0–20	1.46 ± 0.10b	24.81 ± 2.56a	22.87 ± 2.36a	1.94 ± 0.63a	18.41 ± 3.61b	4.08 ± 0.06abcd	1.46 ± 0.11a	0.08 ± 0.02ab	10.67 ± 0.80a	6.57 ± 0.49ab	0.03 ± 0.01a	2.67 ± 0.83abcd	2.63 ± 0.55 cd	36.02 ± 16.19a
	20–40	1.51 ± 0.05C	23.10 ± 1.26AB	21.47 ± 1.38AB	1.63 ± 0.17A	18.20 ± 2.32BC	4.22 ± 0.46ABCD	1.21 ± 0.18AB	0.07 ± 0.01AB	10.39 ± 1.29AB	5.03 ± 1.09ABC	0.03 ± 0.00A	1.56 ± 0.59AB	2.73 ± 0.50DE	24.19 ± 10.35AB
RP4	0–20	1.48 ± 0.13b	24.98 ± 4.61a	23.03 ± 4.32a	1.96 ± 0.36a	20.68 ± 1.95bc	4.05 ± 0.07abc	1.66 ± 0.18ab	0.10 ± 0.01ab	11.76 ± 3.54abc	6.55 ± 1.95abc	0.04 ± 0.01a	2.31 ± 0.40abcd	1.25 ± 0.30ab	25.83 ± 8.53a
	20–40	1.56 ± 0.05C	20.31 ± 1.83A	18.17 ± 2.31A	2.14 ± 0.55A	17.80 ± 1.33B	4.06 ± 0.06ABC	1.27 ± 0.20ABC	0.07 ± 0.01AB	9.17 ± 1.57AB	5.02 ± 1.37ABC	0.03 ± 0.00A	1.70 ± 0.58AB	1.29 ± 0.29ABC	18.21 ± 8.36A
RP5	0–20	1.49 ± 0.07b	25.05 ± 3.30a	23.25 ± 3.31a	1.80 ± 0.13a	21.47 ± 2.55bc	3.78 ± 0.06a	1.85 ± 0.18ab	0.11 ± 0.01bc	10.88 ± 1.35ab	11.07 ± 1.78c	0.04 ± 0.01a	3.22 ± 1.03bcd	1.38 ± 0.47ab	39.69 ± 5.77a
	20–40	1.43 ± 0.06BC	25.24 ± 1.95AB	23.08 ± 1.48AB	2.15 ± 0.64A	18.86 ± 0.91BC	3.83 ± 0.07AB	1.29 ± 0.13ABC	0.07 ± 0.01AB	8.66 ± 0.57A	5.80 ± 0.98ABC	0.03 ± 0.00A	1.99 ± 0.79ABC	1.46 ± 0.47ABC	19.94 ± 5.71A
RPal	0–20	1.36 ± 0.07b	29.52 ± 2.92a	26.65 ± 2.88a	2.86 ± 1.28ab	26.76 ± 4.56b	4.42 ± 0.16cde	2.25 ± 0.68ab	0.12 ± 0.03bcd	16.98 ± 1.76cd	3.76 ± 0.90a	0.08 ± 0.01d	1.39 ± 0.33a	0.87 ± 0.17a	44.43 ± 11.90ab
	20–40	1.46 ± 0.06BC	26.59 ± 2.62AB	24.06 ± 2.58AB	2.52 ± 0.60AB	22.11 ± 2.59BC	4.35 ± 0.16BCD	1.51 ± 0.31BCD	0.09 ± 0.02AB	15.72 ± 3.78C	2.93 ± 0.44A	0.07 ± 0.01D	0.49 ± 0.03A	0.92 ± 0.20A	30.38 ± 4.98ABC
RPar	0–20	1.46 ± 0.07b	25.55 ± 2.61a	23.18 ± 2.35a	2.37 ± 0.56a	22.37 ± 2.77bc	4.13 ± 0.23abcd	1.77 ± 0.24ab	0.11 ± 0.01b	16.35 ± 3.47bc	10.14 ± 1.86c	0.05 ± 0.01abc	2.09 ± 0.00abc	1.95 ± 0.29bc	78.35 ± 7.50c
	20–40	1.55 ± 0.08C	21.87 ± 2.07A	19.46 ± 2.54A	2.41 ± 0.97A	19.43 ± 4.71BC	4.07 ± 0.12ABC	1.17 ± 0.21AB	0.08 ± 0.01AB	11.53 ± 2.05AB	7.35 ± 2.06BCD	0.04 ± 0.01AB	1.73 ± 0.31AB	2.17 ± 0.34CDE	44.03 ± 13.15BCD
APP	0–20	1.40 ± 0.08b	27.03 ± 3.52a	24.93 ± 3.32a	2.10 ± 0.56a	26.65 ± 4.48c	4.62 ± 0.07e	2.49 ± 0.33b	0.17 ± 0.05d	13.83 ± 2.78abc	5.28 ± 1.36ab	0.12 ± 0.02e	4.99 ± 1.13e	3.00 ± 0.20d	66.72 ± 6.38bc
	20–40	1.28 ± 0.11AB	32.64 ± 5.61BC	29.84 ± 5.05BC	2.80 ± 0.77AB	26.15 ± 4.60CD	4.72 ± 0.10D	2.13 ± 0.34DE	0.15 ± 0.04C	10.98 ± 0.99AB	4.33 ± 1.16AB	0.11 ± 0.01E	3.33 ± 0.50BC	2.98 ± 0.24E	56.24 ± 13.36D
EP	0–20	1.32 ± 0.05b	31.58 ± 2.57a	28.56 ± 2.28a	3.02 ± 0.91ab	8.62 ± 1.65a	4.68 ± 0.16e	1.46 ± 0.64a	0.07 ± 0.03ab	13.04 ± 1.74abc	2.83 ± 0.38a	0.04 ± 0.00abc	2.49 ± 0.61abcd	1.00 ± 0.27a	32.77 ± 11.05a
	20–40	1.46 ± 0.17BC	25.87 ± 4.90AB	23.28 ± 4.54AB	2.59 ± 0.53AB	9.10 ± 1.98A	4.75 ± 0.17D	0.70 ± 0.29A	0.05 ± 0.02A	11.33 ± 2.13AB	2.21 ± 0.56A	0.03 ± 0.01A	1.86 ± 1.17AB	0.93 ± 0.18A	23.99 ± 10.47AB
BP	0–20	1.50 ± 0.16b	25.48 ± 7.58a	23.18 ± 7.39a	2.30 ± 0.23a	18.59 ± 3.65bc	4.55 ± 0.19de	1.47 ± 0.25a	0.05 ± 0.02a	14.66 ± 1.28abc	6.79 ± 3.97abc	0.06 ± 0.02bcd	2.74 ± 0.74abcd	0.76 ± 0.58a	36.96 ± 8.08a
	20–40	1.45 ± 0.16BC	27.12 ± 7.74AB	24.68 ± 7.43AB	2.44 ± 0.49A	19.59 ± 5.16BC	4.57 ± 0.20CD	1.32 ± 0.40ABC	0.06 ± 0.02A	12.81 ± 0.95BC	4.16 ± 1.33AB	0.06 ± 0.02CD	2.25 ± 1.33ABC	1.04 ± 0.97AB	36.46 ± 15.85ABCD
SF	0–20	1.31 ± 0.15b	31.72 ± 6.98a	28.96 ± 6.44a	2.76 ± 0.81ab	22.84 ± 4.60bc	4.20 ± 0.55abcde	2.24 ± 0.66ab	0.09 ± 0.02ab	11.27 ± 2.94ab	9.31 ± 4.25bc	0.04 ± 0.00abc	3.83 ± 1.51de	1.45 ± 0.15ab	50.42 ± 21.08ab
	20–40	1.37 ± 0.17ABC	29.84 ± 6.66AB	27.28 ± 6.03AB	2.56 ± 0.88AB	21.43 ± 5.34BC	4.19 ± 0.60ABCD	1.96 ± 0.60CDE	0.07 ± 0.03AB	10.83 ± 0.65AB	9.61 ± 4.48D	0.04 ± 0.00AB	3.73 ± 1.69C	1.57 ± 0.22ABC	45.02 ± 18.77BCD
TR	0–20	1.00 ± 0.12a	46.50 ± 8.14b	42.30 ± 8.02b	4.20 ± 0.85b	42.63 ± 6.66d	3.90 ± 0.09ab	3.95 ± 0.90c	0.16 ± 0.03 cd	22.20 ± 4.91d	8.45 ± 1.52bc	0.06 ± 0.02 cd	1.87 ± 0.34ab	1.00 ± 0.27a	83.87 ± 12.83c
	20–40	1.16 ± 0.06A	40.71 ± 6.16C	36.53 ± 5.99C	4.18 ± 1.67B	33.22 ± 6.60D	3.75 ± 0.17A	2.32 ± 0.58E	0.11 ± 0.03BC	19.83 ± 2.71D	8.45 ± 1.61CD	0.05 ± 0.01BC	1.00 ± 0.40A	1.08 ± 0.27AB	49.21 ± 8.73CD
Land-use															
F		13.498	14.773	13.014	8.046	31.791	17.321	20.875	18.489	20.417	12.285	65.417	13.862	28.088	19.716
P value		<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Depth															
F		7.309	7.395	8.090	0.005	11.021	0.031	45.823	30.589	17.740	15.542	4.065	31.382	1.406	46.596
P value		.008	.008	.005	.946	.001	.861	<.001	<.001	<.001	<.001	.047	<.001	.239	<.001
Interaction															
F		1.668	1.359	1.306	0.500	1.396	0.488	2.706	1.215	1.018	1.996	0.586	0.716	0.132	2.120
P value		.092	.205	.233	.899	.187	.906	.004	.288	.437	.037	.836	.721	1.000	.026

Notes: Values are means and SD (n = 5). For a given soil depth, different lowercase or uppercase letters indicate significant difference at P < .05 (one-way ANOVA).

[a] APP, areca palm plantation; BP, banana plantation; EP, eucalyptus plantation; RP1, RP2, RP3, RP4, and RP5, monoculture rubber plantations at the age of 4, 13, 20, 28, and 33 yr, respectively; RPal, rubber plantation intercropped with *Alpinia oxyphylla*; RPar, rubber plantation intercropped with areca palm; SF, secondary forest; TR, tropical rainforest.

[b] AK, available K; AN, ammonium N; AP, available P; BD, bulk density; CP, capillary porosity; NCP, non-capillary porosity; NN, nitrate N; SMC, soil moisture content; SOM, soil organic matter; TK, total K; TN, total nitrogen; TOP, total porosity; TP, total P.

TABLE 3 Results of principal component analysis and weight values of each soil physiochemical property

Soil properties[a]	PC1	PC2	PC3	PC4	PC5	Norm	Communalities	Weight 1	Weight 2
BD, g cm^{-3}	**−0.931**	−0.301	0.054	0.003	0.011	2.382	0.960	0.080	
TOP, %	**0.930**[b]	0.315	−0.060	−0.047	−0.056	2.386	0.973	0.081	0.198
CP, %	**0.912**	0.317	−0.074	0.004	−0.060	2.342	0.941	0.078	
NCP, %	0.709	0.178	0.060	−0.393	−0.004	1.843	0.692	0.058	
SMC, %	0.468	**0.714**	−0.289	0.103	−0.165	1.623	0.850	0.071	
pH	−0.073	−0.009	**0.904**	−0.037	0.281	1.230	0.902	0.075	
SOM, %	0.528	**0.749**[b]	−0.172	−0.029	0.036	1.731	0.871	0.073	0.220
TN, %	0.262	0.857	−0.024	0.167	0.055	1.417	0.835	0.070	
AN, mg kg^{-1}	0.370	0.605	0.015	**−0.538**[b]	−0.128	1.387	0.809	0.067	0.194
NN, mg kg^{-1}	0.084	0.211	**−0.797**	−0.081	0.448	1.192	0.894	0.074	
TP, (P_2O_5)%	0.136	0.703	**0.513**[b]	0.224	0.076	1.288	0.831	0.069	0.165
AP (mg kg^{-1})	−0.100	0.074	0.060	0.222	**0.917**[b]	0.950	0.910	0.076	0.223
TK, (K_2O)%	−0.056	0.193	0.057	0.864	0.171	0.912	0.819	0.068	
AK, mg kg^{-1}	0.291	0.741	−0.084	−0.109	0.267	1.333	0.724	0.060	
Eigenvalue	6.328	2.101	1.721	0.940	0.921				
% of variance	45.199	15.006	12.296	6.718	6.575				
Cumulative %	45.199	60.205	72.501	79.219	85.794				

Note. Values in bold are considered highly weighted. Weight 1 refers to total data set based on the 14 properties; Weight 2 refers to the data set based on the five important properties.
[a]AK, available K; AN, ammonium N; AP, available P; BD, bulk density; CP, capillary porosity; NCP, non-capillary porosity; NN, nitrate nitrogen; SMC, soil moisture content; SOM, soil organic matter; TK, total K; TN, total N; TOP, total porosity; TP, total P.
[b]These values showed the most important Comprehensive Assessment Index of Soil Physiochemical Properties.

TABLE 4 Correlation coefficients among the soil physicochemical properties

	BD	TOP	CP	NCP	SMC	pH	SOM	TN	AN	NN	TP	AP	TK	AK
BD	1	−.953**	−.939**	−.689**	−.653**	.134	−.725**	−.509**	−.530**	−.171	−.312**	.081	.014	−.500**
TOP		1	.994**	.662**	.680**	−.130	.728**	.497**	.579**	.175	.304**	−.131	−.067	.502**
CP			1	.579**	.686**	−.137	.725**	.498**	.554**	.175	.303**	−.115	−.040	.494**
NCP				1	.376**	−.031	.478**	.307**	.539**	.111	.200*	−.192*	−.235**	.373**
SMC					1	−.317**	.825**	.688**	.531**	.325**	.429**	−.103	.103	.611**
pH						1	−.179	−.063	−.020	−.551**	.398**	.261**	.100	−.005
SOM							1	.813**	.620**	.316**	.465**	.055	.037	.670**
TN								1	.478**	.208**	.636**	.151	.257**	.621**
AN									1	.156	.312**	−.224*	−.273**	.539**
NN										1	−.182*	.285**	.043	.352**
TP											1	.195*	.308**	.451**
AP												1	.300**	.159
TK													1	.135
AK														1

Note. AK, available K; AN, ammonium N; AP, available P; BD, bulk density; CP, capillary porosity; NCP, non-capillary porosity; NN, nitrate N; SMC, soil moisture content; SOM, soil organic matter; TK, total K; TN, total N; TOP, total porosity; TP, total P.
*Significant at the .05 probability level.
**Significant at the .01 probability level.

quality among the 12 studied sites, (b) the CAISPP values of RPs were significantly lower than TR and APP ($P < .05$), and (c) the use of intercropping appears to improve soil quality in RPs by comparing the CAISPP values of monoculture and intercropped RPs.

3.2.3 | Important soil physicochemical properties for CAISPP

Important soil physicochemical properties for the CAISPP of different land-use types were determined based on the

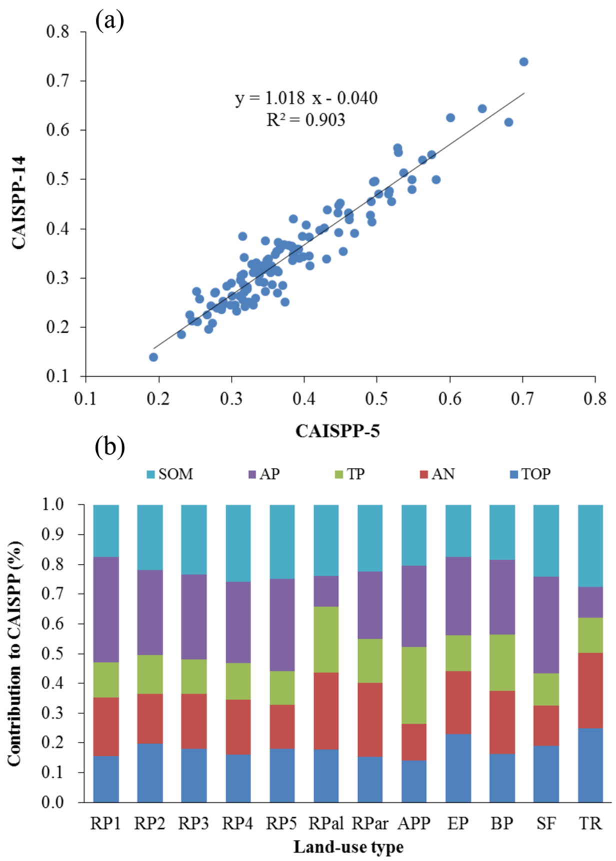

FIGURE 3 The (a) linear relationships between Comprehensive Assessment Index of Soil Physiochemical Property based on the five important properties data set (CAISPP-5) and on the total 14 important properties data set (CAISPP-14) values (n = 120) and (b) the individual contributions of the five soil properties to CAISPP-5 in different land-use types. Five soil properties are as follows: AN, ammonium N; AP, available P; SOM, soil organic matter; TOP, total porosity; TP, total phosphorus. APP, areca palm plantation; BP, banana plantation; EP, eucalyptus plantation; RP1, RP2, RP3, RP4, and RP5: monoculture rubber plantations at the age of 4, 13, 20, 28, and 33 yr, respectively; RPal, RPar-rubber plantations intercropped with *Alpinia oxyphylla* and areca palm; SF, secondary forest; TR, tropical rainforest.

absolute factor loading values (≥0.50) of each PC and the norm values (within 10% of the highest values) (Shao et al., 2020). Pearson correlation analysis was used to examine the relationships among these properties to reduce redundancy (Table 4). In PC1, the absolute factor loading values of BD, TOP, CP, NCP, and SOM were ≥0.50. Among these soil properties, TOP had the highest norm value at 2.386; BD and CP had norm values within 10% of the highest value. Because TOP, BD, and CP were significantly correlated with each other, TOP was selected as the first important soil property for the CAISPP. Similarly, SMC, TP, AN, and AP were selected as the second, third, fourth, and fifth important soil property for CAISPP, respectively.

To test the accuracy of selection results on the important soil physicochemical properties, CAISPP-5 values, including TOP, SOM, TP, AN, and AP, were established. The CAISPP-5 values were significantly correlated with CAISPP values based on the 14 soil properties (Figure 3a), which indicated that TOP, SOM, TP, AN, and AP were important properties for soil quality assessment. Among all of the five important soil physicochemical properties, AP contributed 25.45% to CAISPP-5, followed by SOM (22.35%), AN (19.42%), and TOP (18.10%); TP had the lowest contribution (14.69%) (Figure 3b).

3.3 | Factors influencing soil physicochemical properties

The contribution of each influential factor (i.e., climate, geographical location, vegetation cover, and soil condition) to the total variance in the soil physicochemical properties was quantified by redundancy analysis, leading to the following results: (a) The four types of influential factors interacted and, collectively, explained 51% of the variation in the soil physicochemical properties across the study area (Figure 4a). (b) Climate variables accounted for the lowest proportion (24%) of the variation in the soil physicochemical properties, followed by soil condition (29%), while both geographical location and vegetation cover together accounted for the largest proportion (45%). (c) The interaction of vegetation cover, geographical location, and climate explained 22% of the variation in the soil physicochemical properties, while the interaction of vegetation cover, geographical location, and soil condition explained 21%; and four-way interaction explained only 2% of the variability in the soil physicochemical properties. (d) All four types of factors together explained the same proportion of variance in the soil physicochemical properties as land-use type and soil depth combined (Figure 4b,c), which indicated that land-use type and soil depth were important for explaining variability in the soil physicochemical properties.

4 | DISCUSSION

4.1 | Effects of rubber tree age on soil physicochemical properties

Soil physical properties and most chemical properties in the surface soil layer (0–40 cm) under monoculture RPs varied less with increasing tree age (Table 2). Three soil chemical properties (i.e., pH, NN, and TK) showed significant differences among the investigated monoculture RPs but did not change with tree age. The significant differences of both soil NN and TK contents for the monoculture RPs can be attributed to human activity, such as fertilization. There were significant negative correlations between soil NN contents

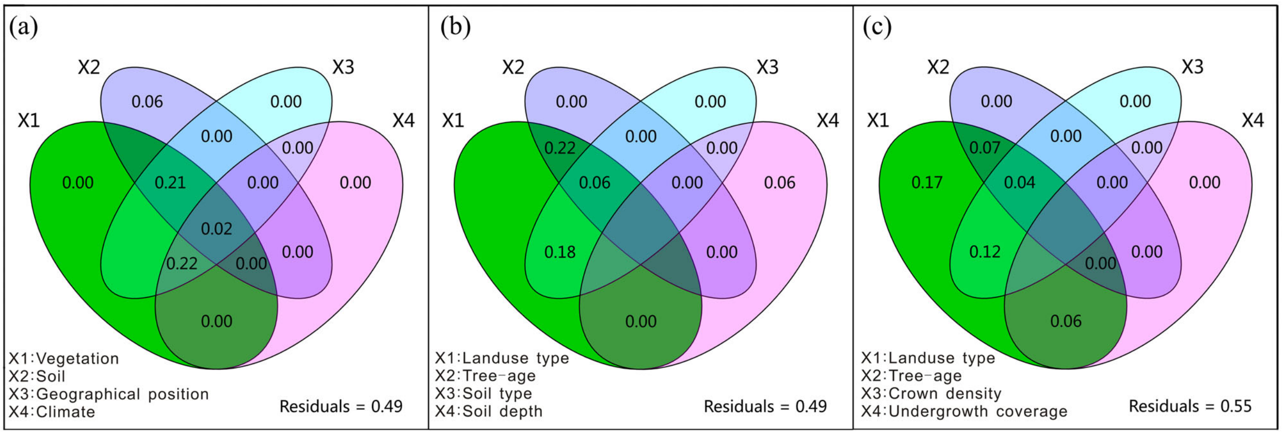

FIGURE 4 Redundancy analysis of influential factors (vegetation, soil, climate, and geographical position) for soil physicochemical properties across the study area. The proportion of the total variance accounted for by the factors and their interactions are shown.

and pH (Table 4), which indicated that nitrogen fertilizer could aggravate soil acidity in the monoculture RPs.

The effects of rubber tree age on soil physicochemical properties were not significant, and three soil chemical properties (pH, NN, and TK) were notably affected by human activities. In addition, mean CAISPP values did not appear to change significantly for RPs of different age. Those results were inconsistent with a previous study showing that the age of rubber trees strongly affected soil physicochemical properties (Yasin et al., 2010), which was attributed to the RPs being converted from natural forests. In this study, however, over the past 66 yr the RPs have been generated with young rubber trees after felling the old ones.

4.2 | Effects of intercropping on soil physicochemical properties in RPs

Within a geographic region and under similar climatic conditions, monoculture and intercropped RPs varied little in terms of their physical soil properties (Table 2). However, the soil chemical properties of monoculture RPs, such as soil AN, TP, and AK, were significantly lower than those of intercropped RPs. Accordingly, the CAISPP values showed that of intercropped RPs had better soil quality than monoculture RPs. These findings show that, consistent with some previous studies (Chen et al., 2019; Liu, Nie, et al., 2018; Liu et al., 2019), intercropping improves soil quality in RPs.

4.3 | Soil physicochemical properties affected by RPs converted from other land-use types

In this study, most soil physical properties in the monoculture RP differed from those in TR but varied little from the other four land-use types (SF, EP, APP, and BP). Soil physical properties were influenced by many factors, such as plant litter cover, plant roots, intercropped plants, geographical conditions, and anthropogenic activities (Duffera et al., 2007; Xiong et al., 2008). Soil bulk density was significantly higher in the monoculture RP than in TR, while the other four soil physical properties (TOP, CP, NCP, and SMC) were significantly lower; this, can be attributed to the complexity of the system of plants, plant litter and roots interacting in natural rainforest on Hainan Island characterized by less human interference (Liu et al., 2020).

Tropical rainforest was also considered to keep high levels of soil nutrients and maintain the stability of the system. Destruction of TR for agricultural use may cause the rapid leaching of nutrients and a loss of ecosystem fertility (Jordan & Herrera, 1981; Trumbore et al., 2015). Similar results were acquired in this study, which substantiated and quantified the four soil chemical properties (SOM, AN, TP, and AK) being significantly lower in the monoculture RP than in TR ($P < .05$). Following the same trend, soil TN was slightly lower, while available P and TK were slightly higher in the monoculture plantations compared with TR, which can be attributed to additional commercial fertilizers enriching the RP soils.

According to the CAISPP values, the conversion of TR to monoculture RPs will cause poor soil physicochemical properties on Hainan Island. Besides, the mean CAISPP values of RPs were significantly lower than areca palm plantation with higher vegetation cover and steep slope, which indicated that natural management (Lan et al., 2017) was an effective approach to improve soil quality of artificial forests.

5 | CONCLUSIONS AND OUTLOOK

Effects of RP creation on soil quality were quantitatively assessed by comparing the soil physicochemical properties of monoculture RPs of different ages, intercropped RPs, and five other land-use types that are common on Hainan Island. The following results have been obtained: (a) Introducing a comprehensive assessment index of soil physicochemical properties CAISPP and suitably using PCA and redundancy analysis has provided a wide spectrum of measures to quantify soil quality and to identify the factors influencing soil quality. (b) The CAISPP values of RPs were significantly lower than TR and APP, and it was higher in intercropped versus monoculture RPs. (c) Soil organic matter, TOP, AN, TP, and AP appeared to be main limiting factors of soil quality. (d) Land-use type interacted with climatic, geographical, edaphic factors and collectively explained 51% of the variation in the soil physicochemical properties.

These results lead to the following conclusions: The conversion of TR to RPs as well as to other land-use types (e.g., EP, BP, and SF) will generate poor soil physicochemical properties, thus the TR with its high soil quality should be protected. In addition, growing areca palms and *Alpinia oxyphylla* within RPs could improve the soil physicochemical properties and soil quality on Hainan Island.

To fully assess soil quality future work is needed focusing on the effects of soil depth using samples taken over a greater vertical range (at least 1 m deep), and also on additional soil properties (e.g., soil organic C, biomass C, field capacity, catalase, sucrose, urease, and phosphatase). Here, studies on sampling to depths of at least 1 m (preferably 2 m) (Lal, 2009) and soil quality indicators covering a wide range of soil properties (Guo et al., 2017) need to be taken into account.

In addition, by using continuous sampling at fixed study sites, the effects of land-use changes on soil quality could be assessed at both seasonal and annual scales, and the effects of land-use managements could also be considered. According to the high correlation of CAISPP values calculated using the five important soil physicochemical properties with all the 14 soil physicochemical properties in this study (Figure 3a), a minimum CAISPP (based on the important soil physicochemical properties selected by the results of principal component analysis) could be established in the future studies to decrease the cost of soil quality assessment (Qi et al., 2009; Rezaei et al., 2006).

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AUTHOR CONTRIBUTIONS

Rui Sun: Conceptualization; Data curation; Funding acquisition; Investigation; Writing-original draft. Zhixiang Wu: Funding acquisition; Supervision. Guoyu Lan: Software. Chuan Yang: Data curation; Investigation. Klaus Fraedrich: Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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