https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Biogeosciences Discussions
Open Access

Effects of tropical rainforest conversion to rubber plantation on soil quality in Hainan Island, China

Rui Sun[a,b], Guoyu Lan[a,b*], Chuan Yang[a,b], Zhixiang Wu[a,b], Banqian Chen[a,b], Klaus Fraedrich[c]

[a] Rubber Research Institute, Chinese Academy of Tropical Agricultural Sciences, Haikou 571101, China

[b] Hainan Danzhou Agro-ecosystem National Observation and Research Station, Danzhou 571737, China

[c] Max Planck Institute for Meteorology, Hamburg 20146, Germany

[*] **Corresponding Author:**

Guoyu Lan, No. 4, Xueyuan Road, Longhua District, Haikou 571101, China. Email: langyrri@163.com.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Biogeosciences Discussions

Abstract

Land-use changes can alter soil properties and thus affect soil quality. Our understanding of how forest conversion (from tropical rainforest to rubber plantations) affects soil properties and soil quality is limited. An ideal testing ground for analyzing such land-use change and its impacts is Hainan Island, the largest tropical island in China. Based on 21 soil physicochemical and biological properties, a soil quality index (SQI) employed principal component analysis to assess soil quality changes from the conversion of tropical rainforests to rubber plantations. The results showed that (i) soil available potassium, available phosphorus, microbial biomass carbon, cellulose decomposition, acid phosphatase, and urease were vital soil properties for soil quality assessment on Hainan Island. (ii) The SQI of rubber plantations decreased by 26.48% compared to tropical rainforests, while four investigated soil properties (soil pH, total phosphorus, cellulose decomposition, and actinomyces) increased. (iii) The SQI of both the tropical rainforests and rubber plantations showed significant spatial differences, which, under tropical rainforests, was more sensitive to seasonal changes than those under rubber plantations. (iv) Structural equation modeling suggested that forest conversion directly impacted soil quality and, indirectly impacted soil qualities' spatial variation by their interaction with soil types and geographical positions. Overall, though the conversion of tropical rainforest to rubber plantation did not decrease all soil properties, the tropical rainforest with its high soil quality should be protected.

Keywords: rubber plantation; tropical rainforest; soil properties; soil quality index;

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

structural equation modeling

1. Introduction

The rubber tree (*Hevea brasiliensis*), an economically valuable forest species, is a large source of natural rubber and is grown in more than 40 tropical countries worldwide (Warren-Thomas, 2015). Due to the increasing development of tire manufacturing and high prices of rubber, the land-mass of rubber plantations has expanded rapidly over the last 20 years in tropical Asia (Ahrends et al., 2015; Warren-Thomas et al., 2015; Lang et al., 2017), which is currently the world's most prolific region for rubber production (FAO, 2017). The conversion of tropical rainforests to rubber plantations in tropical Asia accompanies the continuously rising demand for rubber worldwide (De Blécourt et al., 2014; Allen et al., 2015; Hassler et al., 2017; Guillaume et al., 2018), which generally has negative impacts on soils and ecosystem services and threatens biodiversity and human livelihoods (Qiu, 2009; Ziegler et al., 2009; Tan et al., 2011; Ahrends et al., 2015; Liu et al., 2019; Singh et al., 2021). Hence, the response of rubber plantation expansion at the expense of tropical rainforest degradation on the environment - especially soil quality - has recently become a research focus.

Soil quality is a critically important capacity of soil within ecosystems, functioning not only as sustenance for biological productivity but also in the maintenance of environmental quality and promotion of plant and animal health (Doran and Parkin, 1994; Karlen et al., 2003; Shao et al. 2020; Li et al. 2020). Soil quality can be assessed based on a set of soil properties that affect soil functions (Lal,

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

1998), such as physical, chemical, and biological soil properties (Yakovchenko et al., 1996; Gil-Sotres et al., 2005; Griffiths et al., 2010; Nosrati et al., 2011; Davari et al., 2020). Evaluating soil quality generally involves three main steps: definition and selection of soil properties, scoring soil properties, and soil quality index calculation (Andrews et al., 2004; Chen et al., 2013). At present, the comprehensive soil quality evaluation methods mainly include soil quality cards and test kits (Ditzler and Tugel, 2002), grey correlation method (Yang et al., 2010), fuzzy methods (Torbert et al., 2008; Yue-Ju et al., 2010; Xue et al., 2010), soil quality indices (Andrews et al., 2004; Masto et al., 2008; Nakajima et al., 2015; Nabiollahi et al., 2017; Zhang et al., 2019; Shao et al., 2020; Jahany and Rezapour, 2020; Jin et al., 2021), and soil quality index area (Kuzyakov et al., 2020). Out of all the methods, the soil quality index (SQI) approach has been applied frequently because of its flexibility and simplicity (Derakhshan-Babaei et al., 2021; Zhang et al., 2021).

Soil quality can be affected by land use and land-use changes (Marzaioli et al., 2010; Moges et al., 2013; Raiesi, 2017; Yu et al., 2018; Pham et al., 2018; Davari et al., 2020). Particularly, land-use changes can influence soil degradation (Vityakon, 2007; Nabiollahi et al., 2018; Nosrati and Collins, 2019), soil physical and chemical quality (Deng et al., 2016; Liu et al., 2018; Wang et al., 2019; Sun et al., 2021), soil biological quality (Berkelmann et al., 2018; Cai et al., 2018), etc. The conversion of tropical rainforests to rubber plantations, a typical land-use change in tropical regions, has been the focus of many previous studies looking at the land-use change affecting soil properties and functions, such as soil physical and chemical properties (Chen et

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

al., 2019; Sun et al., 2021), soil nutrients and fertility (Chiti et al., 2014; De Blécourt et al., 2014; Guillaume et al., 2015; Allen et al., 2015; Hassler et al., 2017; Maranguit et al., 2017), soil respiration (Goldberg et al., 2017; Zhao et al., 2018), and soil microbial communities (Krashevska et al., 2015; 2019; Kerfahi et al., 2016; Wang et al., 2017; Berkelmann et al., 2018; Lan et al., 2017a; 2020). A soil quality index was also established based on soil's physical and chemical properties to comprehensively assess the effects of rubber plantations on the soil after being converted from tropical rainforest (Sun et al., 2021; Zou et al., 2021). Chemical properties were found to contribute more to the soil quality index than the physical properties (Sun et al., 2021; Zou et al., 2021), and biological properties were rarely considered.

Hainan Island is the largest tropical island in China. It is a major producer of natural rubber, with an 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 size and number of rubber plantations have been expanding rapidly on the island at the expense of losing forested land and agricultural land (Zhai et al., 2012; 2014; Chen et al., 2016; Sun et al., 2020), which overall has decreased tropical rainforest area. Therefore, Hainan Island was recognized as an ideal testbed for analyzing this specific land-use change (from tropical rainforests to rubber plantations) and its impacts. A soil quality index (SQI) based on a weighted summation of soil physical, chemical, and biological properties was established in this study, aiming (i) to assess soil quality of tropical rainforests and rubber plantations comprehensively, and (ii) to quantify the impact of the land-use change (from tropical

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

rainforests to rubber plantations) on soil quality variations on Hainan Island. Thereby, tests of the following hypotheses are required: (i) soil quality, which deteriorates by the conversion of tropical forests to rubber plantations, and (ii) the spatial variation of soil quality, which is affected by the interaction of land-use change with soil types, geographical position, and climatic variables.

2. Materials and methods

2.1. Study area

Hainan Island (18°09′-20°10′ N and 108°37′-111°03′ E, Fig. 1) is the largest island in Southern China, with a geographical area of 33,920 km^2. It is also the largest island in the Indo-Burmese biodiversity hotspot (Myers et al., 2000; Wikramanayake et al., 2002), characterized by a tropical monsoon climate. The climate is warm and humid, with a rainy season from May to October and a dry season from November to April (Wu, 2008; Sun et al., 2017). The annual average temperature varies from 23.4 ~ 24.7 °C across the study area, while the mean annual precipitation ranges from 1392.3 mm to 2173.8 mm.

The central part of Hainan Island is mountainous, containing primary forest composed of a mix of tropical rainforest and monsoon forest. The tropical forest, accounting for 17.3% of the island's area, is mainly distributed in the mountains in the south-central region at altitudes above 500 m. Rubber plantations are located in the lowlands surrounding the central mountainous area, where transportation is more accessible, and water sources are nearby (Sun et al., 2020; Fig.1).

The study sites included four different soil types: laterite, lateritic red soil, red soil, and yellow soil. The soil data (with a resolution of 1:1 000 000), was 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).

2.2. Soil sampling and experimental design

Soil samples were collected from tropical rainforest and rubber plantation on Hainan Island in January 2018 and July 2018. Five sites were selected for this study representative of the major tropical rainforest districts of Hainan (Fig. 1), i.e., Bawang mountain (BW), Diaoluo mountain (DL), Wuzhi mountain (WZ), Yinge mountain (YG), and Jianfeng mountain (JF). For rubber plantations, five sites were also selected in the northeast, northwest, center, southeast and southwest of the island, respectively: Haikou (HK), Danzhou (DZ), Qiongzhong (QZ), Wanning (WN), and Ledong (LD). Note that, mature rubber plantations (25 to 30 years of age) were chosen for each site to avoid the variable rubber plantation age on soil quality. And intensive management practices were utilized in rubber plantations, such as latex harvest, and the application of fertilizers (Lan et al., 2017). In order to facilitate latex harvest, rubber trees were fertilized once or twice a year using compound fertilizer at a rate of 1-1.5 kg per tree and organic fertilizers at a rate of 20-25 kg per tree.

Study sites characteristics are given in Table 1. For each site, thirteen sample plots were selected within an area of one square kilometer. A five-point sampling method was used, and compound soil samples were obtained from each plot. There were a total of 65 samples collected from both the rubber plantation and tropical

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

rainforest sites. We sampled twice, once in the rainy season (July) and once in the dry season (January), making for a total of 260 soil samples (130 from rubber plantations and 130 from the tropical rainforest). After removing the litter layer, using a sterilized steel drill, a 5-cm diameter soil core was collected from 0 to 20 cm depth, homogenized, and passed through a 2-mm mesh sieve. Soil samples for physicochemical analysis were put in a sterilized self-sealing bag and stored at 4 °C and were then transported to the laboratory for analysis.

2.3. Soil analysis

A total of twenty-one soil physical (WC: soil water content), chemical (pH, SOM: soil organic matter, TN: total nitrogen, NN: nitrate-nitrogen, AN: ammonium nitrogen, TP: total phosphorus, AP: available phosphorus, TK: total potassium, and AK: available potassium), and biological properties (MBC: microbial biomass carbon, RQ: microbial respiratory quotient, CD: cellulose decomposition, URE: urease, ACP: acid phosphatase, CAT: catalase, CEL: cellulose, SI: sucrose invertase, BAC: bacteria, FUN: fungi, and ACT: actinomyces) were determined to be soil indicators for soil quality assessment.

Soil physical and chemical properties were quantified using standard techniques recommended by a guide to soil physical and chemical analysis (Institute of Soil Science, Chinese Academy of Sciences, 1978). Detailed protocols for measuring soil water content are available (see Deng et al. 2016; Chen et al., 2019; Zhang et al., 2019). Soil pH was measured in a 1:1 soil-water suspension with a pH meter (pHS-2, Leici, China). Soil organic matter was determined by the potassium dichromate

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Biogeosciences Discussions Open Access EGU

oxidation method. TN was determined using 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; TK and AK were measured by flame photometry (Soil Science Society of China, 2000).

Soil biological properties were measured, including soil microbial function (MBC, RQ, and CD), soil microbial quantity (BAC, FUN, and ACT), and enzymatic activity (URE, ACP, CAT, SI, and CEL). MBC was measured by the chloroform fumigation method (Ross, 1990). RQ was titrated by alkali absorption, and CD was decomposed by the embedding sheet method (Xu and Zheng, 1986). URE, ACP, CAT, CEL, and SI were determined using sodium phenol sodium hypochlorite colorimetry, colorimetric method of benzene disodium phosphate, potassium permanganate titration, nitrosalicylic acid colorimetry, and the 3, 5-dinitrosalicylate colorimetric method, respectively (Guan, 1986). Measurement of bacteria, fungi, and actinomyces included DNA extraction and PCR amplification using Illumina MiSeq sequencing and bioinformatic analysis pipelines referred to in a previous study (Lan et al., 2020).

2.4. Soil quality assessment method

Based on the twenty-one physical, chemical, and biological soil properties, a soil quality index (SQI) was established employing principal component analysis (PCA) to comprehensively assess soil qualities in spatial variation and seasonal changes under tropical rainforests and rubber plantations on Hainan Island.

First, all the selected soil properties were scored using the scoring function

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

"more is better" (Andrews et al., 2002; Shao et al., 2020) according to the soil functions of each soil property. The equation of the scoring function "more is better" (Eq. (1)) is as follows:

$$f(x) = \begin{cases} 0.1, & x \le L \\ 0.9 \times \dfrac{x-L}{U-L} + 0.1, & L < x < U \\ 1, & x \ge U \end{cases} \qquad (1)$$

where $f(x)$ is the linear score of soil properties, x is the value of soil properties, and L and U are the lower and upper threshold values of the property, respectively.

Second, all the soil properties of tropical rainforests and rubber plantations were grouped into components for PCA. The weights of the properties were calculated using Eq. (2) based on the values of their communalities. Communality describes the proportion of variance in each soil property explained by the PCA model. The larger the communality, the higher the proportion of an indicator's variance can be explained by the factors (Brejdaet al., 2000; Imaz et al., 2010; Chen et al., 2013; Zhang et al., 2016).

$$W_i = C_i \Big/ \sum_{i=1}^{n} C_i \qquad (2)$$

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

Finally, after all the soil properties were scored and weighted, SQIs were calculated using the PCA-based Soil Quality Index equation (Eq. (3)):

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

$$SQI = \sum_{i=1}^{n} W_i P_i \qquad (3)$$

where W_i is the weight of each soil property, P_i is the score of each soil property, and n is the number of soil properties.

Except for calculating the weight of each soil property, the PCA can be used to select vital soil properties for assessing soil quality (Ngo-Mbogba et al., 2015). Principal components (PCs) are sets of indicators with large eigenvalues and factor loading. Only the PCs with eigenvalues $\geqslant 1$ (Brejda et al., 2000) and PCs that explained at least 5% of the variation in the data (Mandal et al., 2008) were selected. According to Andrews and Carroll (2001), soil properties with weighted absolute values within 10% of each PC's the highest soil property value were selected. However, in the process of calculating the factor load of each soil property by PCA and the data structure is simplified, some important soil properties' information can be lost (Yemefack et al., 2006). The norm value, which is the magnitude (length) of the vector representing the variable in the multi-dimensional space spanned by the set of PCs, was introduced to avoid this defect (Yemefack et al., 2006). The higher the norm value is, the stronger its ability to represent the overall soil quality information for further interpretation. The equation of the norm is:

$$N_{ik} = \sqrt{\sum_{i}^{k} \left(U_{ik}^2 \lambda_{ik} \right)} \qquad (4)$$

where N_{ik} is the comprehensive loading of the i-th soil variable on the first k PCs, λ_{ik} is the eigenvalue of the PC, and U_{ik} is the loading of the i-th soil variable on PC$_k$. Soil properties receiving N_{ik} within 10% of the highest norm values were considered the most important for assessing soil quality (Chen et al., 2013; Zhang et al., 2016).

2.5. Statistical analysis

One-way analyses of variance (ANOVA) and *Tukey* HSD post hoc tests were used to assess the significant difference ($P < 0.05$) of the investigated soil properties and soil quality between tropical rainforests and rubber plantations in wet and in dry seasons. A radar diagram was drawn to show each of the soil properties, and soil functions changed by converting tropical rainforests to rubber plantations (Kuzyakov et al., 2020). Pearson correlation analysis (PeCA) was conducted to identify relationships among measured soil properties. Structural equation model (SEM) was established to reveal hypothetical relationships based on the assumption that the spatial variation of soil quality is affected by land-use change with soil types, geographical position, and climatic variables.

3. Results

3.1. Soil properties under tropical rainforests and rubber plantations

Descriptive statistics of the measured soil properties are shown in Table 2. Soil pH was acidic in the investigated rubber plantations and tropical rainforests. Most soil chemical and biological properties of tropical rainforests were significantly higher than those of rubber plantations, such as SOM, TN, TK, NN, AN, AP, AK, RQ, URE, ACP, CAT, SI, and CEL. However, Soil pH, TP, CD, and ACT, increased noticeably with the conversion of natural tropical rainforest to monoculture rubber plantations.

Soil TN, TP, AP, URE, and SI varied significantly between seasons in both

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

rainforests and rubber plantations; the concentration of these properties increased from dry to rainy seasons. These results suggested that seasonal patterns substantially affected the chemical and biological properties of the soil, and thus, the soil quality.

3.2. Soil quality changes from tropical rainforests to rubber plantations

SQI values of the investigated tropical rainforest and rubber plantations on Hainan Island were calculated based on the soil property score and weights (Table 3), ranging from 0.358 to 0.418 for tropical rainforests and from 0.229 to 0.325 for rubber plantations (Fig. 2a). The SQI values of tropical rainforests were significantly higher than rubber plantations ($P < 0.05$), which indicated that the conversion of natural tropical rainforest to monoculture rubber plantations would deteriorate soil quality. For the seasonal difference, the wet season SQI values were significantly higher than those in the dry season under tropical rainforests conditions. At the same time, there were no significant differences for rubber plantations (Fig. 2b), indicating that the soil quality under tropical rainforests was more sensitive to seasonal changes than those under rubber plantations.

To show each soil property and soil functions change by the conversion from tropical rainforests to rubber plantations, a radar diagram was constructed for both the soils under tropical rainforests and rubber plantations (Fig.3), assuming the averaged soils under tropical rainforests as natural soil. Our study found that most soil properties and functions decreased when converting tropical rainforests to rubber plantations. In contrast, soil TP, CD, and ACT increased by 59%, 91%, and 94%, respectively (Fig.3). In addition, the radar diagram indirectly reflects the most

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

sensitive (AK, ACP, CEL, TP, CD, ACT) and resistant (WC, MBC) soil properties by comparing the soils of rubber plantations and tropical rainforests (Fig. 3).

3.3. Important soil properties for soil quality assessment

Important soil properties for SQI values under the tropical rainforests and rubber plantations on Hainan Island were determined based on the absolute factor loading values (≥0.50) of each PC and the norm values (within 10% of the highest values) (Shao et al. 2020). PeCA examined the relationships among these properties to reduce redundancy (Table 4). PCA results showed that the first six components had eigenvalues>1, with values ranging from 1.168 to 5.771, each explaining at least 5.561% of the data variation and accounting for 68.539% of the total variance (Table 3). Thus, the first six components were selected. In PC1, the absolute factor loading values of NN, AK, SOM, pH, TN, URE, ACP, CAT, SI, and CEL were ≥0.50. Among these soil properties, ACP had the highest norm value of 2.08, NN, SOM, TN, and CEL had norm values within 10% of the highest value. As ACP, NN, SOM, TN, and CEL significantly correlated, ACP was selected as the first important soil property. Similarly, the other five components, AK, AP, MBC, CD, URE, and FUN, were also selected.

The accuracy analysis of the selected soil properties for quality assessment, SQI-M (including ACP, AK, AP, MBC, CD, and URE), showed that the SQI-M values significantly correlated with SQI values of the total soil properties (Fig. 4a). From the six soil properties, ACP contributed 26.91% to SQI-M, followed by URE (15.82%), AK (14.18%), MBC (13.58%), and AP (10.01%), FUN and TP had the lowest

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

contribution (9.79% and 9.71%) (Fig.4b).

3.4. Factors influencing soil quality

A structural equation model was established to explain the relationships between the soil quality index and its influential factors (Fig. 5). The influential factors, which may drive variation in soil quality, are related to climate (temperature and precipitation), geographical location (latitude, longitude, and altitude), land-use change, and soil type. Our structural equation model explained 57% of the variation in SQI values for the tropical rainforests and rubber plantations on Hainan Island. The land-use change (from rubber plantations to tropical rainforests) played the most significant positive role in the spatial variation of SQI, followed by the climate. Land-use type, soil type, and geographical position also interacted with each other. Hence, there were some direct and indirect effects of land-use type on the soil quality.

4. Discussion

4.1. Soil properties affected by tropical rainforests converted to rubber plantations

The conversion of tropical rainforests to rubber plantations decreased most soil chemical and biological properties on Hainan Island. Soil nutrient status (SOM, TN, TK, NN, AN, AP, and AK), soil microbial function (RQ), soil microbial quantity (BAC and FUN), and enzyme activities (URE, ACP, CAT, SI, and CEL), generally displayed a net lower level in rubber plantations than in tropical rainforests, which was consistent with many previous studies (Allen et al., 2015; Balasubramanian et al., 2020; Singh et al., 2021).

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

However, four investigated soil properties, i.e, soil pH, TP, CD, and ACT, were demonstrated to increase by converting tropical rainforest to rubber plantations on Hainan Island. The soil pH change of tropical forests to rubber plantations was consistent with the previous studies in Sumatra, Indonesia (Allen et al., 2015; 2016), opposite the earlier study of the Xishuangbanna region of Yunnan Province, China (Liu et al., 2019). The soil TP in rubber plantations was greater than the adjacent native forest on Hainan Island. The greater TP concentrations on rubber plantations could be caused by fertilization and the net transfer of phosphorus from dead vegetables, litter, and decaying roots to soil (Yang et al., 2010a; Wang et al., 2017).

4.2. Soil quality affected by tropical rainforests converted to rubber plantations

Our previous study has found that the comprehensive assessment indices based on fourteen soil physical and chemical properties of rubber plantations were significantly lower than those of tropical rainforests on Hainan Island (Sun et al., 2021). Similarly, as in Xishuangbanna (southwest China) the soil quality index value based on 23 soil physical and chemical properties of the rubber plantation decreased by 15.50%, compared to the primary rainforest (Zou et al., 2021). The previous studies also found that chemical properties contributed more to the soil quality index than the physical properties (Sun et al., 2021; Zou et al., 2021), with the biological properties were rarely considered. Hence, soil chemical and biological properties were the focus of this study. And the results indicated that the soil quality index value of the investigated rubber plantations decreased by 26.48%, compared to the primary rainforests on the tropical island.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Comparing various SQI between studies is complex and partly impossible because of the diverse soil properties and weighting factors (Kuzyakov et al., 2020). Hence, a radar diagram was applied to show each of the soil properties and soil function changes. It was found that most of the soil properties and functions decreased by the conversion of tropical rainforests to rubber plantations on Hainan Island. Taking into account that the soil quality would significantly decrease from high to low plant diversity on rubber plantations (Hemati et al., 2020), interplanting (Liu et al., 2018a, 2019; Chen et al., 2019; Sun et al., 2021; Zou et al., 2021) and natural management (Lan et al., 2017a) were considered as alternative mechanisms to improve soil quality on monoculture rubber plantations.

4.3. Factors influencing soil quality

Land-use change (from rubber plantations to tropical rainforests), interacting with soil type and geographical position, played the most critical positive role on the SQI variation (Fig.5). SQI variation illustrated that soil quality was negatively affected by the conversion of tropical rainforests to rubber plantations. The spatial variation of SQI was significant on both the rubber plantations and tropical rainforests of Hainan Island (Fig. 2a), indicating that spatial variability played an important role in soil quality. Previous studies have been found that spatial variability (e.g., soil depth intervals) surpasses land-use change effects on soil biochemical properties of converted lowland landscape in Sumatra, Indonesia (Allen et al., 2016).

Seasonal changes also played a role in soil quality. According to the SQI values, tropical rainforests in the wet season were significantly higher than those in the dry

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

season. However, there were no significant differences in SQI values for rubber plantations, which can be attributed to the fertilization in dry seasons. Although the effect of seasonal change on the SQI values under rubber plantations was relatively small, it controlled some important soil chemical and biological properties (e.g., TN, TP, AP, URE, and SI) as well as the bacterial communities in soils of rubber plantations in tropical region of Hainan (Lan et al., 2018; 2020).

5. Conclusions

The soil quality of rubber plantations decreased compared to the tropical rainforests on Hainan Island, with soil AK, AP, MBC, CD, ACP, and URE as vital soil properties. However, four investigated soil chemical and biological properties (soil pH, TP, CD, and ACT) increased by the conversion of tropical rainforest to rubber plantations. Except for the land-use change, spatial variability and seasonal changes played essential roles in soil quality, and soil quality under tropical rainforests was more sensitive to seasonal changes than rubber plantations. In this sense, the conversion of tropical rainforest to rubber plantations results in significant changes in soil quality; thus, the tropical rainforest with its high soil quality should be protected.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgments

We would like to acknowledge the financial support of the High-level Talent Project of Hainan Basic and Applied Basic Research Program (Natural Science) (2019RC335; 320RC733), National Natural Science Foundation of China (31770661), Finance Science and Technology Project of Hainan Province (ZDYF2019145), and the Earmarked Fund for China Agriculture Research System (CARS-33-ZP3).

References

Ahrends, A., Hollingsworth, P.M., Ziegler, A.D., Fox, J.M., Chen, H., Su, Y., Xu, J., 2015. Current trends of rubber plantation expansion may threaten biodiversity and livelihoods. Global Environ. Chang. 34, 48–58.

Allen, K., Corre, M.D., Kurniawan, S., Utami, S.R., Veldkamp, E., 2016. Spatial variability surpasses land-use change effects on soil biochemical properties of converted lowland landscapes in Sumatra, Indonesia. Geoderma 284, 42–50.

Allen, K., Corre, M.D., Tjoa, A., Veldkamp, E., 2015. Soil Nitrogen-Cycling Responses to Conversion of Lowland Forests to Oil Palm and Rubber Plantations in Sumatra, Indonesia. Plos One 10(7), e0133325.

Andrews, S., Karlen, D., Cambardella, C., 2004. The soil management assessment framework: a quantitative soil quality evaluation method. Soil Sci. Soc. Am. J. 68(6), 1945–1962.

Andrews, S.S., Carroll, C.R., 2001. Designing a soil quality assessment tool for sustainable agroecosystem management. Ecol. Appl. 11(6), 1573–1585.

Andrews, S.S., Karlen, D.L., Mitchell, J.P., 2002. A comparison of soil quality indexing methods for vegetable production systems in Northern California. Agr. Ecosyst. Environ. 90, 25–45.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Balasubramanian, D., Zhang, Y. P., Grace, J., Sha, L. Q., Jin, Y., Zhou, L.G., Lin, Y. X., Zhou, R. W., Gao, J. B., Song, Q. H., Liu, Y. T., Zhou, W. J., 2020. Soil organic matter as affected by the conversion of natural tropical rainforest to monoculture rubber plantations under acric ferralsols. Catena 195, 104753.

Berkelmann, D., Schneider, D., Engelhaupt, M., Heinemann, M., Christel, S., Wijayanti, M., Meryandini, A., Daniel, R., 2018. How rainforest conversion to agricultural systems in Sumatra (Indonesia) affects active soil bacterial communities. Front. Microbiol. 9, 2381.

Brejda, J.J., Moorman, T.B., Karlen, D.L., Dao, T.H., 2000. Identification of regional soil quality factors and indicators. I. Central and Southern High Plains. Soil Sci. Soc. Am. J. 64, 2115–2124.

Cai, Z., Zhang, Y., Yang, C.,Wang, S., 2018. Land-use type strongly shapes community composition, but not always diversity of soil microbes in tropical China. Catena 165, 369–380.

Chen, B., Li, X., Xiao, X., Zhao, B., Dong, J., Kou, W., Qin, Y., Yang, C., Wu, Z., Sun, R., Lan, G., Xie, G., 2016. Mapping tropical forests and deciduous rubber plantations in Hainan Island, China by integrating PALSAR 25-m and multi-temporal Landsat images. Nt. J. Appl. Earth. Obs. 50, 117-130.

Chen, C., Liu, W., Wu, J., Jiang, X., Zhu, X., 2019. Can intercropping with the cash crop help improve the soil physico-chemical properties of rubber plantations? Geoderma 335, 149–160.

Chen, Y.D., Wang, H.Y., Zhou, J.M., Xing, L., Zhu, B.S., Zhao, Y.C., Chen, X.Q.,

2013. Minimum data set for assessing soil quality in farmland of northeast China. Pedosphere 23, 564–576.

Chiti, T., Grieco, E., Perugini, L., Rey, A., Valentini, R., 2014. Effect of the replacement of tropical forests with tree plantations on soil organic carbon levels in the Jomoro district, Ghana. Plant Soil 375, 47–59.

Davari, M., Gholami, L., Nabiollahi, K., Homaee, M., Jafari, H.J., 2020. Deforestation and cultivation of sparse forest impacts on soil quality (case study: West Iran, Baneh). Soil Tillage Res. 198, 104504.

De Blécourt, M., Hänsel, V.M., Brumme, R., Corre, M.D., Veldkamp, E., 2014. Soil redistribution by terracing alleviates soil organic carbon losses caused by forest conversion to rubber plantation. Forest Ecol. Manag. 313, 26–33.

Deng, Y.S., Xia, D., Cai, C.F., Ding S.W., 2016. Effects of land uses on soil physic-chemical properties and erodibility in collapsing-gully alluvial fan of Anxi County, China. J. Integr. Agr. 15, 1863–1873.

Derakhshan-Babaei, F., Nosrati, K., Mirghaed, F.A., Egli, M., 2021. The interrelation between landform, land-use, erosion and soil quality in the Kan catchment of the Tehran province, central Iran. Catena, 204, 105412.

Ditzler, C.A., Tugel, A.J., 2002. Soil quality field tools: experiences of USDA-NRCS Soil Quality Institute. Agron. J. 94 (1), 33–38.

Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., et al. (Eds.), Soil Science Society of America Book Series no. 35(special publication), pp. 3–21.

Food and Agriculture Organization (FAO), 2017. FAOSTAT http://faostat3.fao.org/faostatgateway/go/to/home/E, Accessed date: 26 February 2017.

Gil-Sotres, F., Trasar-Cepeda, C., Leir´os, M., Seoane, S., 2005. Different approaches to evaluating soil quality using biochemical properties. Soil Biol. Biochem. 37 (5), 877–887.

Goldberg, S.D., Zhao, Y., Harrison, R.D., Monkai, J., Li, Y., Chau, K., Xu, J., 2017. Soil respiration in sloping rubber plantations and tropical natural forests in Xishuangbanna, China. Agric. Ecosyst. Environ. 249, 237–246.

Griffiths, B., Ball, B., Daniell, T., Hallett, P., Neilson, R., Wheatley, R., Osler, G., Bohanec, M., 2010. Integrating soil quality changes to arable agricultural systems following organic matter addition, or adoption of a ley-arable rotation. Appl. Soil Ecol. 46 (1), 43–53.

Guan, S.Y., 1986. Study Way of Soil Enzymes. Agriculture press, Beijing. Reference to a chapter in an edited book: Chapter 12.

Guillaume, T., Damris, M., Kuzyakov, Y., 2015. Losses of soil carbon by converting tropical forest to plantations: erosion and decomposition estimated by $\delta^{13}C$. Glob. Change Biol. 21, 3548–3560.

Guillaume, T., Kotowska, M.M., Hertel, D., Knohl, A., Krashevska, V., Murtilaksono, K., Scheu, S., Kuzyakov, Y., 2018. Carbon costs and benefits of Indonesian rainforest conversion to plantations. Nat. Commun. 9, 2388.

Hassler, E., Corre, M.D., Kurniawan, S., Veldkamp, E., 2017. Soil nitrogen oxide fluxes from lowland forests converted to smallholder rubber and oil palm

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

plantations in Sumatra, Indonesia. Biogeosciences 14, 2781–2798.

Hemati, Z., Selvalakshmi, S., Xia, S., Yang, X., 2020. Identification of indicators: Monitoring the impacts of rubber plantations on soil quality in Xishuangbanna, Southwest China. Ecol. Indic. 116, 106491.

Imaz, M.J., Virto, I., Bescansa, P., Enrique, A., Fernandez-Ugalde, O., Karlen, D.L., 2010. Soil quality indicator response to tillage and residue management on semi-arid Mediterranean cropland. Soil Tillage Res. 107, 17–25.

Institute of Soil Science, Chinese Academy of Sciences, 1978. Soil physical and chemical analysis. Shanghai Science and Technology Press.

Jahany, M., Rezapour, S., 2020. Assessment of the quality indices of soils irrigated with treated wastewater in a calcareous semi-arid environment. Ecol. Indic. 109, 105800.

Jin, H.F., Shi, D.M., Lou, Y.B., Zhang, J.L., Ye, Q., Jiang, N., 2021. Evaluation of the quality of cultivated-layer soil based on different degrees of erosion in sloping farmland with purple soil in China. Catena 198, 105048.

Karlen, D.L., Ditzler, C.A., Andrews, S.S., 2003. Soil quality: why and how? Geoderma 114 (3-4), 145–156.

Kerfahi, D., Tripathi, B.M., Dong, K., Go, R., Adams, J.M., 2016. Rainforest conversion to rubber plantation may not result in lower soil diversity of bacteria, fungi, and nematodes. Microb. Ecol. 72, 359-371.

Krashevska, V., Klarner, B., Widyastuti, R., Maraun, M., Scheu, S., 2015. Impact of tropical lowland rainforest conversion into rubber and oil palm plantations on

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

soil microbial communities. Biol. Fertil. Soils 51, 697–705.

Krashevska, V., Kudrin, A.A., Widyastuti, R., Scheu, S., 2019. Changes in nematode communities and functional diversity with the conversion of rainforest into rubber and oil palm plantations. Front. Ecol. Evol. 7.

Kuzyakov, Y., Gunina, A., Zamanian, K., Tian, J., Luo, Y., Xu, X., Yudina, A., Aponte, H., Alharbi, H., Ovsepyan, L., Kurganova, I., Ge, T., Guillaume, T., 2020. New approaches for evaluation of soil health, sensitivity and resistance to degradation. Front. Agr. Sci. Eng. 7(3): 282–288.

Lal, R., 1998. Soil quality and agricultural sustainability. Ann Arbor press, Chelsea, Michigan.

Lan, G., Li, Y., Jatoi,M.T., Tan, Z.,Wu, Z., Xie, G., 2017a. Change in soil microbial community compositions and diversity following the conversion of tropical forest to rubber plantations in Xishuangbanna, Southwest China. Trop. Conserv. Sci. 10.

Lan, G., Li, Y., Wu, Z., Xie, G., 2017b. Impact of tropical forest conversion on soil bacterial diversity in tropical region of China. Eur. J. Soil. Biol. 83, 91–97.

Lan, G., Wu, Z., Li, Y., Chen, B., 2020. The drivers of soil bacterial communities in rubber plantation at local and geographic scales. Arch. Agron. Soil Sci. 66 (3), 258–369.

Lan, G., Wu, Z., Yang, C., Sun, R., Chen, B., Zhang, X., 2020 .Tropical rainforest conversion into rubber plantations results in changes in soil fungal composition, but underling mechanisms of community assembly remain unchanged. Geoderma, 375, 114505.

Lan, G.Y., Li, Y.W., Lesueur, D., Wu, Z.X., Xie, G.S., 2018. Seasonal changes impact soil bacterial communities in a rubber plantation on Hainan Island, China. Sci. Total Environ. 626c, 826–834.

Lang, R., Blagodatsky, S., Xu, J., Cadisch, G., 2017. Seasonal differences in soil respiration and methane uptake in rubber plantation and rainforest. Agr. Ecosyst. Environ. 240, 314–328.

Li, P., Wu, M. C., Kang G. D., Zhu, B. J., Li, H. X., Hu, F., Jiao, J. G., 2020. Soil quality response to organic amendments on dryland red soil in subtropical China, Geoderma, 373, 114416,

Liu, C., Liang, M., Nie, Y., Tang, J., Siddique, K.H.M., 2019. The conversion of tropical forests to rubber plantations accelerates soil acidification and changes the distribution of soil metal ions in topsoil layers. Sci. Total Environ. 696, 134082.

Liu, C., Nie, Y., Rao, X., Tang, J., Siddique, K.H.M., 2019. The effects of introducing Flemingia macrophylla to rubber plantations on soil water content and exchangeable cations. Catena 172, 480–487.

Liu, C., Nie, Y., Zhang, Y., Tang, J., Siddique, K.H.M., 2018a. Introduction of a leguminous shrub to a rubber plantation changed the soil carbon and nitrogen fractions and ameliorated soil environments. Sci. Rep.-U.K. 8, 17324.

Liu, D., Huang Y.M., An S.S., Sun H.Y., Bhople P., Chen Z.W., 2018. Soil physicochemical and microbial characteristics of contrasting land-use types along soil depth gradients. Catena 162, 345–353.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Mandal, U.K., Warrington, D.N., Bhardwaj, A.K., Bartal, A., Kautsky, L., Minz, D., Levy, G.J., 2008. Evaluating impact of irrigation water quality on a calcareous clay soil using principal component analysis. Geoderma 144, 189–197.

Maranguit, D., Guillaume, T., Kuzyakov, Y., 2017. Land-use change affects phosphorus fractions in highly weathered tropical soils. Catena 149, 385-393.

Marzaioli, R., D'Ascoli, R., De Pascale, R., Rutigliano, F.A., 2010. Soil quality in a Mediterranean area of Southern Italy as related to different land-use types. Appl. Soil Ecol. 44 (3), 205–212.

Masto, R.E., Chhonkar, P.K., Singh, D., Patra, A.K., 2008. Alternative soil quality indices for evaluating the effect of intensive cropping, fertilisation and manuring for 31 years in the semi-arid soils of India. Environ. Monit. Assess. 136 (1–3), 419–435.

Moges, A., Dagnachew, M., Yimer, F., 2013. Land use effects on soil quality indicators: a case study of Abo-Wonsho Southern Ethiopia. Appl. Environ. Soil Sci. 2013, 784989.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853–858.

Nabiollahi, K., Golmohamadi, F., Taghizadeh-Mehrjardi, R., Kerry, R., Davari, M., 2018. Assessing the effects of slope gradient and land-use change on soil quality degradation through digital mapping of soil quality indices and soil loss rate. Geoderma 318, 16–28.

Nabiollahi, K., Taghizadeh-Mehrjardi, R., Kerry, R., Moradian, S., 2017. Assessment

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

of soil quality indices for salt-affected agricultural land in Kurdistan Province, Iran. Ecol. Indicators 83, 482–494.

Nakajima, T., Lal, R., Jiang, S., 2015. Soil quality index of a crosby silt loam in central Ohio. Soil Tillage Res. 146, 323–328.

Ngo-Mbogba, M., Yemefack, M., Nyeck, B., 2015. Assessing soil quality under different land cover types within shifting agriculture in South Cameroon. Soil Tillage Res. 150, 124–131.

Nosrati, K., Collins, A.L., 2019. A soil quality index for evaluation of degradation under land-use and soil erosion categories in a small mountainous catchment, Iran. J. Mountain Sci. 16 (11), 2577–2590.

Nosrati, K., Feiznia, S., Van Den Eeckhaut, M., Duiker, S.W., 2011. Assessment of soil erodibility in Taleghan Drainage Basin, Iran, using multivariate statistics. Phys. Geogr. 32 (1), 78–96.

Pham, T.G., Nguyen, H.T., Kappas, M., 2018. Assessment of soil quality indicators under different agricultural land-uses and topographic aspects in Central Vietnam. Int. Soil Water Conserv. Res. 6 (4), 280–288.

Qi, Y., Darilek, J.L., Huang, B., Zhao, Y., Sun, W., Gu, Z., 2009. Evaluating soil quality indices in an agricultural region of Jiangsu Province, China. Geoderma 149 (3–4), 325–334.

Qiu, J., 2009. Where the rubber meets the garden. Nature 457, 246–247.

Raiesi, F., 2017. A minimum data set and soil quality index to quantify the effect of land-use conversion on soil quality and degradation in native rangelands of upland arid and semiarid regions. Ecol. Indic. 75, 307–320.

Ross, D.J., 1990. Measurements of microbial biomass c and n in grassland soils by fumigation-incubation procedures: influence of inoculum size and the control. Soil Biol. Biochem. 22, 289–294.

Shao, G. D., Ai, J. J., Sun Q. W., Hou, L. Y., Dong, Y. F., 2020. Soil quality assessment under different forest types in the Mount Tai, central Eastern China, Ecol. Indic. 115, 106439.

Singh, A. K., Liu, W., Zakari, S., Wu. J., Yang, Bin., Jiang, X., Zhu, X., Zou, X., Zhang, W., Chen, C., Singh, R., Nath, A. J., 2021. A global review of rubber plantations: Impacts on ecosystem functions, mitigations, future directions, and policies for sustainable cultivation. Sci. Total Environ. 796, 148948.

Soil Science Society of China, 2000. Methods of soil agricultural chemical analysis. Beijing: China agricultural science and technology press.

Statistical Bureau of Hainan Province, 2019. Hainan Statistical Yearbook. China Statistics Press, (in Chinese with English abstract).

Sun, R., Wu, Z., Chen, B., Lan, G., Qi, D., 2017. Change Features of Precipitation Events in Hainan Island from 1959 to 2013. Chin. J. Trop. Crops 38, 2176–2182.

Sun, R., Wu, Z., Chen, B., Qi, D., Yang, C., 2016. Spatio-temporal patterns of climatic changes in Hainan Island in recent 55 years. Journal of Meteorological Research and Application 37, 1–7.

Sun, R., Wu, Z., Chen, B., Yang, C., Qi, D., Lan, G., Fraedrich, K., 2020. Effects of land-use change on eco-environmental quality in Hainan Island, China. Ecol.

Indic. 109, 105777.
Sun, R., Wu, Z., Lan, G., Yang, C., Fraedrich, K., 2021. Effects of rubber plantations on soil physicochemical properties on Hainan Island, China. J. Environ. Qual. https://doi.org/10.1002/jeq2.20282.
Tan, Z., Zhang, Y., Song, Q., Liu, W., Deng, X., Tang, J., Deng, Y., Zhou, W., Yang, L., Yu, G., Sun X., Liang N., 2011. Rubber plantations act as water pumps in tropical China. Geophys. Res. Lett. 38, L24406.
Torbert, H., Krueger, E., Kurtener, D., 2008. Soil quality assessment using fuzzy modeling. Int. Agrophys. 22 (4), 365–370.
Vityakon, P., 2007. Degradation and restoration of sandy soils under different agricultural land uses in northeast Thailand: a review. Land Degrad. Dev. 18 (5), 567–577.
Wang, H., Zhang, G.H., Li, N.N., Zhang, B.J., Yang, H.Y., 2019. Variation in soil erodibility under five typical land uses in a small watershed on the Loess Plateau, China. Catena 174, 24–35.
Wang, J., Ren, C., Cheng, H., Zou, Y., Bughio, M.A., Li, Q., 2017. Conversion of rainforest into agroforestry and monoculture plantation in China: consequences for soil phosphorus forms and microbial community. Sci. Total Environ. 595, 769-778.
Warren-Thomas, E., Dolman, P.M., Edwards, D.P., 2015. Increasing demand for natural rubber necessitates a robust sustainability initiative to mitigate impacts on tropical biodiversity. Conserv. Lett. 8, 230–241.
Wikramanayake, E.D., Dinerstein, E., Louks, C.J., Olson, D.M., Morrison, J.,

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Lamoreux, J., McKnight, M., Hedao, P., 2002. Terrestrial Ecoregions of the Indo-Pacific: A Conservation Assessment. Island Press, Washington, District of Columbia and Covelo, California.

Wu, J., 2008. The Contribution of Different Synoptic Systems to the Precipitation and Its Change over Hainan Island (Dissertation). Lanzhou University.

Xu, G.H., Zheng, H.Y., 1986. Manual of methods for soil microbial analysis. Beijing: Agriculture press. 227-243.

Xue, Y.J., Liu, S.G., Hu, Y.M., Yang, J.F., 2010. Soil quality assessment using weighted fuzzy association rules. Pedosphere 20 (3), 334–341.

Yakovchenko, V., Sikora, L.J., Kaufman, D.D., 1996. A biologically based indicator of soil quality. Biol. Fertil. Soils 21 (4), 245–251.

Yang, K., Zhu, J.-J., Yan, Q.-L., Sun, O.J., 2010a. Changes in soil P chemistry as affected by conversion of natural secondary forests to larch plantations. For. Ecol. Manag. 260, 422–428.

Yang, Q.Y., Yang, J.S., Yao, R.J., Huang, B., Sun, W.X., 2010. Comprehensive evaluation of soil fertility by GIS and improved grey relation model. Trans. Chinese Soc. Agri. Eng. 24, 53–56.

Yemefack, M., Jetten, V.G., Rossiter, D.G., 2006. Developing a minimum data set for characterizing soil dynamics in shifting cultivation systems. Soil Tillage Res. 86 (1), 84–98.

Yu, P.J., Han, D.L., Liu, S.W., Wen, X., Huang, Y.X., Jia, H.T., 2018. Soil quality assessment under different land uses in an alpine grassland. Catena 171, 280–287.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Biogeosciences Discussions

Yue-Ju, X., Shu-Guang, L., Yue-Ming, H., Jing-Feng, Y., 2010. Soil quality assessment using weighted fuzzy association rules. Pedosphere 20 (3), 334–341.

Zhai, D., Cannon, C.H., Slik, J.W.F., Zhang, C., Dai, Z., 2012. Rubber and pulp plantations represent a double threat to Hainan's natural tropical forests. J. Environ. Manage. 96, 64–73.

Zhai, D., Xu, J., Dai, Z., Cannon, C. H., Grumbine, R. E., 2014. Increasing tree cover while losing diverse natural forests in tropical Hainan, China. Reg. Environ. Change 14, 611–621.

Zhang, G.L., Bai, J.H., Xi, M., Zhao, Q.Q., Lu, Q.Q., Jia, J., 2016. Soil quality assessment of coastal wetlands in the Yellow River Delta of China based on the minimum data set. Ecol. Indic. 66, 458–466.

Zhang, J.L., Zhou, L.L., Ma, R.M., Jia, Y.F., Yang, F., Zhou, H.Y., Cao, X.Y., 2019. Influence of soil moisture content and soil and water conservation measures on time to runoff initiation under different rainfall intensities. Catena 182, 104172.

Zhang, Y.H., Xu, X.L., Li, Z.W., Liu, M.X., Xu, C.H., Zhang, R.F., Luo, W., 2019. Effects of vegetation restoration on soil quality in degraded karst landscapes of southwest China. Sci. Total Environ. 650, 2657–2665.

Zhang, Z., Ai, N., Liu, G., Liu, C., Qiang, F., 2021. Soil quality evaluation of various microtopography types at different restoration modes in the loess area of Northern Shaanxi. Catena 207, 105633.

Zhao, Y. li, Goldberg, S.D., Xu, J. chu, Harrison, R.D., 2018. Spatial and seasonal variation in soil respiration along a slope in a rubber plantation and a natural

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

forest in Xishuangbanna, Southwest China. J. Mt. Sci. 15, 695-707.

Ziegler, A. D., Fox, J. M., Xu, J., 2009. The rubber juggernaut. Science 324, 1024–1025.

Zou, X., Zhu, X., Zhu, P., Singh, A. K., Zakari, S., Yang, B., Chen, C., Liu, W., 2021. Soil quality assessment of different *Hevea brasiliensis* plantations in tropical China, J. Environ. Manage. 285, 112147.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

List of Figures

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Biogeosciences
Discussions
Open Access

decomposition; UR, urease; ACP, acid phosphatase; FUN, fungi.

Fig.5 Structural equation model (SEM) analysis of the effects of land-use changes, soil types, climatic variables, and geographic position on the soil quality index (SQI). Red arrows indicate negative effects and green arrows represent positive effects. Numbers adjacent to arrows are path coefficients (*p* values) indicating the effect size of the relationship, and *p* values are as follows: **p* <0.05; ***p* <0.01; ****p* <0.001. CFI: Comparative Fit Index; RMSEA: Root Mean Square Error of Approximation.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Biogeosciences
Discussions

List of Tables

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Biogeosciences Discussions
Open Access
EGU

Table 1 Site characteristics for tropical rainforests and rubber plantations.

Site name	Longitude (°)	Latitude (°)	Elevation (m)	Forest type	Soil type	Precipitation (mm)	Temperature (℃)
Danzhou (DZ)	109.58	19.56	112	Rubber plantation	Laterite	1831.5	23.6
Qiongzhong (QZ)	109.74	19.26	156	Rubber plantation	Lateritic red soil	2067.3	23.5
Ledong (LD)	109.22	18.75	170	Rubber plantation	Laterite	1661.3	24.5
Wanning (WN)	110.13	18.67	51	Rubber plantation	Laterite	1786.5	24.7
Haikou (HK)	110.57	19.70	102	Rubber plantation	Laterite	1863.4	24.2
Diaoluo (DL)	109.86	18.73	958	Rainforest	Red soil	1921.3	24.2
Jianfeng (JF)	108.88	18.73	950	Rainforest	Yellow soil	1392.3	24.7
Bawang (BW)	109.13	19.08	575	Rainforest	Red soil	1602.1	24.3
Yingge (YG)	109.56	19.05	620	Rainforest	Red soil	2067.8	23.6
Wuzhi (WZ)	109.68	18.91	820	Rainforest	Yellow soil	2173.8	23.4

Notes: Soil type data was 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). The precipitation and temperature data of each site was obtained from the results of a reference (Sun et al. 2016).

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Biogeosciences Discussions
Open Access
EGU

Table 2 Soil properties under tropical rainforests and rubber plantations on Hainan Island.

Soil properties		Rubber plantation			Tropical rainforest		
		Dry season	Wet season	Annual	Dry season	Wet season	Annual
WC	%	32.08±9.23a	28.17±9.65a	30.13±9.61A	31.08±11.13a	32.17±8.29a	31.63±9.79A
AN	mg/kg	12.28±5.03a	12.49±6.92a	12.39±6.03A	14.18±4.03ab	16.45±6.46b	15.31±5.49B
NN	mg/kg	7.35±3.79a	6.53±3.17a	6.94±3.50A	10.34±3.93b	15.69±7.86c	13.01±6.75B
AP	mg/kg	2.62±0.95a	3.92±2.61b	3.27±2.06A	1.79±0.48ab	7.1±6.13c	4.45±5.09B
AK	mg/kg	27.12±13.05a	31.63±17.15a	29.37±15.35A	72.23±36.82b	84.92±41.64b	78.58±39.67B
SOM	%	1.48±0.86a	1.65±0.89a	1.56±0.88A	2.68±0.95b	3.06±0.67b	2.87±0.84B
pH		4.71±0.34ab	4.87±0.51b	4.79±0.44A	4.6±0.33a	4.59±0.76a	4.59±0.59B
TN	g/kg	0.94±0.39a	1.62±0.69c	1.28±0.65A	1.34±0.34b	2.82±0.74d	2.07±0.94B
TP	(P_2O_5)%	0.06±0.04b	0.07±0.04c	0.06±0.04A	0.03±0.01a	0.05±0.04b	0.04±0.03B
TK	(K_2O)%	1.18±1.09a	1.47±1.15ab	1.33±1.12A	1.73±0.74b	1.41±0.79ab	1.57±0.78B
MBC	mg/kg	0.07±0.02b	0.04±0.05a	0.05±0.04A	0.04±0.04a	0.05±0.06ab	0.05±0.05A
RQ	mg/kg	115.91±67.15a	118.31±83.11a	117.11±75.27A	218.98±75.95b	117.28±53.48a	168.13±82.99B
CD	%	0.66±0.38bc	0.68±0.43c	0.67±0.41A	0.51±0.36b	0.19±0.09a	0.35±0.31B
UR	mg/kg	46.28±32.52a	71.95±37.19b	59.11±37.11A	62.16±25.66ab	109.7±52.83c	85.93±47.46B
ACP	mg/kg	1522.2±543.98b	1007.04±513.99a	1264.62±587.14A	3424.72±464.48c	3264.83±982.59c	3344.77±769.72B
CAT	ml/g	0.69±0.31b	0.46±0.29a	0.57±0.32A	1.09±0.45c	0.94±0.26c	1.01±0.37B
SI	mg/kg	2714.24±1648.49a	4398.23±1768.33b	3556.23±1901.06A	5956.87±2971.49c	8156.99±4850.99d	7056.93±4156.32B
CEL	mg/kg	20.15±19.15a	26.05±6.97a	23.1±14.66A	58.53±25.65c	44.97±19.65b	51.75±23.75B
BAC	10^6/g	1.31±3.01a	2.97±7.23ab	2.14±5.58A	2.00±2.21ab	4.73±11.27b	3.36±8.20A
FUN	10^4/g	0.82±1.34a	0.71±0.90a	0.76±1.14A	1.27±1.93a	0.92±1.45a	1.09±1.71A
ACT	10^5/g	0.49±1.25ab	0.92±1.75b	0.71±1.53A	0.55±1.27ab	0.18±0.28a	0.37±0.94B

Notes: Different lower-case (or upper-case) letters indicate significant difference at $P < 0.05$ (one-way ANOVA). The measured soil properties are: WC, soil water content; SOM, soil organic matter; TN, total nitrogen; NN, nitrate nitrogen; AN, ammonium nitrogen; TP, total phosphorus; AP, available phosphorus; TK, total potassium; AK, available potassium; MBC, microbial biomass carbon; RQ, microbial respiratory quotient; CD, cellulose decomposition; NF, nitrogen fixation; UR, urease; ACP, acid phosphatase; CAT, catalase; CEL, cellulose ; SI, sucrose invertase; BAC, bacteria; FUN, fungi; ACT, actinomyces.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Table 3 Results of principal component analysis and weight values of each soil property.

Soil properties	PC1	PC2	PC3	PC4	PC5	PC6	Norm	Communalities	Weight1	Weight2
WC	0.457	-0.562	0.011	0.383	-0.030	0.228	1.539	0.725	0.050	
AN	0.395	0.482	0.257	0.462	-0.017	-0.229	1.430	0.721	0.050	
NN	**0.726**	-0.269	0.205	-0.170	-0.381	-0.074	1.888	0.821	0.057	
AP	0.237	0.160	**0.653**[a]	-0.134	-0.514	0.268	1.293	0.862	0.060	0.160
AK	0.550	**0.631**[a]	-0.043	-0.134	0.119	-0.189	1.722	0.771	0.054	0.161
SOM	**0.838**	-0.080	0.013	0.101	0.247	0.101	2.044	0.791	0.055	
PH	-0.496	0.484	0.266	0.079	0.206	0.365	1.563	0.733	0.051	
TN	**0.777**	-0.071	0.487	-0.115	0.017	-0.006	1.994	0.859	0.060	
TP	0.102	-0.476	0.427	0.208	0.446	-0.084	1.176	0.668	0.046	
TK	-0.244	0.789	-0.014	-0.089	0.024	0.134	1.464	0.708	0.049	
MBC	0.051	0.371	0.291	**0.617**[a]	-0.275	0.015	1.092	0.681	0.047	0.158
RQ	0.251	0.129	-0.610	0.238	-0.132	0.293	1.153	0.611	0.042	
CD	-0.358	-0.158	-0.028	**0.501**[a]	0.138	-0.052	1.089	0.426	0.030	0.083
UR	0.650	0.092	0.211	-0.055	**0.502**[a]	-0.276	1.723	0.806	0.056	0.120
ACP	**0.830**[a]	0.275	-0.269	-0.078	0.040	-0.008	2.084	0.845	0.059	0.162
CAT	0.619	0.221	-0.349	0.097	0.161	0.346	1.664	0.708	0.049	
SI	0.733	0.083	0.004	-0.135	-0.146	0.069	1.783	0.589	0.041	
CEL	**0.793**	-0.018	-0.271	0.173	-0.053	0.069	1.955	0.740	0.051	
BAC	-0.006	0.250	0.168	-0.284	0.360	0.298	0.786	0.390	0.027	
FUN	0.019	0.275	-0.255	0.007	-0.178	**-0.629**[a]	0.920	0.568	0.039	0.156
ACT	-0.208	0.490	0.206	0.189	0.059	-0.053	1.035	0.368	0.026	
Eigenvalue	5.771	2.838	1.931	1.377	1.308	1.168				
% of Variance	27.481	13.514	9.196	6.556	6.231	5.561				
Cumulative %	27.481	40.995	50.191	56.747	62.978	68.539				

Notes: Bold font values are considered highly weighted. [a] Values are the most important properties for the results of SQI-M. Weight 1 refers to total data set; Weight 2 refers to the important properties data set. The measured soil properties are: WC, soil water content; SOM, soil organic matter; TN, total nitrogen; NN, nitrate nitrogen; AN, ammonium nitrogen; TP, total phosphorus; AP, available phosphorus; TK, total potassium; AK, available potassium; MBC, microbial biomass carbon; RQ, microbial respiratory quotient; CD, cellulose decomposition; NF, nitrogen fixation; UR, urease; ACP, acid phosphatase; CAT, catalase; CEL, cellulose ; SI, sucrose invertase; BAC, bacteria; FUN, fungi; ACT, actinomyces.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Table 4 Correlation coefficients among the soil properties.

	WC	AN	NN	AP	AK	SOM	pH	TN	TP	TK	MBC	RQ	CD	UR	ACP	CAT	SI	CEL	BAC	FUN	ACT
WC	1	0.00	0.37**	0.02	-0.17**	0.51**	-0.35**	0.37**	0.26**	-0.51**	0.07	0.12	0.06	0.15*	0.22**	0.22**	0.25**	0.37**	-0.15*	-0.19**	-0.30**
AN		1	0.16**	0.19**	0.45**	0.28**	0.03	0.30**	0.00	0.13*	0.49**	0.05	-0.07	0.35**	0.34**	0.22**	0.18**	0.32**	0.02	0.12*	0.19**
NN			1	0.44**	0.20**	0.50**	-0.56**	0.66**	0.12	-0.37**	-0.04	0.03	-0.27**	0.30**	0.52**	0.22**	0.52**	0.52**	-0.09	-0.01	-0.22**
AP				1	0.13*	0.08	0.14*	0.49**	0.01	0.10	0.23**	-0.14*	-0.19**	0.00	0.02	-0.01	0.27**	0.08	0.07	-0.10	0.08
AK					1	0.39**	-0.07	0.38**	-0.23**	0.38**	0.12	0.15*	-0.27**	0.50**	0.67**	0.37**	0.41**	0.34**	0.07	0.16**	0.12
SOM						1	-0.26**	0.67**	0.21**	-0.26**	-0.01	0.17**	-0.21**	0.56**	0.68**	0.53**	0.53**	0.66**	0.02	-0.04	-0.17**
pH							1	-0.26**	-0.07	0.50**	0.14*	-0.16*	0.11	-0.26**	-0.34**	-0.06	-0.34**	-0.47**	0.19**	-0.03	0.36**
TN								1	0.29**	-0.20**	0.06	-0.05	-0.30**	0.63**	0.48**	0.24**	0.59**	0.43**	0.05	-0.08	-0.14*
TP									1	-0.38**	-0.07	-0.16*	0.08	0.28**	-0.19**	-0.07	-0.08	0.05	-0.04	-0.17**	-0.42
TK										1	0.17**	0.08	0.01	-0.08	0.00	-0.00	-0.09	-0.19**	0.14*	0.08	0.32**
MBC											1	0.04	0.04	0.02	0.04	0.04	-0.01	0.01	0.02	0.06	0.15*
RQ												1	-0.05	-0.06	0.31**	0.36**	0.17**	0.40**	-0.04	0.09	-0.06
CD													1	-0.17**	-0.33**	-0.25**	-0.20**	-0.18**	-0.08	-0.05	0.08
UR														1	0.49**	0.32**	0.41**	0.37**	0.12	-0.00	-0.09
ACP															1	0.64**	0.59**	0.66**	0.07	0.13*	-0.09
CAT																1	0.45**	0.61**	0.03	-0.00	-0.08
SI																	1	0.52**	-0.01	0.02	-0.04
CEL																		1	-0.07	0.06	-0.13*
BAC																			1	-0.04	0.06
FUN																				1	0.09
ACT																					1

Notes: * $P < 0.05$, ** $P < 0.01$. The measured soil properties are: WC, soil water content; SOM, soil organic matter; TN, total nitrogen; NN, nitrate nitrogen; AN, ammonium nitrogen; TP, total phosphorus; AP, available phosphorus; TK, total potassium; AK, available potassium; MBC, microbial biomass carbon; RQ, microbial respiratory quotient; CD, cellulose decomposition; NF, nitrogen fixation; UR, urease; ACP, acid phosphatase; CAT, catalase; CEL, cellulose ; SI, sucrose invertase; BAC, bacteria; FUN, fungi; ACT, actinomyces.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

Biogeosciences
Discussions
Open Access

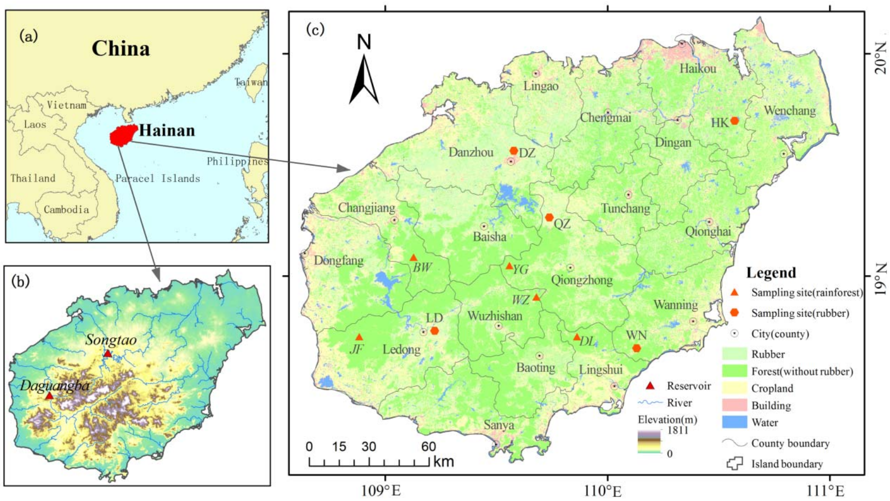

Fig.1 Maps of the geographic position, topography, and soil sampling sites of Hainan Island, China: (a) location of Hainan Island (red); (b) topography and drainage of Hainan Island; (c) spatial distribution of soil sampling sites in tropical rainforests and rubber plantations.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

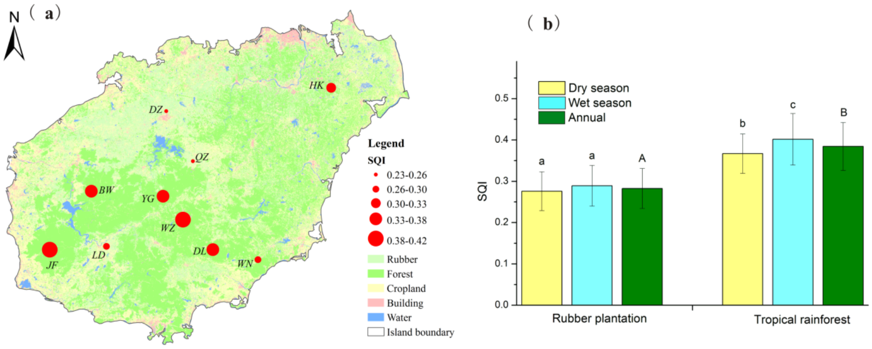

Fig. 2 Soil quality index (SQI) values under rubber plantations and tropical rainforests on Hainan Island: (a) spatial distribution; (b) temporal variation. Different lower-case (or upper-case) letters indicate significant difference at $P < 0.05$ between the seasonal (or annual) SQI values of rubber plantations and tropical rainforests.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

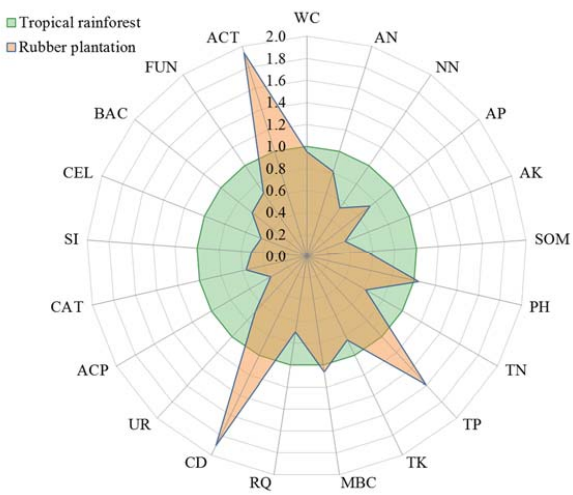

Fig.3 Radar diagram for soil properties changing by the conversion from tropical rainforests to rubber plantations on Hainan Island. The measured soil properties are: WC, soil water content; SOM, soil organic matter; PH, soil pH; TN, total nitrogen; NN, nitrate nitrogen; AN, ammonium nitrogen; TP, total phosphorus; AP, available phosphorus; TK, total potassium; AK, available potassium; MBC, microbial biomass carbon; RQ, microbial respiratory quotient; CD, cellulose decomposition; NF, nitrogen fixation; UR, urease; ACP, acid phosphatase; CAT, catalase; CEL, cellulose ; SI, sucrose invertase; BAC, bacteria; FUN, fungi; ACT, actinomyces.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

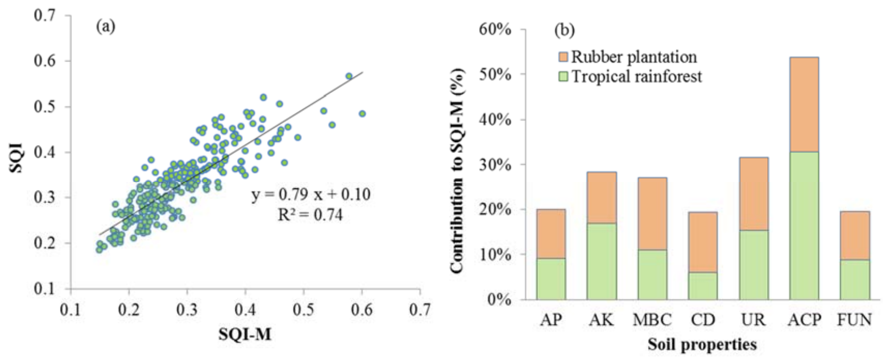

Fig.4 (a) Scatter diagram and linear relationships between SQI-M and SQI values (n = 260) and (b) individual contributions of soil properties to the soil quality indicator SQI-M based on the seven important properties (SQI is the soil quality indicator based on the total soil properties). The measured soil properties are: AP, available phosphorus; AK, available potassium; MBC, microbial biomass carbon; CD, cellulose decomposition; UR, urease; ACP, acid phosphatase; FUN, fungi.

https://doi.org/10.5194/bg-2021-303
Preprint. Discussion started: 8 December 2021

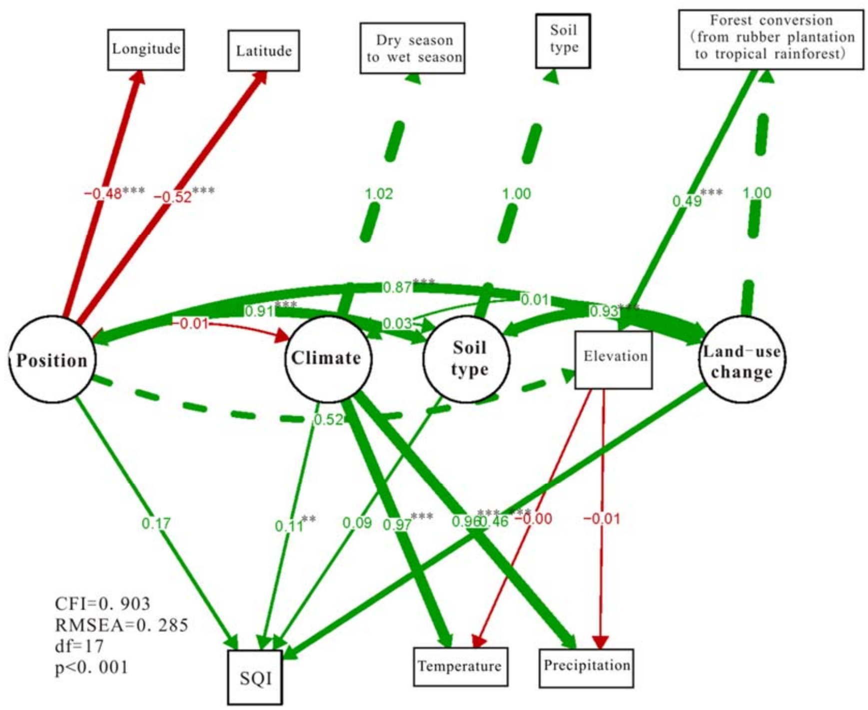

Fig.5 Structural equation model (SEM) analysis of the effects of land-use changes, soil types, climatic variables, and geographic position on the soil quality index (SQI). Red arrows indicate negative effects and green arrows represent positive effects. Numbers adjacent to arrows are path coefficients (*p* values) indicating the effect size of the relationship, and *p* values are as follows: *p <0.05; **p <0.01; ***p <0.001. CFI: Comparative Fit Index; RMSEA: Root Mean Square Error of Approximation.