The stability of soil organic carbon across topographies in a tropical rainforest

Yamin Jiang [1] , **Huai Yang** [2, 3] , **Qiu Yang** [1] , **Wenjie Liu** [Corresp., 1, 4] , **Zhaolei Li** [1, 4] , **Wei Mao** [1] , **Xu Wang** [1] , **Zhenghong Tan** [1]

[1] Hainan University, College of Ecology and Environment, Haikou, China

[2] International Center for Bamboo and Rattan, BeiJing, China

[3] Chinese Academy of Forestry, Jianfengling National Key Field Research Station for Tropical Forest Ecosystem, Research Institute of Tropical Forestry, Hainan, China

[4] Northern Arizona University, Center for Ecosystem Science and Society, Flagstaff, USA

Corresponding Author: Wenjie Liu
Email address: liuwj@hainanu.edu.cn

Mechanisms of soil organic carbon (SOC) stability are still unclear in forests ecosystems. In order to unveil the influences of topography on the SOC stability, the 60ha dynamic plot of a tropical montane rainforest were selected in Jianfengling, in Hainan Island, and soil was sampled from 60 quadrats. The chemical fractions of SOC were detected with 13C CPMAS/NMR and path analyses were used to explore the mechanisms of SOC stability in the two local topographies (flat areas and steep areas). The chemical fractions of SOC showed alkyl carbon > O-alkyl carbon > carboxyl carbon > aromatic carbon. The decomposition index (DI) values were greater than 1 in different topographies and the averaged DI value was 1.29, which indicated that the SOC in the study area were stable. The influencing factors of SOC stability varied in topographies, where SOC, soil moisture (SM), ammoniacal nitrogen (NH_4^+-N, AN) were the main influencing factors in the relative flat areas (RF), as well as SM and AN were the main factors in the relative steep areas (RS). More SOC and AN strengthened the SOC stabilization, while higher soil moisture lowered SOC stability. Inertia index (II) also higher in RS than that in RF, indicating that local topography significantly affects SOC content and SOC stability through changing soil environment factors. Topography cannot be neglected in considering SOC stability and further C budgets.

The stability of soil organic carbon across topographies in a tropical rainforest

Yamin Jiang[a, 1], Huai Yang[b, c, 1], Qiu Yang[a], Wenjie Liu[a, d,*], Zhaolei Li[a, d,*], Wei Mao[a], Xu Wang[a], Zhenghong Tan[a]

[a] College of Ecology and Environment, Hainan University, Haikou 570228, China;

[b] International Center for Bamboo and Rattan, Beijing100102, China;

[c] Jianfengling National Key Field Research Station for Tropical Forest Ecosystem, Research Institute of Tropical Forestry, Chinese Academy of Forestry, Ledong 510520, China;

[d] Center for Ecosystem Science and Society, Northern Arizona University, Flagstaff, AZ 86011, USA

1 The two authors contributed equally.

[*] Corresponding author. E-mail address: liuwj@hainanu.edu.cn and zhaoleilee@sdau.edu.cn.

Abstract: Mechanisms of soil organic carbon (SOC) stability are still unclear in forests ecosystems. In order to unveil the influences of topography on the SOC stability, the 60ha dynamic plot of a tropical montane rainforest were selected in Jianfengling, in Hainan Island, and soil was sampled from 60 quadrats. The chemical fractions of SOC were detected with 13C CPMAS/NMR and path analyses were used to explore the mechanisms of SOC stability in the two local topographies (flat areas and steep areas). The chemical fractions of SOC showed alkyl carbon > O-alkyl carbon > carboxyl carbon > aromatic carbon. The decomposition index (DI) values were greater than 1 in different topographies and the averaged DI value was 1.29, which indicated that the SOC in the study area were stable. The influencing factors of SOC stability varied in topographies, where SOC, soil moisture (SM), ammoniacal nitrogen (NH_4^+-N, AN) were the main influencing factors in the relative flat areas (RF), as well as SM and AN were the main factors in the relative steep areas (RS). More SOC and AN strengthened the SOC stabilization, while higher soil moisture lowered SOC stability. Inertia index (II) also higher in RS than that in RF, indicating that local topography significantly affects SOC content and SOC stability through changing soil environment factors. Topography cannot be neglected in considering SOC stability and further C budgets.

Keywords: soil organic carbon stability; topography; tropical forest; 13C CPMAS/NMR; path analysis

1. Introduction

Soil organic carbon (SOC) of forests plays an important role in the global carbon cycle (Pan et al. 2011). Changes in SOC storage can significantly impact the global carbon cycle and climate change (Stockmann et al. 2013). SOC stability is the ability of soil organic matter to resist disturbance and restore original level under current conditions (Wiesmeier et al. 2014). This high SOC stability would be beneficial to the accumulation of SOC (Schmidt et al. 2011). The SOC stabilization mechanisms that are commonly accepted include chemical stabilization, physical stabilization, and biochemical stabilization (Christensen 1996; Fontaine et al. 2007; Six et al. 2002). In terms of chemical stabilization, SOC consists of chemical fractions with different stability and has long been considered as the decisive mechanism of SOC stability (Yang et al. 2020). Solid 13CNMR technology is one of the methods to dissect SOC chemical fractions and has been applied into tropical forest soil stability research. Previous studies illustrated that the composition of SOC chemical fractions are affected by soil microorganisms, soil properties, and carbon input (ElberlingBreuning-Madsen & Knicker 2013; González-Pérez et al. 2008; Ktigel-Knabner 1997; LorenzLal & Jiménez 2010). Topographic factors, such as elevation, slope, concavity and convexity, affect water flow and erosion, plants growth and litter decomposition, and hence influence SOC content and quality (Fernández-RomeroLozano-García & Parras-Alcántara 2014; SunZhu & Guo 2015). As such there is inherent heterogeneity in SOC stability associated with the spatial variability of topographic factors. However, studies on SOC stability influencing factors mainly focused on tree species, soil minerals protection or altitude (Angst et al. 2018) rather than topography.

Topography itself is a comprehensive factor, thus, it should be taken into consideration in SOC stability. Topography dominates the allocation of water and heat resources, which affects the spatial allocation of vegetation and may thus the quantity and quality of SOC (SunZhu & Guo 2015). In addition, the movement of water and nutrients due to different topography types contributes to soil properties heterogeneity (TsuiChen & Hsieh 2004). Studies found topography influences nutrients availability in tropical forests, and the heterogeneity of nutrient cycling may influence the dynamics of SOC across diverse tropical landscapes (Cleveland et al. 2011; Randerson et al. 2009; Townsend et al. 2011). We hypothesized that nutrients would be the key influencing factors of SOC stability.

The Jianfengling montane rainforest is one of the best preserved tropical primeval forest in China (Li et al. 2012). Previous studies found terrain heterogeneity in this area had a strong effect on the soil properties (Shi 2012) and pointed that SOC stability is significantly influenced by soil properties (Liu et al. 2007). Soil properties on varying topographic positions also have distinctive characteristics under micro-climate conditions (Zhu et al. 2014), which fundamentally influences nutrients, hydrological processes, and hence the SOC stability across topographies. However, it lacks systematic investigations to particularly address how topographies influence the SOC stability via changing soil properties. The objectives of this study are to investigate the differences in soil properties and SOC stability at four topographic positions, and to identity the mechanisms of SOC stability in different topographies in tropical rainforests. To address this objective, we collected soils from 60 quadrats in the 60ha dynamic plot in different topographical areas in the

Jiangenling tropical montane rainforest. The stability of SOC was demonstrated by SOC chemical fractions which were analyzed by 13C-NMR.

2. Materials and Methods

The study area, a 60ha dynamics plot in the tropical montane rain forest (18.23° – 18.50°N, 108.36° – 109.05°E) with an elevation being 800 – 1000 m, located in Jianfengling, in the southwest region of Hainan Island, China(Li & Zhou 2002). The climate of studied area is tropical rainy climate, with a mean annual precipitation of 1700 – 2600 mm, and a mean annual temperature of 20 – 25°C (Yang et al. 2016). The main plant species are Lauraceae, Rubiaceae, Fagaceae, Myrtaceae (Li & Zhou 2002) and the soil belongs to Ultisols order according to USDA Soil Taxonomy.

Based on the survey technical specification of the Center for Tropical Forest Science, Smithsonian Institute, the 60 ha dynamics plot was divided into 1500 quadrats, each 20 m × 20 m in size. Figure 1 shows the distribution of the 60 randomly selected soil sampling sites from the 1500 quadrats. In each sampling site, cutting ring method was used to obtain topsoil (0-10 cm) samples (each sample including four replications). In total, 240 soil samples were collected and brought back to the laboratory. A part of soil sample was stored under 4℃ to measure acid phosphatase activity (APA). The rest of soil sample were air-dried and ground into 1 mm to analyze soil total nitrogen (TN), total phosphorus (TP), available phosphorus (AP), soil pH, and SOC chemical fractions.

Soil samples were pretreated with 10% (v/v) HF solutions before solid-state 13C-CPMAS NMR analysis, to remove Fe^{3+} and Mn^{2+} in soil, improving the signal/noise ratio. In detail, 10 g ground soil sample was vibrated for 2 hours after adding 50 ml HF solutions and then centrifuged with a centrifuge (3,000 rpm) for 10 minutes to remove the suspension. The above steps were repeated five times to get the precipitate (Mathers et al. 2002). The precipitate was washed 5 times with 50 ml deionized water to remove residual hydrofluoric acid, then freeze-dried for further analysis. The fractions of SOC were measured with 13C CPMAS/NMR, 4 mm probe pulse sequence. CPTOSS 13C resonant frequency is 100.38 MHz, 1 H resonant frequency is 399.16 MHz, rotate speed is 5 kHz, and the contact time is 3 ms, a cycle time is 1 s, sampling frequency of 4 k. According to previous study (Baldock et al. 1992), different peaks represent different C compounds: 0 – 45 ppm is alkyl carbon, 45 – 110 ppm is O-alkylcarbon, 110 – 160 ppm is aromatic carbon, and 160 – 220 ppm is carbonyl carbon. Total of 240 soil samples were detected in the Analytical Center of Institute of Chemistry Chinese Academy of Sciences (Beijing City). MestRe-C software was used to analyze chemical fractions of SOC. We used two indices, decomposition index (DI) and inertia index (II), to represent SOC stability.

$$DI = \frac{\text{alkyl carbon}}{\text{O} - \text{alkyl carbon}} \quad (1)$$

$$II = \frac{\text{alkyl carbon } + \text{aromatic carbon}}{\text{o} - \text{alkyl carbon } + \text{carboxyl carbon}} \quad (2)$$

The DI can reflect microbial processing with higher ratios indicating losses of more labile C relative to poorer-quality C compounds (Cusack et al. 2011), therefore, the higher ratio, the more stable is the SOC (Chen 2012; Ostertag et al. 2008). The higher II value means more alkyl carbon and aromatic carbon exist in the SOC, indicating higher SOC stability (Ostertag et al. 2008), which is benefit to SOC accumulation.

Soil organic carbon and total N contents were determined by the $K_2Cr_2O_7$–H_2SO_4 oxidation method and Kjeldahl procedure respectively (Liu et al. 2012). Soil total phosphorus (TP) were extracted by semimicro kelvin method and determined by automatic flow analyzer (PROXIMA 1022/1/1, ALLIANCE instruments, France). Soil ammoniacal nitrogen (NH_4^+-N) contents were extracted using 2 M KCl on an orbital shaker for 1 h under ambient temperature and then the suspension was filtered. The extracts were analyzed by a continuous flow analytical system (SKALAR San++, SKALAR Co., Netherlands). Soil available phosphorus (AP) was determined by the ammonium chloride-hydrochloric acid extraction method (Bao 2000), and acid phosphatase activity (APA) was determined by the phosphoric acid bisacid colorimetric method (Guan 1986). Soil moisture (SM) was represented as the ratio of dry soil weight to soil water weight after fresh soil samples were dried at 105°C in 24 h. Soil pH was detected by the potentiometric method, where 10 g air-dried soil was put in 25 ml beaker and added with distilled water and kept for 30 minutes, and then the suspension's pH value was measured with corrected pH meter.

To investigate the effects of local topography on soil properties, we binned each data point into a topography type based on elevations, slopes and convexities by fuzzy *C*-mean clustering cluster analysis (Xu et al. 2015). Four topography types were identified, the flap area, the relative steep area, the steep area and the mountaintop area. We then performed one-way ANOVAs to test the differences of soil properties between topography groups. The soil property was significant different if P value was ≤0.05. All results are shown as mean ± SE. Path analysis provides a way to examine the multiple relationships between SOC stability and environmental factors. Thus, path analytic framework was applied to examine the influencing factors of SOC stability in different topographies. To get the eligible results of path analyses with enough data in each topography, we classified the flat and the top area into the relative flat (RF) areas and the rest two types into the relative steep (RS) areas.

All analyses were conducted using SPSS Version 20 and figures were generated by Origin (version 92 E).

3. Results

3.1. Soil properties in different topography types

Soil properties varied in different topographies. To be specific, soil organic carbon increased from flat to top, where the contents of SOC was 29.66 g/kg in flat areas and 41.97 g/kg in top areas. Soil TN tended to increase in top area, in which the contents of TN were 1.47 g/kg in flat areas and 1.78 g/kg in top areas. However, soil C:N ratios were similar in different topographies. The contents of AN, TP, SM were also the highest in the top areas, whereas the contents of pH were the highest in the flat areas (Figure 2. Table 1).

3.2. SOC components in different topography types

The alkyl carbon, averaged 41.67% of the SOC, contributed the most to the SOC chemical fractions in the four different topography types (Figure 3). The aromatic carbon which accounted only 2.61%, contributed the lowest to SOC. The O-alkyl carbon and carboxyl carbon took up 33.08% and 22.80%, respectively. As illustrated in figure 4, the overall distributions of four fractions of SOC were similar in different topography types. However, alkyl carbon and carboxyl carbon proportions were significantly altered by topography. The content of alkyl carbon increased from flat to top, where the content was 38.87% in flat areas and 43.34% in top areas, but the content of carboxyl carbon decreased from flat to top, where the content was 24.78% in flat areas and 21.24% in top areas.

3.3. SOC stability index in local topography types

In the four topographies, decomposition index (DI) was all higher than 1, and inertia index (II) were all higher than 0.7. The DI was not significantly different among topographies, while II was significantly different in different topographies with the lowest II value in flat areas (0.72) and the highest value in steep areas (0.91) (Figure 5).

3.4. Influencing factors of SOC stability in different topography types

Figure 6 showed the influencing factors and mechanisms of SOC stability were different in different topography types. In the RF areas, SOC, AN and SM together explained 52% variability of SOC stability. SOC and AN positively and directly affected SOC stability, high SOC and AN could strengthen SOC stability. SM negatively and directly influenced SOC stability, however the direct negative effect of SM was partly offset by the indirect positive effect of SM on AN and SOC, thus, SM contributed a little in total effects of SOC stability.

In the RS areas, SM and AN also affected SOC stability. The effect direction was the same as in the RF areas. The effect of SM was larger than that of AN on SOC stability. Increasing SM would decrease SOC stability, this negative effect was partly offset by its indirect effect on AN. AN positively and directly affected SOC stability.

Soil AN and SM were the same influencing factors of SOC stability in the RF areas and the RS areas, however the effect forces were different. In detail, SM was the negligible limiting factor in the RF areas, whereas SM was the most important limiting factor in the RS areas. The results of path analyses illustrated that R square of the models was 0.53 in the RF areas, while it was 0.42 in the RS areas (Table S1).

4. Discussion

The chemical fractions of SOC in different topography areas are characterized by alkyl carbon > O-alkyl carbon > carboxyl carbon > aromatic carbon. The SOC fractions ranking order is similar to those of subtropical evergreen board-leaved forest and Masson pine in China (Shang et al. 2013), subtropical natural forest, hoop pine plantation in Australia (ChenXu & Mathers 2004). The alkyl carbon accounted for the most of the SOC fractions, indicating a higher percentage of passive carbon in SOC. The DI (alkyl carbon/O-alkyl carbon) at plot scale was 1.29, which is higher than moist semi-deciduous tropical forest soils in Ghana (1.25) (ElberlingBreuning-Madsen & Knicker 2013), old live oak forest (0.87) and old-growth dry tropical forests (0.70) in Costa Rica (LorenzLal & Jiménez 2010), plantations in the subtropics of China (Pinus massoniana, Castanopsis hystrix, Michelia macclurei, Mytilaria laosensis, all < 0.8)(Wang 2010), evergreen broad-leaved forest (0.76), Cunninghamia lanceolata forest (0.89), Cryptomeria fortune forest (0.78), and coniferous and broad-leaved mixed forest (0.53) in the subtropics of China (Zhang et al. 2015). The DI in different topography types were all higher than 1, indicating a rather stable SOC in the tropical montane rainforest of Jiangfengling, Hainan Island (González-Pérez et al. 2008)

Path analysis showed SOC contents only affected SOC stability in RF areas, while AN and SM affected SOC stability in both topographies. Studies found the interaction between SOC and mineral surfaces could stabilize SOC, whereby stable organic-mineral bonds were formed through anion and inner-sphere ligand-exchange reaction (Wiesmeier et al. 2019). Tropical forest with highly weathered soils contains high concentrations of iron (Sanchez 1976) that could protect C from microbes and enhance SOC stability. The SOC only affected SOC stability in RF areas might be due to the SOC content in RF areas was significantly higher than that in the RS areas (37.21 > 31.32 g/kg, $P < 0.01$).

SOC stability depends not only on its chemical characteristics, but also on soil microenvironment (Yang et al. 2020). Soil biotic community and the soil microenvironment were key factors affecting the SOC stability (Schmidt et al. 2011; Yang et al. 2018). Soil N, especially in the bioavailable forms, such as ammoniacal nitrogen is an essential component of all living organisms. Soil N dynamics are mainly driven by microbe (Levy-BoothPrescott & Grayston 2014) and microbes mainly assimilate of AN (Cheng et al., 2015); however, others found nitrogen addition negatively affects soil microbial growth, composition and function (Chen et al. 2018). The soil AN content in the study area is rather high, which is about 40.4 mg/kg while the value in Amazon pristine forest is 5.7 mg/kg(Hamaoui et al. 2016) and 2.12 mg/kg in a secondary tropical forest in Southern China (Wang et al. 2014). Therefore, microorganism activities and functions might be suppressed by the high AN content in this area, resulting in a slow decomposition rates and consequently high SOC stability in this tropical forest.

Soil moisture is a key factor influencing SOC mineralization in terrestrial ecosystems (LiuZhang & Wan 2009; MoyanoManzoni & Chenu 2013). Soil moisture could affect SOC decomposition directly or indirectly. Topography influences soils by the transport of fine soil particle, base of slopes and positions of lower slope which called depositional areas tend to have high organic materials and water-holding capacity (Chapin IIIMatson & Vitousek 2012). The above process consequently results in active carbon accounted more compared with the stubborn carbon, indicating the low DI and II in RF. This explained why SM was the negative influencing factor of SOC stability in RS and RF areas (Figure 6). Moreover, SOC in flap areas was the most unstable carbon in the four topography types (Figure 4). In terms of indirectly ways, decomposition of soil organic matter depends on factors such as soil mineralogy, redox potential and electron acceptor availability, which are controlled by soil water regimes (RoJi & Lee 2018). Studies found increase soil water content benefits dissolved organic carbon dissolution and nutrients transfer and stimulate the activity of microorganisms which involved in organic carbon decomposition (Goebel et al. 2007). The higher SM resulted in higher rates of substate supply to microbes and higher microbial growth. In addition, soil moisture availability could affect the vegetation distribution and structure (D'Odorico et al. 2007; Ruiz-Sinoga et al. 2011), then, affect the amount and quality of litter, which in turns influences the soil organic matter decomposition rate (Rodríguez-Iturbe & Porporato 2007). On the other hand, AN is water soluble nitrogen which is vulnerably influenced by soil water. Hence, SM could negatively affect SOC stability by positively influencing the soil microbe and AN content.

5. Conclusions

Our synthesis on the effects of small-scale topography on SOC stability in a tropical mountain rain forest showed that topographic heterogeneity altered SOC stability via changing soil nutrients and soil moisture. Our findings indicated that SOC is rather stable in the tropical montane rainforest topsoil, AN and SM were the main influencing factors of SOC stability both in RF and RS areas. Further, SOC and AN are positive promoting factors while SM is limiting factors in study areas. Accordingly, soil nutrients were the key influencing factors in RF areas but not the RS areas. We hypothesized nutrients be the key influencing factor in study areas was not fully confirmed. Considering the path analysis model explained less than 50% in the RS areas, thus other factors remain to be further explored.

Acknowledgments

We are grateful to Jianfengling National Key Field Research Station for Tropical Forest Ecosystem for providing their assistance in field work.

Conflict of interest

The authors declare no competing financial interests.

References

Angst G, Mueller KE, Eissenstat DM, Trumbore S, Freeman KH, Hobbie SE, Chorover J, Oleksyn J, Reich PB, and Mueller CW. 2018. Soil organic carbon stability in forests: Distinct effects of tree species identity and traits. *Glob Chang Biol* 25:1529-1546. 10.1111/gcb.14548

Baldock JA, Oades JM, Waters AG, Peng X, Vassallo AM, and Wilson MA. 1992. Aspects of the chemical structure of soil organic materials as revealed by solid-state 13C NMR spectroscopy. *Biogeochemistry* 16:1-42.

Bao s. 2000. *Soil agrochemical analysis* BeiJing: Chinese Agriculture Press.

Chapin III FS, Matson PA, and Vitousek PM. 2012. *Principles of terrestrial ecosystem ecology*. New York, USA: Springer.

Chen C, Xu Z, and Mathers N. 2004. Soil Carbon Pools in Adjacent Natural and Plantation Forests of Subtropical Australia. *Soil Science Society of America Journal* 68:282-291.

Chen x. 2012. The effects of major environmental changes on soil organic carbon fractions in subtropical forests Doctor. Chinese Academy of Sciences.

Chen X, Deng Q, Lin G, Lin M, and Wei H. 2018. Changing rainfall frequency affects soil organic carbon concentrations by altering non-labile soil organic carbon concentrations in a tropical monsoon forest. *Sci Total Environ* 644:762-769. 10.1016/j.scitotenv.2018.07.035

Christensen B. 1996. *Carbon in primary and secondary organomineral complexes. In: chapter,Structure and Organic Matter Storage in Agricultural Soils*. New York: CRC Lewis Publishers.

Cleveland CC, Townsend AR, Taylor P, Alvarez-Clare S, Bustamante MMC, Chuyong G, Dobrowski SZ, Grierson P, Harms KE, Moulton BZ, Marklein A, Parton W, Porder S, Reed SC, Sierra CA, Silver WL, Tanner EVJ, and Wieder aWR. 2011. Relationships among net primary productivity, nutrients and climate in tropical rain forest: a pan-tropical analysis. *Ecol Lett* 14:1313-1317.

Cusack D, Silver W, Torn M, Burton S, and Firestone M. 2011. Changes in microbial community characteristics and soil organic matter with nitrogen additions in two tropical forests. *Ecology* 92:621-632. 10.1890/10-0459.1

D'Odorico P, Caylor K, Okin GS, and Scanlon TM. 2007. On soil moisture-vegetation feedbacks and their possible effects on the dynamics of dryland ecosystems. *Journal of Geophysical Research: Biogeosciences* 112:1-10. 10.1029/2006jg000379

Elberling B, Breuning-Madsen H, and Knicker H. 2013. Carbon sequestration in iron-nodules in moist semi-deciduous tropical forest soil. *Geoderma* 200-201:202-207. 10.1016/j.geoderma.2013.03.001

Fernández-Romero ML, Lozano-García B, and Parras-Alcántara L. 2014. Topography and land use change effects on the soil organic carbon stock of forest soils in Mediterranean natural areas. *Agriculture, Ecosystems & Environment* 195:1-9. 10.1016/j.agee.2014.05.015

Fontaine S, Barot S, Barre P, Bdioui N, Mary B, and Rumpel C. 2007. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature* 450:277-280. 10.1038/nature06275

Goebel M-O, Woche SK, Bachmann J, Lamparter A, and Fischer WR. 2007. Significance of Wettability-Induced Changes in Microscopic Water Distribution for Soil Organic Matter Decomposition. *Soil Science Society of America Journal* 71:1593-1599. 10.2136/sssaj2006.0192

González-Pérez M, Vidal Torrado P, Colnago LA, Martin-Neto L, Otero XL, Milori DMBP, and Gomes FH. 2008. 13C NMR and FTIR spectroscopy characterization of humic acids in spodosols under tropical rain forest in southeastern Brazil. *Geoderma* 146:425-433. 10.1016/j.geoderma.2008.06.018

Guan S. 1986. *Soil enzyme and research methods*. BeiJing: Chinese Agriculture Press.

Hamaoui GS, Rodrigues JLM, Bohannan BJM, Tiedje JM, and Nüsslein K. 2016. Land-use change drives abundance and community structure alterations of thaumarchaeal ammonia oxidizers in tropical rainforest soils in Rondônia, Brazil. *Applied Soil Ecology* 107:48-56. 10.1016/j.apsoil.2016.05.012

Ktigel-Knabner I. 1997. 13C and 15N NMR spectroscopy as a tool in soil organic matter studies. *Geoderma* 80:243-270.

Levy-Booth DJ, Prescott CE, and Grayston SJ. 2014. Microbial functional genes involved in nitrogen fixation, nitrification and denitrification in forest ecosystems. *Soil Biology and Biochemistry* 75:11-25. 10.1016/j.soilbio.2014.03.021

Li Y, Xu H, Luo T, and al. e. 2012. *Permanent monitoring and research dataset of Chinese ecosystem:forest ecosystem. Jianfengling Station.Bio-species checklist*. BeiJing: Chinese Agriculture Press.

Li Y, and Zhou G. 2002. *Research and conservation of tropical forest and the biodiversity, Hainan Island*. BeiJing: Chinese Forestry Press.

Liu MQ, X Y C, J H G, X L H, and F H. 2007. Soil Biota on Soil Organic Carbon Stabilization. *Advances in Earth Science* 22:152-158.

Liu W, Chen S, Qin X, Baumann F, Scholten T, Zhou Z, Sun W, Zhang T, Ren J, and Qin D. 2012. Storage, patterns, and control of soil organic carbon and nitrogen in the northeastern margin of the Qinghai–Tibetan Plateau. *Environmental Research Letters* 7:035401. 10.1088/1748-9326/7/3/035401

Liu W, Zhang ZHE, and Wan S. 2009. Predominant role of water in regulating soil and microbial respiration and their responses to climate change in a semiarid grassland. *Global Change Biology* 15:184-195. 10.1111/j.1365-2486.2008.01728.x

Lorenz K, Lal R, and Jiménez JJ. 2010. Characterization of soil organic matter and black carbon in dry tropical forests of Costa Rica. *Geoderma* 158:315-321. 10.1016/j.geoderma.2010.05.011

Mathers NJ, Xu Z, Berners-Price SJ, Perera MCS, and Saffigna PG. 2002. Hydrofluoric acid pre-treatment for improving 13C CPMAS NMR spectral quality of forest soils in south-east Queensland, Australia. *Aust J Soil Res* 40:655-674.

Moyano FE, Manzoni S, and Chenu C. 2013. Responses of soil heterotrophic respiration to moisture availability: An exploration of processes and models. *Soil Biology and Biochemistry* 59:72-85. 10.1016/j.soilbio.2013.01.002

Ostertag R, Marín-Spiotta E, Silver WL, and Schulten J. 2008. Litterfall and Decomposition in Relation to Soil Carbon Pools Along a Secondary Forest Chronosequence in Puerto Rico. *Ecosystems* 11:701-714. 10.1007/s10021-008-9152-1

Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG, Ciais P, Jackson RB, Pacala SW, McGuire AD, Piao S, Rautiainen A, Sitch S, and Hayes D. 2011. A large and persistent carbon sink in the world's forests. *Science* 333:988-993. 10.1126/science.1201609

Randerson JT, Hoffman FM, Thornton PE, Mahowald NM, Lindsay K, Lee Y-H, Nevison CD, Doney SC, Bonan G, StÖCkli R, Covey C, Running SW, and Fung IY. 2009. Systematic assessment of terrestrial biogeochemistry in coupled climate-carbon models. *Global Change Biology* 15:2462-2484. 10.1111/j.1365-2486.2009.01912.x

Ro H-M, Ji Y, and Lee B. 2018. Interactive effect of soil moisture and temperature regimes on the dynamics of soil organic carbon decomposition in a subarctic tundra soil. *Geosciences Journal* 22:121-130. 10.1007/s12303-017-0052-2

Rodríguez-Iturbe I, and Porporato A. 2007. *Ecohydrology of Water-controlled Ecosystems: Soil Moisture and Plant Dynamics*. United Kingdom: Cambridge University Press.

Ruiz-Sinoga JD, Gabarrón Galeote MA, Martinez Murillo JF, and Garcia Marín R. 2011. Vegetation strategies for soil water consumption along a pluviometric gradient in southern Spain. *Catena* 84:12-20. 10.1016/j.catena.2010.08.011

Sanchez P. 1976. *Properties and management of soils in the tropics*. New York, USA: John Wiley and Sons.

Schmidt MW, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kogel-Knabner I, Lehmann J, Manning DA, Nannipieri P, Rasse DP, Weiner S, and Trumbore SE. 2011. Persistence of soil organic matter as an ecosystem property. *Nature* 478:49-56. 10.1038/nature10386

Shang SY, Jiang PK, Song ZL, Li YF, and Lin L. 2013. Composition and stability of organic carbon in the top soil under different forest types in subtropical China. *Acta Ecologica Sinica* 33:0416-0424.

Shi L. 2012. Study on the spatial heterogeneity of soil physical and chemical properties of primary tropical montane rainforest. Master. Chinese Academy of Forestry.

Six J, Conant RT, Paul EA, and Paustian K. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil* 241:155-176. 10.1023/A:1016125726789

Stockmann U, Adams MA, Crawford JW, Field DJ, Henakaarchchi N, Jenkins M, Minasny B, McBratney AB, Courcelles VdRd, Singh K, Wheeler I, Abbott L, Angers DA, Baldock J, Bird M, Brookes PC, Chenu C, Jastrow JD, Lal R, Lehmann J, O'Donnell AG, Parton WJ, Whitehead D, and Zimmermann M. 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems & Environment* 164:80-99. 10.1016/j.agee.2012.10.001

Sun W, Zhu H, and Guo S. 2015. Soil organic carbon as a function of land use and topography on the Loess Plateau of China. *Ecological Engineering* 83:249-257. 10.1016/j.ecoleng.2015.06.030

Townsend AR, Cleveland CC, Houlton BZ, Alden CB, and White JWC. 2011. Multi-element regulation of the tropical forest carbon cycle. *Frontiers in Ecology and the Environment* 9:9-17. 10.1890/100047

Tsui C-C, Chen Z-S, and Hsieh C-F. 2004. Relationships between soil properties and slope position in a lowland rain forest of southern Taiwan. *Geoderma* 123:131-142. 10.1016/j.geoderma.2004.01.031

Wang F, Li J, Wang X, Zhang W, Zou B, Neher DA, and Li Z. 2014. Nitrogen and phosphorus addition impact soil N(2)O emission in a secondary tropical forest of South China. *Sci Rep* 4:5615. 10.1038/srep05615

Wang H. 2010. Soil carbon sequestration and the related processes in four subtropical plantations in southern China Doctor Doctor. Chinese Academy of Forestry.

Wiesmeier M, Schad P, von Lützow M, Poeplau C, Spörlein P, Geuß U, Hangen E, Reischl A, Schilling B, and Kögel-Knabner I. 2014. Quantification of functional soil organic carbon pools for major soil units and land uses in southeast Germany (Bavaria). *Agriculture, Ecosystems & Environment* 185:208-220. 10.1016/j.agee.2013.12.028

Wiesmeier M, Urbanski L, Hobley E, Lang B, von Lützow M, Marin-Spiotta E, van Wesemael B, Rabot E, Ließ M, Garcia-Franco N, Wollschläger U, Vogel H-J, and Kögel-Knabner I. 2019. Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. *Geoderma* 333:149-162. 10.1016/j.geoderma.2018.07.026

Xu H, Li Y, Lin M, Wu J, Luo T, Zhou Z, Chen D, Yang H, Li G, and Liu S. 2015. Community characteristics of a 60 ha dynamics plot in the tropical montane rain forest in Jianfengling, Hainan Island. *Biodiversity Science* 23:192-201. 10.17520/biods.2014157

Yang H, Yi-De LI, Hai REN, Tu-Shou LUO, Ren-Li C, Wen-Jie LIU, De-Xiang C, Han XU, Zhang Z, Ming-Xian LIN, Qiu Y, Hai-Rong YAO, and Guo-Yi Z. 2016. Soil organic carbon density and influencing factors in tropical virgin forests of Hainan Island, China. *Chinese Journal of Plant Ecology* 40:292-303. 10.17521/cjpe.2015.0314

Yang J, Li A, Yang Y, Li G, and Zhang F. 2020. Soil organic carbon stability under natural and anthropogenic-induced perturbations. *Earth-Science Reviews* 205:103199. 10.1016/j.earscirev.2020.103199

Yang J, Li G, Qian Y, Yang Y, and Zhang F. 2018. Microbial functional gene patterns related to soil greenhouse gas emissions in oil contaminated areas. *Sci Total Environ* 628-629:94-102. 10.1016/j.scitotenv.2018.02.007

Zhang Y, Hu HB, Huang YJ, and li TS. 2015. Effects of different vegetation restoration models on molecular structure and stability of soil organic carbon. *Research of Environmental Sciences* 28:1870-1878.

Zhu H, Wu J, Guo S, Huang D, Zhu Q, Ge T, and Lei T. 2014. Land use and topographic position control soil organic C and N accumulation in eroded hilly watershed of the Loess Plateau. *Catena* 120:64-72. 10.1016/j.catena.2014.04.007

Figure 1

Distribution of soil sampling sites in the 60ha plot in tropical forests

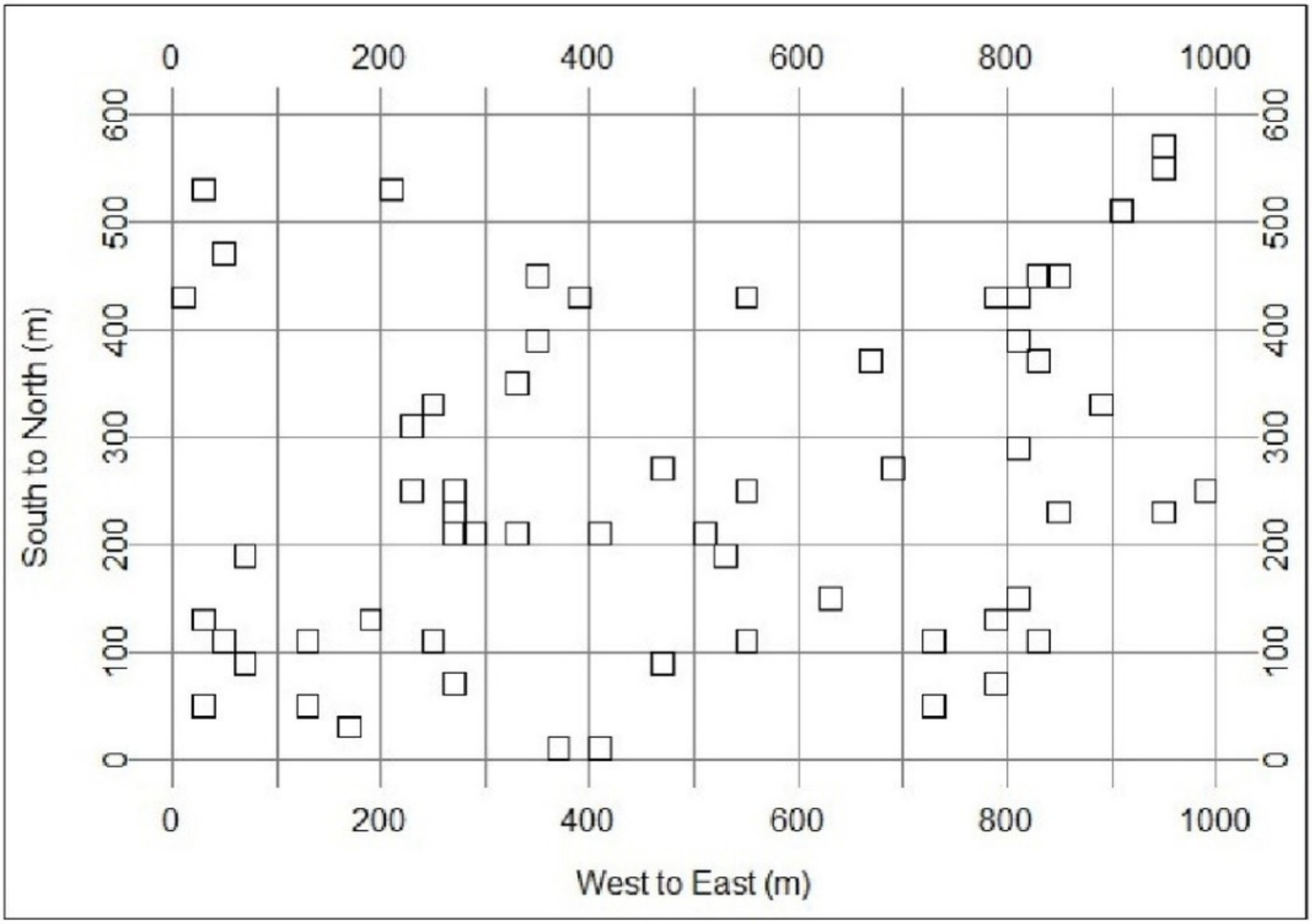

Figure 2

The changes of soil SOC (a), TN (b) and C:N ratio (c) among four topographies. The different lowercases mean significant differences among topographies (P < 0.05)

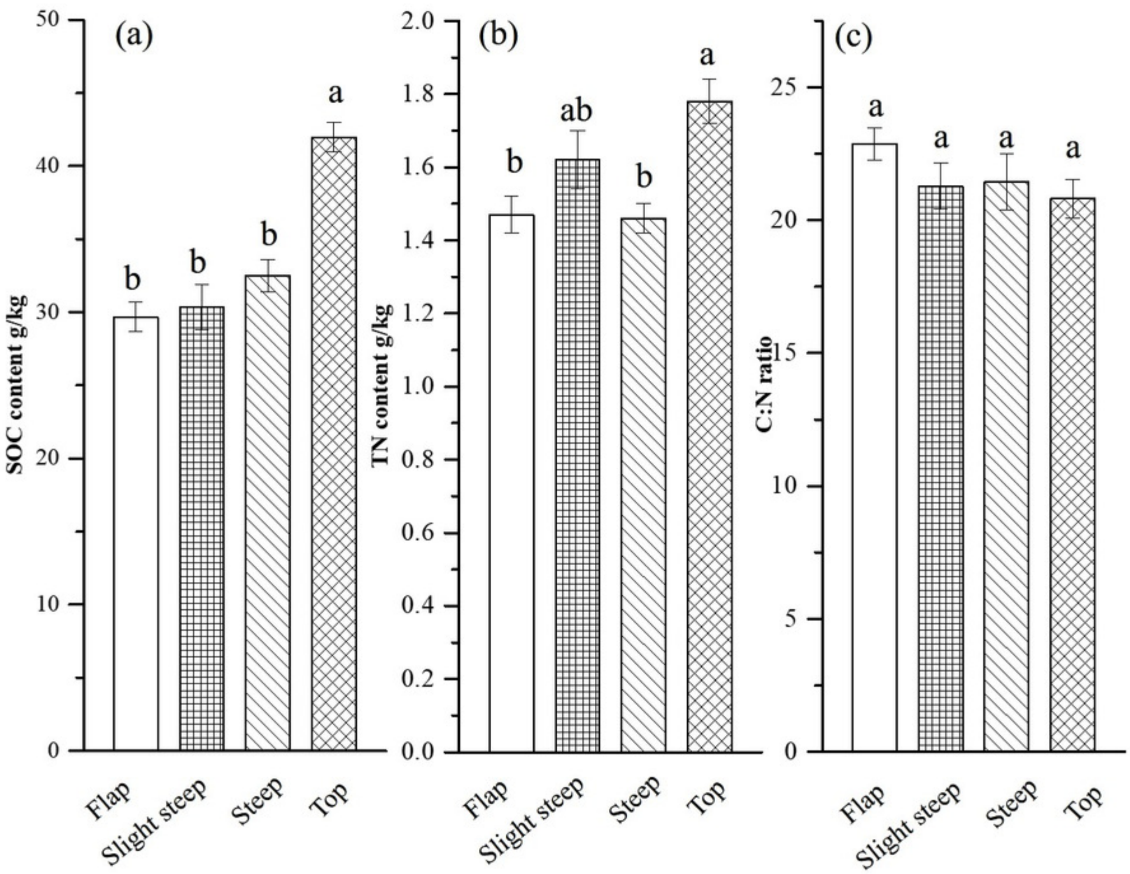

Figure 3

The distributions of SOC components in this tropical rainforest. Errors Bars represent the standard error (SE)

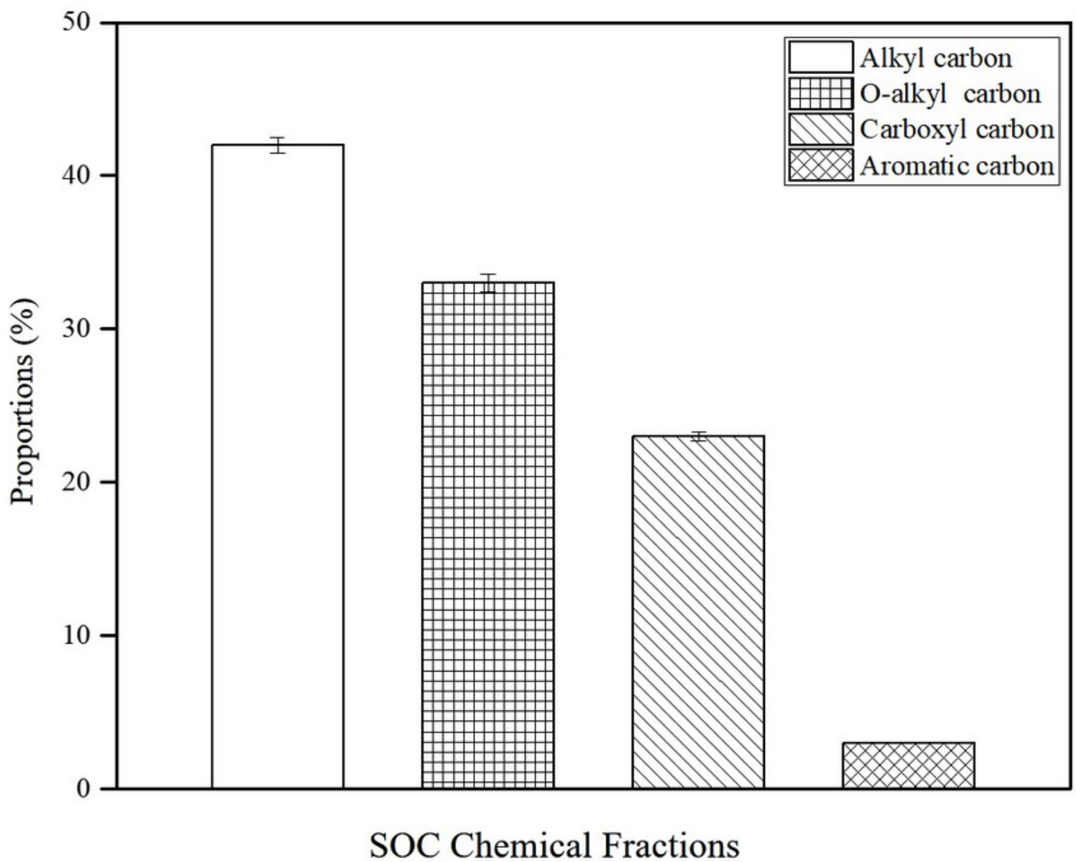

Figure 4

The comparisons of SOC fractions in the four topography types. (a) alkyl carbon, (b)O-alkyl carbon, (c) carboxyl carbon, and (d) aromatic carbon. Errors Bars represent the standard error. The different lowercases mean significant differences among topogra

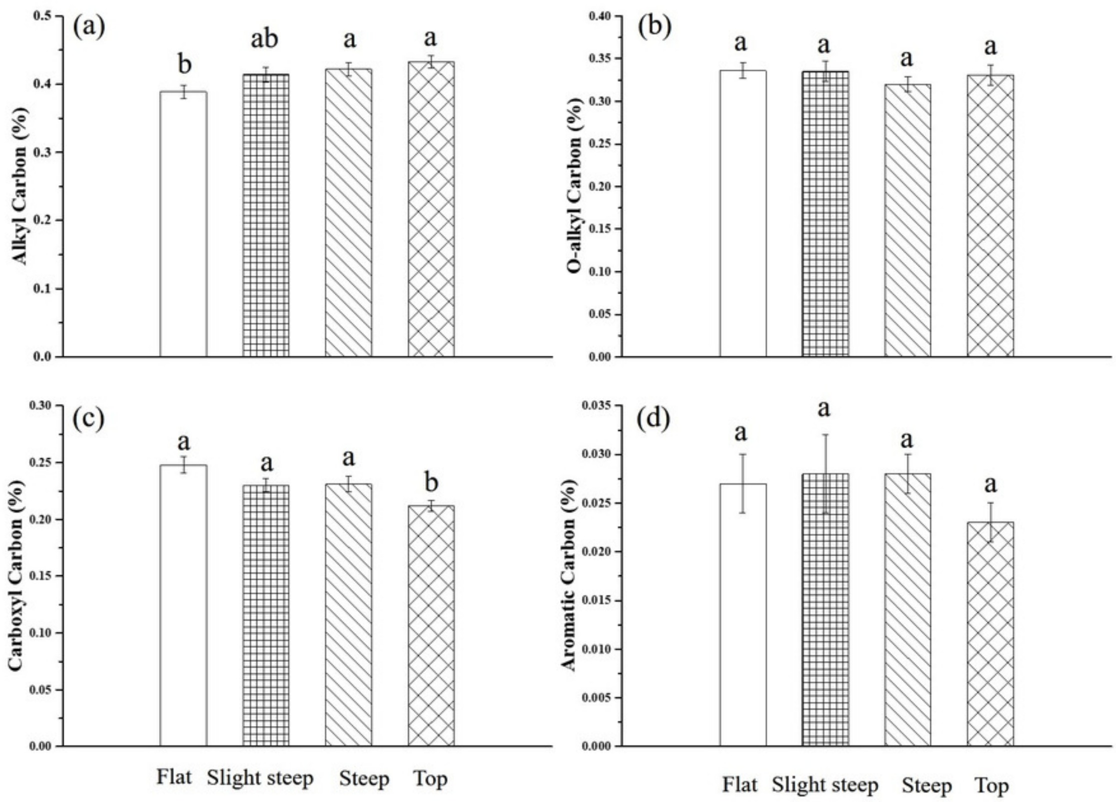

Figure 5

Difference of decomposition index (DI) and inertia index (II) among topographies. (a) decomposition index, (b) inertia index. Errors Bars represent the standard error. The same letter means variables in the different topography types are not significantly

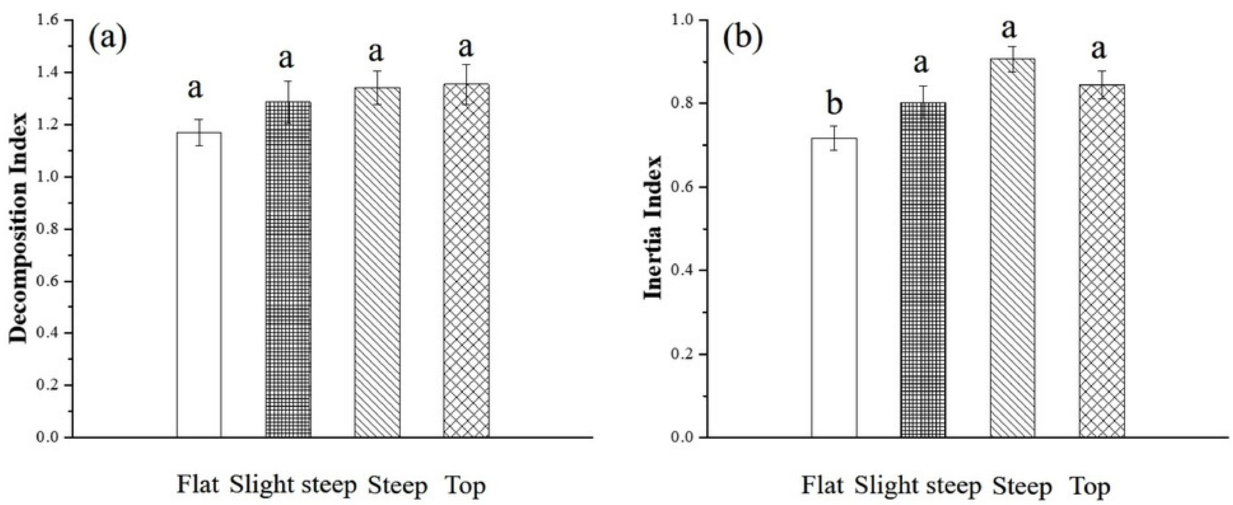

Figure 6

Influencing factors and mechanisms of SOC stability in two topographies. Values aside the straight line are direct path coefficient, and values aside the curve are indirect path coefficient. The direction of arrow is the effect direction.

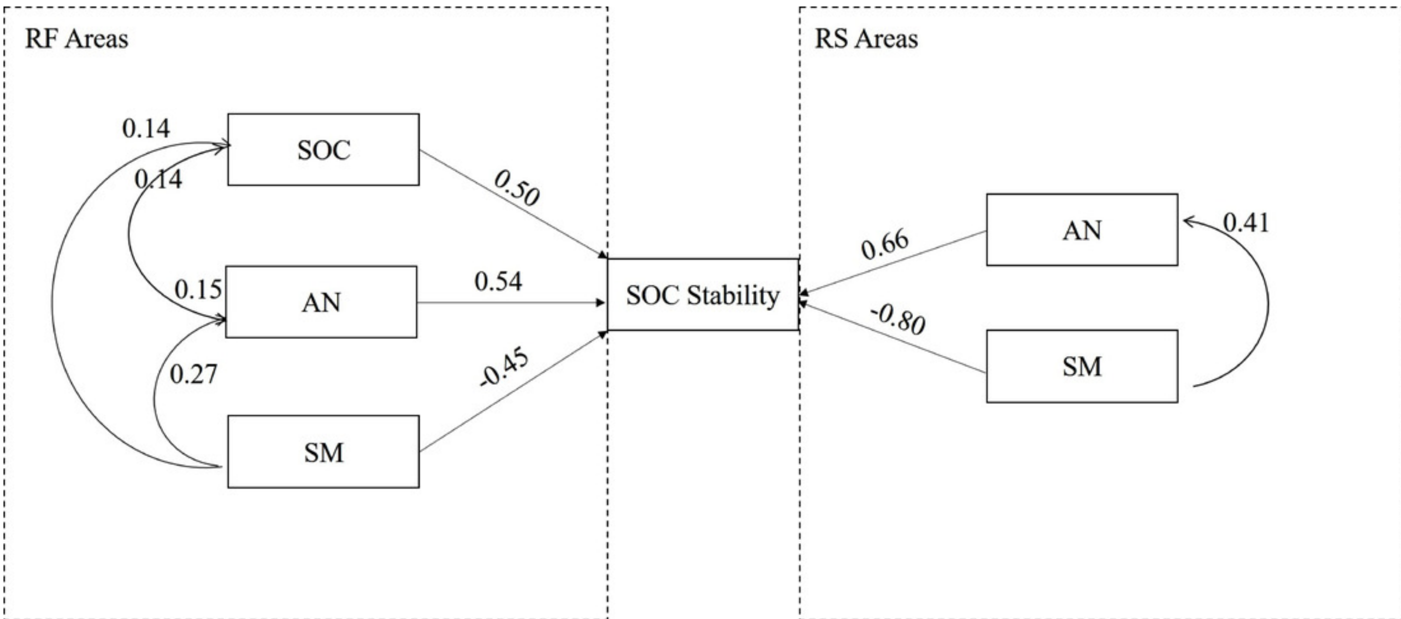

Table 1(on next page)

Soil properties in different topographic areas (n=60)

Table 1. Soil properties in different topographic areas (n=60)

Variables	Flat (n=12)	Slight steep (n=16)	Steep (n=13)	Top (n=19)	Average (n=60)
AN (mg/kg)	30.29±6.04bc	42.16±4.32ab	29.21±5.69c	53.03±3.41a	40.40±2.62
TP (mg/kg)	74.12±5.64b	82.50±5.62ab	77.66±5.07b	90.91±3.68a	82.40±2.54
AP (mg/kg)	2.71±0.18a	3.03±0.10a	2.92±0.08a	2.30±0.11a	2.93±0.06
C:P ratio	468.65±34.09a	433.61±25.56a	442.74±43.57a	407.08±24.19a	434.20±15.36
N:P ratio	20.56±1.42a	20.26±0.66a	20.39±1.46a	19.68±0.96a	20.16±0.54
SM	20.88±1.66cb	21.20±1.52b	16.86±0.83dc	25.28±1.22a	21.49±0.77
pH	4.42±0.05a	4.32±0.05b	4.31±0.04ab	4.15±0.02c	4.28±0.02

Abbreviation: AN was ammoniacal nitrogen; TP was total phosphorus; AP was available phosphorus; C:P ratio was calculated as SOC/ TP; N:P ratio was calculated as TN/TP; SM was soil moisture, and n was sample size. All values were expressed as mean values ± SE. The different lowercases mean significant differences among topographies ($P < 0.05$).

Table 2 (on next page)

Table S1 The parameters of path analysis for SOC stability in the two different topography types <!--[if !supportAnnotations]--> <!--[endif]--> <!--[if !supportAnnotations]--> <!--[if !supportAnnotations]--> <!--[endif]-->

Table S1. The parameters of path analysis for SOC stability in the two different topography types

Topography type	Factors	SCC	DPC	SOC	AN	SM	Decision coefficient	Determination coefficient	R square of the model
Relative flat areas	SOC	0.52	0.50	-	0.15	-0.13	0.27	0.26	0.53
	AN	0.45	0.54	0.14	-	-0.23	0.19	0.24	
	SM	-0.05	-0.45	0.14	0.27	-	-0.16	0.02	
Relative Steep areas	SM	-0.40	-0.80		0.41		0.00	0.32	0.42
	AN	0.16	0.66			-0.50	-0.22	0.11	