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Active Soil Organic Carbon Pools Decrease with Increased Time since Land-Use Transition from Rice Paddy Cultivation to Areca Nut Plantations under the Long-Term Application of Inorganic Fertilizer

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Abstract: Many croplands in the tropics of China have been converted over the last decades into areca nut plantations due to their high economic returns. This land-use transition was accompanied by changes in agricultural practices such as soil moisture regimes and fertilizer inputs, which may affect soil organic carbon (SOC) and its fractions, especially in tropical soils with low fertility and high nitrogen loss. Yet, how the time since land-use transition from rice paddy cultivation to areca nut plantations affects soil carbon dynamics and their underlying mechanisms in the tropics of China remains elusive. Here, areca nut plantation soils with different ages (2, 5, 10, 14, and 17 years) and paddy fields in the tropical region of China were investigated. The study result indicates that the contents of dissolved organic carbon (DOC), particulate organic carbon (POC), easily oxidized organic carbon (EOC), light organic carbon (LFOC), and microbial biomass carbon (MBC) decreased significantly with increased time since land-use transition from rice paddy cultivation to areca nut plantations. Similarly, the ratios of DOC/SOC, MBC/SOC, POC/SOC, LFOC/SOC, and EOC/SOC decreased significantly with increased time since land-use transition. Compared with the paddy soil, the carbon pool management index decreased by 36.6–76.7% under the areca nut plantations, concluding that increasing the time since land-use transition from rice paddy cultivation to areca nut plantations with high application rates of chemical fertilizers resulted in reduced soil active carbon fractions and SOC supply capacity. Therefore, agricultural practices such as the use of organic fertilizers should be applied to improve the soil's ability to supply organic carbon in managed plantation ecosystems in the tropics of China.

Keywords: soil organic C; organic C supply capacity; long-term fertilization; land-use change

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1. Introduction

The areca nut, a perennial evergreen woody plant of the Palmaceae, is one of the most important commercial crops in the tropics and has substantial economic value [1]. In recent years, areca nut has become the second largest commercial crop in the tropics of China, with an area of approximately 102,500 ha, making it the primary economic source in this region [2]. Over the last decades, many croplands in the tropics of China have been converted into areca nut plantations due to their high economic returns [3]. For example, many paddy fields were converted into areca nut plantations in Hainan province, which was accompanied by changes in agricultural practices (e.g., soil moisture and fertilizer inputs) [4]. To increase profit, excess fertilizers and water were used in areca nut plantations than paddy fields; however, nitrogen (N) fertilization may cause soil degradation, nitrogen leaching, and low water and nitrogen use efficiency, especially under high temperature and moisture conditions, ultimately negatively affecting the crop yield [5]. Long-term planting of areca nut not only reduces the yield but also adversely impacts the transformation of soil nutrients [5]. Increasing soil carbon (C) storage, which is an important index to measure soil quality, is beneficial to increasing renewable water resources, promoting crop yield, improving biodiversity, and strengthening element cycling [6]. Maintaining and improving soil C content is crucial for the sustainability of areca nut plantations [1]. Thus, exploring the impact of land-use transition from rice paddy cultivation to areca nut plantations on C stocks and its potential mechanisms in tropical soils is important for agricultural management to improve areca nut production and soil C sequestration.

Soil organic carbon (SOC) is generally divided into stable and active C pools [7]. Stable C fractions, whose turnover time can be thousands of years, are not affected by land use or human interference [8]. Active organic C, however, is highly susceptible to mineralization and decomposition [8]. Although soil reactive C fractions (e.g., soil particulate organic C (POC), light fraction organic C (LFOC), dissolved organic C (DOC), and easily oxidizable organic C (EOC) account for a low proportion of total SOC; they are more sensitive to land-use change and can better reflect soil C pools balance and soil fertility [2]. Previous studies have generally focused on how the conversion of croplands to natural ecosystems leads to an increase in SOC storage [9]. For instance, converting croplands to forests resulted in an increase of 18–19% in SOC storage globally [10]. In contrast, previous studies reported that the conversion of paddy fields to dry land significantly reduced SOC and its fractions [11]. Concomitantly, increased soil moisture may improve conditions for microorganisms, resulting in enhanced decomposition of soil organic matter [12]. Yet, it is still unclear how the content of SOC and its fractions change over time after converting paddy fields into areca nut plantations in the tropical region of China.

The fertilizer application rate of paddy fields is generally low, and paddy fields have higher soil C content due to long-term flooding [4]. However, in order to achieve high yield and efficiency, the fertilization inputs of areca nut plantations must be higher than those of paddy fields [4]. Differences in management practices (e.g., soil moisture and fertilizer inputs) between paddy and areca nuts resulted in significant differences in soil properties [13]. The higher long-term application of inorganic N has resulted in a severe loss of soil nutrients and a significant reduction in organic C in areca nut cultivation. Previous studies have reported that long-term N, phosphorus (P), and potassium (K) fertilization decreased the SOC content of organic pools [14]. In addition, soil C sequestration capacity decreases with reducing soil moisture content [15]. Previous studies have reported that the contents of DOC and EOC were significantly increased due to the high water content in paddy fields [16], mainly due to reduced soil organic matter decomposition [17]. However, the low water supply in areca nut plantations is not conducive to soil C sequestration [18]. Yet, it remains unknown how and why the time since land-use transition from rice paddy cultivation to areca nut plantations affects soil SOC and active C fractions. We hypothesized that active soil organic C pools decrease with increased time since land-use transition from rice paddy cultivation to areca nut plantations due to long-term fertilization.

To address the above hypothesis, soil samples from areca nuts plantations, which were converted from tropical paddy fields, with different plantation ages (2, 4, 5, 10, 14, and 17 years) were collected. The current study aims to evaluate how and why SOC and its fractions change over time after converting tropical paddy soils to areca nut plantations.

2. Materials and Methods

2.1. Soil Samples Site

The study site was located in Beishan village (19°6′ N, 110°32′ E) in the southeast of Hainan province, China, where paddy and areca nut plantations were mainly cultivated. It has a tropical monsoon climate, with an average annual rainfall of 2000 mm and an average annual temperature of 24.3 °C. The soils in this area are Ultisols, according to the FAO classification. In this study, rice fields were converted to areca nut plantations, and all areca nut plantations with different conversion ages received the same management practices. The content of nutrients for different fertilization treatments is presented in Table 1.

Table 1. Fertilizer inputs (kg $ha^{-1}y^{-1}$) of the treatments in soil tested.

Land Use	Urea	Super-Phosphate	Potassium Oxide	Rice Straw
	(kg ha^{-1} y^{-1})	(kg ha^{-1} y^{-1})	(kg ha^{-1} y^{-1})	(kg ha^{-1} y^{-1})
Paddy	180–200	80–100	150–200	1000–2000
A2	350–400	220–260	200–250	without
A5	350–400	220–260	200–250	without
A10	350–400	220–260	200–250	without
A14	350–400	220–260	200–250	without
A17	350–400	220–260	200–250	without

The A2, A5, A10, A14, and A17 represent the cultivation durations of the areca nut plantations.

In June 2023, soil samples were collected from farms that converted from rice fields to areca nut plantations 2, 4, 5, 10, 14, and 17 years ago (hereinafter referred to as A2, A5, A10, A14, and A17, respectively). Soil samples from adjacent paddy fields were collected and used as a control. Three replicates for each areca nut plantation and the paddy soil were selected. At each site, five plots (approximately 1 $\times$ 1 m) were selected and randomly sampled over 20 cm. Litters were removed from the soil prior to sampling, then a sample of the topsoil (0–20 cm) was taken using a soil auger with a diameter of 5 cm, and then all samples were mixed to form a composite sample. Litter, roots, and other impurities present in the composite sample were removed, and the soil was then sieved (2 mm mesh).

2.2. Soil Properties Analysis

The soil's physical and chemical properties were analyzed according to the Soil and Agricultural Chemistry Analysis [19]. The pH of the soil sample was measured using a pH meter at a soil/water ratio of 1:2.5 (w/w). The SOC was determined using the potassium dichromate–sulfuric acid external heating method. The soil total nitrogen (TN) was determined using the semi-micro-Kjeldahl method. The soil-available potassium (AK) was determined using a flame photometer, while the soil-available phosphorus (AP) was determined using the molybdenum blue colorimetry method.

2.3. Determination of Soil Active Organic C

Soil microbial biomass C (MBC) and N (MBN) were determined by the chloroform fumigation method [20]. Soil-dissolved organic C (DOC) was determined using the method described by Zsolnay [21] by a Shimadzu automatic SOC analyzer. Determination of light fraction organic C (LFOC) was performed by the density gradient method described by Gregorich [22]. Easily oxidizable soil organic C (EOC) was determined using the $KMnO_4$ oxidation method [23]. Particulate organic C (POC) was determined by the particle size method described by Camberdella and Elliott [24].

2.4. Calculation of the Soil Carbon Pool Management Index

The soil C pool management index (CPMI) was calculated as follows [25]:

$$\text{CPMI} = \text{CPI} \times \text{LI} \times 100$$

where CPI is the C pool index and LI is the C pool activity index, and they are computed as follows:

$$\text{CPI} = \text{SOCs} \times \text{SOCr}^{-1}$$

where SOCs and SOCr are the SOC content of a given treatment and the reference soil, respectively. In this experiment, the paddy field was used as the reference soil.

$$LI = Ls \times Lr^{-1}$$

where Ls and Lr^{-1} represent the C pool activity of the treatment and reference soil (the paddy field), respectively.

$$L = EOC \times NLC^{-1}$$

where L is the carbon pool activity. EOC is the content of easily oxidizable organic C, while NLC refers to nonlabile C, which is the content of inactive organic C, calculated as the difference between SOC and EOC.

2.5. Statistical Analysis

The experimental data were collated using Excel 2021. The one-way analysis of variance and multiple comparisons ($p < 0.05$) were performed using IBM SPSS 25.0 statistical software. Correlation analysis was performed using bivariate correlation analyses and curve-fitting methods. Structural equation models (SEMs) were constructed using AMOS software (version 25) to examine the effects of land utilization type on soil properties and C components.

3. Results

3.1. Soil Physicochemical and Biological Properties

Our study showed that SOC concentration was significantly higher in the rice cultivations (20.87 g C kg^{-1}; Table 2) than in the areca nut plantations (11.92–17.05 g C kg^{-1}). Soil pH, TN, AK, MBC, and MBN were also significantly higher in the rice cultivations than in the areca nut plantations, but the opposite was true for AP and NH_4^+ concentrations (Table 2). The soil C/N ratio tended to increase in response to land-use change from rice cultivations to areca nut plantations, especially at A14 and A17. The results also showed that MBC and MBN significantly decreased with increased time since land-use transition from rice paddy cultivations to areca nut plantations (Table 2).

Table 2. Soil basic properties of studied soils under different land uses.

Parameter	Paddy	A2	A5	A10	A14	A17
SOC (g C kg^{-1})	20.87 ± 0.41 a	11.92 ± 0.65 d	13.14 ± 0.33 cd	12.16 ± 0.38 d	14.63 ± 0.87 c	17.05 ± 1.49 b
TN (g N kg^{-1})	1.92 ± 0.05 a	1.26 ± 0.17 c	1.22 ± 0.02 c	1.15 ± 0.05 c	1.31 ± 0.07 c	1.51 ± 0.11 b
C/N	10.86 ± 0.08 ab	9.60 ± 1.42 b	10.75 ± 0.08 ab	10.6 ± 0.36 ab	11.20 ± 0.07 a	11.26 ± 0.19 a
NH_4^+ (mg kg^{-1})	15.46 ± 1.00 a	8.71 ± 1.59 b	7.31 ± 0.40 bc	6.65 ± 0.81 c	5.81 ± 0.13 c	5.99 ± 0.53 c
NO_3^- (mg kg^{-1})	3.93 ± 0.4 c	8.86 ± 0.35 bc	12.27 ± 2.54 ab	16.49 ± 3.79 a	11.33 ± 3.13 ab	5.34 ± 0.23 c
pH	5.8 ± 0.01 a	5.48 ± 0.16 b	5.04 ± 0.01 c	4.68 ± 0.16 c	4.84 ± 0.14 c	5.34 ± 0.23 c
CEC (mmol kg^{-1})	4.03 ± 2.61 a	3.99 ± 2.50 a	4.75 ± 1.31 a	3.88 ±7.71 a	4.03 ± 5.04 a	4.39 ± 6.41 a
AP (mg kg^{-1})	34.78 ± 7.67 c	119.20 ± 11.8 a	116.89 ± 9.86 a	127.37 ± 6.67 a	79.13 ± 4.92 b	87.50 ± 6.11 b
AK (mg kg^{-1})	392.30 ± 0.00 a	146.39 ± 2.43 d	146.13 ± 6.28 d	260.03 ± 14.4 b	134.34 ± 28.4 d	180.89 ± 8.88 c
MBC (mg kg^{-1})	242.31 ± 10.1 a	191.94 ± 9.17 b	135.27 ± 13.7 c	112.61 ± 0.94 d	85.84 ± 4.15 e	83.62 ± 4.89 e
MBN (mg kg^{-1})	35.11 ± 4.11 a	23.76 ± 4.37 d	19.93 ± 4.94 bc	14.36 ± 0.83 cd	11.97 ± 0.55 d	11.22 ± 0.94 d

The A2, A5, A10, A14, and A17 represent the cultivation durations of the areca nut plantations. SOC: soil organic carbon, TN: soil total nitrogen, C/N: carbon to nitrogen ratio, NH_4^+: soil ammonium–nitrogen, NO_3^-: soil nitrate–nitrogen, CEC: soil cation exchange capacity, AP: soil available phosphorus, AK: soil available potassium, MBC: soil microbial carbon, and MBN: soil microbial nitrogen. Values are mean ± standard error (n = 3). Different letters indicate significant differences in different soils ($p < 0.05$).

3.2. Active SOC Pools

We found that land-use transition from rice paddy cultivations to areca nut plantations significantly increased all studied active SOC pools (DOC, EOC, POC, and LFOC) in the short term (e.g., A2) but decreased them in the long term (e.g., A5–A17) (Figure 1). Active SOC pools in the second year of transition from rice cultivation to areca increase and after that decrease in time. At the same time, SOC decreased in the second year in all the studied years (Table 3).

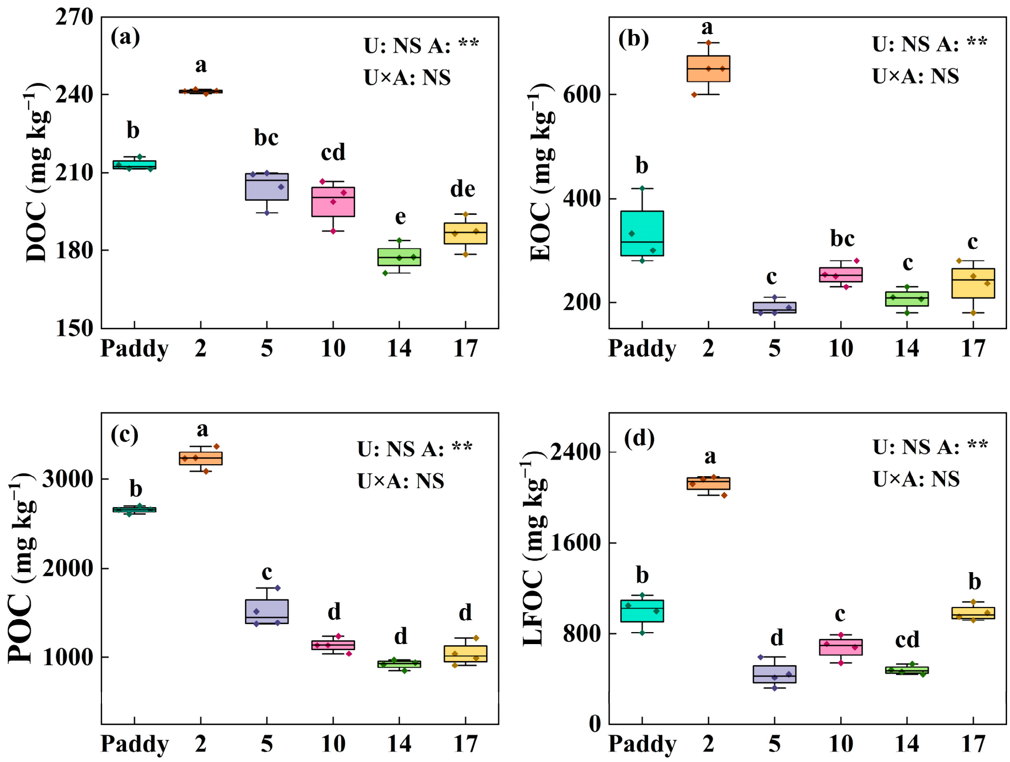

Figure 1. Effects of different land uses on the content of organic C fractions. The 2, 5, 10, 14, and 17 represent the cultivation durations of the areca nut plantations. DOC: dissolved organic carbon, EOC: easily oxidizable organic carbon, POC: particulate organic carbon, LFOC: light fraction organic carbon, and MBC: soil microbial carbon. Different lowercase letters in the figure represent significant differences between treatments ($p < 0.05$). In the results of two-factor ANOVA, U represents different utilization methods and A represents time treatment. U × A represents the interaction effect of different utilization modes and time processing; NS: no significant difference; **: $p < 0.01$. (**a**–**d**) indicates the subgraph number in the caption.

Table 3. The ratio of active fractions to SOC under different land uses.

Parameter	POC/SOC	EOC/SOC	DOC/SOC	LFOC/SOC	MBC/SOC
Paddy	12.73 ± 0.14 b	1.60 ± 0.34 b	1.02 ± 0.02 d	4.80 ± 0.84 bc	1.16 ± 0.04 b
A2	27.18 ± 1.20 a	5.49 ± 0.75 a	2.03 ± 0.13 a	17.88 ± 1.85 a	1.62 ± 0.15 a
A5	11.55 ± 1.80 b	1.45 ± 0.17 b	1.56 ± 0.04 b	3.35 ± 1.04 c	1.03 ± 0.10 bc
A10	9.37 ± 0.62 c	2.09 ± 0.28 b	1.63 ± 0.02 b	5.57 ± 0.89 b	0.93 ± 0.04 c
A14	6.29 ± 0.07 d	1.42 ± 0.25 b	1.21 ± 0.12 cd	3.28 ± 0.56 c	0.59 ± 0.04 d
A17	6.12 ± 0.82 d	1.41 ± 0.42 b	1.41 ± 0.08 c	5.85 ± 1.18 b	0.50 ± 0.09 d

The A2, A5, A10, A14, and A17 represent the cultivation durations of the areca nut plantations. The same lowercase letters suggest no significant difference between different planting years of areca nut and rice at 0.05 level.

3.3. Relationship between SOC and Its Fractions and Environmental Factors

Our study revealed that SOC increased significantly with increasing the time since land-use transition ($p < 0.01$; Figure 2a). However, DOC and DOC/SOC, MBC and MBC/SOC, POC and POC/SOC, LFOC and LFOC/SOC, and EOC and EOC/SOC decreased significantly with increased time since land-use transition ($p < 0.01$; Figure 2b–k). Soil NH_4^+ concentration had a significant and positive relationship with DOC and MBC ($p < 0.01$; Figure 2o,p). Soil MBC content increased significantly with increased DOC, POC, and soil pH ($p < 0.01$; Figure 2l–n). Soil DOC had a significant and positive relationship with EOC, POC, and, soil pH ($p < 0.01$; Figure 2q–s). Soil EOC was positively correlated to LFOC ($p < 0.01$; Figure 2t). We also found that SOC had a significant and positive correlation with NLC and CPI (p < 0.001; Figure 3). The EOC, LFOC, DOC, POC, and MBC were positively correlated to LI and CPMI (p < 0.001; Figure 3). The structural equation model (SEM) showed that land-use transition indirectly reduced LFOC, POC, and MBC, as well as EOC, by decreasing TN and soil pH and increasing the soil's C/N ratio.

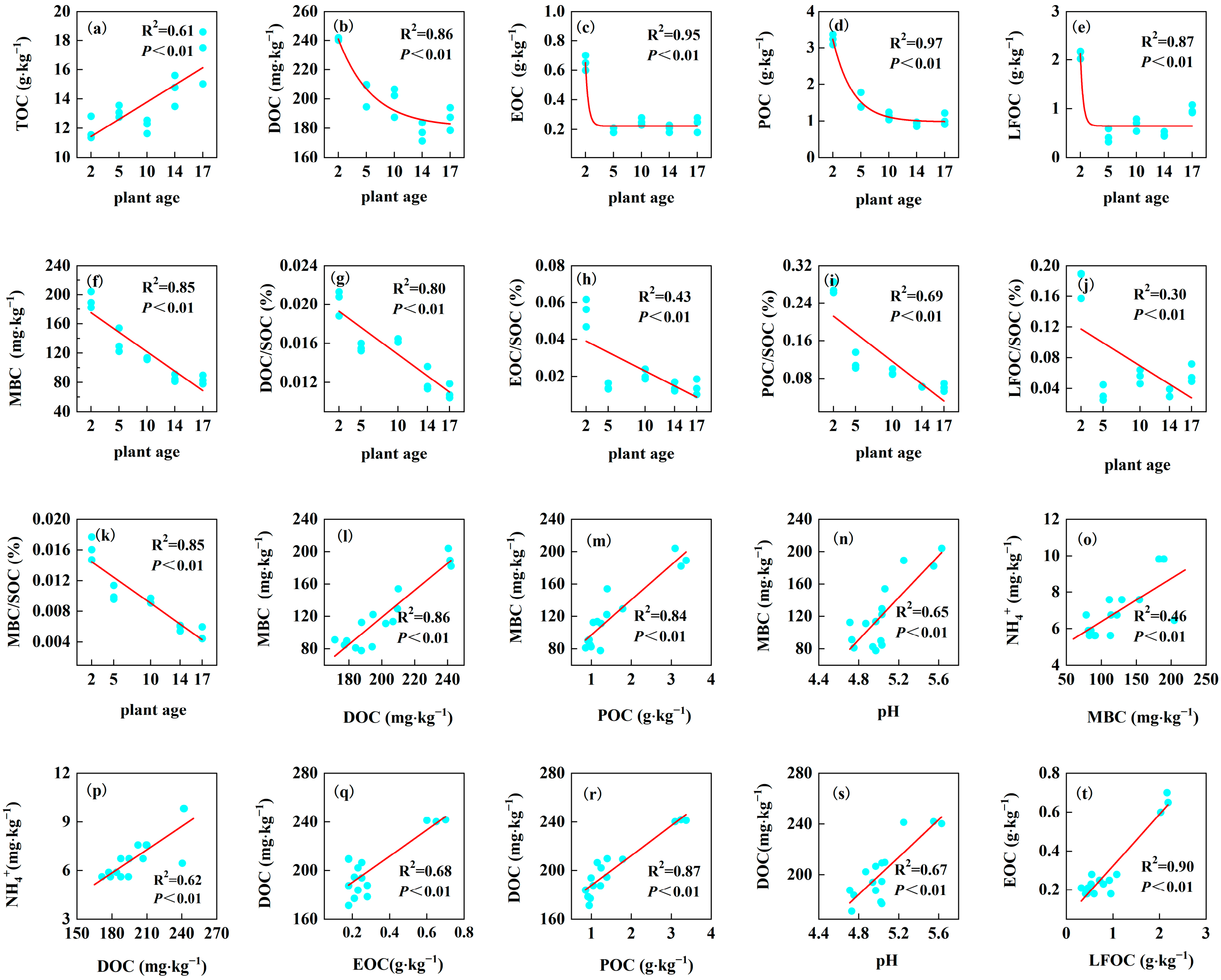

Figure 2. Correlation between planting years of areca nut and organic C and its fractions. Plant age represents the cultivation durations of the areca nut plantations. TOC: soil organic carbon, NH_4^+: soil ammonium-nitrogen, DOC: dissolved organic carbon, EOC: easily oxidizable organic carbon, POC: particulate organic carbon, LFOC: light fraction organic carbon, and MBC: soil microbial carbon. (**a**–**t**) indicates the subgraph number in the caption.

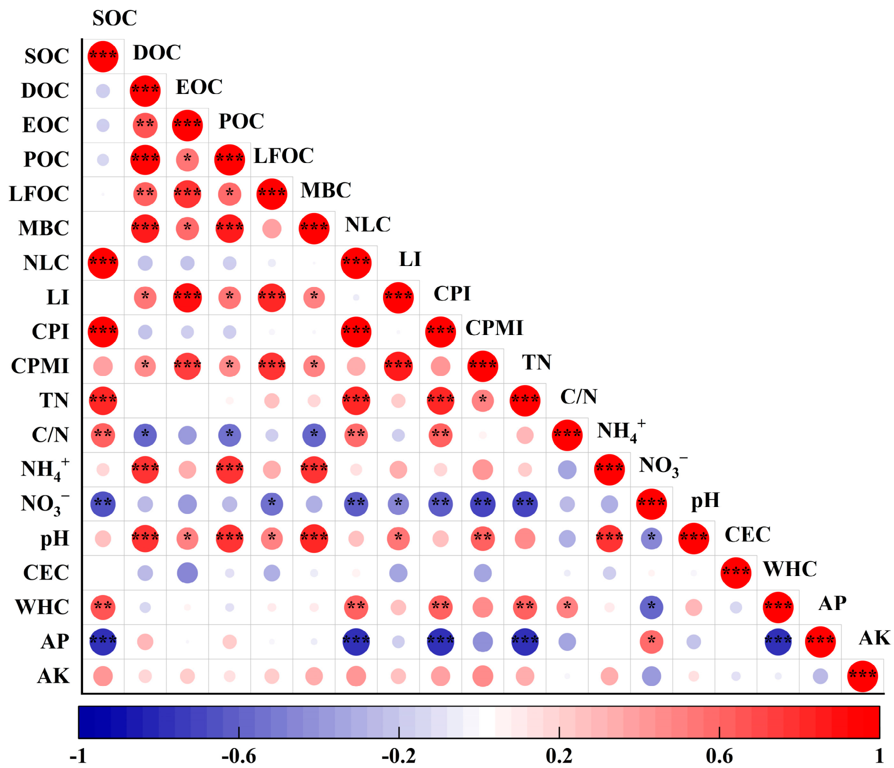

Figure 3. Correlation analysis of soil organic C and its fractions to soil properties. * Significant correlation at 0.05; ** Significant correlation at 0.01; *** Significant correlation at 0.001. SOC: soil organic carbon, DOC: dissolved organic carbon, EOC: easily oxidizable organic carbon, POC: particulate organic carbon, LFOC: light fraction organic carbon, MBC: soil microbial carbon, NLC: nonlabile carbon, LI: carbon pool activity index, CPI: carbon pool index, CPMI: carbon pool management index, TN: soil total nitrogen, C/N: carbon to nitrogen ratio, NH_4^+: soil ammonium–nitrogen, NO_3^-: soil nitrate–nitrogen, CEC: soil cation exchange capacity, WHC: water-holding capacity, AP: soil available phosphorus, AK: soil available potassium.

3.4. Areca Nut Plantations Reduced Soil Organic C Supply Capacity

The NLC and CPI were significantly decreased after the paddy field was converted into areca nut plantations (Table 4). Compared with paddy fields, the NLC and CPI were significantly decreased by 30–45% and 18–43%, respectively, in response to land-use transition. Similarly, the CPMI was significantly decreased in response to land-use transition (Table 4). Compared with paddy fields, the CPMI was significantly decreased by 36.6%, 76.7%, 73.3%, 68.3%, and 52.9% at A2, A5, A10, A14, and A17, respectively.

Table 4. Effects of land-use change on soil organic C supply capacity.

Parameter	NLC (g C kg^{-1})	L	LI	CPI	CPMI
Paddy	20.54 ± 0.48 a	6.85 ± 1.62 a	1.00 ± 0.00 a	1.00 ± 0.00 a	100.00 ± 0.00 a
A2	11.27 ± 0.85 d	7.30 ± 0.19 a	1.10 ± 0.25 a	0.57 ± 0.03 d	63.39 ± 16.8 b
A5	12.95 ± 0.42 cd	2.46 ± 0.16 c	0.37 ± 0.08 b	0.63 ± 0.01 bc	23.33 ± 5.11 d
A10	11.91 ± 0.49 d	3.01 ± 0.21 bc	0.46 ± 0.12 b	0.58 ± 0.03 d	26.70 ± 7.18 d
A14	14.42 ± 1.08 c	2.97 ± 0.31 bc	0.45 ± 0.09 b	0.70 ± 0.07 c	31.73 ± 9.62 cd
A17	14.42 ± 1.85 b	3.95 ± 0.75 b	0.58 ± 0.09 b	0.82 ± 0.07 b	47.13 ± 3.50 c

The A2, A5, A10, A14, and A17 represent the cultivation durations of the areca nut plantations, NLC: nonlabile carbon, L: carbon pool activity index, LI: carbon pool activity index, CPI: carbon pool index, and CPMI: carbon pool management index. The same lowercase letters suggest no significant difference between different planting years of areca nut and rice at 0.05 level.

4. Discussion

This study showed that the conversion of paddy fields to areca nut plantations significantly reduced SOC content. Although the long-term land-use transition (e.g., A14 and A17) significantly increased SOC content relative to the short-term transition (e.g., A2–A10), significant reductions in active C fractions with increased time since land-use transition were observed. The decrease in TN and soil pH and the increase in soil C/N ratio were the main reasons for the reduction in active SOC pools and SOC supply capacity in response to land-use change. These findings are significant for implementing appropriate agricultural management to improve and maintain SOC stocks in areca nut plantations.

We mainly focused on the mechanism of SOC supply capacity degradation under land-use change. Combining soil physicochemical properties with soil C fractions can more intuitively show the main factors influencing the SOC supply capacity under land-use change (Figure 4). The results of this study confirm that the SOC and MBC were significantly reduced by the conversion of paddy fields to areca nut plantations (Table 1). Short soil flooding time increases soil aeration and the number of aerophilic microorganisms, which ultimately may accelerate the decomposition of soil organic matter after the conversion of rice fields to areca nut plantations [26]. In addition, the conversion of rice fields to areca nut plantations resulted in a decrease in root exudation, plant residue, and soil animal and microbial activities, decreasing SOC and MBC [27]. This study also showed that the DOC (A5–A17) decreased significantly with the conversion of paddy fields to areca nut plantations (Figure 1). The reason may be that about 50–70% of DOC is adsorbed by iron and aluminum oxides and hydroxides, resulting in increased DOC in paddy fields [28]. The POC is an energy source and unstable organic C reservoir for microorganisms [29]. The results of this study show that POC decreased significantly (A5–A17) after the conversion of paddy fields to areca forests (Figure 1). Our results show a significant and positive correlation between soil pH and POC (Figures 3 and 4). The decrease in microbial activity caused by long-term flooding and the decrease in soil pH caused by long-term fertilization leads to a decrease in soil POC content [30]. Previous studies have also reported that LFOC is affected by organic matter input and decomposition rate [31]. The EOC is directly involved in the nutrient supply of plants and microorganisms, which is the most available component of SOC [32]. The results show that soil TN and POC were significantly positively correlated with LFOC and EOC, respectively (Figures 3 and 4). Moreover, the conversion of paddy fields to areca nut plantations significantly decreased the LFOC and EOC (A5–A17) (Figure 1). This may be due to the high temperature and rapid decomposition of large amounts of straw and roots in paddy fields increasing the content of TN and POC, which resulted in the accumulation of LFOC and EOC [33]. On the other hand, most areca plantations are roughly managed, with less tree litter and sparse understorey vegetation, resulting in a reduction in the LFOC and EOC [34]. The DOC, EOC, POC, and LFOC in A2 were significantly higher than in paddy fields (Figure 1). The reason is that in the short term, the residue of straw and root system in paddy fields will supplement the SOC content, resulting in an increase in the contents of DOC, EOC, POC, and LFOC [35].

Soil DOC, MBC, LFOC, and EOC were significantly positively correlated with pH (Figure 3). Soil POC and MBC are directly affected by pH (Figure 4). In this study, soil POC and MBC decreased with the increased age of areca nut plantations (Figure 1). In addition, The POC/SOC and MBC/SOC ratios showed the same trends as the POC and MBC concentrations, which showed that the long-term planting of areca nut resulted in a decrease in soil POC and MBC concentrations. This may be related to soil acidification due to long-term fertilization, which affects soil structure and its microbial activity [36]. Soil POC and MBC were influenced by soil structure and soil permeability [9]. Previous studies have reported that POC accumulates under the physical protection of the stable structure of soil aggregates [37]. Good air permeability can promote soil fertility, which increases microbial activity [38]. The proliferation of soil microbes significantly increases the MBC content of the soil [39]. Our study also revealed that soil POC and MBC decreased significantly with the increased age of areca nut plantations. This may be due to the fact that areca nut plantation management is no-till, with poor soil aggregate structure and permeability [40].

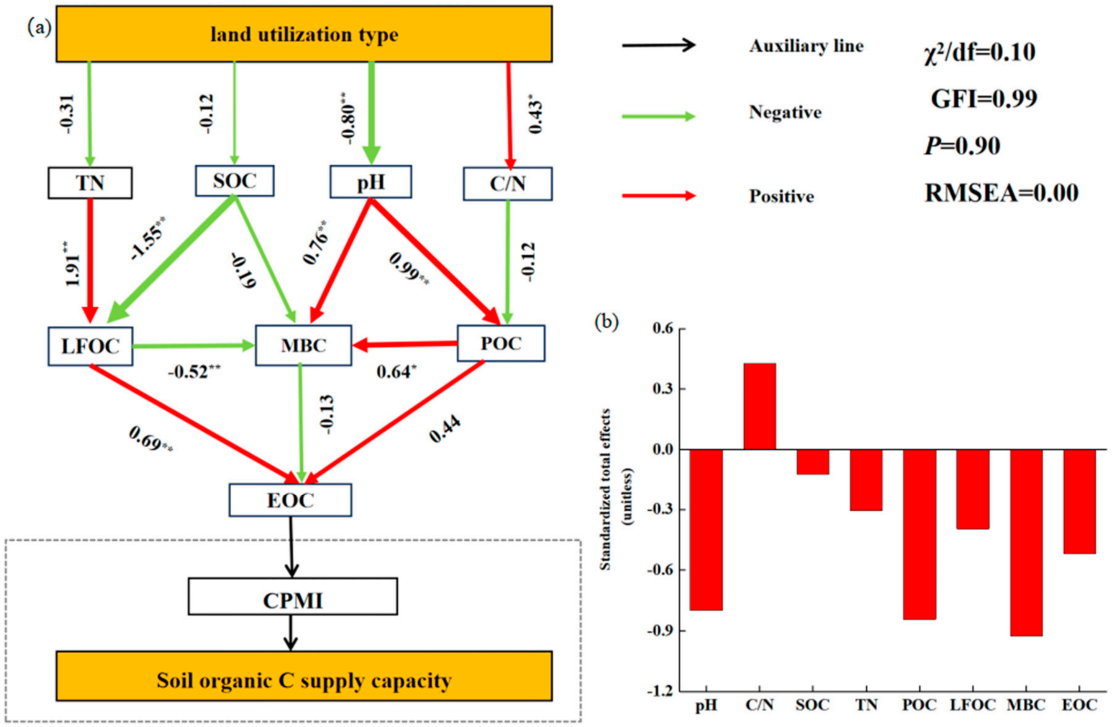

Figure 4. Direct and indirect effects of soil properties and soil C fractions on soil C pool under land-use change. TN: soil total nitrogen, SOC: soil organic carbon, C/N: carbon to nitrogen ratio, POC: particulate organic carbon, LFOC: light fraction organic carbon, MBC: soil microbial carbon, and EOC: easily oxidizable organic carbon. Line width indicates normalized path coefficient strength. Black arrows and red arrows indicate positive and negative significant relationships. χ^2/df, chi−square/degrees of freedom; p, probability level; GFI, goodness−of−fit index; RMSEA, root mean squared error of approximation. Significance levels of each predictor are $p < 0.01$. * Significant correlation at 0.05; ** Significant correlation at 0.01; (**a**,**b**) indicates the subgraph number in the caption.

In agricultural production, CPMI is one of the most commonly used soil management indicators, which helps to reveal the response of organic C to changes in soil management practices and serves as a comprehensive measure of the quantity and quality of organic C. The higher the CPMI of the soil, the higher the SOC content, and the greater the nutrient storage in the organic matter [41]. The conversion of paddy fields to areca nut plantations not only reduced SOC and EOC (A5–A17) but also significantly reduced CPMI contents (Table 3). The CPMI decreased significantly with the increase in the planting age of areca plantations. It showed an increasing trend at A10 but was significantly lower than that of the paddy fields. Rice cultivation is conducive to maintaining and improving the soil C pool management index, which is related to the relatively slow decomposition and transformation of organic C due to the lack of oxygen under flood conditions [42]. From the calculation formula of the soil C pool management index, it can be seen that the decrease in SOC and EOC will lead to a decrease in the soil C pool management index. Therefore, the management of long-term areca nut plantations should have some measures, such as increasing the application of organic fertilizer, to increase soil organic matter.

5. Conclusions

The effects of the time since land-use transition from rice paddy cultivation to areca nut plantations on soil organic carbon and its fractions were studied through an incubation study. The easily oxidized organic carbon, light organic carbon, particulate organic carbon, microbial biomass carbon, and dissolved organic carbon decreased with the increased age of areca nut plantations. The decreases in soil pH and soil total nitrogen were the main factors leading to the decrease in soil organic carbon and its fractions. Long-term areca nut plantations decreased the soil C pool management index, which was mainly related to the decrease in soil organic matter and pH. Therefore, agricultural practices such as lime and organic fertilization can be applied to improve soil's ability to supply organic C. The study of soil organic carbon fractions is essential for achieving sustainable agricultural development.

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