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Carbon Stock Dynamics in Rubber Plantations Along an Elevational Gradient in Tropical China

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Abstract: Carbon (C) losses due to the conversion of natural forests adversely affect the biotic and abiotic components of terrestrial ecosystems. In tropical China, rubber cultivation often extends from its traditional range to elevations of up to 1400 m. However, C stock in rubber plantations along elevation gradients is poorly understood. In this study, we investigated biomass and C stock along elevation gradients in two age groups (8- and 12-year-old) of rubber monoculture plantations in Xishuangbanna, Southwest China. The C distribution across various tree sections, ranging from aboveground biomass (AGB) to belowground biomass (BGB), including litter, big dead branches, and different soil depths were measured. A significant negative correlation was observed between AGB, BGB, litter, and total ecosystem C stocks and elevation gradients in both age groups. However, no correlation was observed between the total soil C stock and elevation gradients in 8-year-old rubber plantations, while significant decline was detected in 12-year-old rubber plantations. The highest ecosystem C stock of 197.90 Mg C ha^{-1} was recorded at 900 m in 8-year-old plantations; whereas, in 12-year-old rubber plantations, the highest value of 183.12 Mg C ha^{-1} was found at 700 m. The total ecosystem C stock decreased to their lowest level at 1000 m in both the 8-year-old and 12-year-old plantations, ranging between 113.05 Mg C ha^{-1} and 125.75 Mg C ha^{-1}, respectively. Moreover, total ecosystem C stock significantly decreased from 51.55% to 8.05% and from 42.96% to 11.46% between 700 m and 1100 m, in both 8-year-old and 12-year-old plantations, respectively. Regardless of elevation gradients, the total ecosystem C stock of 12-year-old rubber plantations was 1.98% greater than that of 8-year-old rubber plantations. Biomass was the second largest contributor, while soil accounted for 82% to 90%, and the other components contributed less than 2% of the total ecosystem C stock in both age groups. These fluctuations in C stock along elevation gradients in both 8- and 12-year-old plantations suggested that rubber growth, biomass, and C stock capacity decreased above 900 m, and that age and elevation are key factors for biomass and C stock in rubber monoculture plantations.

Keywords: elevation gradients; age effect; rubber monoculture plantations; carbon stock

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1. Introduction

Global warming is a major research issue globally, potentially causing significant adverse effects on forest composition, structure, and biological processes [1–3]. Tropical forests, which account for 45% of the global forest area, play a central role in regulating carbon (C) dioxide and store over 50% of terrestrial C [4–6]. However, C losses due to land use change in the tropics are estimated at 1.1 Gt C per year [5,7], adversely affecting the biotic and abiotic components of the Earth's ecosystems [3,8,9]. Furthermore, estimations of C stocks in deforested tropical forest areas are uncertain because of inaccurate biomass measurements and C concentrations [10]. Therefore, it is necessary to quantify the exact amount of C stock that is lost due to deforestation to mitigate global warming effects [11].

Global consumption of natural rubber (*Hevea brasiliensis*) latex reached 13.8 Mt in 2018 and is projected to increase to 16.1 Mt by 2025 [12]. As a result, rubber monoculture plantations in tropical regions are rapidly expanding at the expense of primary and secondary forests [13]. In tropical Southeast Asia, rubber cultivation is not a traditional agricultural practice [14]. After it originated from the Amazon basin, rubber cultivation began commercially in the 1950s [15]. Rubber has since become one of the most rapidly cultivated commercial crops in Southeast Asia [16,17], with 90% of the region's natural forests converted into rubber monoculture plantations due to income generated by latex commercialization [18]. The total area of rubber cultivation has increased from 5.5 Mha to 9.9 Mha globally over the last three decades, reached 1.2 Mha in tropical China [12], and is predicted to continue increasing over the next twenty years [19,20]. Initially, rubber cultivation in tropical regions was confined to elevations less than 800 m above sea level (a.s.l.), the natural upper range for rubber species distribution [21,22]. However, in Southwest China, rubber cultivation has extended to elevations of up to 1400 m due to land availability [23], despite studies showing that such a shift is not profitable [24,25]. This expansion into relatively high elevations has led to the conversion of species-rich tropical forests into rubber plantations, resulting in biodiversity loss, reduced biomass C stock, and increased C emissions [18]. While previous studies have reported biomass and C stocks along elevation gradients in forest ecosystems globally [26–28], there is limited information on the fluctuations in biomass and C stock in rubber plantations along the elevation gradients in tropical China. Accurate estimation of rubber tree biomass and C stocks along different elevation gradients is needed to predict the global C budget and its effects on the future regional climate cycle.

Carbon stock in forests occurs through photosynthesis, primarily in aboveground vegetation, and is transferred to belowground vegetation, including roots, soil, litter, and dead wood [29]. For example, Liu et al. [30] estimated that 68% of biomass C is stock in the aboveground part and more than 45% of total ecosystem C is stock in the soil regardless of rubber plantation age in tropical China. Ziegler et al. [31] reported that, in Southeast Asia, the total ecosystem C stock of rubber plantations ranged from 93 to 376 Mg C ha^{-1}; whereas the total ecosystem C stock of swidden systems ranged from 62 to 329 Mg C ha^{-1}. However, these studies do not provide comprehensive information on C stock dynamics of rubber plantations along elevational gradients [31]. Understanding the effects of environmental factors on C exchanges and their role in the global C cycle is necessary to inform policymakers [32]. Elevation gradients are natural scientific predictors for investigating climatic factors and their effects on ecological processes; whereas stand age provides information for assessing C stock dynamics [33–35].

Therefore, the aims of this study are as follows: (i) to evaluate biomass C stock and their allocation along an elevation gradient in two different aged (8- and 12-year-old) rubber monoculture plantations in Xishuangbanna, Southwest China; (ii) to understand how the total C stock in these rubber monoculture plantations is distributed among aboveground and belowground sections, including litter, big dead branches, and different soil depths; and (iii) to investigate the effects of stand age on the biomass and C stock of rubber monoculture plantations.

2. Materials and Methods

2.1. Study Site and Stand Description

This study involved rubber monocultures plantations with stand ages of 8 and 12 years in Xishuangbanna, Southwest China (Figure 1). It covers an area of 26,660 ha (22°04′–22°17′ N, 100°32′–100°44′ E), with an elevation range of 539 to 2304 m. The weather conditions feature a distinct combination of dry (November–April) and wet (May–October) seasons. The annual precipitation fluctuates from 1200 to 1700 mm, and the mean temperature varies from 18 to 22 °C [36]. The soil is classified into two main categories: Ferralsols, which are the major type of soil, and Regolsols, which are the minor type of soil [37].

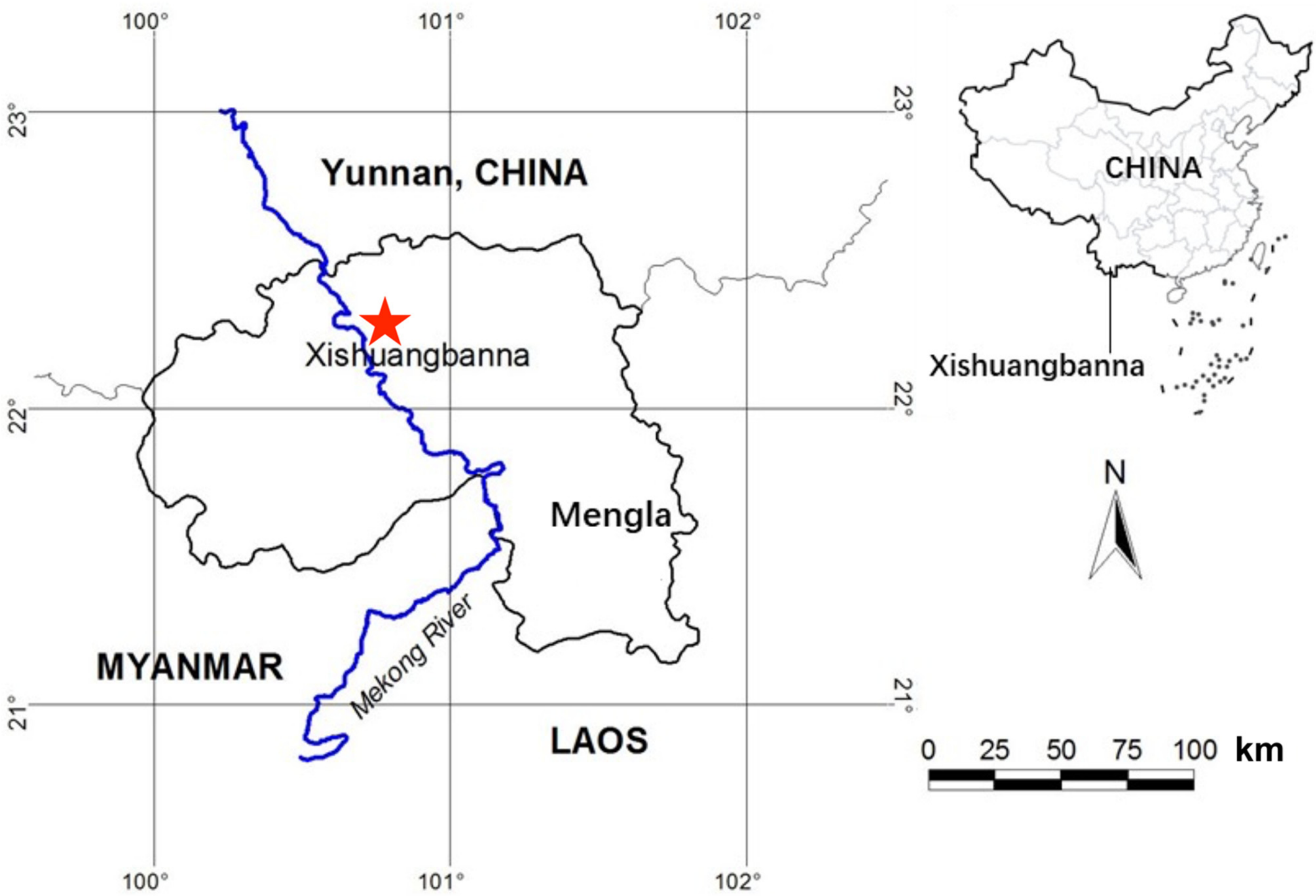

Figure 1. Study site of rubber monoculture plantations is located in Xishuangbanna, Southwest China.

Ten stands of two aged groups (8- and 12-year-old) of rubber monoculture plantations were established along five elevation gradients in 2015 (Table 1). At each elevation gradient, six sampling plots (20 m × 25 m) were established in each age group with planting specifications of 6 m × 2.5 m (inter and intra row spacing, respectively). The topographic features, such as slope and elevation in both the 8- and 12-year-old rubber plantations were recorded (Table 1).

Table 1. Stand characteristics of 8- and 12-year-old rubber monoculture plantations along five elevation gradients.

Age	Elevation (m)	Longitude	Latitude	Slope (°)	Planting Spacing (m)	DBH (cm)	Height (m)
8-Year-old	700	100°40′33.58″	22°07′53.10″	25	6 × 2.5	16.56 ± 0.13 a	12.46 ± 0.16 a
	800	100°39′53.21″	22°08′51.55″	30	6 × 2.5	15.95 ± 0.45 a	11.94 ± 0.74 a
	900	100°37′47.52″	22°13′26.74″	30	6 × 2.5	15.21 ± 0.26 a	11.38 ± 0.85 a
	1000	100°37′44.91″	22°13′26.89″	25	6 × 2.5	13.22 ± 0.79 b	9.83 ± 0.38 b
	1100	100°36′46.93″	22°14′25.33″	25	6 × 2.5	11.87 ± 0.74 b	8.52 ± 0.14 c

Table 1. *Cont.*

Age	Elevation (m)	Longitude	Latitude	Slope (°)	Planting Spacing (m)	DBH (cm)	Height (m)
12-Year-old	700	100°40′03.48″	22°07′49.81″	30	6 × 2.5	17.82 ± 0.86 a	14.35 ± 0.58 a
	800	100°40′38.58″	22°08′36.33″	25	6 × 2.5	17.23 ± 0.81 ab	13.87 ± 0.48 ab
	900	100°37′47.62″	22°13′26.79″	30	6 × 2.5	16.94 ± 0.78 b	13.26 ± 0.39 b
	1000	100°37′44.69″	22°13′28.65″	25	6 × 2.5	16.07 ± 0.60 c	12.42 ± 0.37 c
	1100	100°36′47.46″	22°14′24.47″	30	6 × 2.5	15.64 ± 0.52 c	11.35 ± 0.53 c

Note: Values are means ± SE. Means followed by different lowercase letters in the same column indicate significant differences in 8- and 12-year-old rubber monoculture plantations along five elevation gradients according to Tukey's HSD test ($p < 0.05$).

2.2. Field Sampling and Measurements

The diameter at breast height (1.3 m, DBH) and height were measured for all rubber trees in each plot within 8- and 12-year-old plantations with DBH tape and a clinometer, respectively. Aboveground biomass (AGB) and belowground biomass (BGB) of different components of rubber trees was estimated according to our previous allometric biomass models for the Xishuangbanna area of China [38].

For litter collection, ten litter traps (0.5 m^2 each) were placed 5 m apart in each plot and collected monthly from January to December 2015. Litterfall samples of rubber trees were sorted into leaves, branches, flowers/fruits, and miscellaneous, and the litter amount per unit area and the annual litter amount were measured. Litter samples were divided into two subsamples. One subsample of litter was oven-dried to a constant weight at 70 °C to calculate the fresh-to-dry biomass ratio; the other subsample was used for chemical element analysis. To collect big dead branches, we randomly set up six collection traps (5 m × 4 m) and collected them once every month. The number of big dead branches per unit area and their annual amount were measured. After measurement, we divided the big dead branches into two subsamples: one was oven-dried to a constant weight at 70 °C to calculate the fresh-to-dry biomass ratio, and the other was used for chemical element analysis.

In December 2015, three soil profiles were dug at depths of 110 cm at the upper, middle, and lower 3 positions in each plot, and soil samples were collected from six soil depths (0–10, 10–30, 30–50, 50–70, 70–90, and 90–110 cm). Equal amounts of soil samples taken from the same depth in the same plot were thoroughly mixed to obtain composite soil samples. The composite soil samples were air-dried at room temperature and sieved with a 2 mm mesh to remove gravel and vegetation. For the measurement of soil bulk density, soil samples were collected from each soil depth, and the soil bulk density was calculated by dividing the weight of the soil after oven-drying the soil samples to a constant weight at 105 °C over the core volume.

Elemental analysis was conducted to measure the C concentrations in litter and big dead branches, as well as in soil samples, via a Vario Max CNS elemental analyzer (ELEMENTAR, Germany). Dried biomass was multiplied with the reference C conversion to calculate the above- and belowground C stocks of rubber trees [30,39]. The C stock in the litter biomass components and big dead branches was calculated by multiplying their oven-dried biomass by their respective C concentrations. The soil C stock was estimated from the C concentrations at each soil depth multiplied by their bulk density and depth interval.

2.3. Statistical Analysis

Variations in rubber tree biomass, biomass C stock, litter C concentrations, soil C concentrations, and soil bulk density along elevational gradients were tested via one-way ANOVA, followed by Tukey's honest significant difference test when ANOVA was significant. The relationships among elevation gradients, age, tree component C stock, soil C stock and total ecosystem C stock were assessed via linear modeling. All the analyses were conducted in R version 4.0.3 (R-Foundation for Statistical Computing, Vienna, Austria).

3. Results

3.1. Tree Biomass Partitioning

A negative correlation was observed between the total biomass of above- and belowground sections of rubber trees and elevation gradients in both age groups of rubber monoculture plantations (Table 2). However, no significant difference in total biomass and various components was noted across elevation gradients ranging from 700 to 900 m in the 8-year-old plantations. Notably, a significant decline in biomass was observed at 1000 m and 1100 m compared with below 900 m in the 8-year-old plantations. By contrast, 12-year-old plantations presented a similar elevational trend and an obvious decrease in total biomass and various components at 900 m. Across all the elevation gradients, stems contributed the most biomass, followed by roots, branches, and foliage, in both age groups.

Table 2. Rubber tree biomass (Mg ha^{-1}) of 8- and 12-year-old rubber monoculture plantation along five elevation gradients.

Age	Elevation (m)	Stem	Branch	Foliage	Root	Total
8-Year-old	700	31.64 ± 1.81 a	8.82 ± 0.50 a	1.58 ± 0.07 a	11.62 ± 0.46 a	53.66 ± 2.85 a
	800	29.27 ± 0.87 a	8.18 ± 0.24 a	1.51 ± 0.05 a	11.36 ± 0.36 a	50.32 ± 1.52 a
	900	27.75 ± 0.79 a	7.75 ± 0.22 a	1.42 ± 0.04 a	10.65 ± 0.25 a	47.57 ± 1.29 a
	1000	18.93 ± 0.35 b	5.34 ± 0.10 b	1.09 ± 0.02 b	8.86 ± 0.19 b	34.21 ± 0.66 b
	1100	14.39 ± 0.59 c	4.07 ± 0.16 c	0.84 ± 0.03 c	6.87 ± 0.26 c	26.17 ± 1.05 c
12-Year-old	700	41.84 ± 1.78 a	11.60 ± 0.49 a	1.97 ± 0.08 a	13.90 ± 0.54 a	69.31 ± 2.89 a
	800	37.04 ± 0.71 b	10.30 ± 0.20 b	1.81 ± 0.05 ab	13.18 ± 0.49 ab	62.33 ± 1.45 ab
	900	33.58 ± 0.98 b	9.33 ± 0.27 b	1.63 ± 0.04 b	11.75 ± 0.33 b	56.29 ± 1.62 b
	1000	27.14 ± 0.75 c	7.56 ± 0.21 c	1.35 ± 0.03 c	9.88 ± 0.22 c	45.93 ± 1.21 c
	1100	23.95 ± 0.72 c	6.67 ± 0.20 c	1.19 ± 0.03 c	8.66 ± 0.24 c	40.46 ± 1.19 c

Note: Values are means ± SE. Means followed by different lowercase letters in the same column indicate significant differences in 8- and 12-year-old rubber monoculture plantations along five elevation gradients according to Tukey's HSD test ($p < 0.05$).

3.2. Litter Biomass and C Concentration

Litter biomass was negatively correlated with elevation and significantly decreased along elevation gradients in both age groups of rubber monoculture plantations (Table 3). The highest litter biomass was observed at 700 m and the lowest at 1100 m. Across all elevation gradients, leaves contributed the most biomass, followed by twigs and big dead branches; whereas miscellaneous and flowers/fruits contributed the least biomass in both age groups (Table 3). While litterfall components of both age groups, including leaf, twig, flower/fruits, miscellaneous, and big dead branches, varied in percent C concentrations between 44% and 51% along elevation gradients.

Table 3. Litter biomass (Mg ha^{-1}) of 8- and 12-year-old rubber monoculture plantation along five elevation gradients.

Age	Elevation (m)	Leaf	Twig	Flowers/Fruits	Miscellaneous	BDB	Total
8-Year-old	700	4.17 ± 0.25 a	0.50 ± 0.10 a	0.04 ± 0.02 a	0.08 ± 0.00 a	0.17 ± 0.05 ab	4.95 ± 0.43 a
	800	2.48 ± 0.25 b	0.66 ± 0.09 a	0.09 ± 0.08 a	0.12 ± 0.02 ab	0.33 ± 0.10 a	3.67 ± 0.55 b
	900	2.39 ± 0.08 b	0.37 ± 0.06 a	0.01 ± 0.00 a	0.06 ± 0.00 b	0.09 ± 0.05 ab	2.90 ± 0.19 bc
	1000	2.55 ± 0.33 b	0.75 ± 0.08 a	ND	0.06 ± 0.01 b	0.12 ± 0.04 ab	3.47 ± 0.46 b
	1100	1.63 ± 0.21 b	0.49 ± 0.22 a	ND	0.05 ± 0.01 b	0.06 ± 0.03 b	2.23 ± 0.47 c

Table 3. *Cont.*

Age	Elevation (m)	Leaf	Twig	Flowers/Fruits	Miscellaneous	BDB	Total
12-Year-old	700	4.80 ± 0.24 a	0.23 ± 0.03 a	0.30 ± 0.07 a	0.09 ± 0.01 a	0.21 ± 0.06 a	5.62 ± 0.40 a
	800	3.23 ± 0.19 b	0.30 ± 0.07 a	0.02 ± 0.01 b	0.06 ± 0.01 b	0.43 ± 0.20 a	4.04 ± 0.48 b
	900	2.63 ± 0.13 bc	0.36 ± 0.08 a	ND	0.05 ± 0.01 b	0.20 ± 0.07 a	3.23 ± 0.28 bc
	1000	3.20 ± 0.18 b	0.43 ± 0.08 a	ND	0.04 ± 0.00 b	0.15 ± 0.07 a	3.82 ± 0.34 bc
	1100	2.31 ± 0.16 dc	0.32 ± 0.06 a	0.02 ± 0.02 b	0.03 ± 0.00 b	0.10 ± 0.04 a	2.78 ± 0.29 c

Note: Values are means ± SE. Means followed by different lowercase letters in the same column indicate significant differences in 8- and 12-year-old rubber monoculture plantations along five elevation gradients according to Tukey's HSD test ($p < 0.05$). BDB (Big dead branches). ND (Not detected).

3.3. Tree Components C Stock

Significant negative correlation was observed between the total biomass C stock (AGB and BGB) and elevation gradients in both age groups of rubber monoculture plantations (Figure 2a,b). The C stock of AGB showed a decreasing trend with elevation gradients, declining from 54.06% to 7.33%, in 8-year-old plantations, and from 43.05% to 11.26%, in 12-year-old plantations, between 1100 m and 700 m. This decline in AGB C stock between 1100 m and 700 m was more pronounced than that in the BGB C stock, which varied from 40.88% to 2.24% and from 39.56% to 5.23%, in the 8- and 12-year-old plantations, respectively. Comparatively, the highest biomass C stock in AGB and BGB components were stored at 700 m; whereas the lowest were observed at 1100 m in both age groups. However, the total biomass C stock increased with plantation age and ranged from 11.41 Mg C ha^{-1} to 23.39 Mg C ha^{-1}, in the 8-year-old plantations, and from 17.41 Mg C ha^{-1} to 30.21 Mg C ha^{-1}, in the 12-year-old plantations.

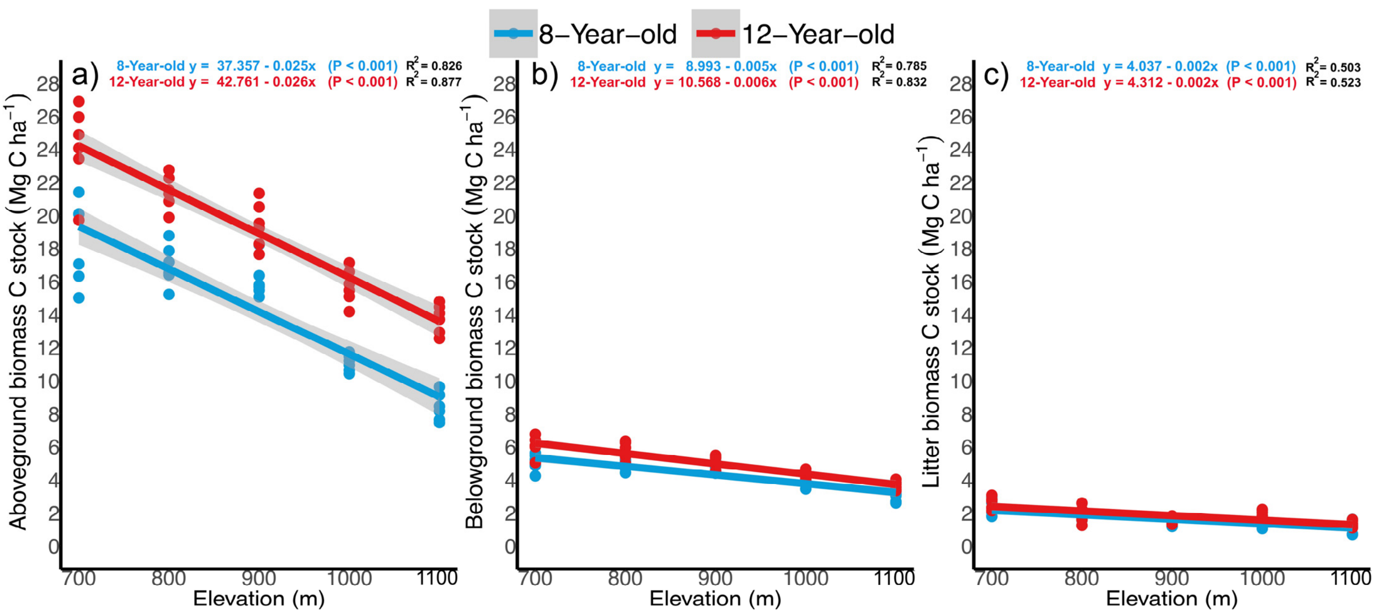

Figure 2. Relationship between elevation (m) and (**a**) aboveground biomass C stock (Mg C ha^{-1}), (**b**) belowground biomass C stock (Mg C ha^{-1}) and (**c**) litter C stock (Mg C ha^{-1}) in 8-year-old and 12-year-old rubber monoculture plantation along five elevation gradients.

Litter C stock in both 8- and 12-year-old plantations were also negatively correlated with elevation gradients (Figure 2c) and varied from 1.06 Mg C ha^{-1} to 2.35 Mg C ha^{-1}, in the 8-year-old plantations, and from 1.33 Mg C ha^{-1} to 2.65 Mg C ha^{-1}, in the 12-year-old plantations. Litter C stock between 1100 m and 700 m decreased from 54.88% to 26.26%, in the 8-year-old plantations, and from 49.89% to 27.54%, in the 12-year-old plantations.

Both age groups presented around a 30% decline in litter C stock at 1100 m compared with 700 m.

3.4. Soil C Concentration and Stock

The elevation gradients and soil depth significantly influenced the soil C concentrations without an interaction effect in both age groups of rubber monoculture plantations (Figure 3c,d). The average soil C concentration decreased significantly with increasing soil depth in both age groups. However, it fluctuated with increasing elevation at the 110 cm depth, with the highest values observed at 800 m and 700 m in the 8- and 12-year-old plantations, respectively, while the lowest values were found at 1000 m in both age groups. By contrast, the average soil bulk density increased with soil depth, ranging from 0.88 g cm^{-3} to 1.28 g cm^{-3} and from 0.91 g cm^{-3} to 1.29 g cm^{-3} in the 8- and 12-year-old plantations, respectively (Figure 3a,b). Across all elevation gradients, the highest soil bulk density was found at 900 m, and the lowest was found at 700 m in both age groups.

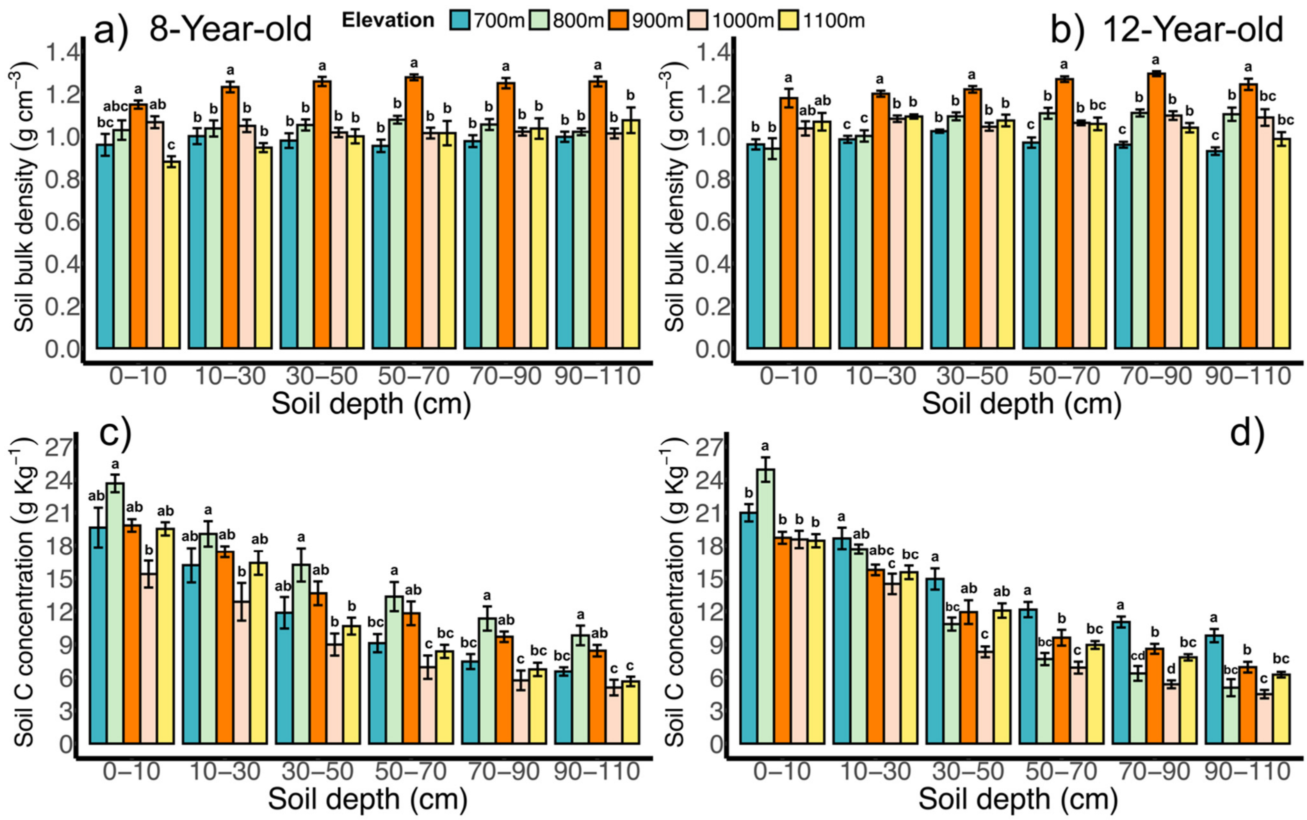

Figure 3. Soil bulk density in (**a**) 8-year-old and (**b**) 12-year-old, and soil C concentration in (**c**) 8-year-old and (**d**) 12-year-old rubber monoculture plantation along five elevation gradients. Bars with different lowercase letters indicate significant differences among the same soil depth of 8-year-old and 12-year-old rubber monoculture plantations along five elevation gradients according to Tukey's HSD test ($p < 0.05$). Vertical bars show ± SE.

There was only a significant negative correlation between the total soil C stock and elevation gradients in the 12-year-old rubber plantations (Figure 4a). The total soil C stock at 110 cm depth decreased across the elevation gradients and fluctuated, with the highest values of 175.77 Mg C ha^{-1} and 153.51 Mg C ha^{-1} at 900 m and the lowest values of 96.49 Mg C ha^{-1} and 103.90 Mg C ha^{-1} at 1000 m in both 8- and 12-year-old plantations, respectively (Table 4). Compared with 12-year-old plantations, soil C stock in the 8-year-old plantations decreased at 700 m (32.36 Mg C ha^{-1}), 1100 m (14.72 Mg C ha^{-1}), and 1000 m (7.42 Mg C ha^{-1}); whereas it increased at 800 m (44.92 Mg C ha^{-1}) and 900 m

(22.27 Mg C ha^{-1}) (Table 4). In both age groups, 59.73% to 60.12% of soil C was stored within the 0–50 cm depth along each elevation gradient. However, soil C stock declined with soil depth, ranging from 42.92 Mg C ha^{-1} at 10−30 cm to 9.03 Mg C ha^{-1} at 90−110 cm, in the 8-year-old plantations, and from 35.31 Mg C ha^{-1} at 10−30 cm to 9.65 Mg C ha^{-1} at 90−110 cm, in the 12-year-old plantations (Table 4). Regardless of elevation gradients, total soil C stock at the 110 cm soil depth were slightly high in the 8-year-old plantations.

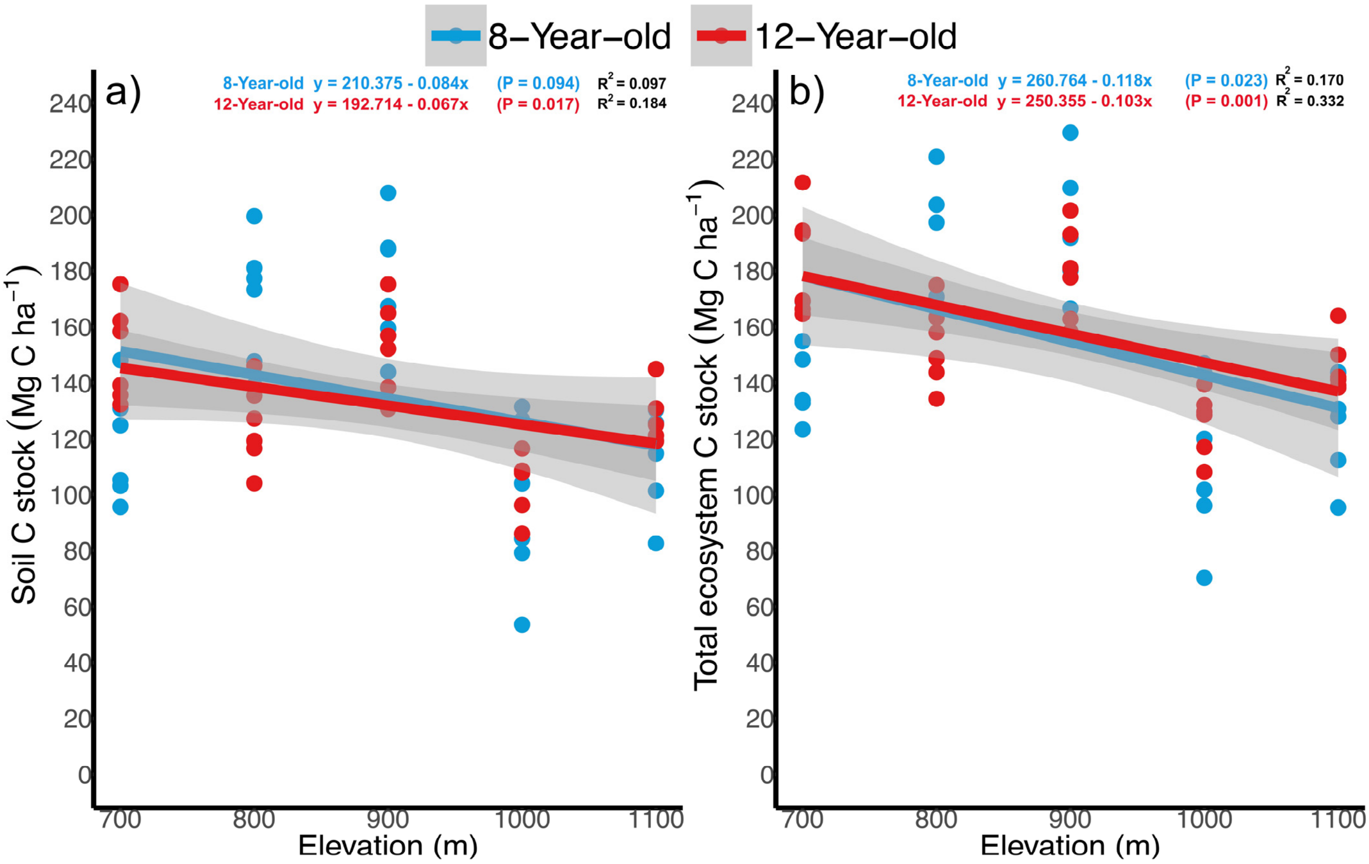

Figure 4. Relationship between elevation (m) and (**a**) soil C stock (Mg C ha^{-1}) and (**b**) total ecosystem C stock (Mg C ha^{-1}) in 8-year-old and 12-year-old rubber monoculture plantation along five elevation gradients.

Table 4. Soil C Stock (Mg C ha^{-1}) in 8- and 12-year-old monoculture rubber plantation along five elevation gradients.

Age	Depth (cm)	0–10	10–30	30–50	50–70	70–90	90–110	Total
8-Year-old	700 m	18.39 ± 0.80 ab	31.87 ± 2.12 bc	22.91 ± 2.37 b	17.31 ± 1.56 b	14.44 ± 1.18 b	13.00 ± 0.67 b	117.91 ± 1.45 b
	800 m	24.17 ± 0.48 a	39.13 ± 1.38 ab	33.83 ± 2.66 a	28.61 ± 2.68 a	23.79 ± 2.07 a	20.11 ± 2.05 a	169.64 ± 1.89 a
	900 m	22.80 ± 0.83 b	42.92 ± 1.50 a	34.36 ± 2.96 a	30.19 ± 2.82 a	24.25 ± 1.41 a	21.25 ± 1.54 a	175.77 ± 11.06 a
	1000 m	16.47 ± 1.55 b	26.86 ± 3.58 c	18.40 ± 2.27 b	14.11 ± 2.29 b	11.61 ± 1.72 b	9.03 ± 1.30 b	96.49 ± 12.72 b
	1100 m	17.19 ± 0.81 b	30.92 ± 1.87 bc	21.25 ± 1.5 b	16.93 ± 1.42 b	13.89 ± 1.28 b	12.11 ± 1.16 b	112.29 ± 8.08 b
12-Year-old	700 m	19.12 ± 0.5 a	26.25 ± 3.69 ab	34.83 ± 2.10 a	27.05 ± 2.31 a	22.88 ± 1.97 a	20.14 ± 1.66 a	150.27 ± 2.04 a
	800 m	23.26 ± 0.95 a	35.31 ± 0.92 ab	23.79 ± 1.58 ab	17.03 ± 1.35 b	14.17 ± 1.59 b	11.16 ± 1.71 c	124.71 ± 1.35 ab
	900 m	21.67 ± 1.20 a	33.26 ± 3.58 a	31.71 ± 3.14 a	25.24 ± 2.26 a	22.85 ± 1.47 a	18.78 ± 2.07 ab	153.51 ± 13.71 a
	1000 m	19.24 ± 0.99 a	31.26 ± 1.74 b	17.33 ± 0.94 b	14.61 ± 1.09 b	11.81 ± 0.89 b	9.65 ± 0.63 c	103.90 ± 6.28 b
	1100 m	19.66 ± 0.85 a	33.99 ± 1.55 ab	25.78 ± 1.00 a	18.94 ± 1.00 ab	16.26 ± 0.62 b	12.39 ± 0.80 bc	127.01 ± 5.82 ab

Note: Values are means ± SE. Means followed by different lowercase letters in the same column indicate significant differences among soil depths of 8-year-old and 12-year-old rubber monoculture plantations along five elevation gradients according to Tukey's HSD test ($p < 0.05$).

3.5. Total Ecosystem C Stock

A significant negative correlation was observed between total ecosystem C stock and elevation gradients in both age groups of rubber monoculture plantations (Figure 4b). The total ecosystem C stock was relatively high in the 12-year-old rubber plantations and fluctuated with elevation gradients in both age groups, ranging from 113.05 Mg C ha^{-1} at 1000 m to 197.90 Mg C ha^{-1} at 900 m, in the 8-year-old plantations, and from 125.75 Mg C ha^{-1} at 1000 m to 183.12 Mg C ha^{-1} at 700 m, in the 12-year-old plantations. Across all elevation gradients, the soil was the largest C pool, accounting for 82.08% to 90% and 82.6% to 87.14% of the total ecosystem C stock in both 8- and 12-year-old plantations, respectively (Figure 5). Biomass was the second-largest contributor, and litter contributed less than 2% of the total ecosystem C stock across all elevation gradients in both age groups (Figure 5). However, the total biomass C stock significantly decreased from 51.55% to 8.05% and from 42.96% to 11.46% between 1100 m and 700 m in both 8- and 12-year-old plantations, respectively. Regardless of elevation gradients, the total ecosystem C stock of 12-year-old plantations was 1.98% greater than that of 8-year-old plantations.

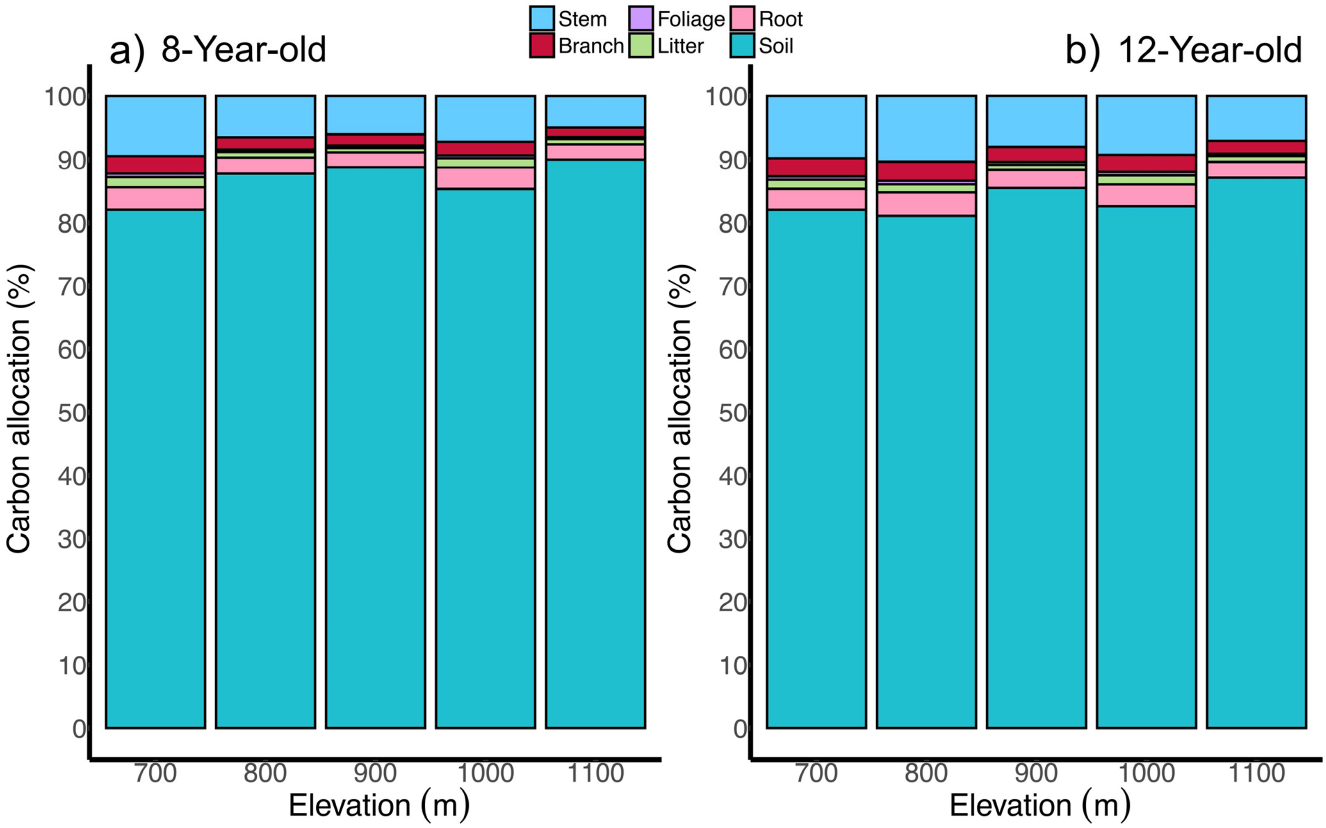

Figure 5. Allocation of total ecosystem C stocks (%) in different compartments (stem, branch, leaf, litter, root and soil) of (**a**) 8-year-old and (**b**) 12-year-old rubber monoculture plantation along five elevation gradients.

4. Discussion

4.1. Effect of Elevation Gradient on Biomass C Stock

Previous studies in tropical regions have shown that the growth rates of rubber trees are profoundly affected by age, soil types, and climatic conditions [38,40–42]. However, to date, no study has explained the effects of age and elevation gradient on the biomass C stock of rubber trees. In the present study, the highest tree C stock in 8- and 12-year-old rubber plantations was observed at 700 m, which was lower than those reported in a 7-year-old rubber plantation (45 m a.s.l.) in Rio de Janeiro, Brazil [43], and a 12-year-old rubber plantation (500 m a.s.l.) in Minas Gerais, Brazil [21]. These variations in the tree C stock illustrate the negative effect of the elevation gradient on the biomass C stock of rubber plantations. The C stock of trees at lower elevations, specifically at 700 m, varied between 23.39 Mg C ha^{-1}, in 8-year-old rubber plantations, and 30.21 Mg C ha^{-1}, in 12-

year-old rubber plantations. These values were lower than the average tree C stock of 55.3 Mg C ha^{-1} in 9-year-old plantations in Southwest China, planted at an elevation of 590 m [44], and higher than the tree C stock of 13- and 7-year-old plantations in tropical China, planted at elevations between 620 m and 587 m, respectively [30]. Additionally, the reported value of the tree C stock of 61.4 Mg C ha^{-1} by Li et al. [45] at elevations under 800 m in rubber plantations surpassed our findings. Above 700 m, there was a significant reduction in the tree C stock in both 8- and 12-year-old rubber plantations. At 1100 m, the lowest tree C stock ranged from 17.41 Mg C ha^{-1}, in 12-year-old rubber plantations, to 11.41 Mg C ha^{-1}, in 8-year-old rubber plantations. Therefore, this significant reduction in the tree C stock at relatively high elevations explains the elevation-related impact on the biomass C stock in rubber plantations. Notably, in Xishuangbanna, China, the biomass C stock in tropical seasonal rainforests was reported to be 165.9 Mg C ha^{-1} by Lü et al. [46]. Consequently, at 700 m, the biomass C stock of rubber monoculture plantations experienced a loss of 135.69 Mg C ha^{-1} in 12-year-old rubber plantations and 142.51 Mg C ha^{-1} in 8-year-old rubber plantations compared to tropical seasonal rainforests. At higher elevations of 1100 m, the biomass C stock of rubber monoculture plantations experienced further C losses of 148.49 Mg C ha^{-1} in 12-year-old rubber plantations and 154.49 Mg C ha^{-1} in 8-year-old rubber plantations compared to tropical seasonal rainforests.

The leaf litter C concentrations along all the elevation gradients in the 8- and 12-year-old plantations were lower than those in the 7- and 12-year-old rubber plantations in southern Côte d'Ivoire [47], and higher than those in the rubber plantation at an elevation between 700 m and 830 m in Xishuangbanna, China [48]. The average litter C concentrations along all elevation gradients in the 8- and 12-year-old plantations were lower than those in the 7- and 13-year-old plantations in tropical China, which are planted at elevations ranging from 587 m and 620 m, respectively [30], and in the 7- and 9-year-old plantations in Southwest China, which are planted at an elevation of 590 m [44]. The highest litter C stock in 8-year-old rubber plantations (2.35 Mg C ha^{-1}) was observed at 700 m, which exceeded the litter C stock reported in the 7-year-old rubber plantations of tropical China (1.42 Mg C ha^{-1}), planted at an elevation range of 580–595 m [30], in Southwest China (1.8 Mg C ha^{-1}), planted at an elevation range of 587 m [44], and rubber plantations in Xishuangbanna, China, planted at an elevation range of 700–830 m [48]. However, the litter C stock in 8-year-old rubber plantations decreased at 700 m compared with that in 9-year-old plantations in Southwest China (3.6 Mg C ha^{-1}), planted at an elevation range of 590 m [44]. Above 900 m, the litter C stock in 8-year-old rubber plantations was lower than that in regional rubber plantations. In 12-year-old rubber plantations at 700 m, the highest litter C stock of 2.65 Mg C ha^{-1} was greater than that in 13-year-old rubber plantations in tropical China (2.35 Mg C hm^{-1}), planted at an elevation range of 600–620 m [30], but lower than the litter C stock in 14-year-old rubber plantations (4.1 Mg C ha^{-1}) in western Ghana and Mato Grosso in Brazil [49]. However, the litter C stock along all elevation gradients in both the 8- and 12-year-old plantations decreased relative to that in the secondary forest in Xishuangbanna, China (2.7 Mg C ha^{-1}) [48], and the greatest reduction was observed above 900 m. The observed variations in the litter C stock explain the effects of age and elevation gradients on the litter C stock in rubber monoculture plantations.

4.2. Effect of Elevation Gradient on Soil C Stock

The soil C stock in the topsoil at 0–50 cm depth in 8-year-old rubber plantations at an elevation of 700 m was lower than that in 7-year-old rubber plantations in tropical China (580 m a.s.l.) [30], Southwest China (587 m a.s.l.) [44], and Xishuangbanna, China (700–800 m a.s.l.) [48], but increased at 900 m while experiencing a decline above 900 m. In 12-year-old rubber plantations, the soil C stock in the topsoil at 0–50 cm depth at elevations of 700 m and 900 m was greater than that in 13-year-old rubber plantations in tropical China (580 m a.s.l.) [30] and 9-year-old rubber plantations in Southwest China (587 m a.s.l.) [44], but decreased across other elevation gradients. At an elevation of 900 m, the highest values of soil C stock across a depth of 110 cm were 175.77 Mg C ha^{-1} in 8-year-old rubber plantations and 153.51 Mg C ha^{-1} 12-year-old rubber plantations, which exceeded those reported by de Blécourt et al. [48] in Xishuangbanna, China, planted at elevations between 700 m and 830 m, and rubber plantations in western Ghana and Mato Grosso Brazil [49]. Moreover, the soil C stock observed in our study surpassed that of a 20-year-old rubber plantation in Hainan, China [50], which stores 75.5 Mg C ha^{-1} across a 100 cm soil depth.

The lowest total soil C stock in 8- and 12-year-old rubber plantations was observed at 1000 m, which was lower than the soil C stock in 7- and 13-year-old plantations in tropical China, planted at an elevation between 587 m and 620 m, respectively [30], and the soil C stock in 7- and 9-year-old plantations in Southwest China, planted at an elevation of 590 m [44]. However, the total soil C stock at 1000 m in 8-year-old rubber plantations was greater than that in 7-year-old rubber plantations in Rio de Janeiro, Brazil [43]. These variations in the soil C stock illustrate the effects of age and elevation on the regional soil C stocks in rubber plantations. Notably, at 1000 m, the total soil C stock in 8- and 12-year-old rubber plantations was lower than that in tropical soils in China [51]. However, the soil C stock in the secondary forest in Xishuangbanna, China [48], was reported to be 178.7 Mg C ha^{-1} across 100 cm depth. Consequently, our findings revealed losses of 2.93 Mg C ha^{-1} and 25.19 Mg C ha^{-1} in the soil C stock for both the 8- and 12-year-old rubber plantations at 900 m, and further reductions in the soil C stock above 900 m. This comparison revealed the influences of elevation, age, and land-use history on soil C dynamics in rubber monoculture plantations.

4.3. Effect of Elevation Gradient on Total Ecosystem C Stock

The total ecosystem C stock at 700 m in the 8-year-old rubber plantation (143.65 Mg C ha^{-1}) was lower than that in the 7-year-old rubber plantations in tropical China [30], Southwest China [44], and Rio de Janeiro Brazil [43], but it increased at 800 m and 900 m, while it decreased above 900 m, and presented the lowest total ecosystem C stock (113.05 Mg C ha^{-1}) at 1000 m. The total ecosystem C stock at 700 m and 900 m in the 12-year-old rubber plantations (183.12 Mg C ha^{-1} and 179.56 Mg C ha^{-1}, respectively), was greater than that in the 13-year-old rubber plantations in tropical China [30] and the 14-year-old rubber plantations in Mato Grosso Brazil [21], but decreased above 900 m and reached the lowest total ecosystem C stock (125.75 Mg C ha^{-1}) at 1000 m. The total ecosystem C stock in the secondary forest in Xishuangbanna, China, was 181.4 Mg C ha^{-1} [48]. Therefore, in the present study, the total ecosystem C stock decreased, with a loss of 68.35 Mg C ha^{-1} at 1000 m, in an 8-year-old rubber plantation, and 55.65 Mg C ha^{-1} at 1000 m, in a 12-year-old rubber plantation. By contrast, the total ecosystem C stock in the tropical seasonal rainforest in Xishuangbanna, China, was 260.5 Mg C ha^{-1} [46]. Thus, the total ecosystem C stock in both age groups of rubber plantations decreased, with a loss of 77.38 Mg C ha^{-1} at 900 m, in 12-year-old rubber plantations, and 62.67 Mg C ha^{-1} at 900 m, in 8-year-old rubber plantations. Notably, above 900 m, the contribution of the soil C stock to the total ecosystem C stock decreased at 1000 m, and the contribution of the biomass C stock to the total ecosystem C stock decreased at 1100 m in both 8-year-old and 12-year-old rubber plantations.

A previous study in tropical and temperate mountain forests reported that tree C stock is significantly influenced by stand attributes and decreases with elevational gradients [52]. In the current study, a significant decline in biomass C stock along elevation gradients in both age groups also explains the negative impact of planting rubber monoculture at higher elevations. However, variations in soil C stock along elevation gradients are unpredictable. Previous studies in tropical montane forests have indicated that soil C stock tends to increase with elevation gradients [53,54], but some studies have reported no linear increase or no significant trend with increasing elevation [55,56]. Our study found a significant decline in the total soil C stock in 12-year-old rubber plantations, whereas did not find a strong link between the total soil C stock and elevation gradients in 8-year-old rubber plantations. However, there was a notable decrease in the total soil C stock in rubber monoculture plantations at higher elevations, possibly due to the harsh environmental conditions [57]. Previous studies reported that environmental factors like lower temperatures, nutrient reduction, soil hypoxia, and topography determined the total ecosystem C stock at higher elevations [58–60]. Wittich et al. [61] reported a decline in the nitrogen level at higher elevation gradients in tropical forests, which might be a factor in lower total ecosystem C stock at higher elevations in our study. However, due to the limitations, our study did not quantify the aspect, the physical and chemical properties of soil, or the climatic conditions along elevation gradients. Therefore, it would be critical to investigate the impacts of variations in aspect, soil, and climatic conditions to better predict the total ecosystem C stock in rubber monoculture plantations along elevational gradients.

4.4. Implications of C Storage on the Elevation Gradient

The rapid expansion of rubber monoculture plantations in Xishuangbanna, Southwest China, has increased local economies through latex production [18]; however, this expansion comes at the cost of natural ecosystem degradation [22]. Planting rubber monocultures at relatively high elevations (> 900 m) in Xishuangbanna, China, notably reduces the C stock capacity, highlighting the unsuitability for converting natural tropical forests [46,48]. Although C stock increases with plantation age in our study, peaking at approximately 22 years [30], converting degraded forests with low C stock [62] into rubber monoculture plantations at relatively high elevations could increase C retention [11]. However, challenges such as declining latex prices [63] and biodiversity loss [64] threaten the long-term sustainability of rubber plantations in Xishuangbanna, China [65]. In this context, rubber-based agroforestry systems offer potential alternatives. Min et al. [66] reported that rubber intercropping with annuals was positively correlated with elevation, and Ziggler et al. [31] reported that rubber agroforestry with leguminous species significantly increased the C stock and soil fertility. Understanding how the integration of diverse plant species in rubber monoculture plantations at higher elevation gradients is related to each other and rubber trees is fundamental to our ability to explain the effects of rubber-based agroforestry systems. Therefore, further research is crucial to fully understand the ecological and economic impacts of such systems at higher elevation gradients in Xishuangbanna, Southwest China.

5. Conclusions

Total ecosystem C stock is significantly influenced along elevational gradient in rubber monoculture plantations. In both age groups, the substantial decline in the biomass C stock explains the negative effect of planting rubber monoculture at higher elevation gradients. However, the decline in soil C stock had significant negative elevation correlation in 12-year-old plantations and no significant elevation correlation in 8-year-old plantation, exhibiting the variations of soil C stock to elevational gradients and age of rubber plantations. Whereas a significant decline in litter C stock predicted the C stock lost at higher elevation gradients in both age groups. Moreover, growth, biomass, and C stock potential of rubber monoculture plantations substantially diminished above 900 m, with age and elevation being key factors, regardless of understory vegetation. These findings enhance the understanding of C stock dynamics in rubber monoculture plantations, especially in tropical regions where natural forest ecosystems are jeopardized from agricultural encroachment at higher elevational gradients.

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