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Carbon Storage 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 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 storage in rubber plantations across elevation gradients is poorly understood. In this study, we investigated biomass and C storage along elevation gradients in two age groups (8- and 12-year-old) of rubber monoculture plantations in Xishuangbanna, Southwest China. We investigated 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. A significant negative correlation was observed between total ecosystem C stocks and elevation in both age groups of 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 stocks decreased to its 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. We concluded that the total ecosystem C stocks were negatively correlated with elevation and significantly decreased from 8.05% to 51.55% and 11.46% to 42.96% between 700 m and 1100 m in both 8-year-old and 12-year-old plantations, respectively. However, no correlation was observed between the total soil C stocks and elevation in either age group of rubber plantations. Regardless of elevation gradient, 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 factors contributed less than 2% of the total ecosystem C stock in both age groups. These fluctuations in C stocks along elevation gradients in both 8- and 12-year-old plantations suggested that rubber growth, biomass and C storage capacity decreased above 900 m and that age and elevation are key factors for biomass and C storage in monoculture rubber plantations.

Keywords: elevation gradients; age effect; monoculture rubber plantation; carbon (C) stock

1. Introduction

Global warming is a major research issue globally, potentially causing significant adverse effects on forest composition, structure, and biological processes [1,2]. Carbon (C) losses due to land use changes in the tropics are estimated at 1.1 Gt C per year [3,4], adversely affecting the abiotic and biotic components of the Earth's ecosystems [5,6]. However, estimations of C stocks in deforested tropical forest areas are uncertain because of inaccurate biomass measurements and C concentrations [7]. Therefore, it is necessary to quantify the exact amount of C storage that is lost due to deforestation to mitigate global warming effects [8].

In tropical Southeast Asia, rubber (*Hevea brasiliensis*) cultivation is not a traditional agricultural practice [9]. After it originated from the Amazon basin, rubber cultivation began commercially in the 1950s [10]. Rubber has since become one of the rapidly cultivated commercial crops in Southeast Asia [11,12], with 90% of the region's natural forests converted into monoculture rubber plantations due to income generated by latex commercialization [13]. The total area of rubber cultivation has increased from 5.5 Mha to 9.9 Mha globally over the last three decades [14] and is predicted to continue increasing over the next twenty years [15,16]. Initially, rubber cultivation in tropical Asia was confined to elevations less than 800 m above sea level (asl.), the natural upper range for rubber species distribution [17]. However, in Southwest China, rubber cultivation has extended to elevations of up to 1400 m due to land availability [18], despite studies showing that such a shift is not profitable [19,20]. This expansion into relatively high elevation has led to the conversion of species-rich tropical forests into rubber plantations, resulting in biodiversity loss, reduced biomass C storage, and increased C emissions [13]. While previous studies have reported biomass and C stocks along elevation gradients in forest ecosystems globally [21–23], there is limited information on the fluctuations in biomass and C stocks 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 storage in forests occurs through photosynthesis, primarily in aboveground vegetation, and is transferred to belowground vegetation, including roots, soil, litter, and dead wood [24]. For example, Liu et al. [25] estimated that 68% of biomass C is stored in the aboveground part and more than 45% total ecosystem C is stored in the soil of rubber plantations in tropical China. Ziegler et al. [26] reported that in Southeast Asia, the total ecosystem C stocks of rubber plantations ranged from 93 to 376 Mg C ha^{-1}, whereas the total ecosystem C stocks of swidden systems ranged from 62 to 329 Mg C ha^{-1}. However, these studies lack information on climatic conditions, aspects and elevation [26]. Understanding the effects of environmental factors on C exchanges and their role in the global C cycle is necessary to inform policymakers [27]. Elevation gradients are natural scientific predictors for investigating climatic factors and their effects on ecological processes, whereas stand age provides information for assessing C storage dynamics [28–30].

Therefore, this study aimed to evaluate biomass C storage and allocation along an elevation gradient in two different aged (8- and 12-year-old) rubber monoculture plantations in Xishuangbanna, Southwest China. We also aimed to understand how the total C storage in these rubber plantations is distributed among aboveground and belowground sections, including litter, big dead branches and different soil depths. Finally, we investigated the effects of stand age on the biomass and C stocks of rubber plantations.

2. Materials and Methods

2.1. Study Site and Stand Description

The study was conducted in Naban River basin in Xishuangbanna, Southwest China. It covers an area of 26,660 ha (22°04′ - 22°17′N, 100°32′ - 100°44′E), with an elevation range from 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. 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 [31]. Yang et al. [32] reported that the area of rubber plantations in this region increased from 338 ha to 2858 ha from 1989-2012.

Five stands of rubber monoculture plantations were established along five elevation gradients (Figure 1). Each stand comprised two different age classes of 8- and 12-year-old plantations. Six sampling plots (20 m × 25 m) were established in each age class with planting specifications of 6 m × 2.5 m (inter and intra row spacing, respectively). The topographic features, such as slope, aspect, 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 monoculture rubber plantations along five elevation gradients.

Age	Elevation (m)	Longitude	Latitude	Aspect (°)	Slope (°)	Planting spacing (m)
8-Year-old	700	100°40′33.58″	22°07′53.10″	Southeast (20)	25	6 × 2.5
	800	100°39′53.21″	22°08′51.55″	Southeast (10)	30	6 × 2.5
	900	100°37′47.52″	22°13′26.74″	Southwest (20)	30	6 × 2.5
	1000	100°37′44.91″	22°13′26.89″	Southeast (20)	25	6 × 2.5
	1100	100°36′46.93″	22°14′25.33″	Southeast (30)	25	6 × 2.5
12-Year-old	700	100°40′03.48″	22°07′49.81″	Southeast (15)	30	6 × 2.5
	800	100°40′38.58″	22°08′36.33″	Southeast (20)	25	6 × 2.5
	900	100°37′47.62″	22°13′26.79″	Southwest (24)	30	6 × 2.5
	1000	100°37′44.69″	22°13′28.65″	Southeast (20)	25	6 × 2.5
	1100	100°36′47.46″	22°14′24.47″	Southeast (60)	30	6 × 2.5

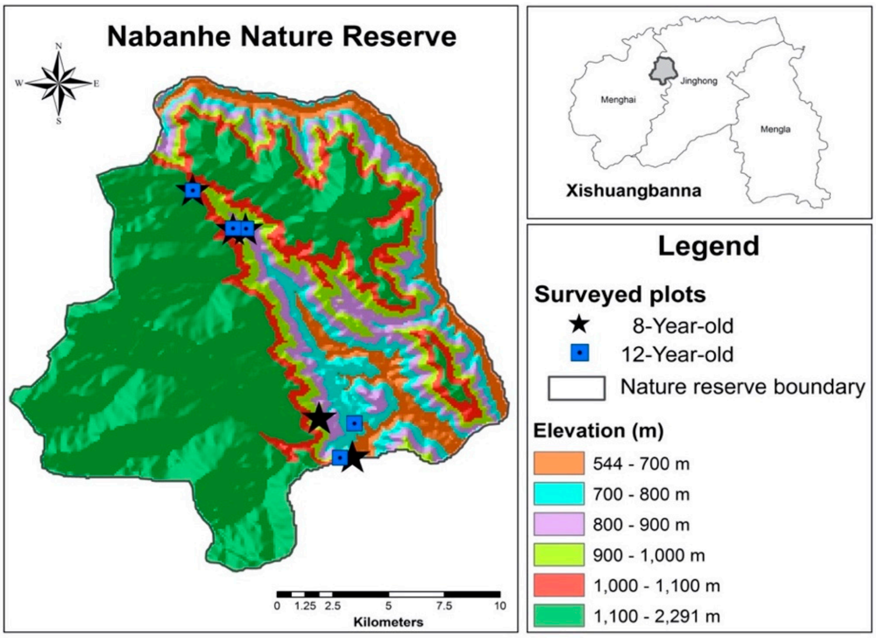

Figure 1. Surveyed plots of two aged (**8**- and **12**-year-old) group monoculture rubber plantations are located at low elevation (700 m) to high elevation (1100 m) of Naban River basin.

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. We estimated the various components of aboveground biomass (AGB) and belowground biomass (BGB) according to allometric biomass models, which were recently established by Yang et al. [33] for the Xishuangbanna.

For litter collection, 10 (0.5 m^2) litter collection traps were set up 5 m apart in each plot and collected once every month. 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.

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 of 105° over the core volume.

Elemental analysis was conducted to measure the C concentration in litter and bid dead branches as well as in soil samples via a Vario Max CNS elemental analyzer. We multiplied the dried biomass and C conversion coefficient (0.45) to calculate the above- and belowground C stocks of rubber tree [25]. We calculated the C stock in the litter and big dead branches by multiplying their oven-dried biomass by their respective C concentrations. The soil C stock was estimated from the C concentration at each soil depth and multiplied by the bulk density and depth interval.

2.3. Statistical Analysis

The effects of elevation gradient on tree biomass, biomass C stocks, litter C concentrations, soil C concentrations and soil bulk density were tested via one-way ANOVA, followed by Tukey's Honest significant difference test when one-way ANOVA was significant. The relationships among elevation, age, tree component C stock, soil C stock and total C stock were assessed via linear modeling with the function *lm*. We conducted all the analyses in R version 4.0.3 (R-Foundation for Statistical Computing, USA).

3. Results

3.1. Tree Biomass Partitioning

A negative correlation was observed between the total biomass of above- and below-ground sections of rubber trees and elevation in both age groups of rubber plantations (Table 2). However, no significant difference in total biomass and various components was noted across elevations ranging from 700–900 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. In contrast, 12-year-old plantations presented a similar elevational trend and an obvious decrease in total biomass and various components from 900 m. Across all the elevation gradients, the total biomass of the above- and belowground tree sections were greater in the 12-year-old plantations than that of 8-year-old plantations. Additionally, 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 monoculture rubber plantation along five elevation gradients.

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

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

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3.2. Litter Biomass and C Concentration

Litter biomass was negatively correlated with elevation and significantly decreased across elevation gradients in both age groups of rubber plantations (Table 3). The highest litter biomass was observed at 700 m and the lowest at 1100 m. The overall litter biomass of the 12-year-old plantations exceeded that of the 8-year-old plantations, ranging from 5.62 Mg ha^{-1} to 2.78 Mg ha^{-1} and from 4.95 Mg ha^{-1} to 2.23 Mg $ha^{-1,}$ respectively. 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. In terms of the litter C concentration, the miscellaneous presented the highest values in both the 8-year-old (51.23 ± 0.99% at 700 m) and 12-year-old (51.22 ± 1.08% at 800 m) plantations, respectively (Figure 2). On the other hand, big dead branches had the lowest values in 8-year-old (44.23 ± 0.53% at 700 m) and 12-year-old (44.29 ± 0.47% at 800 m) plantations, respectively. The leaf litter C concentration ranged from 47.86 ± 0.45% at 700 m to 48.21 ± 0.48% at 1100 m in the 8-year-old plantations and varied from 47.28 ± 0.44% at 700 m to 48.28 ± 0.49% at 1000 m in the 12-year-old plantations.

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

Age	Elevation (m)	Leaf	Twig	Flowers/fruits	Miscellaneous	BDB	Total
8-Year-old	700	4.17 ± 0.25a	0.50 ± 0.10a	0.04 ± 0.02a	0.08 ± 0.00a	0.17 ± 0.05ab	4.95 ± 0.43a
	800	2.48 ± 0.25b	0.66 ± 0.09a	0.09 ± 0.08a	0.12 ± 0.02ab	0.33 ± 0.10a	3.67 ± 0.55b
	900	2.39 ± 0.08b	0.37 ± 0.06a	0.01 ± 0.00a	0.06 ± 0.00b	0.09 ± 0.05ab	2.90 ± 0.19bc
	1000	2.55 ± 0.33b	0.75 ± 0.08a	ND	0.06 ± 0.01b	0.12 ± 0.04ab	3.47 ± 0.46b
	1100	1.63 ± 0.21b	0.49 ± 0.22a	ND	0.05 ± 0.01b	0.06 ± 0.03b	2.23 ± 0.47c
12-Year-old	700	4.80 ± 0.24a	0.23 ± 0.03a	0.30 ± 0.07a	0.09 ± 0.01a	0.21 ± 0.06a	5.62 ± 0.40a
	800	3.23 ± 0.19b	0.30 ± 0.07a	0.02 ± 0.01b	0.06 ± 0.01b	0.43 ± 0.20a	4.04 ± 0.48b
	900	2.63 ± 0.13bc	0.36 ± 0.08a	ND	0.05 ± 0.01b	0.20 ± 0.07a	3.23 ± 0.28bc
	1000	3.20 ± 0.18b	0.43 ± 0.08a	ND	0.04 ± 0.00b	0.15 ± 0.07a	3.82 ± 0.34bc
	1100	2.31 ± 0.16dc	0.32 ± 0.06a	0.02 ± 0.02b	0.03 ± 0.00b	0.10 ± 0.04a	2.78 ± 0.29c

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

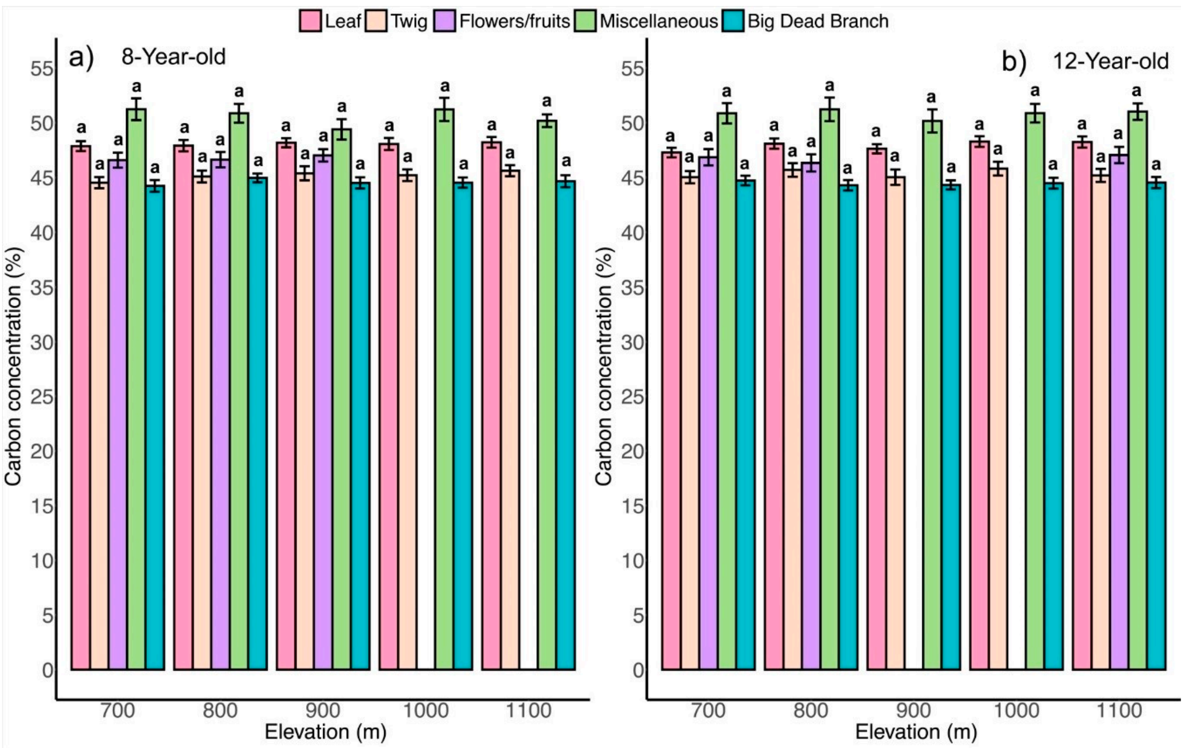

Figure 2. Carbon concentration (%) in different sections of litter (leaf, twig, flowers/fruits, miscellaneous and big dead branches) in (**a**) **8**-year-old and (**b**) **12**-year-old monoculture rubber plantation along five elevation gradients. Bars with different lowercase letters indicate significant differences according to Tukey's HSD test ($P < 0.05$). The missing column was not detected because no samples.

3.3. Tree Components C Stock

We observed a significant negative correlation between the total biomass C stock (AGB and BGB) and elevation in both age groups of rubber plantations (Figure 3a and b). The C stock of AGB showed a decreasing trend with elevation, declining from 7.33% to 54.06% in 8-year-old plantations and 11.26% to 43.05% in 12-year-old plantations between 700 m and 1100 m. This decline in AGB C stock between 700 m and 1100 m was more pronounced than that in the BGB C stock, which varied from 2.24% to 40.88% and from 5.23% to 39.56% in the 8- and 12-year-old plantations, respectively. Comparatively, the highest biomass C stocks in above- and belowground biomass components were stored at 700 m, whereas the lowest were observed at 1100 m in both age groups. However, the total biomass C stocks increased with plantation age and ranged from 23.39 Mg C ha^{-1} to 11.41 Mg C ha^{-1} in the 8-year-old plantations and from 30.21 Mg C ha^{-1} to 17.41 Mg C ha^{-2} in the 12-year-old plantations.

Litter C stocks in both 8- and 12-year-old plantations were also negatively correlated with elevation (Figure 3c) and varied from 2.35 Mg C ha^{-1} to 1.06 Mg C ha^{-1} in the 8-year-old plantations and from 2.65 Mg C ha^{-1} to 1.33 Mg C ha^{-1} in the 12-year-old plantations. Litter C stocks between 700 m and 1100 m decreased from 26.26% to 55.88% in the 8-year-old plantations and from 27.54% to 49.89% in the 12-year-old plantations. Both age groups presented around 30% decline in litter C stocks at 1100 m compared with 700 m.

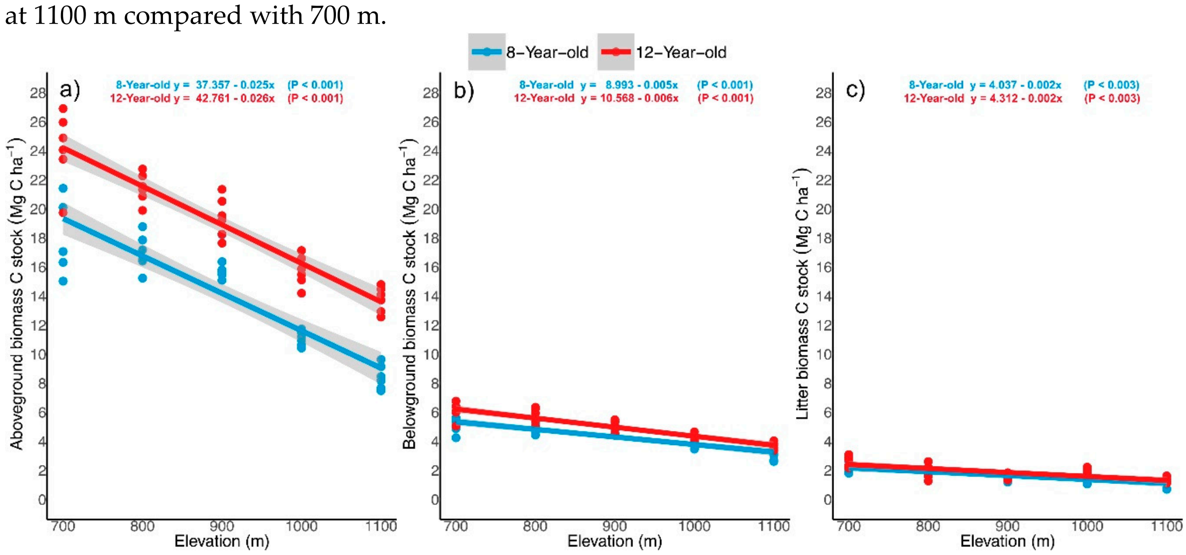

Figure 3. Relationship between elevation (m) and (**a**) aboveground biomass C stock (Mg C ha^{-1}), (**b**) belowground biomass C stock (Mg C ha^{-1}) and (**c**) litter C stock (Mg C ha^{-1}) in **8**-year-old and **12**-year-old monoculture rubber plantation.

3.4. Soil C Concentration and Stock

The elevation gradient and soil depth significantly influenced the soil C concentration without an interaction effect in both age groups of rubber plantations (Figure 4c and 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. In contrast, the average soil bulk density increased with soil depth, ranging from 1.02 g cm^{-3} to 1.07 g cm^{-3} and from 1.02 g cm^{-3} to 1.09 g cm^{-3} in the 8- and 12-year-old plantations, respectively (Figure 4a and 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.

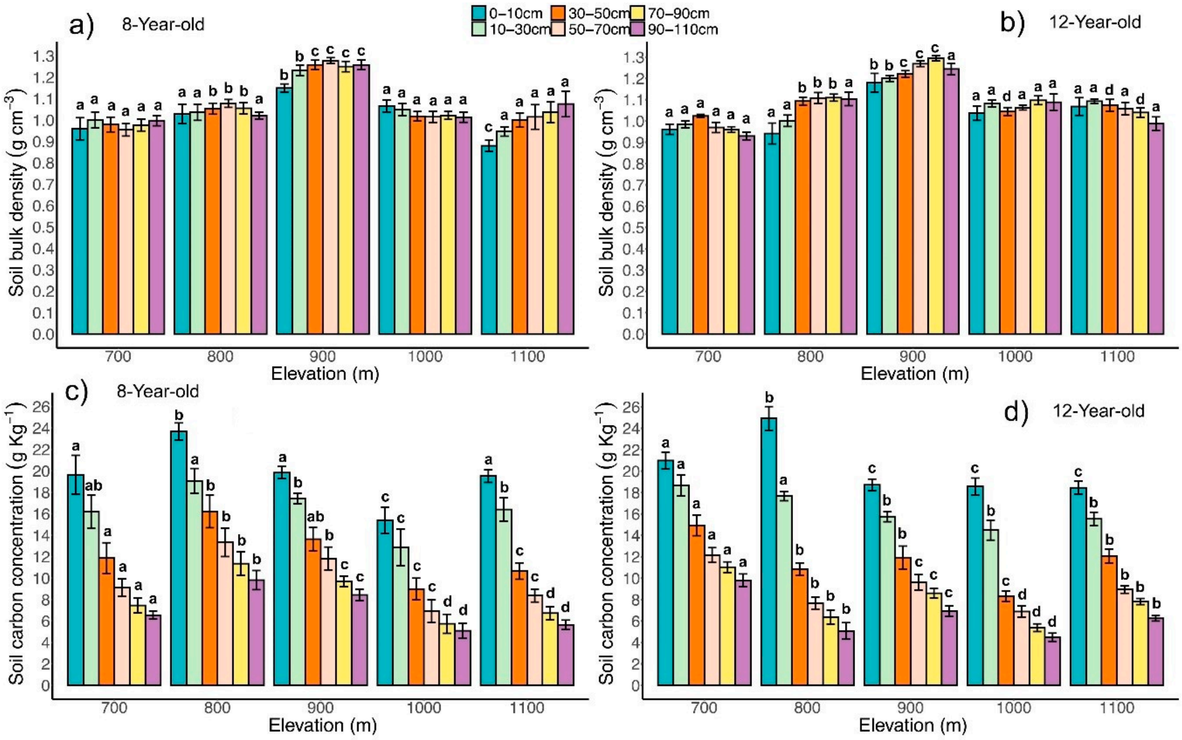

Figure 4. Soil bulk density in (**a**) **8**-year-old and (**b**) **12**-year-old and soil C concentration in (**c**) **8**-year-old and (**d**) **12**-year-old monoculture rubber plantation at each soil depth along five elevation gradients. Vertical bars with different lowercase letters indicate significant differences according to Tukey's HSD test ($P < 0.05$).

No correlation between the total soil C stock and elevation was detected in either age group of rubber plantations (Figure 5a). The total soil C stock at 110 cm depth decreased along the elevation gradient 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}), 1000 m (7.42 Mg C ha^{-1}) and 1100 m (14.72 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}). 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 54.14 Mg C ha^{-1} to 52.60 Mg C ha^{-1} at 0–30 cm and from 15.10 Mg C ha^{-1} to 14.42 Mg C ha^{-1} at 90–110 cm across all elevation gradients in both 8- and 12-year-old plantations. Regardless of elevation gradient, total soil C stocks at the 110 cm soil depth were slightly high in the 8-year-old plantations.

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	700m	18.39 ± 0.80ba	31.87 ± 2.12bc	22.91 ± 2.37b	17.31 ± 1.56b	14.44 ± 1.18b	13.00 ± 0.67b	117.91 ± 1.45b
	800m	24.17 ± 0.48a	39.13 ± 1.38ab	33.83 ± 2.66a	28.61 ± 2.68a	23.79 ± 2.07a	20.11 ± 2.05a	169.64 ± 1.89a
	900m	22.80 ± 0.83b	42.92 ± 1.50a	34.36 ± 2.96a	30.19 ± 2.82a	24.25 ± 1.41a	21.25 ± 1.54a	175.77 ± 11.06a
	1000m	16.47 ± 1.55b	26.86 ± 3.58c	18.40 ± 2.27b	14.11 ± 2.29b	11.61 ± 1.72b	9.03 ± 1.30b	96.49 ± 12.72b
	1100m	17.19 ± 0.81b	30.92 ± 1.87bc	21.25 ± 1.5b	16.93 ± 1.42b	13.89 ± 1.28b	12.11 ± 1.16b	112.29 ± 8.08b
12-Year-old	700m	19.12 ± 0.5a	26.25 ± 3.69ab	34.83 ± 2.10a	27.05 ± 2.31b	22.88 ± 1.97b	20.14 ± 1.66c	150.27 ± 2.04a
	800m	23.26 ± 0.95a	35.31 ± 0.92ab	23.79 ± 1.58ab	17.03 ± 1.35a	14.17 ± 1.59a	11.16 ± 1.71a	124.71 ± 1.35ab
	900m	21.67 ± 1.20a	33.26 ± 3.58a	31.71 ± 3.14a	25.24 ± 2.26b	22.85 ± 1.47b	18.78 ± 2.07bc	153.51 ± 13.71a

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1000m	19.24 ± 0.99a	31.26 ± 1.74b	17.33 ± 0.94b	14.61 ± 1.09a	11.81 ± 0.89a	9.65 ± 0.63a	103.90 ± 6.28b
1100m	19.66 ± 0.85a	33.99 ± 1.55ab	25.78 ± 1.00a	18.94 ± 1.00ab	16.26 ± 0.62a	12.39 ± 0.80ab	127.01 ± 5.82ab

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 monoculture rubber plantations along five elevation gradients according to Tukey's HSD test ($P < 0.05$).

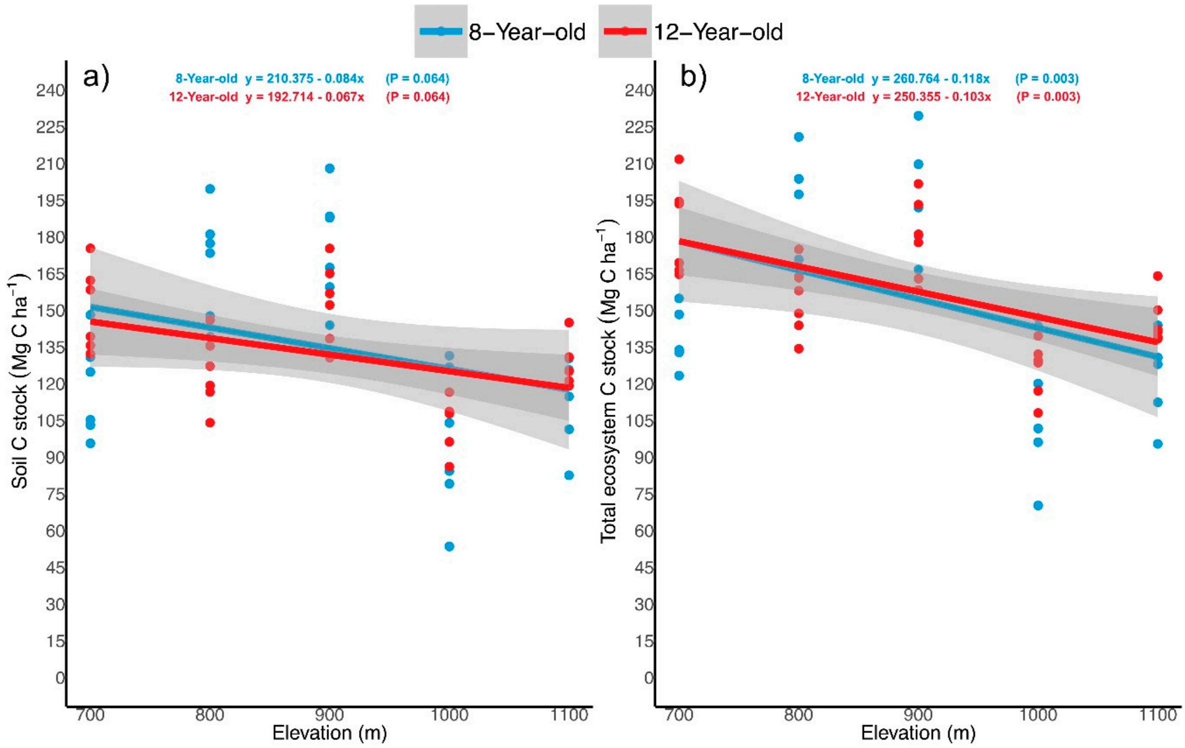

Figure 5. Relationship between elevation (m) and (**a**) soil C stock (Mg C ha^{-1}) and (**b**) total ecosystem C stock (Mg C ha^{-1}) in **8**-year-old and **12**-year-old monoculture rubber plantation.

3.5. Total Ecosystem C Stock

We observed a significant negative correlation between total ecosystem C stocks and elevation in both age groups of rubber plantations (Figure 5 b). The total ecosystem C stocks were relatively high in the 12-year-old rubber plantations and fluctuated with elevation in both age groups, ranging from 197.90 Mg C ha^{-1} at 900 m to 113.05 Mg C ha^{-1} at 1000 m in the 8-year-old plantations and from 183.12 Mg C ha^{-1} at 700 m to 125.75 Mg C ha^{-1} at 1000 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 stocks in both 8- and 12-year-old plantations, respectively (Figure 6). Biomass was the second-largest contributor and litter contributed less than 2% of the total ecosystem C stock across all elevation gradients in both 8- and 12-year-old plantations. However, the total biomass C stock significantly decreased from 8.05% to 51.55% and 11.46% to 42.96% between 700 m and 1100 m in both 8- and 12-year-old plantations. Regardless of elevation gradient, the total ecosystem C stock of 12-year-old plantations were 1.98% greater than that of 8-year-old plantations.

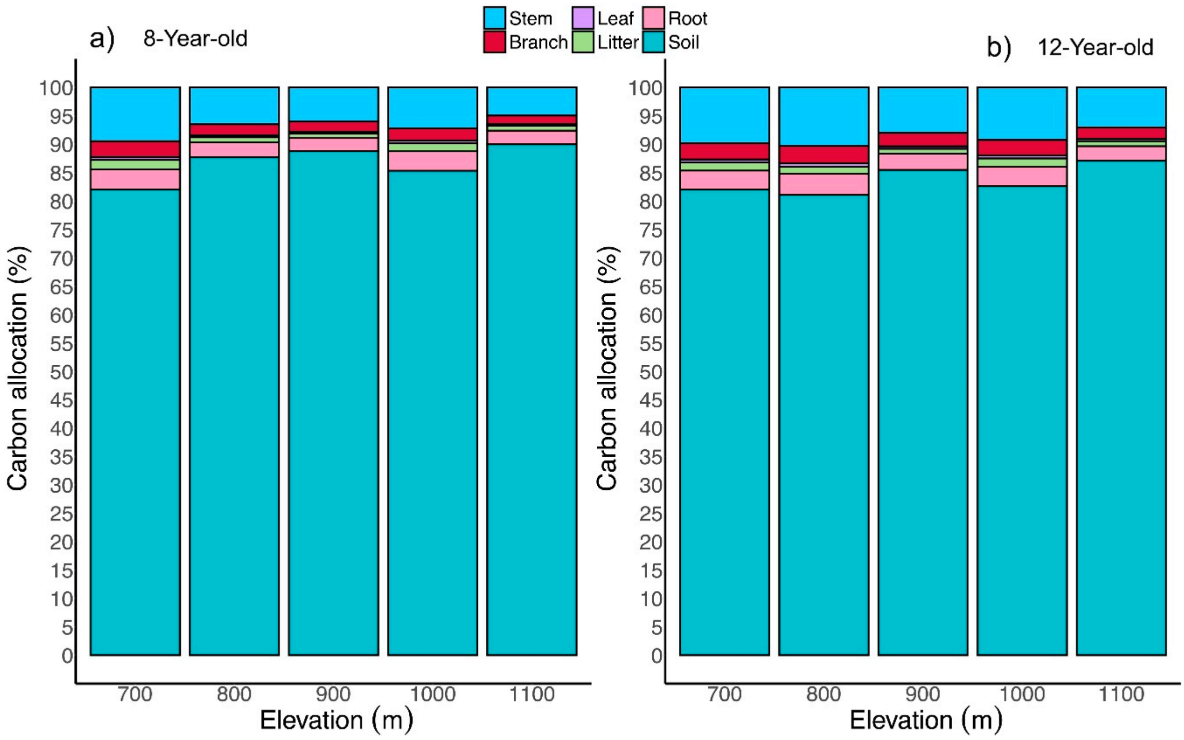

Figure 6. Allocation of total ecosystem C stocks (%) in different compartments (stem, branch, leaf, litter, root and soil) of (**a**) **8**-year-old and (**b**) **12**-year-old monoculture rubber plantation along five elevation gradients.

4. Discussion

4.1. Biomass C Stock

Previous studies in tropical regions have shown that the growth rates of rubber trees are profoundly affected by climate conditions, soil types, age and elevation gradients [32,34–36]. However, to date, no study has explained the effects of age and elevation gradient on the 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 (Figure 3), which was lower than those reported in a 7-year-old rubber plantation (45 m asl) in Rio de Janeiro, Brazil [37], and a 12-year-old rubber plantation (500 m asl) in Minas Gerais, Brazil [38]. These variations in the tree C stock illustrate the negative effect of the elevation gradient on the tree C stock of rubber plantations. The C stock of trees at lower elevations, specifically at 700 m, varied between 30.21 Mg C ha^{-1} in 12-year-old rubber plantations and 23.39 Mg C ha^{-1} in 8-year-old rubber plantations. These values were 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 [25], and lower than the average tree C storage of 55.3 Mg C ha^{-1} in 9-year-old plantations in Southwest China planted at an elevation of 590 m [39]. Additionally, the reported value of the tree C stock of 61.4 Mg C ha^{-1} by Li et al. [40] at elevation 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 tree 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. [41] Consequently, at 700 m, the biomass C stock of rubber trees 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. At higher elevations at 1100 m, the biomass C stock of rubber trees 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.

The leaf litter C concentrations along all the elevation gradients in the 8- and 12-year-old plantations (Figure 3) were lower than those in the 7- and 12-year-old rubber plantations in southern Coˆte d'Ivoire [42] and higher than those in the rubber plantation at an elevation between 700 m and 830 m in Xishuangbanna, China [43]. The average litter C concentrations along all elevation gradients in the 8- and 12-year-old plantations (Figure 2a and b) 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 [25], and in the 7- and 9-year-old plantations in Southwest China, which are planted at an elevation of 590 m [39]. The highest litter C stock in 8-year-old rubber plantations (2.35 Mg C ha^{-1}) was observed at 700 m (Table 3), which exceeded the litter C stock reported in 7-year-old rubber plantations of tropical China (1.42 Mg C ha^{-1}) planted at an elevation range of 580–595 m [25], Southwest China (1.8 Mg C ha^{-1}) planted at an elevation of 587 m [39] and rubber plantations in Xishuangbanna, China planted at an elevation range of 700–830 m [43]. 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 of 590 m [39]. 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 [25] 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 [44]. 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}) [43], and the greatest reduction was observed above 900 m. The observed variations in the litter C stock explain the effects of age and elevation on the litter C stock in rubber plantations.

4.2. 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 (Table 4) was lower than that in 7-year-old rubber plantations in tropical China (580 m asl) [25], Southwest China (587 m asl) [39] and Xishuangbanna, China (700–800 m asl) [43] 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 asl) [25] and 9-year-old rubber plantations in Southwest China (587 m asl) [39] but decreased across other elevation gradients. At an elevation of 900 m, the highest values of soil C stock were observed in both 8- and 12-year-old rubber plantations across a depth of 110 cm, ranging from 175.77 Mg C ha^{-1} to 153.51 Mg C ha^{-1}, which exceeded those reported by de Blécourt et al. [43] in Xishuangbanna, China, planted at elevations between 700 m and 830 m, and rubber plantations in western Ghana and Mato Grosso Brazil [44]. Moreover, the soil C stock observed in our study surpassed that of a 20-year-old rubber plantation in Hainan, China [45], 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 (Table 4), 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 [25], and the soil C stock in 7- and 9-year-old plantations in Southwest China planted at an elevation of 590 m [39]. 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 [37]. These variations in the soil C stock illustrate the effects of age and elevation on the regional soil C stock 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 [46]. However, the soil C stock in the secondary forest in Xishuangbanna, China [43], 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 plantations.

4.3. 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}) (Figure 5a) was lower than that in the 7- year-old rubber plantations in tropical China [25], Southwest China [39], and Rio de Janeiro Brazil [37], 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 (Figure 5b), was greater than that in the 13-year-old rubber plantations in tropical China [25] and the 14-year-old rubber plantations in Mato Grosso Brazil [38] 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} [43]. 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 (Figure 5a and b). In contrast, the total ecosystem C stock in the tropical seasonal rainforest in Xishuangbanna, China, was 260.5 Mg C ha^{-1} [41]. Thus, the total ecosystem C stock in both age groups of rubber plantations decreased, with a loss of 62.67 Mg C ha^{-1} at 900 m in 8-year-old rubber plantations and 77.38 Mg C ha^{-1} at 900 m in 12-year-old rubber plantations (Figure 5a and b). 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 (Figure 6a and b).

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 [13]; however, this expansion comes at the cost of natural ecosystem degradation [17]. Planting rubber monocultures at relatively high elevations (> 900 m) in Xishuangbanna, China (Figure 5), notably reduces the C storage capacity, highlighting the unsuitability for converting natural tropical forests [41,43]. Although C storage increases with plantation age in our study, peaking at approximately 22 years [25], converting degraded forests with low carbon storage [47] into rubber monoculture plantations at relatively high elevations could increase C retention [8]. However, challenges such as declining latex prices [48] and biodiversity loss [49] threaten the long-term sustainability of rubber plantations in Xishuangbanna, China [50]. In this context, rubber-based agroforestry systems offer potential alternatives. Min et al. [51] reported that rubber intercropping with annuals was positively correlated with elevation, and Ziggler et al. [26] 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 elevations is related to each other and rubber trees are 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 elevations in Xishuangbanna, China.

5. Conclusions

The study revealed a significant negative correlation between total ecosystem C stocks and elevation in monoculture rubber plantations. The lowest total ecosystem C stocks were at 1000 m, with 113.05 Mg C ha^{-1} in 8-year-old plantations and 125.75 Mg C ha^{-1} in 12-year-old plantations. The soil contributed 82–90% of the total ecosystem C stock, the biomass was the second-largest, and the litter contributed less than 2% of the total ecosystem C stock. The biomass C stock decreased with elevation, dropping from 8.05% to 51.55% in 8-year-old plantations and 11.46% to 42.96% in 12-year-old plantations between 700 m and 1100 m. The soil C stock had no significant elevation correlation, peaking at 900 m in both age groups. The litter C stock was highest at 700 m in both age groups. The

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total ecosystem C stock in 12-year-old plantations was 1.98% greater than that in 8-year-old plantations. Rubber growth, biomass, and C storage are significantly reduced above 900 m, with age and elevation being key factors, regardless of understory vegetation. These findings enhance the understanding of C stock changes with elevation in rubber plantations.

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