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Yield Performance of Intercropped *Marantha arundinacea* L. (Arrowroot) in Two Rubber Plantation Designs

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Abstract: Developing rubber agroforestry systems is crucial to ensure the sustainable development of natural rubber cultivation. This study focuses on the starch crop *Maranta arundinacea* (arrowroot) and assesses its productivity and influencing factors when intercropped in 6–7-year-old conventional single-row and double-row rubber plantations. We analyze various aspects, including light resources, root distribution, soil nutrients, arrowroot growth characteristics, and product quality. The results indicate that the daily average photosynthetically active radiation (PAR) in the double-row rubber agroforestry system intercropping area ranges from 896.4 to 940.2 μmol·m^{-2}·s^{-1}. Additionally, the rubber tree roots near the intercropping area are less dense (107.0 g cm^{-3}). In contrast, the conventional single-row rubber agroforestry system has a significantly lower daily average PAR of only 145.7 μmol·m^{-2}·s^{-1}, and the nearby rubber tree roots are more abundant (616.2 g cm^{-3}). Although soil nutrient levels were slightly lower in the intercropping area on the double-row treatment compared to the single-row treatment, there was no statistical difference ($p < 0.05$). Arrowroot's photosynthetic capacity in the double-row rubber agroforestry system intercropping area is significantly greater than in the single-row rubber agroforestry system intercropping area. The yield per unit area in the former (23.46–27.47 t·ha^{-1}) is also significantly higher than in the latter (2.87–4.75 t·ha^{-1}, $p < 0.05$), with higher starch content. Therefore, arrowroot exhibits higher productivity when intercropped in double-row rubber agroforestry systems, making it suitable for establishing a "rubber–arrowroot" agroforestry model to enhance the yield per unit area of rubber plantations.

Keywords: agroforestry; *Hevea brasiliensis*; starch crop; productivity

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1. Introduction

Agroforestry is a traditional land use and management method, where perennial woody plants are deliberately arranged together with other cultivated plants and animals within the same land management unit. This creates a managed ecosystem characterized by diverse populations, multiple layers, various products, and numerous benefits [1]. Natural rubber, one of China's strategic resources, primarily originates from the Brazilian rubber tree (*Hevea brasiliensis*). It is mainly cultivated in regions like Hainan, Yunnan, and Guangdong. The growth cycle of rubber trees can exceed 30 years (with an immature stage of about 7–8 years). Rubber trees are essential economic plantation trees in China's tropical regions, covering approximately 1.2 million hectares [2]. In recent years, due to persistently low rubber prices, the profitability of rubber cultivation has significantly decreased. Consequently, measures are urgently needed to enhance production per unit area of rubber plantations. A rubber-based agroforestry system, known as jungle rubber in Indonesia since 1904, has been practiced for many years. Developing rubber-based agroforestry systems is considered one of the primary strategies to increase output per unit area and address the challenges posed by low rubber prices [3–6].

Currently, China's rubber plantations primarily fall into two categories. The first type is the conventional single-row rubber plantation, which employs equal row spacing (e.g., row spacing: 7 m; tree spacing: 3 m). Intercropping in this system mainly occurs during the early stage, typically within 3–4 years after planting. Initially, short-term cash crops like bananas, corn, pineapples, and chili peppers are intercropped. However, as the rubber trees mature, they create heavy shade, and the underground root competition intensifies. Consequently, only a few shade-tolerant crops (such as *Semen amomi* and *Alpinia oxyphylla*) are suitable for intercropping [7–9]. The second type involves using upright rubber varieties and wide–narrow row planting in double-row rubber plantations (e.g., wide-row spacing: 20 m; narrow-row spacing: 4 m; tree spacing: 2 m). This approach helps avoid the development of continuously shaded environments in rubber plantations and reduces underground root competition. This system is more suitable for agroforestry development [10]. Even during the 5–7-year-old stage, sunlight still reaches the intercropped areas, making it possible to grow light-loving crops like *Ficus hirta* Vahl [11]. In areas aged 12–15 years (with a width of 12 m), there is still 2.2–3.7 h of sunlight exposure, allowing intercropping crops such as yam bean and Arabica coffee [2].

Maranta arundinacea L., commonly known as arrowroot, is an annual crop belonging to the Marantaceae family. Its rhizomes are rich in starch, dietary fiber, and total flavonoids, making them highly valuable for culinary and medicinal purposes [12]. Arrowroot thrives in warm, temperate, and semi-shaded environments. It is sensitive to cold, dislikes dry conditions, and is averse to intense sunlight exposure [13]. Arrowroot can survive in environments with poor light conditions and infertile soil, indicating its adaptability to shaded environments [14]. Even under approximately 50% shade, it can yield substantial individual tuber weight [15]. A study by Liang et al. [16] showed that arrowroot intercropped under a 20% canopy closure of the Masson pine forest yielded 1.48 times more than full-sun planting, while under 40% canopy closure, the yield was comparable to full-sun cultivation. However, excessive shading can significantly reduce arrowroot yield and starch content [17].

Considering the demand to increase output per unit area in the rubber plantation industry through intercropping, arrowroot emerges as a valuable and potentially complementary intercrop in agroforestry systems. Establishing a "rubber–arrowroot" model appears feasible and can offer a choice for the widespread application of rubber-based agroforestry models. In relatively high-density systems where taller trees coexist with shorter crops, competition for light, water, and nutrients is a primary factor affecting crop productivity [18,19]. Such competition can influence the photosynthetic physiology, morphology, yield, quality, and other characteristics of intercrops [10,20–22]. Therefore, this study aims to explore the growth performance of arrowroot as an intercrop in both single-row and double-row rubber agroforestry systems. Additionally, it analyzes the environmental factors affecting the productivity of intercropped arrowroot. This research provides technical and theoretical foundations for establishing a "rubber–arrowroot" agroforestry model.

2. Materials and Methods

2.1. Experimental Location

The experiment was carried out at the Chinese Academy of Tropical Agricultural Sciences in Danzhou City, Hainan Province, China. This region features a typical tropical maritime monsoon climate with an annual average temperature of 20.8 to 26.0 °C. The annual rainfall during the experimental period of 2021 and 2022 was 1321 mm and 1005 mm, respectively. The rubber plantations used in the experiment included a conventional single-row rubber plantation and a double-row rubber plantation with wide and narrow rows. These plantations were established in 2016 and featured the upright, fast-growing rubber tree variety certified in 1999, Catas 7-20-59 (female parent: RRIM600; male parent: PR107).

The conventional single-row rubber plantation had a 3 m × 7 m tree-row spacing, resulting in a density of 480 trees per hectare (ha^{-1}). In contrast, the double-row rubber plantation had a wide-row spacing of 20 m and a narrow-row spacing of 4 m, with a tree spacing of 2 m, resulting in a density of 420 trees per ha. Both types of rubber plantations were located in adjacent plots and oriented from east to west.

In June 2021, the rubber trees had an approximate height of 5 m. The conventional single-row rubber agroforestry system had a gap of approximately one meter between the canopies of two rows of trees, while the double-row rubber agroforestry system had a wider gap of approximately 14 m in the central wide row. The light environment is depicted in Figure 1.

Figure 1. The light environments for intercropped arrowroot (*Maranta arundinacea* L.) in two types of rubber agroforestry systems ((**Left**): single-row; (**Right**): double-row).

The experiment was conducted during the immature stage of the rubber trees. The single-row and double-row rubber agroforestry systems are adjacent. The previous intercrop was konjac (*Amorphophallus konjac*) which received high fertilizer inputs (organic manure: 15 t·ha^{-1}; N: 225 kg ha^{-1}; P_2O_5: 150 kg ha^{-1}; K_2O: 300 kg ha^{-1}). The soil at the experimental site had the following baseline characteristics: 12.24 g kg^{-1} organic matter, 0.40 g kg^{-1} total nitrogen, 31.91 mg kg^{-1} available phosphorus, 58.52 mg kg^{-1} available potassium, and a pH of 4.6 [23].

2.2. Experimental Design

The experiment consisted of two intercropping treatments, each with three replicates, namely, intercropped arrowroot (*Maranta arundinacea* L.) in a conventional single-row rubber agroforestry system (S) and a double-row rubber agroforestry system (D). In the traditional single-row rubber agroforestry system and double-row rubber agroforestry system alleys, arrowroot was planted in 3 and 11 rows, respectively, utilizing approximately 42.9% and 45.8% of the rubber plantation's land area. Arrowroot plants were spaced at intervals of 1 m × 0.3 m, and the orientation of the arrowroot rows was aligned with that of the rubber rows. The area for the S treatment plots was 3 m × 10 m, while for the D treatment plots, it was 6 m × 11 m. The planting distances between the rubber trees and arrowroot are depicted in Figure 2. Arrowroot was planted in early April 2021 and early March 2022 and harvested in early January 2022 and mid-November 2022 when the aboveground leaves began to yellow. During the experiment, fertilizer application included 300 kg N ha^{-1}, 100 kg P_2O_5 ha^{-1}, and 100 kg K_2O ha^{-1}, with urea and compound fertilizers used. Approximately 40% of the nitrogen fertilizer was applied during the elongation stage of the main stem, along with all of the phosphorus and potassium fertilizers, while the remaining 60% of the nitrogen fertilizer was applied near the tuber formation stage along with soil amendment. Standard weed control and irrigation were conducted based on weed growth and weather conditions. In terms of production, the rubber trees were planted uniformly on a large scale, and there was no available space in the nearby area for single-crop arrowroot. During the experiment, the middle area of the D treatment was not shaded by rubber trees and served as a reference for the growth of arrowroot in open areas.

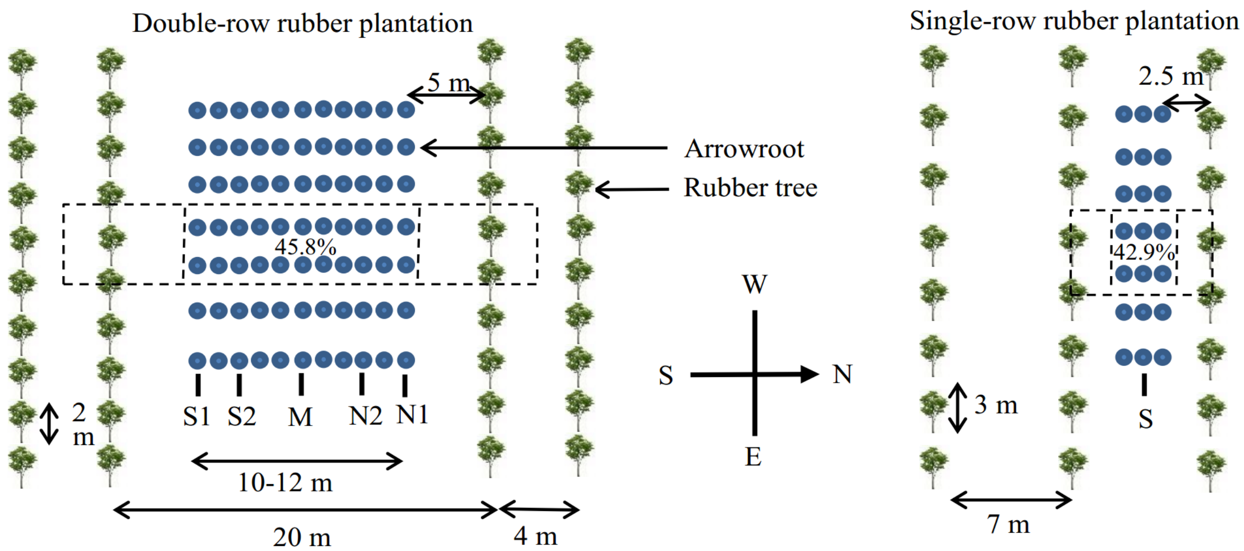

Figure 2. Planting and sampling positions of arrowroot in two different rubber agroforestry systems.

2.3. Measurement Indices and Methods

Since there were 11 rows of arrowroot intercropped in the D treatment, potential variations in environmental factors due to different distances from rubber trees could lead to differences in selected measurement indices. To account for these possible variations, five sampling locations (S1, S2, M, N2, and N1) were established within the arrowroot crops in the D treatment (see Figure 2). This approach allowed for the analysis of potential influences at different sampling locations. The sampling sites were labeled D-S1, D-S2, D-M, D-N2, and D-N1. In the S treatment, where the arrowroot was planted in only 3 rows with relatively minor inter-row differences, observations were focused on the central row and labeled as S.

2.3.1. Agricultural Traits

Agricultural trait measurements that indicate potential arrowroot productivity were conducted during the seedling, elongation, stability, and maturity stages of arrowroot growth [16]. At each observation point, 10 randomly selected plants were measured for plant height (cm) and stem thickness (mm).

Plant height (cm): measured from the base to the top of the arrowroot main stem using a ruler to represent its plant height.

Stem thickness (mm): measured at a point 2–3 cm above the ground from the base of the main stem using a vernier caliper to represent its stem thickness.

The number of arrowroot tillers (per plant) was measured only during the maturity stage.

2.3.2. Yield and Quality

During the maturity stage of arrowroot growth, harvesting was conducted after the above-ground leaves had turned yellow. Nine plants were randomly selected for harvesting at the five D and S treatment sampling locations. The harvested yield (g per plant) was compared to assess yield differences among different sampling locations.

After weighing, a random 1 kg sample of arrowroot tubers was selected, cleaned, sliced, and dried at 85 °C. The dried samples were ground and sieved through an 80-mesh sieve. Starch and crude protein contents (mg per gram) were determined using the anthrone colorimetric and Nessler's reagent methods, respectively [24].

In the D treatment, a sub-area measuring 2 m × 11 m, oriented perpendicular to the planting rows, was selected for whole-area harvesting. In contrast, in the S treatment, the entire plot was harvested for yield measurement (tons per hectare).

2.3.3. Diurnal Variation of Photosynthetically Active Radiation (PAR) and Light Response Curves

In late March 2022 (around the spring equinox), on clear days, measurements of photosynthetically active radiation (PAR) were taken at different canopy levels (50 cm above the ground) in various observation rows from 8:00 A.M. to 5:00 P.M. (hourly measurements were recorded). A BNL-GPRS-8G light meter (Tuopuyunnong Agricultural Co., Hangzhou, China) was used for these measurements. Concurrently, light measurements were also taken in an adjacent open field area (O) to serve as a control. (Given the consistent light conditions in the open field area, this measurement was conducted only once.)

In early September 2022, during the steady period of arrowroot tuber expansion, net photosynthetic rates of arrowroot leaves at the −3 leaf stage were measured using a Li-6800 photosynthesis analyzer. Five plants were selected to measure light response curves, analyzing differences in their photosynthetic capacity. Measurements were conducted from 8:00 A.M. to 11:30 A.M. During the measurements, the flow rate was set at 500 mol s^{-1}, temperature at 30 °C, relative humidity at 70%, and CO_2 concentration at 400 μmol mol^{-1}. For measurements, light intensity gradients ($\mu mol \cdot m^{-2} \cdot s^{-1}$) included 0, 20, 50, 100, 120, 200, 400, 600, 800, 1000, 1200, 1500, 1800, and 2000 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The light saturation and light compensation points of the arrowroot were calculated using the Photosynthesis software (LI-COR Application Note #105) to indicate the demand for light intensity.

2.3.4. Crop Root Density and Soil Nutrients

To analyze the distribution of rubber tree and arrowroot roots in the composite system, a soil excavation method (dimensions: length × width × height = 30 cm × 20 cm × 20 cm) was used to measure root distribution within the 0–20 cm soil layer between the rubber and intercropped crop planting areas. For the D treatment, measurement points were located at distances of 3 m (non-intercropped area) and 4 m (near the intercropped area) from the rubber trees. In the S treatment, measurement points were located at distances of 1.5 m (near the intercropped area) and 3.5 m (within the intercropped area). Roots of rubber and arrowroot were distinguished based on their appearance, odor, color, and the presence of latex. After drying in an oven, the root dry weights were determined to calculate the root density (g m^{-3}).

During the seedling, elongation, stability, and maturation stages of arrowroot growth, soil samples were collected from different sampling locations at 0–20 cm depth. These soil samples were used to analyze the concentrations of inorganic nitrogen (NO_3^- and NH_4^+), available phosphorus, and available potassium (mg kg^{-1}). The measurements were conducted using spectrophotometric methods, flame atomic absorption spectrophotometry, and molybdenum antimony anti-colorimetric methods, respectively [25].

2.4. Data Processing

Data processing and graphing were performed using Microsoft Excel 2016. Significant differences in plant height, stem thickness, tiller number, yield, nutrient content, light saturation point, light compensation point, soil nutrient content, and root density between different treatments (sampling locations) were identified via least significant difference calculations using SPSS 17.0 statistical software with $p < 0.05$ denoting significance.

3. Results

3.1. Plant Height, Stem Thickness, and Tiller Number

Throughout the entire growth period, the arrowroot exhibited a gradual increase in plant height (Figure 3). During the seedling stage, intercropped arrowroot in the S treatment showed significantly faster growth, reaching heights of 52.9 cm and 56.8 cm in 2021 and 2022, respectively, which were significantly higher than the heights of arrowroot in the D treatment at different sampling locations (40.5–43.4 cm and 28.2–34.9 cm). However, during the elongation, steady, and mature stages, there was a trend of the D treatment having taller plant heights than the S treatment. In the steady and mature stages, the plant height in the D treatment was significantly higher than in the S treatment, with increases of 20.9–48.1% and 38.7–69.7% in 2021 and 2022, respectively. Plant heights of D-N1 in the steady stage and D-S1 in the mature stage were significantly lower than that of D-M and the other four sampling locations in 2021, respectively. In 2022, D-S1 and D-M in the seedling stage and D-S2 and D-M in the mature stage were significantly higher than D-N1 and D-S1, respectively ($p < 0.05$).

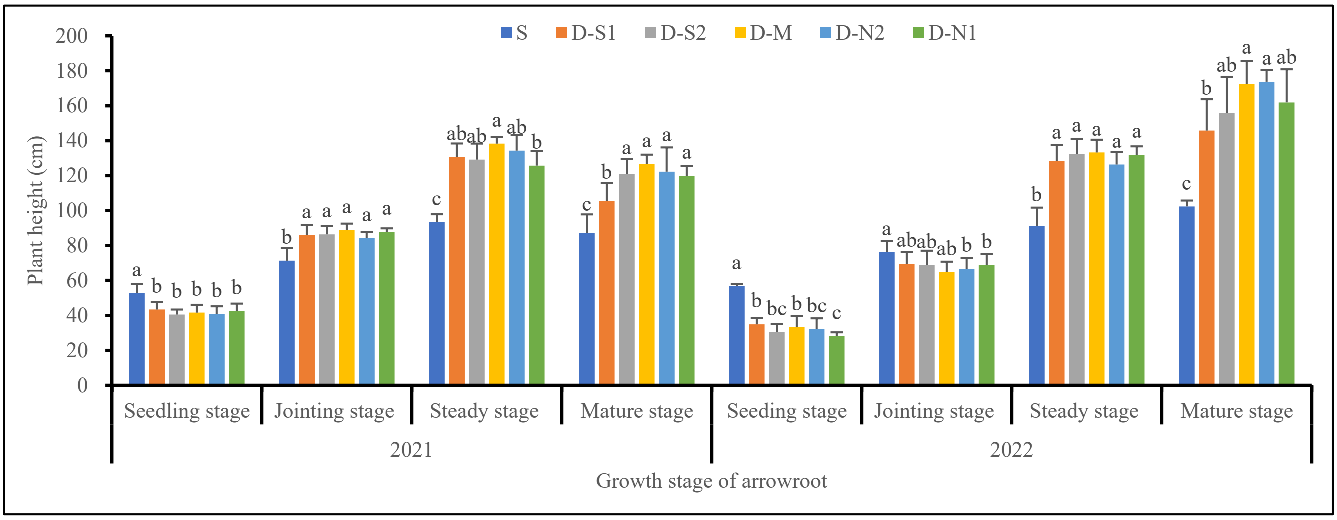

Figure 3. Differences in plant height of arrowroot at different sampling locations during different growth stages in two different rubber agroforestry systems. Different letters represent significant differences between sampling locations ($p < 0.05$).

The data presented in Figure 4 reveal trends in the stem thickness of the arrowroot under different conditions during various growth stages. Generally, across the stages of seedling (10.7–19.3 mm), elongation (14.1–20.8 mm), and stabilization (14.7–21.1 mm), there is a gradual but slight increase in stem thickness. This pattern is attributed to the natural growth progression, although some early-growth stems and leaves tend to wither in the later stages, resulting in a slight decrease in stem thickness (10.9–15.1 mm).

Overall, it is evident that the treatment involving the double-row rubber agroforestry system (D treatment) consistently exhibits greater stem thickness compared to the single-row rubber agroforestry system (S treatment). Specifically, during the seedling stage in 2021 (except for D-S2), the steady period, and the elongation stage in 2022 (except for D-M), the D treatment significantly outperformed the S treatment. Within the D treatment, stem thickness of D-S1 in the jointing stage was significantly lower compared to D-M, D-N2, and D-N1 in 2021. In 2022, D-M was significantly lower than D-S1, D-S2, and D-N2 in the seedling stage. Simultaneously, D-M was significantly lower than D-S2 in the joint stage ($p < 0.05$).

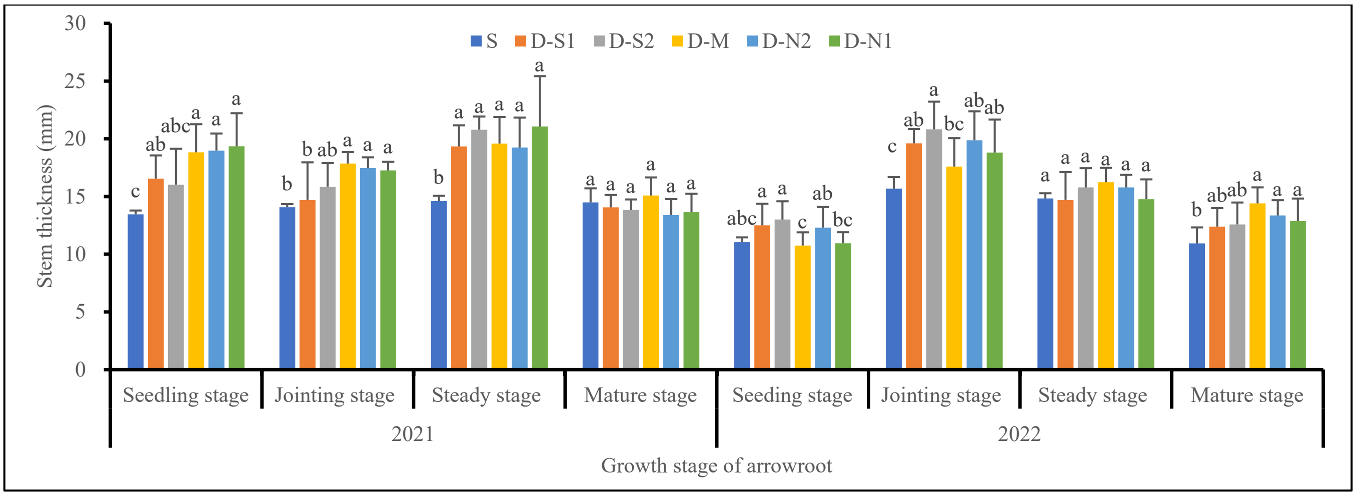

Figure 4. Variations in the thickness of arrowroot stems at different times and sampling locations in two different rubber agroforestry systems. Different letters represent significant differences between sampling locations ($p < 0.05$).

Differences in the number of tillers determined during the mature period of the arrowroot (Figure 5) indicate that in 2021, the number of tillers in the D treatment (ranging from 11.8 to 17.8 per plant) was significantly higher than in the S treatment (5.5 per plant) ($p < 0.05$). Also in 2021, the D-S1 sampling position had significantly fewer tillers compared to the other D treatment sampling positions. In 2022, there was a similar trend, with the number of tillers in the D treatment significantly higher than in the S treatment. Additionally, the D-M sampling position had a significantly higher number of tillers than D-S1 and D-N1.

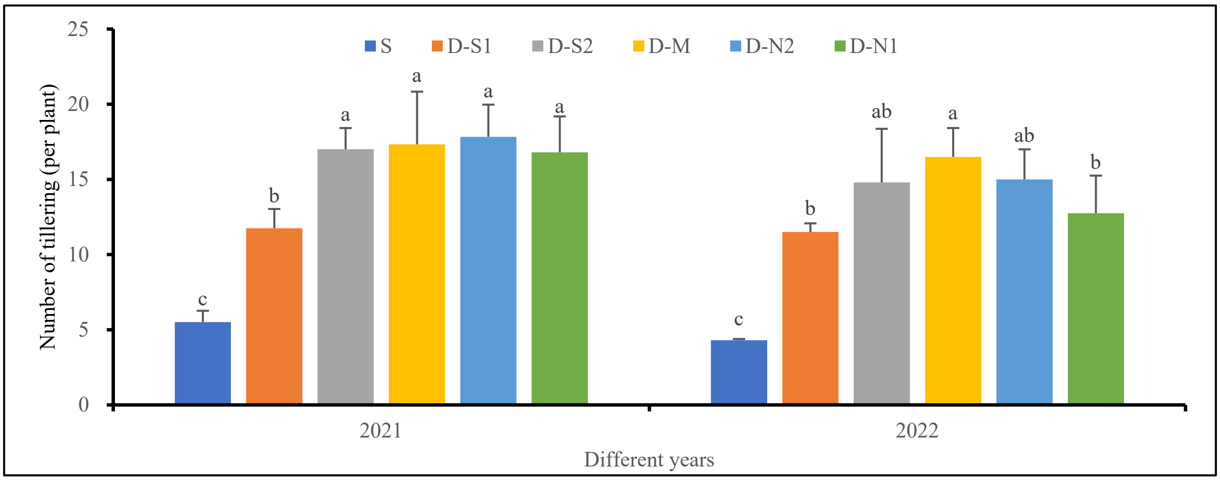

Figure 5. Variation in the number of arrowroot tillers across different sampling locations in two different rubber agroforestry systems. Different letters represent significant differences between sampling locations ($p < 0.05$).

3.2. Yield and Quality

Significant differences in arrowroot yield were observed among different rubber agroforestry system types (Figure 6). In 2021 and 2022, the arrowroot yield per unit area in the D treatment was 27.47 and 23.46 $t \cdot ha^{-1}$, respectively; in the S treatment, it was 4.75 and 2.87 $t \cdot ha^{-1}$, respectively (Figure 6A). In the D treatment, the arrowroot yield showed a trend of being higher in the middle and lower on the sides, with individual plant yields in D-S1 and D-N1 ranging from 68.7% to 89.6% of D-M (702.5–935.5 g $plant^{-1}$). In 2021, the arrowroot yield in D-S1 was significantly lower than that in D-S2 and D-M. In comparison, D-S2 and D-N2 ranged from 76.9% to 99.5% of D-M (Figure 6B, $p < 0.05$).

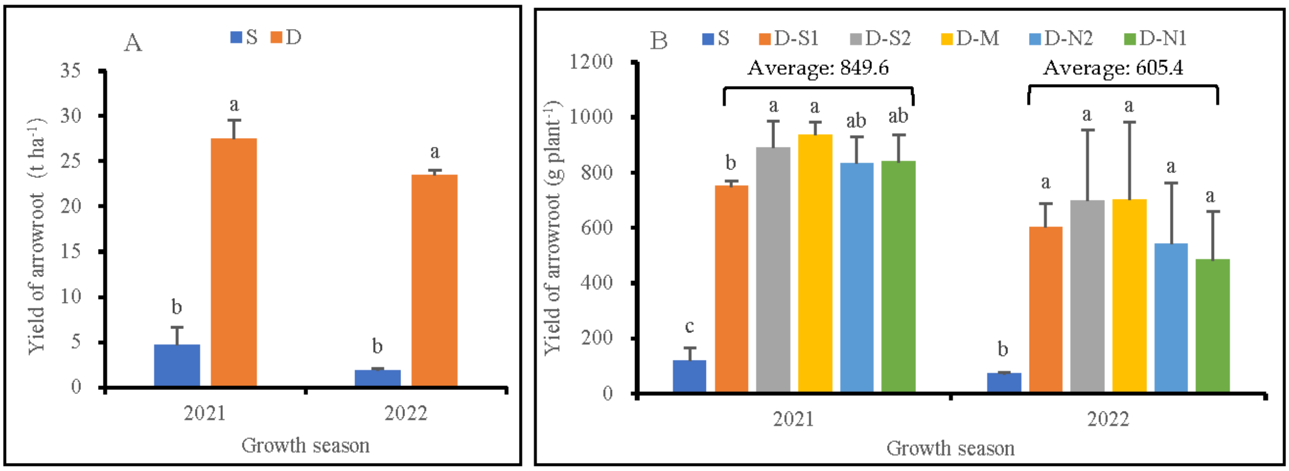

Figure 6. Yield per unit area of arrowroot (**A**) and variations in yield per plant of arrowroot in different sampling locations (**B**) in two different rubber agroforestry systems. Different letters represent significant differences between sampling locations ($p < 0.05$).

Figure 7 illustrates the starch content of the arrowroot among different treatments. In 2021, the starch content in the S treatment was 761.3 mg g^{-1}, while in the D treatment, it ranged from 756.1 to 892.7 mg g^{-1}, with DN-2 significantly higher than S, D-S1, D-S2, and D-N1. In 2022, the starch content in the S treatment was 625.4 mg g^{-1}, while in the D treatment, it ranged from 668.4 to 813.8 mg g^{-1}, with D-S1, D-S2, D-M, and DN-2 significantly higher than S, and D-M significantly higher than D-S1, D-N2, and DN-1 ($p < 0.05$). As for the crude protein content, S showed a trend of being higher than D. In 2021, the S treatment (119.2 mg g^{-1}) was significantly higher than D-S1 and D-N2, while in 2022, the S treatment (168.2 mg g^{-1}) was significantly higher than all positions in the D treatment (68.8–82.6 mg g^{-1}). In the D treatment, the D-N1 crude protein content was significantly higher than in all other sampling locations in 2021 ($p < 0.05$).

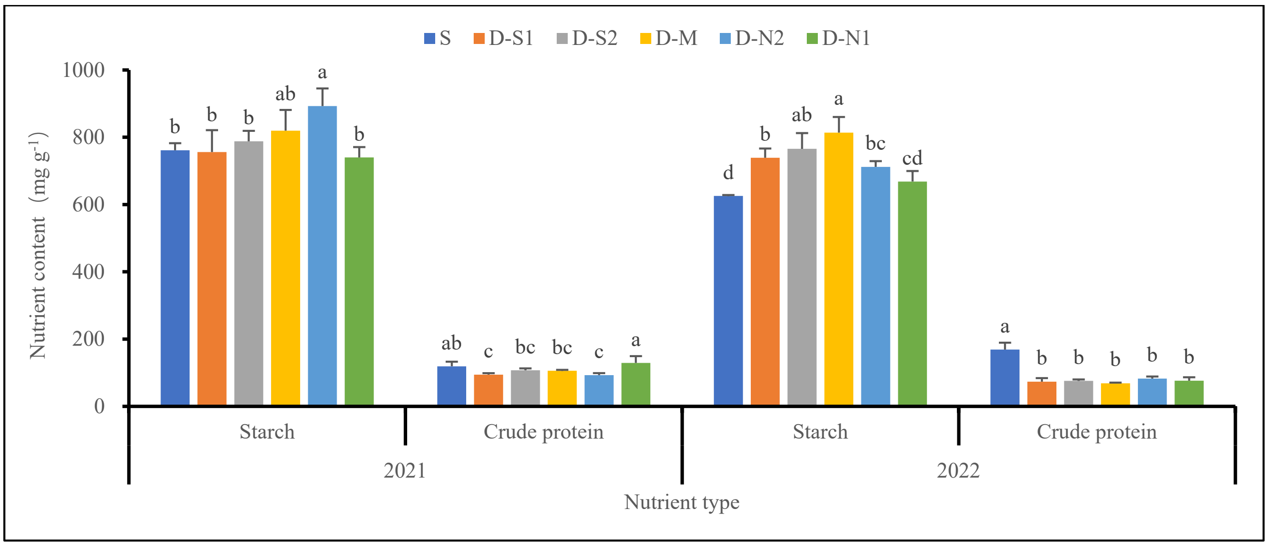

Figure 7. Variations in starch and crude protein content of arrowroot intercropped at different sampling locations in two different rubber agroforestry systems. Different letters represent significant differences between sampling locations ($p < 0.05$).

3.3. Photosynthetically Active Radiation (PAR) and Photosynthetic Capacity

As shown in Figure 8, during the period from 8:00 to 17:00, the PAR (photosynthetically active radiation) in the S treatment ranged from 34.1 to 268.0 μmol·m^{-2}·s^{-1}, significantly lower than in the D treatment, which ranged from 223.4 to 1450.3 μmol·m^{-2}·s^{-1}. The PAR in the D treatment was similar to that in the ambient open area (402.0–1448.0 μmol·m^{-2}·s^{-1}). The diurnal variation of light intensity differed among the treatments, showing a unimodal trend. Due to the shading effect of rubber trees, the average PAR in the S treatment was 145.7 μmol·m^{-2}·s^{-1}, while it was 988.8 μmol·m^{-2}·s^{-1} in the open area (O treatment). In the D treatment, the PAR ranged from 896.4 to 940.2 μmol·m^{-2}·s^{-1} among different positions, and there were no significant differences in average PAR among different sampling positions (p < 0.05).

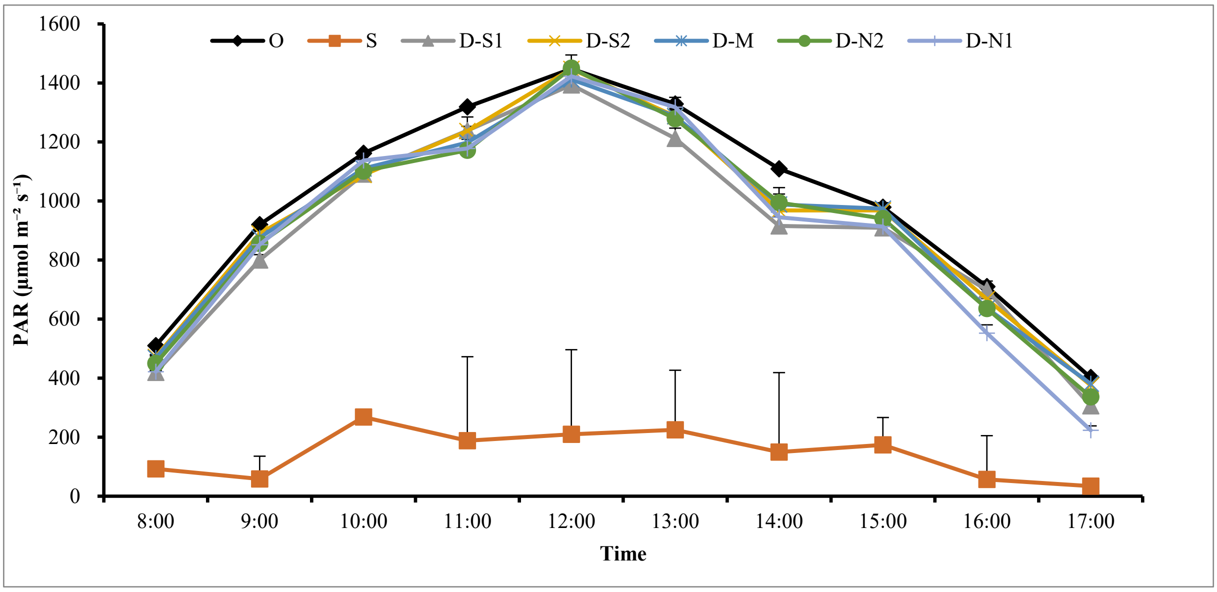

Figure 8. Daily variation of PAR at different sampling locations in two different rubber agroforestry systems.

The photosynthetic capacity of arrowroot (Figure 9) varies significantly among different types of rubber agroforestry systems. In the S treatment, the maximum net photosynthetic rate is 4.4 μmol·m^{-2}·s^{-1}, whereas in the D treatment, the maximum net photosynthetic rate at different sampling locations ranges from 12.8 to 20.1 μmol·m^{-2}·s^{-1}. Specifically, D-M, D-S2, and D-N2 exhibit higher rates than D-S1 and D-N1. The calculations reveal that the light saturation point for the S treatment is 656.7 μmol·m^{-2}·s^{-1}, which is significantly lower than for the five sampling locations of the D treatment (942.4–1290.0 μmol·m^{-2}·s^{-1}). For the D treatment, the light saturation point of D-M (1290 μmol·m^{-2}·s^{-1}) was significantly higher than of D-N1 (942.4 μmol·m^{-2}·s^{-1}). However, there is no significant difference in the light compensation point between the S and D treatments. The light compensation point in D-S1 (6.0 μmol·m^{-2}·s^{-1}) differed significantly from that in D-N2 (11.0 μmol·m^{-2}·s^{-1}) in the D treatment (p < 0.05) (Figure 10).

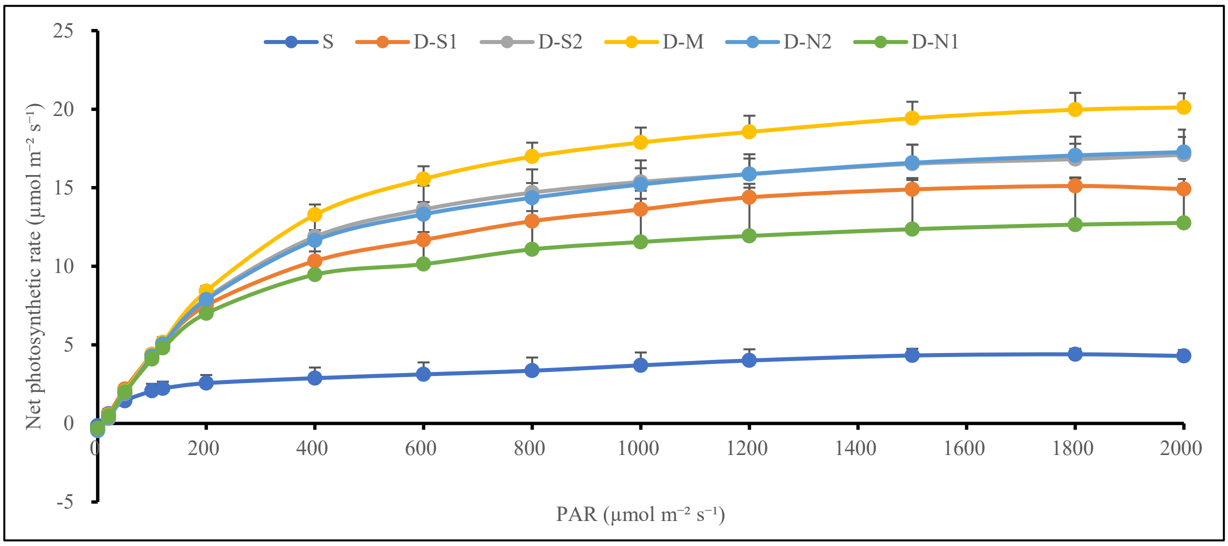

Figure 9. Light response curves for arrowroot across various sampling locations in two different rubber agroforestry systems.

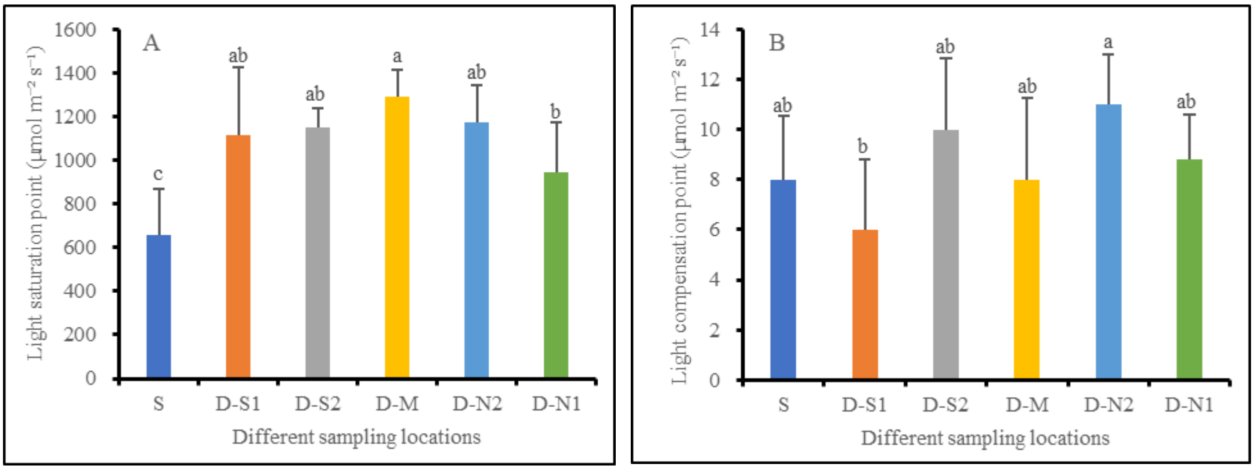

Figure 10. Light saturation (**A**) and light compensation points (**B**) for arrowroot at various sampling locations in two different rubber agroforestry systems. Different letters represent significant differences between sampling locations ($p < 0.05$).

3.4. Root Distribution and Soil Nutrient Content

Table 1 illustrates that the S treatment exhibits a higher rubber tree root distribution than the D treatment. In the S treatment, the root density near the intercropped area (1.5 m from the rubber tree) is 616.2 g m^{-3}, significantly higher than that of the S treatment (3.5 m from the rubber tree, 150.7 g m^{-3}). It is also notably higher than that of the non-intercropped area of the D treatment (3 m from the rubber tree, 250.5 g m^{-3}) and the intercropped area near the D treatment (4 m from the rubber tree, 107.0 g m^{-3}). Root density in the non-intercropped area of the D treatment is significantly higher than that near the intercropped area. There are no arrowroot roots in the S treatment, whereas, in the intercropped area, it is 5.7 g m^{-3}. However, in the intercropped area near the D treatment, the root density of the arrowroot significantly increases to 36.3 g m^{-3} ($p < 0.05$).

Table 1. Root mass density of rubber trees and arrowroot under various treatments.

Treatments	Distance from Rubber Tree Location (m)	Rubber Root Gravimetric Density (g m^{-3})	Arrowroot Gravimetric Density (g m^{-3})
S	1.5	616.2 a	-
	3.5	150.7 c	5.7 b
D	3	250.5 b	-
	4	107.0 c	36.3 a

Note: Different letters represent significant differences between treatments ($p < 0.05$).

Figure 11 depicts the variations in different soil available nutrient levels during different growth stages. Totally, the soil nutrient content in 2021 was higher than in 2022, probably due to the high nutrient input of the previous intercrop. The soil nutrient content decreases gradually as arrowroot grows. Overall, S shows slightly higher nutrient content than D. Regarding soil NO_3^-, except for the seedling and steady stages of 2022, the S treatment's content was significantly higher than that of D at other stages. In 2021, soil NO_3^- content in the S treatment was significantly lower than that of D-M in the seedling stage and D-S2 and D-M in the jointing stage. Similarly, except for the seedling stage of 2021 and the jointing stage of 2022, when the soil NH_4^+ content for the S treatment was significantly higher compared to the D treatment, the NH_4^+ values for the S treatment were generally similar to the D treatment across sampling positions and stages. Except for the mature stage of 2021 and the seedling and mature stages of 2022, the S treatment consistently exhibited significantly higher soil available phosphorus content than D at different growth stages. At the steady stage of 2022, the S treatment's soil available potassium content was significantly higher than D, while in other periods, it showed a trend of remaining steady, decreasing, or increasing. In most cases, there was no significant difference in soil nutrient content across the sampling locations of the D treatment ($p < 0.05$).

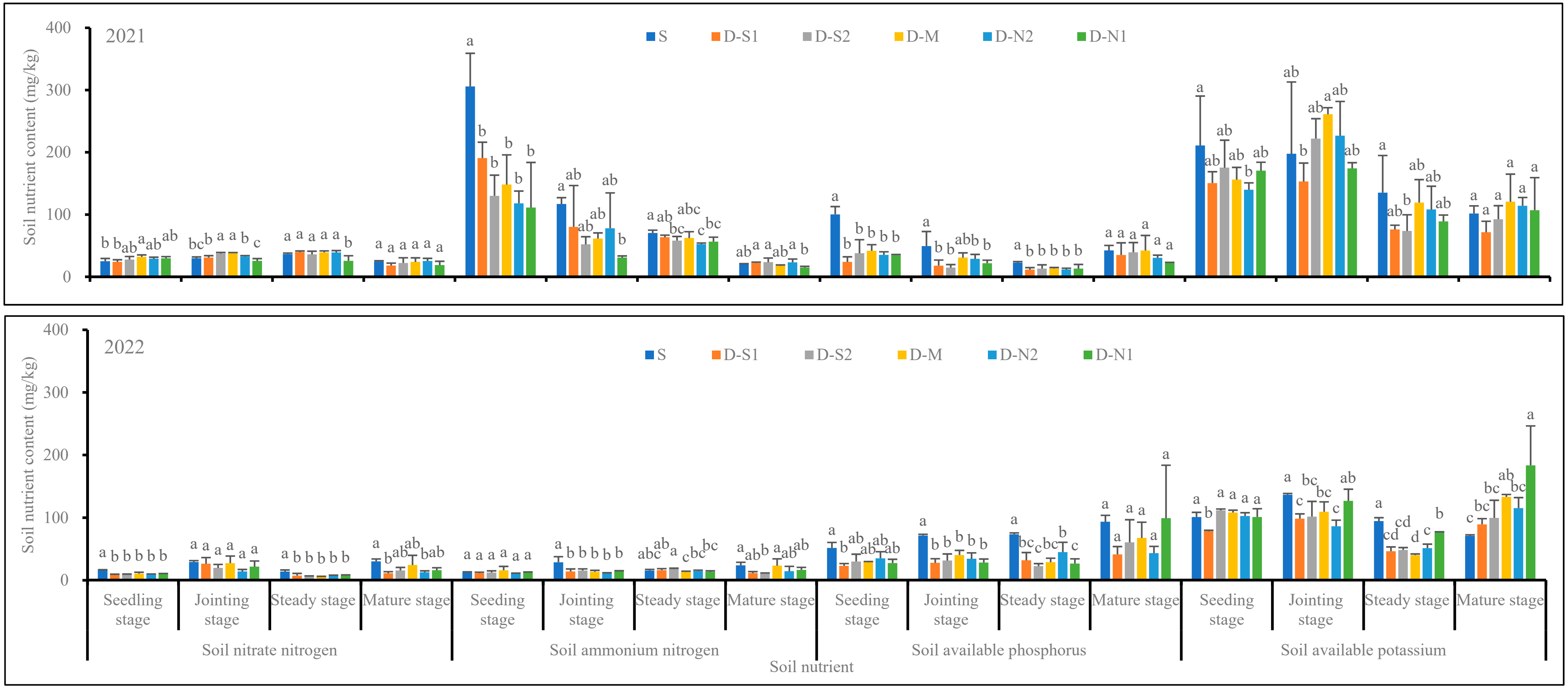

Figure 11. Nutrient content of intercropped arrowroot soils at different sampling locations at various time periods. Different letters represent significant differences between treatments ($p < 0.05$).

4. Discussion

4.1. Productivity Performance of Arrowroot Intercropped in Different Types of Rubber Plantations

Developing agroforestry systems is a vital measure to address the low profitability of monocultural rubber production, by intercropping to enhance overall production and returns from the systems. In agroforestry systems, the productivity of the associated intercrop is the fundamental indicator of system feasibility. In this study, in the double-row rubber agroforestry system, the performance in terms of plant height, stem thickness, and tillering was superior (Figures 3–5), with yields ranging from 23.46 to 27.47 t·ha^{-1} (Figure 6). This yield surpasses the intercropping yields reported by Swadija et al. [26] under coconut trees (60–65% shade) (18.62 t·ha^{-1}) and by Xie et al. [27] under chestnut trees (17.4 t·ha^{-1}). In this study, with rubber trees of 6–7 years of age, the light conditions in the D-M sampling locations are similar to those of open ground. If we consider the arrowroot yield in the D-M sampling locations as similar to those of open ground arrowroot yield, the yield levels in other sampling locations range from 68.7% to 99.5% of D-M (Figure 6B). Compared to the yield potential of crops like soybeans, corn, and peanuts in other agroforestry systems based on rubber, poplar, jujube, etc. (yield potential ranged from 44.3 to 69.3% due to light limitation) [20,28,29], this is also a relatively high level. It is evident that when arrowroot is used as the associated crop in agroforestry systems, different types of forest (garden) systems have varying impacts on arrowroot yields. Moreover, compared to other research results, the yield level in this study is quite promising.

Comparison with other studies on arrowroot cultivation in open ground indicates that the yield levels of different arrowroot varieties from various regions (Yunnan and Guizhou province in China) range from 8.1 to 18.5 t·ha^{-1} (with a plant density of 33,333 plants ha^{-1}, similar to this study) [30,31]. The arrowroot yields obtained in this study are significantly higher than the results of the studies mentioned above, suggesting that arrowroot as an intercrop in a double-row rubber agroforestry system is successful and can be considered as a potential rubber agroforestry model, although the yield of arrowroot in the current study was lower than that reported by Yang et al. [32] (37.5 t·ha^{-1}; Thai arrowroot; with a plant density of 62,500 plants·ha^{-1}). Another proof was that the yield of D-M (702.5 g plant^{-1} in 2022) was similar to that (705.0 g plant^{-1}) observed by Oktafani et al. [15] under full sun light conditions. However, when intercropped in a single-row rubber agroforestry system, arrowroot performed poorly regarding plant height, stem thickness, and tillering. It yielded significantly lower, making it less recommended for intercropping in a single-row rubber agroforestry system at this stand age.

As a starch crop, arrowroot's starch content ranges from 606.1 to 848.5 mg g^{-1} [12,33], consistent with the measurements in the D treatment and slightly higher than in the S treatment (Figure 7). From the perspective of major nutrient components, there is no significant change in the primary nutrient composition of arrowroot intercropped in a double-row rubber agroforestry system, indicating its suitability as an intercrop.

In an agroforestry system, the benefits of intercropping depend on both component crops. This study was conducted during the immature stage of a rubber plantation. So, the rubber yield is not collected. According to the results of other double-row rubber agroforestry systems (rubber trees were planted in 2002 all of the same variety and planting design; 420 trees per hectare), the total rubber yield (from 2010 to 2018) in the double-row rubber plantation accounted for 89.7% of that in the single-row rubber plantation (480 tree per hectare). The difference in rubber yield per tree between the two types of rubber plantations was observed to not be significant. Furthermore, the intercropping of yam bean and Arabica coffee during the early years of the systems maintained higher overall yields compared to monocultural treatments. Without distinct loss of rubber yield, the double-row rubber plantation still allowed intercropping with various priority crops at the mature stage to develop rubber agroforestry systems [2].

4.2. Analysis of the Dominant Factors Affecting Arrowroot Intercropping Productivity

In agroforestry systems, both above-ground and below-ground competitions are critical factors affecting the potential yield of intercrops [34,35]. Typically, in agroforestry systems, the root systems of trees and intercrops partially overlap, leading to competition for soil (and water) nutrients. Lin's [36] study demonstrated that in a 12-year-old double-row rubber agroforestry system, the root density of the rubber trees in the wide rows rapidly decreases with increasing distance from the tree. Beyond 4 m from the tree, the rubber tree root density is already low. This study validates similar results (Table 1), indicating that underground competition between rubber and arrowroot in the D treatment is not intense. In the S treatment, however, the root density of the rubber trees, both within and outside the intercropped area, is relatively high, creating a basis for more intense competition. When examining soil nutrient content throughout the growth period, the overall soil nutrient levels in the S treatment are slightly higher than in the D treatment, probably due to higher biomass accumulation and soil nutrient absorption in the D treatment. This suggests that the S treatment has a stronger nutrient supply capacity than D. However, despite this, the yield in the S treatment significantly decreases. It becomes evident that underground nutrient competition is not the primary factor affecting arrowroot yields in the S treatment.

Despite arrowroot's tolerance for shade and its ability to grow well under 30–56% canopy closure, excessive shading significantly reduces arrowroot yield and starch content [17,37]. In this study, the middle of the D treatment's light levels were relatively close to those of the open ground area, while the S treatment experienced a substantial reduction in light levels, with an average daily PAR only reaching 14.7% of the open ground control (Figure 8). Light is a significant factor influencing photosynthesis and the accumulation of plant products, playing a vital role in the ecological factors affecting growth, development, and physiological metabolism [38,39]. The morphological characteristics and photosynthetic physiology of crops can be affected by light conditions, with shading significantly reducing crop photosynthetic capacity [10]. This study yields similar results, as the S treatment exhibited a significant decrease in photosynthetic capacity under low light conditions, while the D treatment maintained a relatively high photosynthetic capacity (Figure 9), ensuring the arrowroot's yield.

In fact, within the D treatment, there was a decrease in photosynthetic capacity and yield in D-S1 and D-N1 compared to D-S2, D-M, and D-N2 (Figure 9). This decrease is likely due to residual shading effects in D-S1 and D-N1. It's important to note that this study only measured impacts during late March (with equal day and night lengths) and did not cover the entire growth period. In reality, at this stand age, rubber trees are relatively small (with a height of about 5 m), and in different seasons, D-S2, D-M, and D-N2 sampling locations can maintain a light environment similar to open ground, while D-S1 and D-N1 may experience short-term shading effects during the daytime phases in different seasons. In the D treatment, the net photosynthetic rate at different sampling locations is generally close to the light saturation at 800 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Figure 9). It can be observed that the light conditions in the D treatment at this stand are still sufficient to meet the arrowroot's light requirements, thus ensuring a basic level of arrowroot yield. Therefore, in this study, light was the dominant factor affecting the difference in arrowroot yield between the S and D treatments.

5. Conclusions

Based on the research results of the 2021–2022 experiments, in comparison to the intercropping of arrowroot in a conventional single-row rubber agroforestry system, the double-row rubber agroforestry intercropping system provides ample sunlight for arrowroot growth. Additionally, there is less overlap between the root systems of rubber trees and arrowroot. These conditions result in better morphological and photosynthetic performance for intercropped arrowroot, with yield levels ranging from 23.46 to 27.47 $t \cdot ha^{-1}$. Even though there is greater root overlap in the intercropping of arrowroot in a conventional single-row rubber agroforestry system, the soil nutrient levels are relatively high. However, due to a significant reduction in photosynthetically active radiation (PAR), it cannot meet the normal growth requirements of arrowroot, leading to lower yield levels ranging from 2.87 to 4.75 t·ha^{-1}. Light availability is the dominant factor influencing the productivity of arrowroot intercropped in a conventional single-row rubber agroforestry system and a double-row rubber agroforestry system.

In this study with rubber trees of 6–7 years of age, there are no apparent above-ground or below-ground limiting factors when intercropping arrowroot in a double-row rubber agroforestry system. Therefore, this approach represents a suitable rubber agroforestry model that can effectively increase the unit area output of younger-aged rubber plantations.

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