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Research article

Regeneration of Soil Fertility in Relationship with the Diversification of Rubber Agroforestry Systems

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Abstract: Rubber agroforestry is an agricultural system that integrates rubber trees with other compatible crops or trees to optimize land use, improve soil fertility, and enhance biodiversity. This study compares the soil richness of Rubber Agroforestry (RF) plantations with varying species diversity and Rubber Monoculture (RM) plantations. The research was conducted in Phatthalung Province, Thailand, a region with a long history of rubber agroforestry, though some areas are cultivated as rubber monocultures. Soil samples were collected at 0–15 cm and 15–30 cm depths and analyzed for physical characteristics, organic matter content, and nutrient composition. The findings indicate that soil quality is influenced by plantation type, soil depth, and locality. RM and RF plantations exhibit differences in soil physical properties, cation exchange capacity (CEC), organic carbon (OM), total nitrogen, phosphorus, potassium, calcium, and magnesium content. Across all parameters studied, except phosphorus, RF plantations demonstrated higher soil fertility indicators than RM plantations. Additionally, the NDVI analysis from 2017 to 2023 showed that RF plantations had a plant cover of 63%, compared to 58% in RM plantations. The higher plant density in RF plantations contributed to organic matter accumulation, thereby enhancing soil fertility. Conclusion: The study highlights that rubber agroforestry practices contribute to increased soil nutrient levels and organic matter content, underscoring their potential benefits for sustainable land management.

Keywords: Soil property; Soil organic matter; Soil nutrients; Biodiversity; Normalized Difference Vegetation Index (NDVI)

1. Introduction

In Thailand, rubber trees (*Hevea brasiliensis*) serve as the primary cash crop, with rubber tapping being a major source of income for local farmers. Since 2015, the Thai government has actively promoted agroforestry practices to enhance sustainability in rubber cultivation. The Rubber Authority of Thailand (RAOT) has introduced various support programs and initiatives to assist farmers in adopting and managing agroforestry systems. Rubber agroforestry is an agricultural system that integrates rubber trees with other compatible crops or tree species to optimize land use, enhance environmental sustainability, and increase farmers' income. This approach is commonly practiced in rubber-producing regions such as Phatthalung Province [1]. The agroforestry system offers several environmental benefits, including improved soil fertility, reduced soil erosion, enhanced biodiversity, and increased carbon sequestration, making it a more sustainable alternative to monoculture rubber plantations [2]. Diversifying crops through agroforestry can provide farmers with a more stable income stream by reducing financial risks associated with rubber price fluctuations. Farmers can still generate revenue from other crops grown within the agroforestry system if rubber prices decline.

However, implementing and managing rubber agroforestry requires specialized knowledge and expertise due to the complexity of integrating multiple crop species. Rubber agroforestry systems improve soil productivity through diverse plant species that positively affect soil health and fertility. The presence of multiple plant species encourages a diverse soil microbiome, including beneficial bacteria and fungi, which play essential roles in nutrient cycling, organic matter decomposition, and overall soil health. The continuous addition of organic matter from fallen leaves, branches, and root biomass enhances soil structure, water retention capacity, and nutrient availability [2,3,4,5,6]. Additionally, nutrient-rich litter from trees is a natural fertilizer for rubber and companion crops. Many systems incorporate nitrogen-fixing leguminous trees or shrubs, which improve soil fertility by fixing atmospheric nitrogen and making it available to other plants [2,6,7,8]. However, successfully implementing rubber agroforestry requires careful planning and continuous monitoring to maximize its benefits. This study aimed to determine the baseline levels of key soil nutrients (e.g., nitrogen, phosphorus, potassium, micronutrients), soil organic matter, and soil chemical and physical properties in various rubber agroforestry systems and rubber monoculture plantations. Regular soil analysis is essential for making informed decisions on nutrient management in rubber agroforestry systems, ensuring both rubber trees' health and the agroecosystem's long-term sustainability.

2. Methodology

2.1 Study Site Description

2.1.1 Rubber agroforest plantation

Rubber agroforestry is commonly practiced in regions where rubber is a major cash crop and has a strong ecological and economic connection to forested landscapes. One such region is Phatthalung Province in southern Thailand (Fig. 1), where farmers integrate various tree species alongside rubber trees, including mangosteen (*Garcinia mangostana*), salak (*Salacca zalacca*), and timber species such as *Hopea odorata*. In 2020, the total rubber-producing area in Phatthalung Province was recorded at 976,865 rai (156,298 hectares) [9]. However, no distinct classification currently separates rubber agroforestry areas from monoculture rubber plantations. This study focused on two districts, Sribanpot (7.744596º N, 99.890424º E) and Tamod (7.298139º N, 100.015743º E), both of which are upland regions situated near the Khao Banthat mountain range. These districts were selected due to their long history of rubber agroforestry practices and involvement in the Terra Genesis Regenerative Rubber Alliance project, which supports farmers who abstain from using chemical inputs in their rubber plantations and employ agroforestry methods.

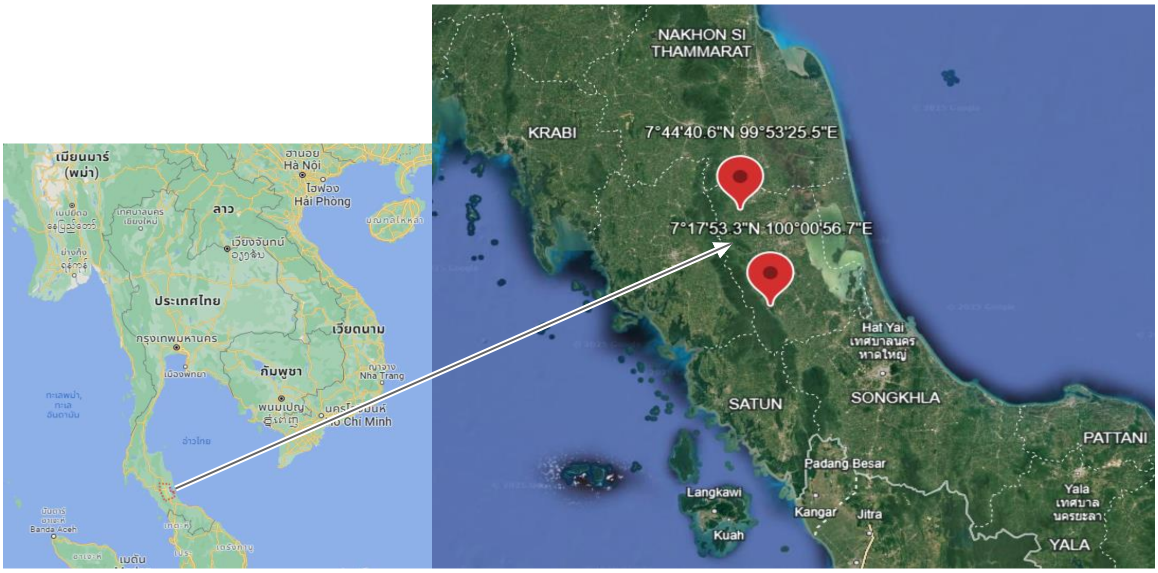

Figure 1. Geographical location of Phatthalung province. (Source: Google Maps).

2.1.2 Explanation of biodiversity data

Since 2020, an inventory of plant species in each forest layer of participating farms has been conducted. This study validated that farmers within the Ethos™ Regenerative Outcome Verification program exhibit higher soil organic matter levels than nearby conventional farms. However, these findings have also contributed to the continuous refinement of the Ethos™ protocol, emphasizing the need for increased rigor in data collection to enhance accuracy while maintaining a feasible and efficient process. The protocol has evolved from sampling one 15×15 m subplot per farm to three 15×15 m subplots for biodiversity and ecosystem health assessments. As of 2024, all Ethos™ participating farms sample three subplots per rubber garden. A garden is a geographically bound zone of active rubber cultivation managed by smallholder rubber farmers. Farmers typically oversee one to three rubber gardens, with a minority managing five to eight gardens. The total landholding per farmer generally remains below five hectares. This investigation also led to an enhancement of the sampling protocols. For assessing tall, medium, and small trees, data collection now includes an actual integer count within the sample areas, whereas other vegetation layers are categorized into predefined ranges. To facilitate data analysis and sample stratification across all participating farms, categorical values were converted into averaged numerical values (Table 1). Additionally, farmer data collectors have undergone further training to recognize patterns across varying levels of regenerative agroforestry complexity. They are now encouraged to provide qualitative observations on biodiversity levels within agroforestry systems. This qualitative perspective is a comparative measure against the numerical data collected at the subplot level, contributing to a more comprehensive understanding of biodiversity within these systems.

Table 1. Five ranges of number of plants at a given canopy layer in 15 x 15 m subplot areas assigned numerical values from 0 to 12.

Categorical answer options	Numerical Value
None observed	0
Few (1- 3 plants)	2
Some (4- 6 plants)	5
Significant (7- 10 plants)	8.5
High (more than 11 plants)	12

2.1.3 Explanation of farmer plant use scoring

Farmers also document the secondary (non-rubber) crops selected for each species/crop they have growing in their rubber agroforest(s). This then yields a potential score from 0 to 38. (see list below) Secondary crop diversity was used as an additional indicator of ecological complexity.

The list of species includes White Meranti, Ironwood, Stink Bean, Betel Nut, Longkong, Durian, Mangosteen, Baege, *Archidendron jiringa*, Bamboo, Banana, Rambutan, Salak, Coconut, Champak, Kratom, African Oil Palm, Macaw Fat, Coffee, Avocado, Galanga, Broadleaf Mahogany, *Dipterocarpus dyeri* Pierre, Vegetables, Pineapple, *Baccaurea motleyana*, Siamese Neem Tree, Cashew Nut, *Acacia mangium*, Syzygium, Passion Fruit, Wild Betel Leaf, *Litsea elliptica* Blume, Champedak, Malacca Teak, Mango, Jackfruit, and Langsat.

2.1.4 Explanation of percentile

The percentile is a measure used in statistics indicating the value below which a given percentage of observations in a dataset falls. The calculation follows these steps:

Determine the percentile value (P).

Calculate the rank (*R*) using the formula:

$$R = \frac{P}{100}(N + 1)$$

Where *N* is the total number of observations.

If *R* is an integer, the percentile corresponds to the value of the observation in an ordered dataset.

If *R* is not an integer, round up and down to the nearest whole numbers to identify the two closest ranks, R_{low} and R_{high}. The percentile value is then interpolated using the formula:

$$Percentile\ Vaulue = Value\ Rlow + (R - Rlow) \times (Value\ Rhigh - Value\ Rlow)$$

The plant species count was used to calculate plant diversification percentages, which were then ranked to classify the rubber agroforestry system. The classification is based on five distinct types, determined by the density and diversity of secondary crops present within rubber plots (Table 2). The classification follows prior studies that identified monoculture, organic, simple polyculture, complex polyculture, modern jungle, and traditional jungle systems [10].

Table 2. Ranking of the layer of secondary crops in rubber agroforest plantation (RF) in 2023.

The layer of secondary crops	RF-V	RF-IV	RF-III	RF-II	RF-I
	Range of Specimens per Subplot				
High layer	3-7	2-8	2-12	2-9	1-9
Medium layer	4-12	2-10	2-12	2-12	2-12
Low layer	10-12	9-12	9-12	8-12	5-12
Cover ground	8-12	9-12	5-12	5-12	2-12
Tubers	6-11	6-12	6-12	5-12	2-12
Epiphytes	5-12	7-12	5-12	2-9	2-9
Plant Diversity Percentile (%)	83-100	62-81	47-60	22-42	5-21

2.2 Experiment Design

2.2.1 Selection of rubber plantation

This study was conducted from May 2023 to July 2023 and compared five types of rubber agroforestry (RF) plantations with rubber monoculture (RM) plantations. A purposive sampling method was employed to pair RF and RM plantations with two replications at each district, resulting in 40 plantations. The RM plantations were selected approximately 1 km from the corresponding RF plantations to minimize external environmental influences. Both RF and RM plantations were in the mature growth stage at the time of the study. The structural characteristics and visual distinctions between RF and RM plantations are presented in Figure 2. The RF plantations included in this study were part of the TGI (Terra Genesis International) project, whereas the RM plantations were not affiliated with this initiative.

2.2.2 Soil sampling

The boundary of each plantation was determined using a smartphone-based GPS. A 2-meter buffer zone from the plot edge was excluded from the soil sampling area to minimize discrepancies. Soil samples were collected using a randomized sampling method based on XY coordinates, selecting 15 points per plot. Samples were taken at two soil depths: 0-15 cm and 15-30 cm, totaling 80 samples across all study sites. Any stones, debris, or plant material were removed from the collected samples before laboratory processing. Subsequently, the soil samples were transported to the Faculty of Technology and Community Development laboratory at Thaksin University, Phatthalung Province. The samples were air-dried in the shade and sieved using a No.10 mesh sieve. Soil physical and nutrient parameters were analyzed, with additional advanced soil analysis conducted at the Prince of Songkhla University Central Analytical Center.

2.2.3 Soil analysis methods

2.2.3.1 Soil properties

The analysis of soil properties, including particle size, color, organic matter content, pH, and electrical conductivity (EC), was performed at the Faculty of Technology and Community Development, Thaksin University, using the following methodologies:

Soil particle size analysis: The hydrometer method was employed to determine soil particle size distribution. The procedure involved oven-drying soil samples, adding a dispersing agent, and mechanically shaking the suspension for 16 hours before transferring it to a sedimentation cylinder. Hydrometer readings were taken at specified time intervals to determine the sand, silt, and clay fractions.

The percentage composition of soil particles was calculated as follows:

$$\%Sand = \frac{(oven\ dry\ soil\ mass) - (Rsand - RC1)}{Oven\ dry\ soil\ mass} \times 100$$

$$\%Clay = \frac{Rclay - RC2}{oven\ dry\ soil\ mass} \times 100$$

$$\%Silt = 100 - (\%Sand + \%Clay)$$

Soil color: Moist soil samples were examined using the Munsell color chart, and soil colors were classified based on hue, value, and chroma.

Soil organic matter (SOM): The Walkley-Black method was used to determine soil organic carbon (SOC) content. The procedure involved oxidation of SOC with potassium dichromate ($K_2Cr_2O_7^2$), reduction of excess dichromate with iron sulfate ($FeSO_4$), and titration to determine the amount of carbon present. Soil organic matter was estimated using the formula: $\%Organic\ Matter\ (OM) = \%organic\ carbon\ (OC) \times 1.7$

Soil pH: Measured using a 1:1 soil-to-water ratio with a calibrated pH meter.

Soil EC: A 1:5 soil-to-water suspension was prepared, and EC was measured using a conductivity meter after allowing for equilibration.

The blue-highlighted text had previously appeared in the original manuscript throughout, but upon reviewing the version sent by the editor, the text was missing, and the order of the headings was also lost. This may have been due to some error in document handling. Therefore, I decided to add the text back in to ensure it aligns with the original manuscript where it had previously appeared.

Rubber Monoculture (RM)
Rubber Agroforest Type I (RF-I)
Rubber Agroforest Type II (RF-II)
Rubber Agroforest Type III (RF-III)
Rubber Agroforest Type IV (RF-IV)
Rubber Agroforest Type V (RF-V)

Figure 2. Rubber monoculture and rubber agroforest types.

2.2.3.2 Soil nutrient analysis

Total soil nitrogen content was determined at Thaksin University using the Kjeldahl method. The procedure involved the digestion of soil samples with concentrated sulfuric acid, conversion of nitrogen to ammonium sulfate, and distillation using sodium hydroxide, followed by titration with sulfuric acid. The nitrogen content was calculated as follows:

$$\%Total\ Nitrogen = \frac{[1.4(V2 - V1) \times N \times 6.25]}{D}$$

where: $V2$ = Volume of HCl used in sample titration, $V1$ = Volume of HCl used in blank titration, = Normality of standard acid, D = Soil dry weight.

Additional parameters, including cation exchange capacity (CEC), available and total phosphorus, potassium, calcium, and magnesium content, were analyzed at the Prince of Songkhla University Central Analytical Center using standard laboratory procedures, including the Bray II method for phosphorus and the NH_4OAc extraction method for cation exchangeable elements.

2.3 Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) was used to assess vegetation health. NDVI values were calculated using satellite-derived reflectance data from the Harmonized Sentinel-2 MSI Level-2A imagery. The formula applied was: $NDVI = \frac{NIR-RED}{NIR+RED}$ Where NIR and NED represent spectral reflectance in the near-infrared and red regions, respectively, NDVI values range from -1 to +1, with higher values indicating denser and healthier.

2.4 Data Analysis

Data were analyzed using ANOVA to compare mean values across different factors, including soil depth, plant density, and study area. Tukey's Honest Significant Difference (TukeyHSD) test was conducted to assess statistically significant differences between groups. Paired t-tests were also performed to make direct comparisons between specific plantation types. To spatially analyze land-use changes, XY coordinates were converted to latitude and longitude, and a 32.2-meter radius buffer was generated around each sampling point, creating 1/3-hectare circular polygons. Deforestation was assessed using the Hansen Global Forest Change v1.10 (2000-2022) [deprecated] | Earth Engine Data Catalog | Google for Developers. https://doi.org/10.1126/science.1244693 and NDVI change over the past five years was evaluated using COPERNICUS_S2_SR_HARMONIZED satellite imagery.

3. Results and Discussion

3.1 Soil Properties

3.1.1 Soil physical properties

The soil color of rubber plantations predominantly falls within brown tones, ranging from dark yellowish brown (10YR2/3) to light reddish brown (2.5YR6/4). The soil at Tamod is characterized by brown to dark brown hues, whereas Sribanpot exhibits variations from bright yellow-brown to dark brown. The soil color of rubber plots differs between monoculture and agroforestry systems, displaying a range of colors from yellow to brown and dark brown (Figure 3). Regarding texture, both areas primarily consist of high clay and silt content, including silty clay, silty clay loam, silt loam, and clay (Figure 4). SOM significantly influences soil color, serving as the primary pigment. The content of SOM is negatively correlated with the soil's hue, value, and chroma, as humus substances tend to absorb the majority of visible wavelengths of light. Other factors, including grain size distribution, chemical and mineralogical composition, land use, and climatic conditions, can modify the relationship between SOM and soil color. In particular, dark minerals may strongly influence the interaction between organic matter and color in certain soils. Pretorius et al. [11] observed a more pronounced impact of organic matter on the color of sandy soils than clay soils, likely due to the smaller external surface area of sand grains, requiring fewer organic colloids for coverage. Consequently, soils' brown and dark coloration, particularly those with high clay content, is associated with elevated organic matter levels.

3.1.2 Soil quality indicators

Soil quality indicators, including pH, EC, CEC, OC, and OM, were examined with three factors: locality (Tamod and Sribanpot), plant density (rubber monoculture and five types of rubber agroforestry), and soil depth (two levels: 0-15 cm and 15-30 cm). The results indicated that locality, plant density, and soil depth significantly affected all parameters except for CEC, which was not significantly impacted by soil depth. When comparing the two models, areas with variations in soil depth and plant density significantly affected EC. Areas with different plant densities demonstrated significant pH, EC, and CEC differences. Focusing on OM content, it was observed that this parameter was influenced by locality, plant density, and soil depth (Table 3). In a study of 40 plantations from both rubber monoculture and five rubber agroforestry types, the pH of natural soils ranged from 4.73 to 5.03, EC was within a non-saline range of 1.70 to 2.51, CEC was very low, ranging from 2.51 to 4.87, and the percentages of OC and OM were deficient, ranging from 1.53% to 2.09% and from 2.63% to 3.78%, respectively. However, rubber agroforestry Type V exhibited superior soil quality (Table 4). Comparing the physical soil quality between RM and RF plantations revealed significant differences. RF plantations had notably higher OM content than RM, with CEC values also significantly higher, emphasizing the marked contrast in soil quality between the two types of plantations. This stark contrast supports that RF systems promote soil richness and nutrient content (Table 5). Soil quality indicators effectively differentiated between rubber cultivation practices. Rubber agroforestry, which has a higher diversity of plants (83-100%), exhibited better soil quality than other systems. Similar findings were reported by Rousseau et al. [12], who found that soil quality indicators (bulk density, sum of bases, pH, and carbon content) could distinguish cacao-based agroforestry systems (AFS) from forests, with cacao AFS conserving soil and providing high levels of soil-related ecological services. An et al. [13] highlighted that planting trees on agricultural land to form agroforestry systems alters SOC biological and thermal stabilities, noting that hedgerow systems may maintain more stable SOC than shelterbelt systems, which can enhance carbon stability, promote carbon sequestration, and contribute to climate change mitigation.

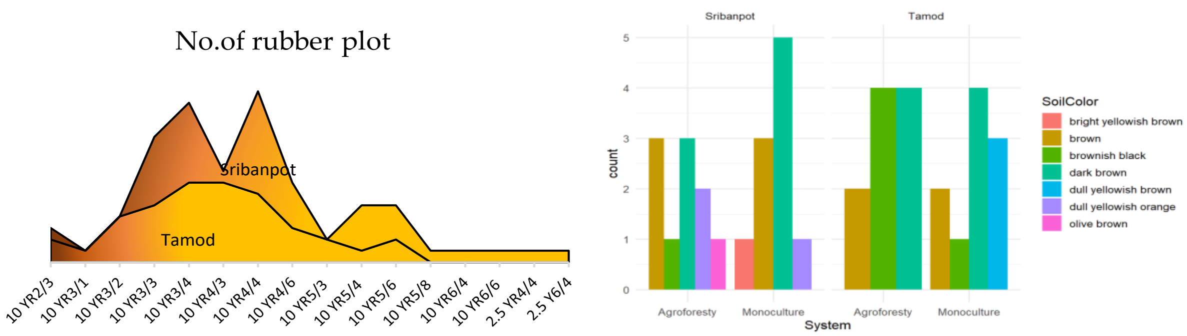

Figure 3. Soil color of rubber plantations (Rubber agroforest and monoculture) at 2 sites of study.

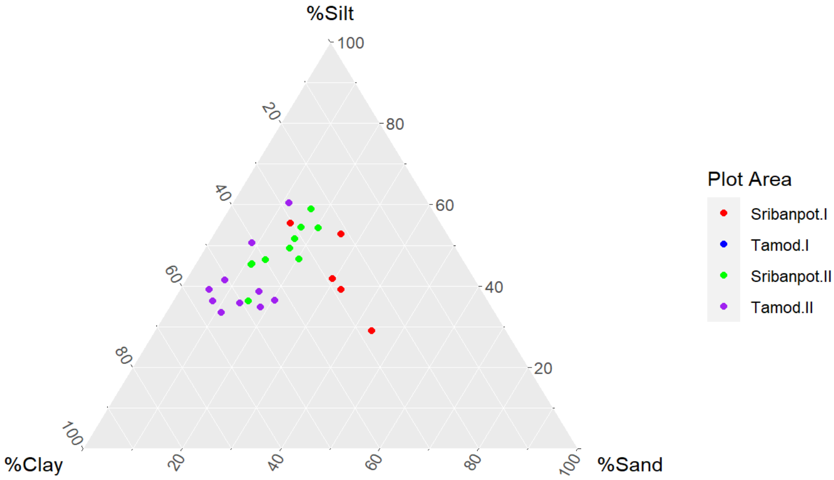

Figure 4. Soil texture of rubber cropping system (Rubber agroforest and monoculture) at 2 sites of study.

Table 3. The value mean square on soil physical properties of rubber cropping system (Rubber agroforest and monoculture) with comparing between-group parameter factors by ANOVA means according to Tukey HSD test.

Model	pH	EC	CEC (cmol/kg)	%OC	%OM
A	1.040***	0.707*	23.718***	4.356**	10.623**
PD	0.377***	2.427***	15.955***	1.222*	2.981*
SD	1.296***	5.204***	0.462 ns	5.006***	12.208***
PD vs SD	0.018 ns	0.055 ns	0.882 ns	0.517 ns	1.262 ns
A vs SD	0.533 ns	2.062***	1.723 ns	0.037 ns	0.091 ns
A vs PD	0.215***	0.518*	25.331***	0.188 ns	0.458 ns
A vs PD vs SD	0.033 ns	0.139 ns	1.168 ns	0.061 ns	0.148 ns

Signif. Codes: [0, 0.001] '***,' [0.001, 0.01] '**,' [0.01, 0.05] '*,' [0.1, 1] no significant 'ns'.
Area(A), Plant Density (PD), Soil Depth (SD)

Table 4. Mean value of soil physical properties of rubber cropping system (Rubber monoculture: RM and Rubber agroforest: RF) with consolidated mean from area, plant density, and soil depth 0-30 cm by ANOVA means according to Tukey HSD test.

Rubber cropping system	pH	EC	CEC (cmol/kg)	%OC	%OM
RM	4.83 ± 0.0139	1.96 ± 0.0513	3.25 ± 0.187	1.53 ± 0.055	2.63 ± 0.0938
RF-I	4.77 ± 0.0565	1.87 ± 0.0858	3.30 ± 0.418	2.20 ± 0.189	3.78 ± 0.325
RF-II	5.03 ± 0.0276	1.70 ± 0.0772	2.70 ± 0.338	1.64 ± 0.120	2.82 ± 0.207
RF-III	4.75 ± 0.0411	1.79 ± 0.0960	4.87 ± 0.448	1.89 ± 0.087	3.24 ± 0.149
RF-IV	4.78 ± 0.0421	2.02 ± 0.110	2.51 ± 0.0870	1.78 ± 0.129	3.06 ± 0.221
RF-V	4.73 ± 0.0582	2.51 ± 0.110	4.16 ± 0.506	2.09 ± 0.150	3.59 ± 0.258
F value	8.132	7.199	5.097	6.758	6.758
Pr (>F)	***	***	***	***	***

Signif. codes: [0, 0.001] '***'

Table 5. Mean value on Rubber monoculture soil physical properties: RM vs Rubber agroforest: RF at soil depth 0-30 cm by ANOVA.

Rubber cropping system	pH	EC	CEC (cmol/kg)	%OC	%OM
RM	4.72	2.05	3.91b	1.53	2.63b
RF	4.75	1.95	4.05a	2.01	3.30a
Pr(>F)	ns	ns	*	ns	*
CV (%)	0.44	5.11	0.25	0.23	4.50

Signif. Codes: [0.01, 0.05] '*,' [0.1, 1] no significant 'ns'.

3.2 Soil Nutrients

Soil nutrient indicators, including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), revealed significant variation in total N, available P, and K across different areas, plant densities, and soil depths. The model indicated no significant variation in total P. However, Ca and Mg significantly differed among areas and plant densities (Table 6). A comparison between RM and five RF types revealed significant variations in total N and Mg content. RF systems exhibited higher soil nutrient levels than monoculture systems (Table 7). This study provides a detailed comparison of nutrient content between RF and RM. RF systems had significantly higher potassium, calcium, and magnesium levels than RM systems. However, no significant difference was observed in the phosphorus content (Table 8). These findings are consistent with studies by Tongkaemkaew et al. [2] and Yuan et al. [14], which suggest that multi-species rubber agroforestry is an environmentally friendly management strategy that enhances ecosystem nutrient cycling, soil fertility restoration, and overall ecosystem services in rubber plantations. Plants growing in nutrient-pool habitats, such as those in RM systems, tend to have high nutrient remobilization, leading to lower litter quality and slower decomposition rates. Consequently, nutrient return to the soil through litterfall is reduced, exacerbating soil degradation in rubber monoculture systems.

Table 6. According to the Tukey HSD test, the mean square of soil nutrient content of the rubber cropping system (rubber agroforest and monoculture) was compared between group parameter factors using ANOVA means.

Model	Total N (mg/kg)	Total P (mg/kg)	Bray II	NH_4OAc Extract (mg/kg)		
			Avail. P (mg/kg)	K	Ca	Mg
A	0.023 ***	403 ns	2836.7 ***	4.6 ns	150869 ***	1180 **
PD	0.008 ***	7185	121.4 ***	146.7 *	13039 ns	479 *
SD	0.047 ***	7349 ns	13.4 *	2898.4 ***	1162 ns	1597 **
PD vs SD	0.001 ns	733 ns	6.7 *	120.2 *	15064 ns	107 ns
A vs SD	0.007 *	3309 ns	24.3 **	720.1 ***	33058 .	474 .
A vs PD	0.002 ns	19103 ***	163.4 ***	703.6 ***	56072 ***	3955***
A vs PD vs SD	0.002 ns	786 ns	8.0 *	168.0 **	13966 ns	206 ns

Signif. Codes: [0, 0.001] '***,' [0.001, 0.01] '**,' [0.01, 0.05] '*', [0.05, 0.1] '.', [0.1, 1] no significant 'ns'.
Area(A), Plant Density (PD), Soil Depth (SD)

3.3 Normalized Difference Vegetation Index (NDVI)

The analysis of the NDVI for agroforestry rubber plantations from 2017 to 2023 revealed that plantation owners did not engage in significant tree felling or land clearing during this period. The stability of NDVI values suggests consistent vegetation cover and minimal disturbances across the observation period. In agroforestry rubber plantations, the average plant density was recorded at 1,099 individuals per 3,215 m², with NDVI values reaching up to 0.63. This is comparatively higher than the NDVI value of 0.58 observed in garden-based plantations, which exhibited a lower plant density of 694 individuals over the same area. Additionally, rubber-based agroforestry systems demonstrated improved soil health, as indicated by higher OM content in the topsoil (0–30 cm depth). RF systems recorded an average OM content of 3.30%, compared to 2.63% in RM plantations (Table 9). These findings suggest that agroforestry practices enhance soil organic content, potentially contributing to greater soil fertility and ecosystem resilience.

As evidenced by the management of agroforestry systems, being largely dependent on landowners or plantation managers, focuses particularly on the selection of shade tree species with high economic value and market demand [15], the economic benefit of secondary crop yields is a key driver for the shift to agroforestry practices. Based on the NDVI values, total carbon stock in forest reserves can be estimated [16,17]. Utilizing the NDVI value and the equation developed for the Leuser Ecosystem area in Sumatra, Indonesia ($Y = 3.827 * X-1.587$, where Y represents carbon stocks and X denotes the NDVI value), the total estimated carbon stock of the forest reserve is approximately 99,557.6 tonnes, with a mean value of about 8.491 tonnes per hectare [17]. These findings underscore the importance of NDVI as a tool for assessing vegetation cover and estimating carbon stock in agroforestry and forest ecosystems.

Table 7. The mean value of soil nutrients content of rubber cropping system (Rubber monoculture: RM and Rubber agroforest: RF) with consolidated mean from area, plant density, and soil depth 0-30 cm by ANOVA.

Rubber cropping system	Total N (mg/kg)	Total P (mg/kg)	Bray II	NH4OAc Extract (mg/kg)		
			Avail. P (mg/kg)	K	Ca	Mg
RM	0.108 ± 0.003	113.0 ± 17.8	8.69 ± 0.793	34.3 ± 1.71	74.2 ± 7.82	17.8 ± 1.68
RF-I	0.126 ± 0.006	74.6 ± 4.2	14.0 ± 3.02	31.8 ±1.41	80.8 ± 11.6	22.7 ± 3.21
RF-II	0.108 ± 0.006	98.2 ± 17.4	7.82 ± 1.12	39.8 ± 4.76	131.0 ± 35.2	23.6 ± 5.59
RF-III	0.145 ± 0.009	130.0 ± 20.8	8.37 ± 1.6	35.3 ± 2.81	98.4 ± 18.0	34.3 ± 6.91
RF-IV	0.141 ± 0.01	92.0 ± 3.22	8.78 ± 1.32	35.3 ± 2.81	137.0 ± 48.6	19.9 ± 2.89
RF-V	0.153 ± 0.01	113.0 ± 18.4	7.00 ± 0.927	37.7 ± 2.2	74.6 ± 15.8	24.9 ± 5.11
F value	11.290	0.459	1.979	0.742	1.923	2.598
Pr(>F)	***	ns	.	ns		*

Signif. Codes: [0, 0.001] '***,' [0.01, 0.05] '*,' [0.05, 0.1] '.', [0.1, 1] no significant 'ns'.

Table 8. Mean value of soil nutrients content Rubber monoculture: RM vs Rubber agroforest: RF at soil depth 0-30 cm by ANOVA.

Rubber cropping system	Total N (mg/kg)	Total P (mg/kg)	Bray II	NH4OAc Extract (mg/kg)		
			Avail. P (mg/kg)	K	Ca	Mg
RM	0.25b	84.32b	3.38	31.36b	89.32b	21.40b
RF	0.31a	99.49a	3.24	36.12a	147.80a	28.92a
Pr(>F)	*	**	ns	*	**	*
CV(%)	1.44	0.03	1.96	0.31	0.37	1.49

Signif. Codes: [0.001, 0.01] '**,' [0.01, 0.05] '*,' [0.1, 1] no significant 'ns'.

Table 9. NDVI and organic content with soil depth 0-30 cm in Rubber monoculture plantation (RM) and Rubber agroforest plantation (RF) in 2017-2023

Rubber cropping system	%OM	Un-cleared of 3215 m circle around each sample (1/3 ha total surface area)	%NDVI (2017-2023)
RM	2.63b	694	58
RF	3.30a	1,099	63
Pr(>F)	*		
CV (%)	4.50		

Signif. codes: [0.01, 0.05] '*'

4. Conclusion

Agroforestry practices in rubber plantations provide significant benefits, not only by enhancing plant species diversity but also by improving the physical and chemical fertility of the soil. In particular, the organic matter content in agroforestry systems tends to be higher than in monoculture rubber plantations. Additionally, nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium are generally more abundant in agroforestry systems. As a result, farmers practicing agroforestry may reduce their reliance on chemical fertilizers, promoting more sustainable agricultural practices. The rubber agroforestry system represents an agricultural method that can contribute substantially to the restoration of agroecosystems. This system integrates rubber cultivation with complementary crops or trees, fostering biodiversity and improving soil health while generating income from rubber production and other secondary yields. Furthermore, agroforestry can tap into carbon markets, providing financial support for practices that sequester carbon dioxide and mitigate climate change. By incorporating trees into agricultural activities, agroforestry enhances carbon storage and delivers a wide range of environmental, social, and economic benefits.

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Reference

[1] Tongkaemkaew, U.; Penot, E.; Chambon, B. Rubber agroforestry systems in mature plantations in Phatthalung Province, Southern Thailand. *Thaksin J.* **2020**, *23*, 78-85.

[2] Tongkaemkaew, U.; Sukkul, J.; Sumkhan, N.; Pangklang, P.; Brauman, A.; Ismail, R. Litterfall, litter decomposition, soil macrofauna, and nutrient contents in rubber monoculture and rubber-based agroforestry plantations. *For. Soc.* **2018**, *2*, 138-149. https://doi.org/10.24259/fs.v2i2.4431

[3] Warren-Thomas, E.; Nelson, L.; Juthong, W.; Bumrungsri, S.; Brattström, O.; Stroesser, L.; Chambon, B.; Penot, E.; Tongkaemkaew, U.; Edwards, D.P.; et al. Rubber agroforestry in Thailand provides some biodiversity benefits without reducing yields. *J. Appl. Ecol.* **2020**, *57*, 17-30. https://doi.org/10.1111/1365-2664.13530

[4] Maria Wang, M.H.; Warren-Thomas, E.; Cherico Wanger, T. Rubber agroforestry: feasibility at scale. Mighty Earth **2021**. Available online: https://research.bangor.ac.uk/portal/files/40328214/Mighty_Earth_Agroforestry_Rubber_Report_May_2021.pdf (accessed on 11 May 2024).

[5] Huang, I.Y.; James, K.; Thamthanakoon, N.; Pinitjitsamut, P.; Rattanamanee, N.; Pinitjitsamut, M.; Yamklin, S.; Lowenberg-DeBoer, J. Economic outcomes of rubber-based agroforestry systems: a systematic review and narrative synthesis. *Agrofor. Syst*. **2023**, *97*, 335-354**.** https://doi.org/10.1007/s10457-022-00734-x

[6] Zhu, X.; Yuan, X.; Lu, E.; Yang, B.; Wang, H.; Du, Y.; Singh, A.K.; Liu, W. Soil splash erosion: An overlooked issue for sustainable rubber plantation in the tropical region of China. *Int. Soil Water Conserv. Res.* **2023**, *11*, 30-42. https://doi.org/10.1016/j.iswcr.2022.05.005

[7] Wu, X.; Lyu, X.; Li, Z.; Gao, B.; Zeng, X.; Wu, J.; Sun, Y. Transport of polystyrene nanoplastics in natural soils: Effect of soil properties, ionic strength and cation type. *Sci. Total Environ*. **2020**, *707*, 136065. https://doi.org/10.1016/j.scitotenv.2019.136065

[8] Silvianingsih, Y.A.; Hairiah, K.; Suprayogo, D.; Van Noordwijk, M. Kaleka agroforest in Central Kalimantan (Indonesia): soil quality, hydrological protection of adjacent peatlands, and sustainability. *Land* **2021**, *10*, 8856**.** https://doi.org/10.3390/land10080856

[9] OAE (Office of Agriculture Economics). Agricultural statistics of Thailand 2022; Ministry of Agriculture and Cooperatives: Bangkok, Thailand, **2023**. (In Thai)

[10] Verhofste, R.; Dunteman, L.; Commons, M.; Kristiansen, O.; Tongkaemkaew, U. Rubber management systems: A progression from extractive to regenerative production. *ASEAN J. Sci. Technol. Rep*. **2024**, *27*, e250789. https://doi.org/10.55164/ajstr.v27i3.250789

[11] Pretorius, M.L.; Van Huyssteen, C.W.; Brown, L.R. Soil color indicates carbon and wetlands: Developing a color-proxy for soil organic carbon and wetland boundaries on sandy coastal plains in South Africa. *Environ. Monit. Assess*. **2017**, *189*, 1-18. https://doi.org/10.1007/S10661-017-6249-Z

[12] Rousseau, G.X.; Deheuvels, O.; Rodriguez Arias, I.; Somarriba, E. Indicating soil quality in cacao-based agroforestry systems and old-growth forests: The potential of soil macrofauna assemblage. *Ecol. Indic*. **2012**, *23*, 535-543. https://doi.org/10.1016/j.ecolind.2012.05.008

[13] An, Z.; Pokharel, P.; Plante, A.F.; Bork, E.W.; Carlyle, C.N.; Williams, E.K.; Chang, S.X. Soil organic matter stability in forest and cropland components of two agroforestry systems in western Canada. *Geoderma* **2023**, *433*, 116463. https://doi.org/10.1016/j.geoderma.2023.116463

[14] Yuan, X.; Yang, B.; Liu, W.; Wu, J.; Li, X. Intercropping with cash crops promotes sustainability of rubber agroforestry: Insights from litterfall production and associated carbon and nutrient fluxes. *Eur. J. Agron*. **2024**, *154*, 127071. https://doi.org/10.1016/j.eja.2023.127071

[15] Hartoyo, A.P.P.; Sunkar, A.; Ramadani, R.; Faluthi, S.H. Normalized Difference Vegetation Index (NDVI) analysis for vegetation cover in Leuser Ecosystem area, Sumatra, Indonesia. *Biodiversitas* **2021**, *22*, 1160-1171. https://doi.org/10.13057/biodiv/d220311

[16] Malik, A.D.; Nasrudin, A.; Parikesit; Withaningsih, S. Vegetation stands biomass and carbon stock estimation using NDVI - Landsat 8 Imagery in Mixed Garden of Rancakalong, Sumedang, Indonesia. *IOP Conf. Ser. Earth Environ. Sci*. **2023**, *1211*, 012015. https://doi.org/10.1088/1755-1315/1211/1/012015

[17] Mey, C.B.J.; Gore, M.L. Biodiversity conservation and carbon sequestration in agroforestry systems of the Mbalmayo Forest Reserve. *J. For. Environ. Sci.* **2021**, *37*, 91-103. https://doi.org/10.7747/JFES.2021.37.2.91