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Research article

The impact of rubber monoculture and agroforestry on soil nutrient dynamics: a comparative analysis

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Abstract

The expansion of rubber monoculture (RM) in tropical regions has led to significant land-use changes, contributing to soil acidification and nutrient depletion. This study evaluates soil nutrient status under three rubber-based land use types (RLUTs) in south-western Karnataka: rubber monoculture (RM), rubber agroforestry (R+AF) and rubber with natural vegetation (R+NV). Results indicated that RM exhibited significantly lower pH, SOC (38 and 71% lower than R+AF and R+NV, respectively) and base cations, but increased soil acidification and exchangeable Al^{3+} and H^+ concentrations (p <0.05). RM exhibited significantly lower available nutrients compared with R+AF and R+NV (p <0.05), with reductions of 48 and 34% for N, 340 and 30% for P, 26 and 243% for Ca, 73 and 142% for Mg, 67 and 208% for Zn, and 57 and 74% for B, respectively. Available P, Zn and B were found deficient in soils, while iron (Fe) and manganese (Mn) were in near toxic concentrations. Soil pH, exchangeable acidity and organic carbon (SOC) are critical in maintaining nutrient availability. SOC was positively correlated with available nutrients, namely N, K, Ca, Fe, Mn, Cu, Zn and B, while soil acidity was negatively correlated with available Ca and Mg content. The study recommends avoiding RM or selecting rubber-based agroforestry systems or naturally managed rubber plantations incorporating legumes, cover crops or medicinal plants to improve nutrient availability.

Keywords: Agroforestry, Micronutrients, Rubber cultivation, Soil acidity, Soil available nutrients

Introduction

Rubber tree (*Hevea brasiliensis*) plantations have undergone rapid expansion throughout South and Southeast Asia (Hemati *et al.*, 2020; Cao *et al.*, 2017). India, currently the fourth-largest producer of natural rubber, is experiencing significant land-use and land-cover (LULC) changes due to rubber cultivation (Vijayan *et al.*, 2024). Over the past three decades, rubber monoculture (RM) has been a major driver of unprecedented economic growth in South Asian countries, leading to a nearly six-fold increase in plantation area (Sun *et al.*, 2021) and around 30 to 74% increase in area in India under rubber cultivation over the past five decades (Vijayan *et al.*, 2024). This expansion has resulted in profound LULC changes, significantly affecting the soil quality (Garousi *et al.*, 2021), carbon (C) storage (Liu *et al.*, 2023), and nutrient cycling (Liu *et al.*, 2019; 2021). Alterations in land use types (LUTs) within rubber plantations significantly accelerate soil acidification by promoting the leaching of key basic cations, including potassium, calcium, and magnesium. This phenomenon poses a considerable risk to the long-term viability of both rubber and forest ecosystems in tropical areas (Liu *et al.*, 2019). The ability of soil to buffer and store nutrients, essential for plant growth, relies heavily on base saturation levels (Kopittke *et al.*, 2017; Rheinheimer *et al.*, 2018). When soil pH drops below 5.5, it leads to the release of extractable and exchangeable aluminium (Al), which restricts root growth and hinders nutrient absorption (Alleoni *et al.*, 2010; Singh *et al.*, 2017; Hubová *et al.*, 2018). Earlier studies confirmed that conversion from the forest to rubber land use, along with rubber monoculture significantly reduces soil essential nutrients, particularly soil phosphorus, potassium and anionic micronutrients (Saentho *et al.*, 2022; Wu *et al.*, 2020), and toxicity of cationic micronutrient content (Liu *et al.*, 2019). These changes degrade soil nutrient stocks over time, highlighting the need for sustainable nutrient management strategies to mitigate soil degradation.

The present study focuses on the primary rubber-growing regions of the tropical South-western parts of Karnataka, key hotspots for rubber cultivation. In these areas, natural rubber is predominantly produced through rubber monoculture (RM), followed by unmanaged rubber plantations with natural vegetation (R+NV) and rubber agroforestry systems (R+AF) in smaller, patchy zones. As part of the Western Ghats Forest ecosystem, these regions are particularly susceptible to land-use changes and have a long history of forest conversion and rubber plantation expansion over the decades (Vijayan *et al.*, 2024). Despite the socio-economic and demographic significance of rubber cultivation, limited research has examined soil nutrient status and/or developed sustainable nutrient management strategies tailored to the various rubber-based land use types (RLUTs). This study aims to assess the soil nutrient status under different RLUTs (RM, R+AF, and R+NV) with the following specific objectives: (i) to evaluate the effects of three selected RLUTs on the status of essential primary, secondary and micronutrients in the soil and (ii) to determine the influence of inherent soil properties on nutrient availability.

Materials and Methods

Site description and soil sampling procedure: The study was conducted in major rubber-growing areas of Karnataka, parts of the coastal area, the Western Ghats escarpment and the Karnataka Plateau. The majority of rubber production is confined to four districts of Karnataka: Dakshina Kannada, Udupi, Shimoga, and Chikmagalur in the coastal and hilly zones (Table 1). Based on the variability in elevation, physiography, soil types, three major rubber-based land use systems (RLUS), *i.e.*, rubber monoculture practice (RM), rubber agroforestry (R+AF) and rubber with natural vegetation (R+NV) were selected from nine taluks (Table 1; Fig 1). Under R+AF, banana and pineapple were major intercrops with rubber, while in Thirthahalli taluk in Shimoga district, rubber was intercropped with cowpea. At each location, the soil was dug down to the bedrock for more than 1.5 m, exposing the pedon and horizon-wise soil samples from each horizon were collected for further laboratory analysis. The depths of soil horizons varied among the pedons. All relevant soil physico-chemical properties were computed for each depth interval (0-30, 30–60 and 60–100 cm), and nutrient concentrations were further estimated at 20-cm intervals using a weighted-mean approach.

Laboratory analysis: Particle size distribution was determined using the International Pipette Method (Mehra and Jackson, 1960). The pH and

Table 1. Site-characteristics of pedons

Land use	Taluks	Agroclimatic zones	Districts	Pedon location	Soil classification (Subgroup)
Rubber mono - cropping (RM)	Uduppi	Coastal zone (Lateritic midlands)	Uduppi	13° 24′ 23.6″ N 74° 46′ 04.2″ E	Typic Kanhaplustults
	Mangalore	Coastal zone (Lateritic midlands)	Dhakshina Kannada	12° 49′ 24.9″ N 74° 52′03.6″ E	Haplic Plinthustults
	Hosa Nagara	Hilly zone (High hills)	Shimoga	14° 00′ 26.2″ N 75° 16′ 59.9″ E	Ustic Kanhaplohumults
Rubber + Agro-forestry (R+AF)	Sullya	Coastal zone (Foot hills)	Dhakshina Kannada	12° 31′ 11.4″ N 75° 38′ 00.4″ E	Ustic Kandihumults
	Beltangadi	Coastal zone (Foot hills)	Dhakshina Kannada	13° 00′ 11.1″ N 75° 26′ 10.3″ E	Ustic Kandihumults
	Thirthahalli	Hilly zone (High hills)	Shimoga	13° 47′ 37.1″ N 75° 22′ 01.4″ E	Ustic Kanhaplohumults
Rubber + Natural vegetation (R+NV)	Kundapura	Coastal zone (Foot hills)	Uduppi	18° 47′ 59.1″ N 74° 53′27.5″ E	Ustic Kandihumults
	Sagar	Hilly zone (High hills)	Shimoga	14° 09′ 05.8″ N 75° 03′ 07.3″ E	Ustic Kandihumults
	N.R. Pura	Hilly zone (High hills)	Chikmagalore	13° 39′ 32.5″ N 75° 30′ 39.5″ E	Ustic Haplohumults

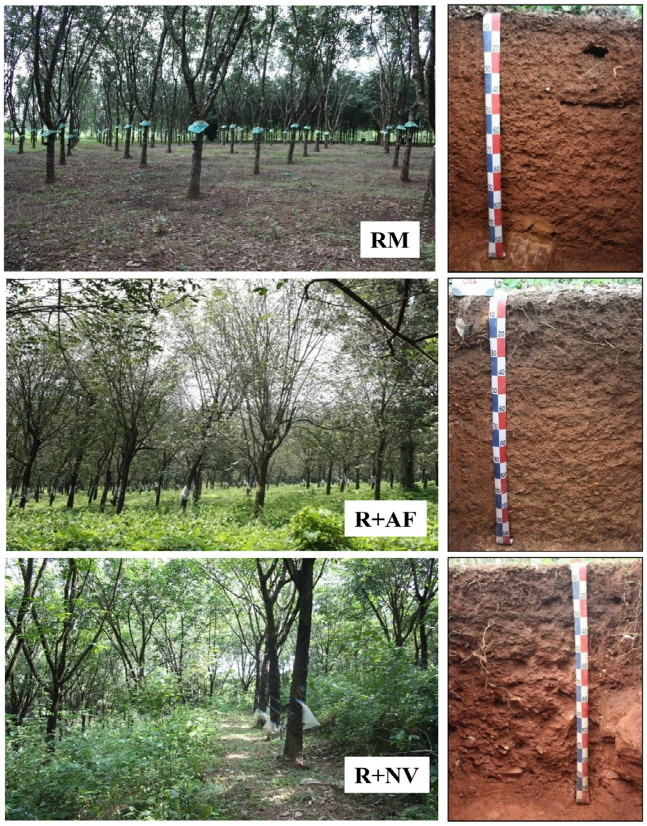

Fig 1. Study sites and pedons under different under rubber-based land use types; RM: Rubber monoculture, R+AF: Rubber agroforestry, R+NV: Naturally managed rubber plantation

electrical conductivity (EC) were measured in soil-water suspension (1:2.5) using a glass electrode and an EC meter, respectively. Total organic carbon (TOC) was determined by dry combustion (1200°C) using a LECO CN analyser. Exchangeable cations and cation exchange capacity (CEC) were extracted using a 1 *N* ammonium acetate solution at pH 7.0 (Reeuwijk, 1992). Exchangeable Al was extracted using 1 *M* KCl and determined by titration. Base saturation (BS) was calculated as the ratio of total exchangeable bases to CEC. Available nitrogen was measured using the alkaline permanganate method (Subbaiah and Asija, 1956), whereas available phosphorus was assessed by extracting soil samples with 0.5 *M* $NaHCO_3$ using a spectrophotometer (Olsen *et al.*, 1954). Available K was extracted with neutral normal ammonium acetate and measured on a flame photometer (Jackson, 1973). Exchangeable calcium and magnesium were estimated by the extraction of soil by 1 *N* ammonium acetate solution at pH 7.0 and determined by an atomic absorption spectrophotometer. Available S was estimated through a spectrophotometer after extraction with 0.15 percent calcium chloride ($CaCl_2$) (Williams and Steinberg, 1959). Available Fe, Mn, Cu and Zn were extracted with 0.005 *M* DTPA, 0.01 *M* $CaCl_2$ and 0.1 *M* triethanolamine (TEA), at a pH of 7.3 and their concentrations were measured using an atomic absorption spectrophotometer (Lindsay and Norvell, 1978). Available boron (B) was analysed through hot water extraction method (Berger and Truog, 1944).

Statistical analysis: Statistical analysis was carried out using the IBM-SPSS-23.0. Differences between the rubber-based land use systems were evaluated with Duncan's multiple range test following one-way ANOVA analysis at $P \leq 0.05$.

Results and Discussion

Vertical distribution of basic soil properties and available nutrients: Soil texture did not show significant variation across the rubber-based land use systems (RLUSs), although a slight increase in clay content was noticed with depth in the R+AF and R+NV systems (Table 2). Surface soil pH differed significantly among RLUSs, following the order R+NV <RM <R+AF ($p < 0.05$; Table 2). The acidification of soil due to the conversion of natural forests to rubber plantations is a major concern (Zhang *et al.*, 2021), with RM inducing the accumulation of exchangeable acidic cations more rapidly than other land use systems (Liu *et al.*, 2019). Total organic carbon (TOC) showed a marked increase in R+NV (71%) and R+AF (38%) compared to RM, with this trend persisting across soil depths (Table 2). These findings align with previous research by Zeng *et al.* (2021) and Pausch and Kuzyakov (2018), which reported that intercropping with crops like pineapple, turmeric, and banana, or the presence of deep-rooted natural vegetation, enhances root biomass and promotes soil carbon accumulation and similar results have been reported in R+NV or R+AF systems compared to that of rubber monoculture. Aluminium (Al) saturation in surface soils (0–20 cm) was highest in R+AF, followed by RM and R+NV. However, across the soil depths, Al saturation followed the trend as RM> R+AF> R+NV ($p < 0.05$). Al toxicity under rubber plantations is increasingly recognized as a challenge contributing to soil degradation (Liu *et al.*, 2019). Continuous rubber monoculture has been linked to a rise in pedogenic acidity due to the release of exchangeable Al^{3+} and H+ ions (Nguyen *et al.*, 2020; Thomas *et al.*, 2020). Base saturation decreased in the order of R+NV> R+AF> RM ($p < 0.05$). Soil basic cations play a critical role in maintaining soil buffering capacity and serve as major reservoirs of plant-available nutrients (Niu *et al.*, 2021; Saha *et al.*, 2024a). High rainfall and increased acidification in RM and R+AF systems result in nutrient leaching, which negatively impacts root development and nutrient availability (Zeng *et al.*, 2021).

Among the primary nutrients, available nitrogen followed the order of R+NV> R+AF> RM ($p < 0.05$; Fig 2a), consistently across all soil depths. The conversion

Table 2. Physico-chemical properties of soil under rubber-based land use types

Soil depth (cm)	Land use systems	Sand	Clay	pH W	EC (dS m^{-1})	SOC (g kg^{-1})	CEC (c mol (p^+ kg^{-1})	Al Saturation (%)	BS (%)
		(%)							
	RM	44.11	40.47	5.28b	0.02	10.4c	6.56b	7.34b	33.68b
0-20	R+AF	47.16	42.89	5.23b	0.027	14.4b	8.64ab	13.07a	38.39b
	R+NV	44.2	43.38	5.69a	0.017	17.8a	10.59a	0.64c	59.08a
	RM	41.28	43.3	5.21	0.02	8.8b	6.28	17.5a	26.37b
20-60	R+AF	45.9	43.5	5.17	0.02	13.4ab	8.89	10.42b	31.7b
	R+NV	42.9	42.8	5.65	0.01	15a	10.67	1.33c	51.9a
	RM	37.9	43.87	5.33	0.02	6.3c	5.73	20.87	34.2
60-100	R+AF	39.3	52.08	5.18	0.03	9.4b	7.12	14.15	36.8
	R+NV	38.9	50.48	5.67	0.02	13.0a	8.41	0.00	49.19

Different lower case letters indicate significant differences among land use types ($P<0.05$); The tested method was one-way analysis of variance (ANOVA) followed by the least significant difference (LSD) test; LUTs are RM: Rubber monoculture, R+AF: Rubber agroforestry, R+NV: Naturally managed rubber plantation; EC: Electrical conductivity; SOC: Soil organic carbon; BS: Base saturation

of natural forests to rubber plantations has been shown to reduce the soil's nitrogen-supplying capacity and the availability of inorganic N (Garousi *et al.*, 2021). High levels of exchangeable acidity had a detrimental effect on phosphorus availability, with critically low levels observed under RM and R+NV ($p<0.05$; Fig 2b). The decline in available P content following the conversion of natural forests to rubber plantations is consistent with the previous studies (Sherman *et al.*, 2006) showing that phosphate anions can be immobilized by Al through sorption or precipitation, leading to reduced P availability. However, available P concentrations improved under the R+AF system, consistent with the findings of Liu *et al.* (2018, 2021). Enhanced fine-root proliferation and higher

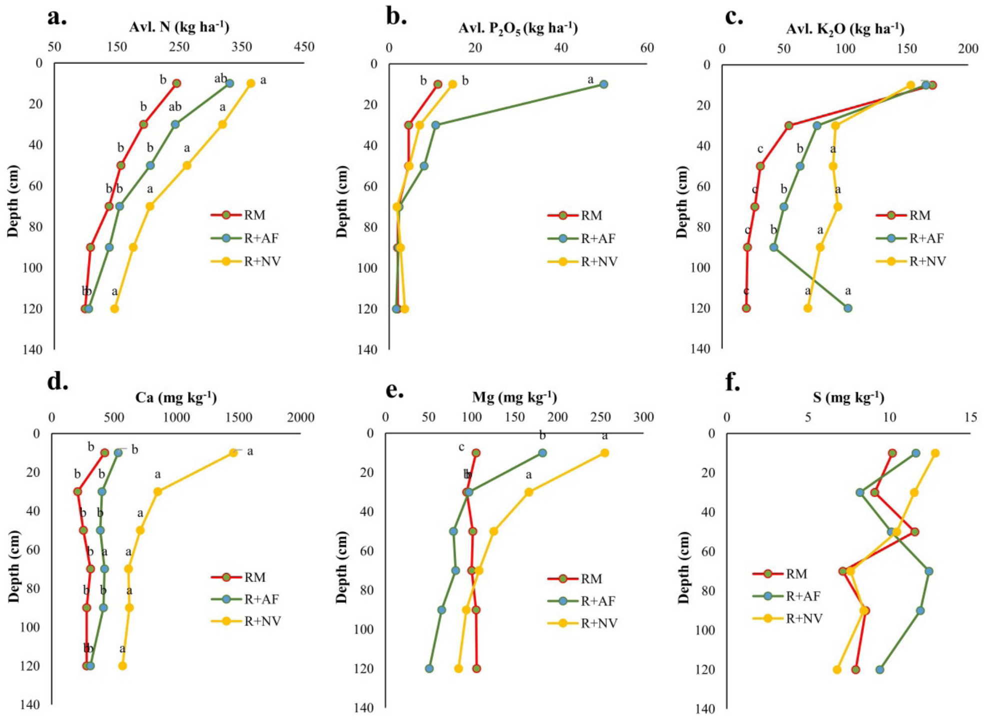

Fig 2. Vertical distribution of available soil nutrients under different rubber-based land use types (RLUTs); (a) Available nitrogen; (b) Available phosphorus, (c) Available potassium, (d) Available calcium, (e) Available magnesium, (f) Available sulphur; Data are expressed as the mean (n = 3) of LUTs and different lowercase letters indicate significant differences among the LUTs ($P<0.05$; The tested method was one-way ANOVA followed by Duncan's Multiple Range Test; Study sites are RM: Rubber monoculture, R+AF: Rubber agroforestry and R+NV: Rubber with natural vegetation

organic matter inputs from root decomposition under R+AF improved phosphorus release by reducing Al–P fixation. Potassium levels were comparable across surface soils but declined significantly with depth, particularly under RM (Fig 2c). Among the secondary nutrients, calcium and magnesium were sufficient in surface soils (Fig. 2d, 2e), but deficient in sub-surface soils under RM. The sharp decline in available Ca and Mg under RM compared to other RLUSs was attributed to nutrient leaching (Liu *et al.,* 2019). Sulphur (S) showed irregular variation with depth (Fig 2f).

Copper, iron, zinc, manganese, and boron are essential for plant enzyme functions, vitamin synthesis, and hormonal regulation (Hänsch and Mendel, 2009). However, excessive levels of micronutrients like Cu, Zn, Fe, and Mn can result in heavy metal pollution, posing environmental and human health risks (Peng *et al.,* 2022). Both Fe and Mn were found at toxic levels across all RLUSs (Fig 3a, 3b), likely due to the acidic soil conditions (Mayanna *et al.,* 2015). Zinc and B were deficient throughout the soil profile under RM, in decreasing order of R+NV > R+AF > RM (p <0.05; Fig 3d, 3e). The conversion of tropical forests to rubber plantations has been shown to reduce soil Zn content due to the reduction of surface soil organic matter (Liu *et al.,* 2019), with continuous RM accelerating the loss of these nutrients.

Relationships between soil available nutrients and soil chemical properties: Soil base cations are crucial for maintaining soil buffering capacity and nutrient storage, serving as a key reservoir of plant-available nutrients (Kopittke *et al.,* 2017; Rheinheimer *et al.,* 2018). This study identified soil acidity and soil organic carbon as the primary factors influencing the availability of macro and micronutrients. A sharp decline in available calcium and magnesium was observed with increasing soil acidity, showing a significant positive correlation with soil pH (p <0.01; R= 0.74 for Ca and 0.67 for Mg) (Fig 4a and d). A similar trend was noticed with the rise in exchangeable Al^{3+} and H^+ concentrations, which negatively correlated with Ca (p <0.01; R = -0.58 for Al^{3+} and -0.49 for H^+) (Fig 4b and 4c) and Mg (p <0.01; R = -0.54 for Al^{3+} and -0.36 for H^+) (Fig 4e and 4f). Calcium plays a key role in ethylene signalling and protein kinase activity during rubber latex production (Zhu *et al.,* 2018a), and its availability at soil exchange sites significantly affects latex yield and quality. In rubber monoculture systems, the lack of vegetation cover intensifies rainfall's kinetic energy (Zhu *et al.,* 2018b), leading to higher leaching of Ca and Mg, thereby reducing their availability. Furthermore, the depletion of these basic cations influences soil pH, which in turn affects the concentration of exchangeable Al^{3+} and H. Soil pH below 5.5 triggers an increase in exchangeable H^+ and Al^{3+} (R= 0.68 and 0.40, respectively; p <0.01), contributing to soil acidification and reducing available Ca and Mg levels (Mulder and Stein, 1994; Saha *et al.,* 2024b). Within the studied RLUSs, RM exhibited significantly lower soil pH and higher levels of exchangeable H^+ and Al^{3+} compared to R+NV and R+AF systems (Table 2), with a corresponding decrease in Ca concentrations (Fig 2d).

SOC was positively correlated with the availability of several nutrients, including available nitrogen (R = 0.90; p <0.01), potassium (R= 0.64; p <0.01), calcium (R = 0.41; p <0.01), iron (R= 0.50; p <0.01), manganese (R= 0.32; p <0.05), copper (R= 0.68; p <0.01), zinc (R= 0.38; p < 0.01), and boron (R= 0.31; p <0.05) (Fig 5). SOC plays a pivotal role in the availability of nutrients under rubber-based systems, significantly affecting the levels of primary, secondary, and micronutrients (Gerke 2022; Chen *et al.,* 2019). RM systems showed significantly lower SOC content compared to R+AF and R+NV (p <0.05; Table 2), leading to lower levels of available N, P, K, Ca, Mg, Fe, Mn and Zn. Organic matter contributes substantially to the availability of micronutrients, and its loss, particularly in continuous monoculture systems, results in decreased levels of soil available zinc and boron (p <0.05; Fig 3d and 3e). R+NV and R+AF systems had received higher amounts of root and litter input through deep-rooted natural vegetation or intercropping with pineapple, turmeric and banana, which facilitates SOC enrichment (Saha *et al.,* 2025). Higher organic matter accumulation facilitates organic complexation, which influences

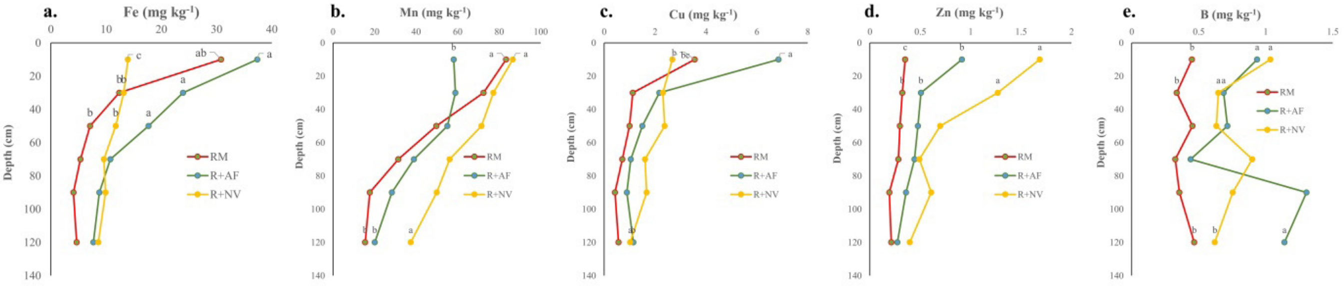

Fig 3. Vertical distribution of available soil micro-nutrients under different rubber-based land use types (RLUTs); Data are expressed as the mean (n = 3) of LUTs and different lowercase letters indicate significant differences among the LUTs (P<0.05; The tested method was one-way ANOVA followed by Duncan's Multiple Range Test; Study sites are RM: Rubber monoculture, R+AF: Rubber agroforestry and R+NV: Rubber with natural vegetation

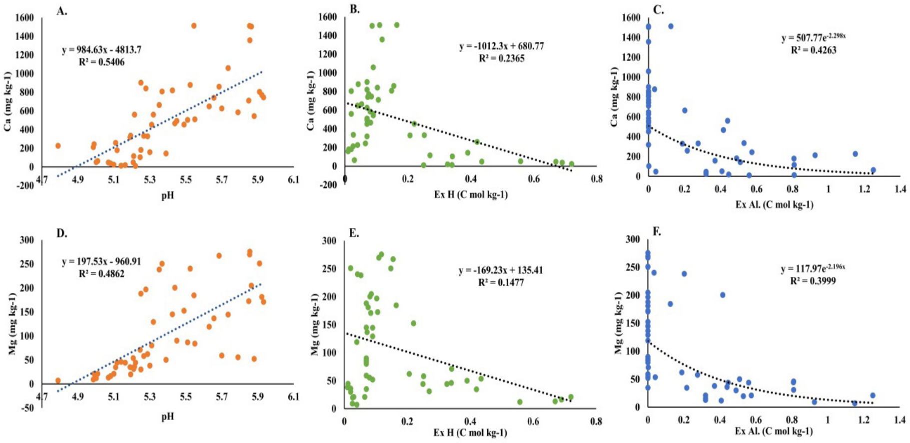

Fig 4. Scatter diagram exhibiting correlation between available Ca and Mg concentration with soil pH, soil exchangeable H^+ and soil exchangeable Al^{3+}

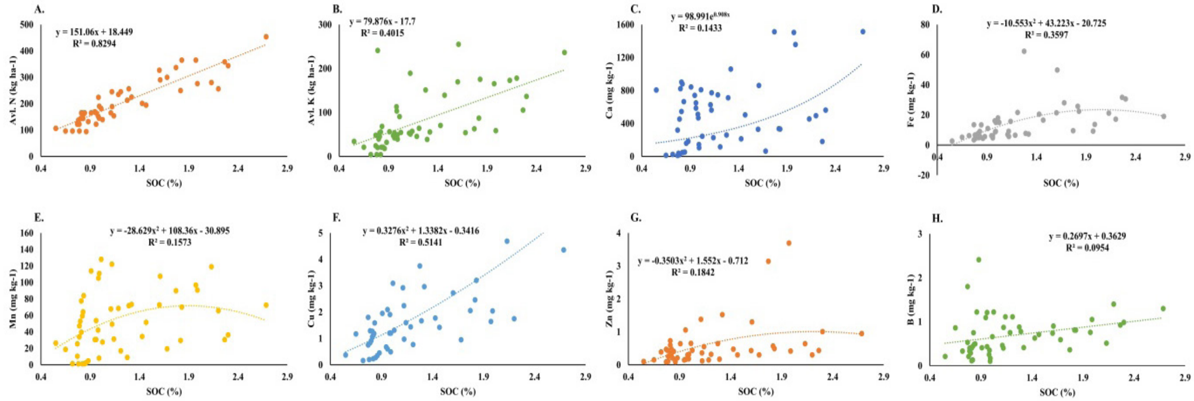

Fig 5. Scatter diagram exhibiting correlation between available nutrient content with soil organic carbon concentration

availability and buffering of micronutrients such as Fe, Zn, Mn and Cu in the soil solution (Gerke, 2000).

Soil micronutrients are more sensitive to SOC than pH, especially in the conversion of tropical forests to rubber plantations, with these effects being most pronounced under RM systems (Liu *et al.*, 2019). To address soil acidification in RM systems, the application of liming materials is recommended as a management strategy for soil restoration. Subsoil incorporation of lime through deep ploughing (Farina *et al.*, 1988; Jayawardane *et al.*, 1995) or surface application of gypsum (Shainberg *et al.*, 1989) is suggested, particularly for managing Ultisols (Nair *et al.*, 2019). Based on the findings, this study strongly advocates for naturally managed rubber cultivation and rubber-based agroforestry as sustainable land management strategies to maintain the availability of macro and micronutrients. Given that SOC is the most sensitive factor controlling nutrient availability, intercropping with legumes, spices, or introducing medicinal plants such as *Piper longum*, wild *Asparagus* species, and *Paris polyphylla* in RM systems could enhance SOM and improve soil nutrient stocks. Converting rubber monoculture to naturally managed rubber ecosystems with diversified crops can help sustain soil health and nutrient availability.

Conclusion

The study highlights the negative impact of continuous rubber monoculture (RM) on soil nutrient depletion and acidification in south-western Karnataka. Results show that RM significantly reduces soil pH and organic carbon (SOC) (38 and 71% lower than R+AF and R+NV, respectively). RM exhibited significantly lower available nutrients compared with R+AF and R+NV (p <0.05), with reductions of 48 and 34% for N, 340 and 30% for P, 26 and 243% for Ca, 73 and 142% for Mg, 67 and 208% for Zn, and 57% and 74% for B, respectively. In contrast, RM showed elevated levels of toxic exchangeable Al^{3+}, H^+, Fe, and Mn. Rubber agroforestry (R+AF) and rubber with natural vegetation (R+NV) systems perform better, with higher SOC and nutrient availability. The study suggests that SOC plays a key role in nutrient retention, and soil acidity is detrimental to exchangeable basic nutrients. To our knowledge, this is the first study to quantitatively demonstrate the substantial decline in SOC and nutrient availability under rubber monoculture compared with agroforestry-based rubber systems in south-western Karnataka. Based on these findings, we recommend adopting rubber agroforestry or naturally managed rubber plantations with legume, cover crop, or medicinal plant intercrops to enhance nutrient cycling and soil health.

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