Pertanika J. Trop. Agric. Sci. 49 (5): 2361 - 2385 (2026)

PERTANIKA JOURNALS

TROPICAL AGRICULTURAL SCIENCE

Journal homepage: http://www.pertanika.upm.edu.my/

Comparison of Plant Nutrient Requirements During the Annual Phenological Development of Young Rubber Trees (*Hevea brasiliensis* Mull. Arg.) Prior to the Rubber Tapping Process in Upland and Lowland Areas

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ABSTRACT

The expansion of rubber plantations in Thailand has led to the conversion of lowland rice fields into rubber cultivation areas. However, the unsuitability of these areas for rubber cultivation has led to slow tree growth and low latex yields. This research investigated the accumulation patterns and interrelationships of plant nutrients in soil and young rubber trees grown in upland and lowland areas prior to tapping throughout the annual phenological development cycle. Four experimental plots were established in Phatthalung Province, Thailand. Soil samples were collected at 0-15 cm depth beneath tree canopies, and leaf samples were collected every 2 months from the 2nd to 10th month after leaf flushing (ALF). Physical and chemical properties of soil and plant nutrient concentrations were analysed. Results indicated distinct nutrient demand patterns between locations. In upland areas, rubber trees showed high demand for Na during the 2nd month ALF; K during the 4th month ALF; N and S during the 6th month ALF; K and Cu during the 8th month ALF; and P, K, Mg, Cu and Zn during the 10th month ALF. In lowland areas, high demand was observed for Ca during the 2nd month ALF; Fe during the 4th month ALF; N and Fe during the 6th month ALF; P, K and Cu during the 8th month ALF; and K and Mg during the 10th month ALF. These findings provide valuable information for developing site-specific nutrient management strategies to enhance tree growth, latex yield and quality.

ARTICLE INFO

Article history:
Received: 28 October 2025
Accepted: 25 September 2026
Published: 30 October 2026

DOI: https://doi.org/10.47836/pjtas.49.5.13

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Keywords: Nutrient accumulation, nutrient dynamics, rubber, pre-tapping rubber trees, soil and plant management

INTRODUCTION

In 2021, Thailand produced approximately one-third of the world's natural rubber

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output (33.81%), totaling 4.75 million tons year^{-1}, out of a global production of 14.05 million tons (Bureau of Agricultural Economic Research, 2023). Thailand's rubber (*Hevea brasiliensis* Mull. Arg.) plantation areas expanded from approximately 30,000 km^2 in 1990 to 39,000 km^2 in 2021, representing a 30% increase. Southern Thailand accounted for approximately 23,000 km^2, or 59% of the country's total rubber plantation areas (Rubber Research Institute, 2010; Office of Agricultural Economics, 2023b). However, many plantations occupy unsuitable areas, particularly lowland sites previously used as paddy fields. These areas experience flooding during the rainy season, adversely affecting tree growth and latex quality. Studies by the Agricultural Extension and Development Region 5 (2004) and the Office of Agricultural Economics (2023a) revealed that paddy field area in southern Thailand decreased from approximately 4,400 km^2 in 2000 to 1,700 km^2 in 2019, representing a reduction of 2,800 km^2 (average 142 km^2 year^{-1}) or 63.63%. This decline resulted primarily from farmers converting rice fields to rubber plantations, which offer higher income and require less intensive management.

Recent climate change has intensified the challenges of rubber cultivation in lowland areas of southern Thailand. The increasing frequency of flash floods and prolonged dry spells (Meteorological Department of Thailand, 2023) creates extreme oscillations between waterlogged and drought conditions. These fluctuations disrupt nutrient availability through alternating oxidation-reduction cycles in soils, accelerate nutrient leaching during heavy rainfall events, and impair root function through repeated stress (Carr, 2012; Kunjet et al., 2013). The synchronisation of nutrient uptake during critical phenological periods becomes increasingly unpredictable, making traditional fertilisation schedules inadequate.

Therefore, investigating the relationship between soil properties and plant nutrient accumulation in upland and lowland rubber plantations (formerly paddy fields) is essential. This research aims to develop appropriate soil and fertiliser management strategies for rubber cultivation that will benefit farmers economically. Implementing proper nutrient management practices can increase rubber farmers' income while reducing unnecessary costs associated with soil management and fertiliser applications in rubber plantations.

Upland and lowland areas are defined as follows: (1) Upland areas have flat to undulating topography without waterlogging, well-drained soil with moderate to rapid permeability, and groundwater levels exceeding 50 cm below the surface. (2) Lowland areas possess low-lying or floodplain topography prone to flooding during the rainy season, poorly drained soil with slow water permeability, and groundwater levels less than 50 cm below the surface, resulting in prolonged soil moisture or flooding.

Two research hypotheses are (1) when soil nutrient levels are lowest, rubber trees have the highest demand for those nutrients during that period, and (2) when leaf nutrient concentrations are lowest, rubber trees have the highest demand for those nutrients during that period. This research aimed to (1) investigate nutrient accumulation and relationships

in soil prior to rubber tapping during annual phenological development (APD) in upland and lowland plantations, and (2) develop appropriate pre-tapping nutrient management guidelines.

MATERIALS AND METHODS

The Experimental Site

The upland rubber plantation was located in Ban Phrao Subdistrict, Pa Phayom District, Phatthalung Province, southern Thailand (experimental site no.1 at 7°49'34.6"N, 99°55'2.0"E, and site no.2 at 7°49'43.4"N, 99°55'4.5"E). Experimental sites no. 1 and no. 2 covered 0.0048 and 0.0128 km², with 6 and 5 year old rubber trees, respectively. The soil is classified as fine-silty, kaolinitic, isohyperthermic, Aquic Kandiudults (in soil taxonomy). This upland area features undulating to rolling topography with 2-5% slope, elevated approximately 20 m above mean sea level, without flooding. The soil formed from riverine sediment deposits with poor drainage, slow surface runoff and moderate permeability. Soil fertility is low but suitable for perennial trees, fruit trees, rubber, oil palms and field crops (Division of Soil Survey and Classification, Department of Land Development, 1987). Surrounding land uses included fruit orchards, rubber plantations, paddy fields and residential communities (Figure 1).

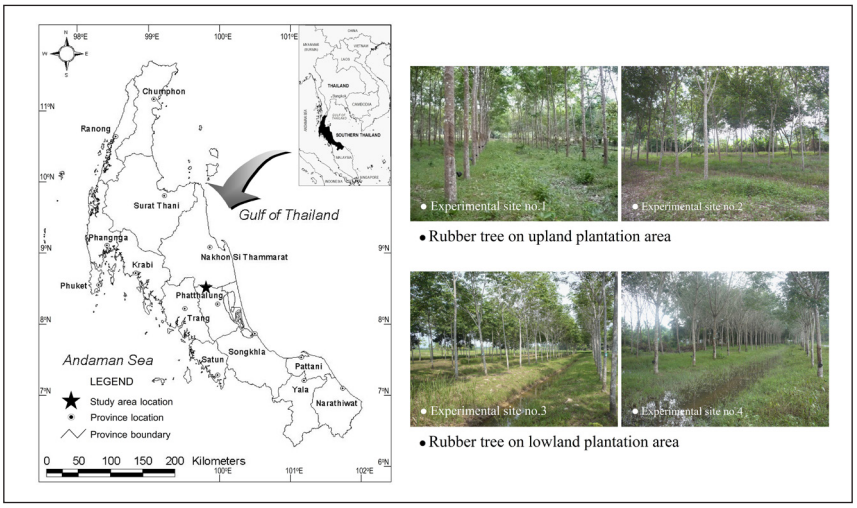

Figure 1. The experimental sites in Pa Phayom District, Phatthalung Province, southern Thailand

The lowland rubber plantation was located in Pa Phayom Subdistrict, Pa Phayom District, Phatthalung Province, southern Thailand (experimental site no.3 at 7°51'44.8"N, 99°57'41.3"E, and site no.4 at 7°51'40.2"N, 99°57'43.2"E). Experimental sites no.3 and no.4 covered 0.0064 and 0.0032 km², with 7 and 6 year old rubber trees, respectively. The soil is

classified as very-fine, kaolinitic, isohyperthermic, Typic Plinthaquults (in soil taxonomy). This lowland area features smooth to nearly flat topography with 0-2% slope, elevated approximately 10 m above mean sea level, experiencing seasonal or year-round flooding. The soil formed from river deposited sediments with poor drainage, slow surface runoff and slow permeability. Soil fertility is low, suitable for rice but unsuitable for perennial trees, rubber, oil palms and field crops due to prolonged waterlogging (Division of Soil Survey and Classification, Department of Land Development, 1987). Surrounding land uses included rubber plantations, paddy fields and residential communities (Figure 1).

Experiments were conducted in 4 plots with young RRIM 600 rubber trees (5-7 years old) prior to tapping: 2 upland and 2 lowland plots with 3×6 m spacing and 10 replicate trees plot^{-1} (Figure 1).

Soil Management in Field

Composite soil samples (4 cores tree^{-1}) were collected at 0-15 cm depth around tree canopies (1.00-1.25 m from the trunk) every 2 months during APD from the 2nd to the 10th month of ALF (5 sampling times). Soil samples at depths of 0 and 30 cm were collected bi-monthly for moisture analysis.

Soil Analysis in Laboratory

Air-dried soils were sieved (2 mm) and analysed for: soil texture by hydrometer (Gee & Bauder, 1986), pH (1:1 soil: water) (McLean, 1982), electrical conductivity (1:1 soil: water) (Rhoades, 1982), organic matter by Walkley-Black method (Nelson & Sommers, 1982), total N by Kjeldahl (Dennis, 1982), exchangeable Ca, Mg, K by 1M ammonium acetate pH 7.0 (Thomas, 1982), available P by Bray 2 (Olsen & Sommers, 1982), available S by 0.01 M $Ca(H_2PO_4)_2$ (Tabatabai, 1982), and extractable Fe, Mn, Cu, Zn by DTPA (Baker & Amacher, 1982; Olson & Roscoe, 1982; Gambrell & William, 1982).

Plant Management in Field

The 1st and 2nd lower leaf pairs (intermediate-aged leaves) were randomly collected from 4 sides (North, South, East and West) of tree canopies (4 leaves side^{-1}), combined into composite samples (16 leaves tree^{-1}) representing each tree across 4 experimental sites. Leaf sampling occurred bi-monthly during APD from the 2nd to the 10th month of ALF (5 sampling times), excluding the 10th-12th month of ALF when leaves had completely abscised.

Plant Nutrient Analysis in Laboratory

Leaves were cleaned with deionised water, oven-dried (68-80°C, 24-48 hours), ground, and sieved (1 mm). Analyses included total N (Kjeldahl), P, S, Fe, Mn, Cu, Zn ($HNO_3/HClO_4$),

K, Ca, Mg, Na (wet digestion) and B (azomethine-H) (Kerven, 1980; Maneepong, 1994; Onthong, 2002; Oweczkin & Kerven, 1980).

Physiological Characteristics of Rubber Trees

Physiological characteristics measured during APD included trunk circumference, trunk diameter (at 1.50 m height), and canopy width.

Statistical Analysis

Analysis of variance (ANOVA) was performed to test differences in soil and plant properties. Means were separated using Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$ using SPSS software.

RESULTS AND DISCUSSION

Rubber Tree Growth and Management

Throughout the APD, upland rubber trees (sites no.1 and no.2) exhibited average trunk circumferences of 54.19 and 23.73 cm, with monthly increases of 0.92 and 1.18 cm (11.04 and 14.20 cm $year^{-1}$), respectively. Average trunk diameters were 34.48 and 15.10 cm, increasing 0.59 and 0.75 cm $month^{-1}$ (7.03 and 9.03 cm $year^{-1}$), respectively. Average canopy diameters measured 8.39 and 2.69 m, respectively. Lowland rubber trees (sites no.3 and no.4) showed average trunk circumferences of 43.42 and 36.45 cm, with monthly increases of 0.49 and 0.61 cm (5.90 and 7.37 cm $year^{-1}$), respectively. Average trunk diameters were 27.63 and 23.20 cm, increasing 0.31 and 0.39 cm $month^{-1}$ (3.75 and 4.69 cm $year^{-1}$), respectively. Average canopy diameters measured 6.02 and 5.56 m, respectively.

Annual physiological assessments clearly demonstrated superior growth of upland rubber trees compared to lowland counterparts. The primary factor was prolonged flooding in lowland areas from seasonal rainfall. Despite farmers' mitigation efforts through raised planting beds and drainage channels, waterlogging remained problematic in lowland plantations while absent in upland areas.

Rubber Tree Characteristics During APD

Rubber trees enter the period of leaf shedding (falling leaves) around the beginning of February. Then the rubber leaves will gradually fall off until the old set of rubber leaves (10th month ALF) completely falls off around the end of March (takes about 2 months). At the same time, when April begins, the rubber trees will enter the leaf flushing period and then enter the stage of rubber leaf development (from the 1st, 2nd, …, 10th month ALF, respectively) until January. (The leaf development period is 10 months, April to January (next year). Then the rubber leaves will begin to shed again. Rubber trees will enter the

period of leaf shedding (falling leaves) again around the beginning of February. The rubber phenological development on the eastern side of southern Thailand (experimental sites) will be delayed by about 1 month compared to that of the western side of southern Thailand.

Soil Physical Properties of Rubber Plantation

Upland soils were dark brown to yellowish brown and gray to dark gray. Soil texture (0 - 15 cm depth) in sites no.1 and no.2 was loamy to sandy clay loam (clay: 23.03-30.21%, silt: 21.14-30.23%, sand: 45.73-48.65%). Soil texture (0-15 cm depth) in sites no.3 and no.4 was clay loam to clay texture (clay: 35.03-38.87%, silt: 36.33-56.67% and sand: 4.58-26.69%).

In upland sites (no.1 and no.2), topsoil (0 cm) moisture ranged 9.90-24.46% and 15.85-17.57%, while subsoil (30 cm) moisture ranged 8.06-20.57% and 11.96-17.01%, respectively (Figures 2A and 2B). In lowland sites (no.3 and no.4), topsoil moisture ranged 18.45-23.88% and 18.12-28.47%, while subsoil moisture ranged 19.56-23.90% and 17.83-22.43%, respectively (Figures 2C and 2D).

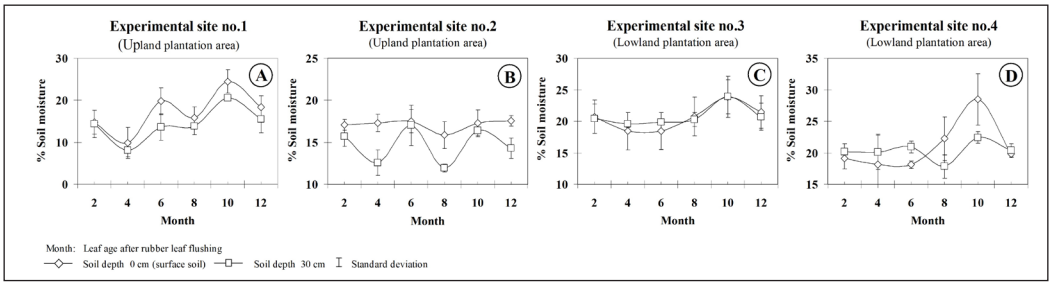

Figure 2. Soil moisture content under rubber tree shade during ADP in upland and lowland areas, (A) Experimental site no.1: Pre-tapping upland area; (B) Experimental site no.2: Pre-tapping upland area; (C) Experimental site no.3: Pre-tapping lowland area; and (D) Experimental site no.4: Pre-tapping lowland area

Lowland clay loam to clay soils with poor drainage and groundwater levels above 50 cm (Division of Soil Survey and Classification, Department of Land Development, 1987) experienced persistent waterlogging at tree bases where roots concentrate, particularly during rainy seasons and tropical storm events. Waterlogging reduced soil aeration, decreasing O_2 availability and impairing active water uptake by roots. Simultaneously, increased soil CO_2 levels reduced root permeability, consequently limiting nutrient absorption. Kungpisadan (2009) surveyed rubber plantations in Pa Bon District, Phatthalung Province, finding that upland trees (groundwater >50 cm depth) exhibited shoot dieback at 7-10 years, while lowland trees (groundwater <50 cm depth) showed dieback symptoms at 2-5 years, depending on plantation drainage conditions.

Soil Chemical Properties of Pre-Tapping Rubber Trees in the Upland Area (Site no.1)

The results of the study found that the amounts of plant nutrients in soils showed no significant difference ($p < .05$), except that avai.S was significantly different ($p < .05$), and exch. Na and ext.Cu were significantly different ($p < .01$) (Figure 3). Soil pH was 5.04-5.60 (Figure 3A). Soil EC was 0.07-0.13 mS cm^{-1} (Figure 3B) and soil OM was 14.48-20.17 g kg^{-1} (Figure 3C). During the 2nd month of ALF, the highest plant nutrients were total N = 1.15 g kg-1, ext.Cu = 3.14 mg kg-1, and ext.Zn = 2.68 mg kg-1 (Figure 3D, 3M and 3N), whereas the lowest plant nutrient was observed. During the 4th month ALF: The highest plant nutrient was exch.K = 0.25 $cmol_c kg^{-1}$ (Figure 3G), while the lowest plant nutrient was total N = 1.02 g kg^{-1} (Figure 3D). During the 6th month ALF: The highest plant nutrients were exch.Ca, Mg and Na = 5.39, 1.24 and 0.090 $cmol_c kg^{-1}$, respectively (Figure 3H, 3I and 3J), whereas the lowest plant nutrient was ext.Mn = 25.04 mg kg^{-1} (Figure 3L). During the 8th month ALF: The highest plant nutrients were avai.P = 220.31 mg kg^{-1}, ext.Mn = 48.76 mg kg^{-1} (Figure 3E and 3L) whereas the lowest plant nutrients were avai.S = 18.06 mg kg^{-1}, exch.K = 0.16 $cmol_c kg^{-1}$ and ext.Fe = 99.24 mg kg^{-1} (Figure 3F, 3G and 3K). During 10th month ALF: The highest plant nutrient was avai.S = 68.12 mg kg^{-1} (Figure 3F) while the lowest plant nutrients were avai.P = 37.69 mg kg^{-1}, Exch.Ca, Mg and Na = 0.31, 0.23 and 0.012 $cmol_c kg^{-1}$, respectively and ext.Fe, Cu and Zn = 141.28, 0.57 and 0.63 mg kg^{-1}, respectively (Figure 3E, 3H, 3I, 3J, 3K, 3M and 3N).

Soil Chemical Properties of Pre-Tapping Rubber Trees in the Upland Area (Site no.2)

The study found that the amounts of plant nutrients in soils showed no significant differences ($p<.01$), except for exchangeable Mg, which showed a significant difference ($p<.05$) (Figure 3). Soil pH was 4.47-5.73 (Figure 3A). Soil EC was 0.05-0.18 mS cm^{-1} (Figure 3B), and soil OM was 9.26-20.92 g kg^{-1} (Figure 3C). During the 2nd month ALF: The highest plant nutrients were avai.P = 128.42 mg kg^{-1}, exch.K and Mg = 0.20 and 1.21 $cmol_c kg^{-1}$, respectively and ext.Zn = 2.03 g kg^{-1} (Figure 3E, 3G, 3I and 3N). The lowest plant nutrients were total N = 0.91 g kg^{-1} and exch.Na = 0.026 $cmol_c kg^{-1}$ (Figure 3D and 3J). During the 4th month ALF: The highest plant nutrient was absent, whereas the lowest plant nutrient was exch.K = 0.13 $cmol_c$ kg^{-1} (Figure 3G). During the 6th month ALF: The highest plant nutrients were avai.S = 30.19 mg kg^{-1}, exch.Ca = 2.94 $cmol_c kg^{-1}$ and ext.Cu = 3.02 mg kg^{-1} (Figure 3F, 3H and 3M), whereas the lowest plant nutrient was ext.Mn = 23.90 mg kg^{-1} (Figure 3L). During the 8th month ALF: The highest plant nutrient was ext.Mn = 139.05 mg kg^{1} (Figure 3L), while the lowest plant nutrients were total N = 0.91 g kg^{-1}, avai.P = 90.08 mg kg^{-1} and ext.Fe and Cu = 58.41 and 1.78 mg kg^{-1}, respectively (Figure 3D, 3E, 3K and 3M). During the 10th month ALF: The highest plant nutrients were total N = 1.68 g kg^{-1}, avai.S = 30.19 mg kg^{-1}, exch.Na = 0.061 $cmol_c kg^{-1}$ and ext.Fe = 100.71 mg kg^{-1} (Figure 3D, 3F, 3J and 3K), whereas

the lowest plant nutrients were exch.Ca and Mg = 1.65 and 0.76 $cmol_c kg^{-1}$, respectively and ext.Zn = 1.39 g kg^{-1} (Figure 3H, 3I and 3N).

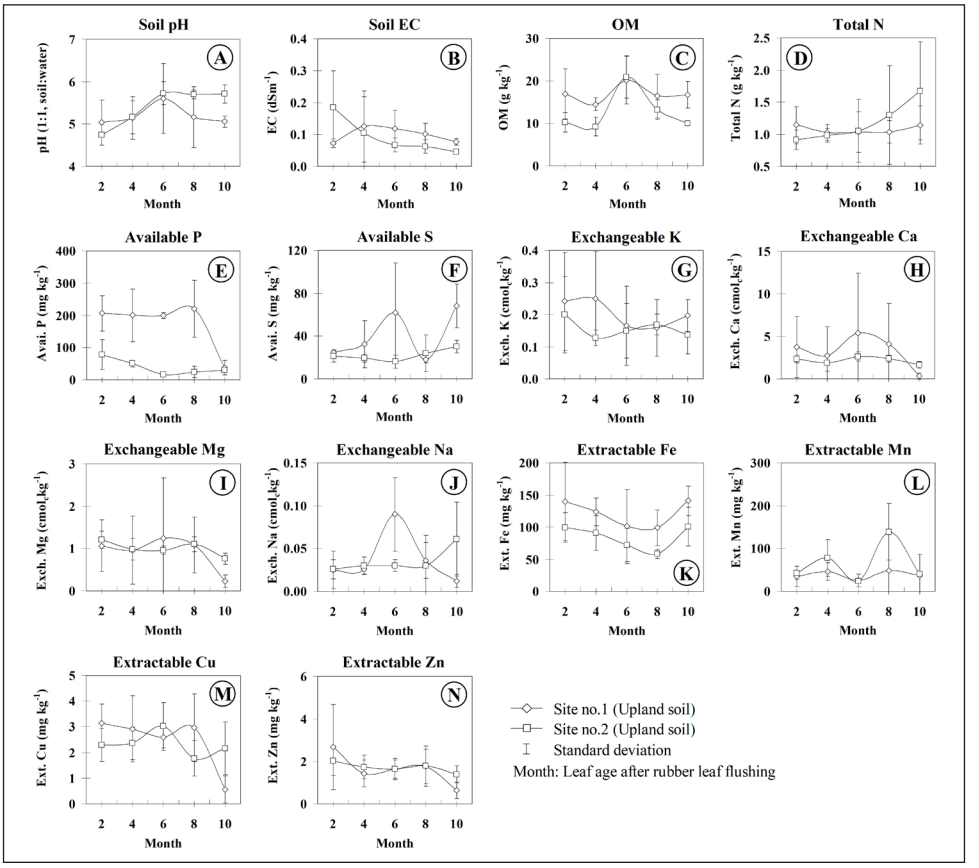

Figure 3. Some soil properties under the shade of rubber trees during APD of rubber trees grown in upland areas: (A) = Soil pH, (B) = Soil EC, (C) = Soil OM, (D) = Total N, (E) = Exchangeable Ca, (F) = Exchangeable Mg, (G) = Exchangeable K, (H) = Exchangeable Na, (I) = Available P, (J) = Available S, (K) = Extractable Fe, (L) = Extractable Mn, (M) = Extractable Cu and (N) = Extractable Zn

Soil Chemical Properties of Pre-Tapping Rubber Trees in the Lowland Area (Site no.3)

The results of the study found that the amounts of plant nutrients in soils showed no significant difference ($p < .05$), except that ext.Mn showed a significant difference ($p < .05$) and avai.P, exch.K and ext.Fe showed significant differences ($p < .01$) (Figure 4). Soil pH was 5.09-5.46 (Figure 4A). Soil EC was 0.10-0.05 mS cm^{-1} (Figure 4B) and soil OM was 20.35-15.94 g kg^{-1} (Figure 4C). (1) During the 2nd month ALF: The highest plant nutrient was ext.Cu (1.51 mg kg^{-1}) (Figure 4M), while the lowest plant nutrients were total N = 1.13 g kg^{-1}, avai.P = 3.69 mg kg^{-1} and exch.Ca = 2.17 $cmol_c kg^{-1}$ (Figure 4D, 4E and 4F). (2) During 4th month ALF: The highest plant nutrients were

avai.S = 40.25 mg kg^{-1} and exch.K and Mg = 0.18 and 1.01 $cmol_c kg^{-1}$ respectively (Figure 4F, 4G and 4I), whereas the lowest plant nutrients were ext.Fe, Cu and Zn = 64.92, 1.31 and 0.53 mg kg^{-1}, respectively (Figure 4K, 4M and 4N). (3) During 6th month ALF: The highest plant nutrient was ext.Zn = 0.72 mg kg^{-1} (Figure 4N) while the lowest plant nutrients were avai.S = 26.32 mg kg^{-1} and ext.Mn = 218.38 mg kg^{-1} (Figure 4F and 4L). (4) During the 8th month ALF: The highest plant nutrients were total N = 2.08 g kg^{-1}, avai.P = 6.45 mg kg^{-1} and exch.Ca and Mg = (3.88 and 1.01 $cmol_c kg^{-1}$, respectively and ext.Mn = 218.38 mg kg^{-1} (Figure 4D, 4E, 4H, 4I and 4L), whereas the lowest plant nutrient was exch.Na = 0.040 $cmol_c kg^{-1}$ (Figure 5J). (5) During the 10th month ALF: The highest plant nutrients were exch.Na = 0.096 $cmol_c kg^{-1}$ and ext.Fe = 115.02 mg kg^{-1} (Figure 4J and 4K), whereas the lowest plant nutrients were exch.K and Mg = 0.09 and 0.64 $cmol_c kg^{-1}$, respectively (Figure 4G and 4I).

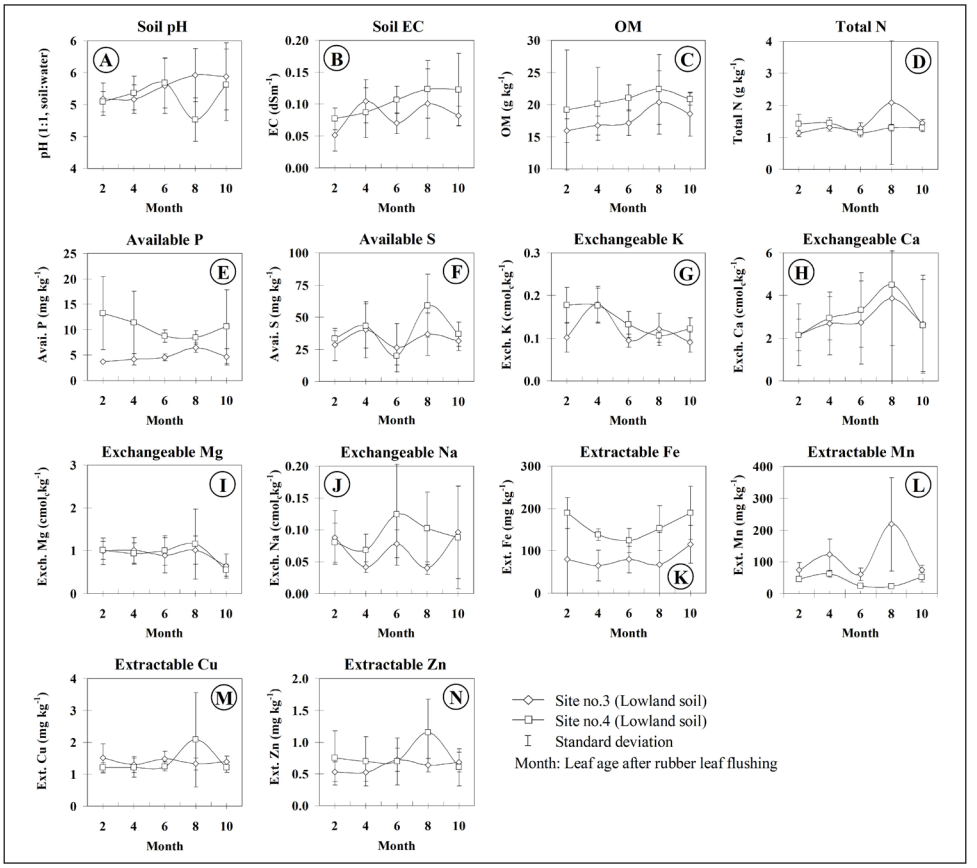

Figure 4. Some soil properties under the shade of rubber trees during APD of rubber trees grown in lowland areas: (A) = Soil pH, (B) = Soil EC, (C) = Soil OM, (D) = Total N, (E) = Exchangeable Ca, (F) = Exchangeable Mg, (G) = Exchangeable K, (H) = Exchangeable Na, (I) = Available P, (J) = Available S, (K) = Extractable Fe, (L) = Extractable Mn, (M) = Extractable Cu and (N) = Extractable Zn

Soil Chemical Properties of Pre-Tapping Rubber Trees in the Lowland Area (Site no.4)

The results of the study found that the amounts of plant nutrients in soils showed no significant difference ($p < .05$), except that avai.S, exch.K and ext.Mn showed significant differences ($p < .01$) (Figure 4). Soil pH was 5.05-5.34 (Figure 4A). Soil EC was 0.12-0.12 mS cm^{-1} (Figure 4B), and soil OM was 19.19-22.38 g kg^{-1} (Figure 4C). During the 2nd month ALF: The highest plant nutrients were avai.P = 13.25 mg kg^{-1}, exch.K = 0.18 $cmol_c kg^{-1}$, ext.Fe = 189.60 mg kg^{-1} (Figure 4E, 4G and 4K) whereas the lowest plant nutrients were exch.Ca = 2.16 $cmol_c kg^{-1}$ and ext.Cu = 1.21 mg kg^{-1} (Figure 4H and 4M). During the 4th month ALF: The highest plant nutrients were total N = 3.73 g kg^{-1}, exch.K = 0.18 $cmol_c kg^{-1}$, and ext.Mn = 62.04 mg kg^{-1} (Figure 4D, 4G and 4L), whereas the lowest plant nutrients were exch.Na = 0.068 $cmol_c kg^{-1}$ and ext.Cu = 1.21 mg kg^{-1} (Figure 4J and 4M). During the 6th month ALF: The highest plant nutrients were exch.Na = 0.124 $cmol_c kg^{-1}$ (Figure 4J, while the lowest plant nutrients were total N = 1.14 g kg^{-1}, avai.S = 19.83 mg kg^{-1}) and ext.Fe = 124.39 mg kg^{-1} (Figure 4D, 4F and 4K). During 8th month ALF: The highest plant nutrients were exch.Ca and Mg = 4.50 and 1.16 $cmol_c kg^{-1}$, respectively and ext.Cu and Zn = 2.09 and 1.16 mg kg^{-1}, respectively (Figure 4H, 4I, 4M and 4N), while the lowest plant nutrients were avai.P and S = 8.47 and 59.03 mg kg^{-1}, respectively, exch.K = 0.11 $cmol_c kg^{-1}$ and ext.Mn = 22.68 mg kg^{-1} (Figure 4E, 4F, 4G and 4L). During the 10th month ALF: There were no highest plant nutrients, whereas the lowest plant nutrients were exch.Mg = 0.55 $cmol_c kg^{-1}$ and ext.Cu and Zn = 1.21 and 0.61 mg kg^{-1} (Figure 4I, 4M and 4N).

Rubber soils in both upland and lowland areas exhibited moderate to low nutrient levels necessary for rubber growth (Table 1). High rainfall (seasonal and off-seasonal) maintained elevated soil moisture beneath tree canopies. While promoting microbial decomposition of OM, OM levels remained sufficient for rubber growth. However, OM was susceptible to leaching by rainfall (Sutthipradit, 1993), evidenced by lower OM in upland versus lowland soils (Figures 3C and 4C; Table 1). Additionally, nutrients were readily leached by rainfall, and extremely acidic conditions limited nutrient solubility for plant uptake (Department of Soil Science, 2001). Conversely, phosphorus, resistant to loss, accumulated more than other nutrients. Available P exceeding 45 mg kg^{-1} indicates excessive amounts for plant growth (Kheoruenromn, 1990; Im-Erb, 1991), particularly in upland rubber soils. Nutrient levels in experimental sites aligned with Suchartkul's (2011) findings for RRIM 600 rubber soils in southern Thailand (Chumphon, Surat Thani, Nakhon Si Thammarat): OM = 6.0-23.0 g kg^{-1}, avai.P and S = 0.3-28.0 and 17.0-38.0 mg kg^{-1}, exch.K, Ca, Mg, Na = 18.0-113.0, 18.0-576.0, 3.0-144.0, 3.9-40.0 mg kg^{-1}, ext.Fe, Mn, Cu, Zn, B = 13.5-97.5, 0.5-110.2, 0.03-1.48, 0.14-1.40, 0.14-0.61 mg kg^{-1}, respectively. Values also corresponded with mangosteen soil analyses by Nilnond et al. (1995) and Pechkeo (1999, 2007), reporting N, P, K, Ca, Mg, S, B concentrations of 0.76-1.25 g kg^{-1}, 2.45-61.69 mg kg^{-1}, 0.10-0.26, 0.09-2.43, 0.05-0.50 $cmol_c$ kg^{-1}, 1.85-15.32, 0.16-0.84 mg kg^{-1}, respectively.

Table 1
The results of soil fertility assessment for rubber growth in experimental sites (upland and lowland areas)

Soil Properties	Soil Fertility Level															
	Experimental Site No.1 (Upland Areas)				Experimental Site No.2 (Upland Areas)				Experimental Site No.3 (Lowland Areas)				Experimental Site No.4 (Lowland Areas)			
	Soil Analysis Result[1/]	Low	Medium	High	Soil Analysis Result[1/]	Low	Medium	High	Soil Analysis Result[1/]	Low	Medium	High	Soil Analysis Result[1/]	Low	Medium	High
Soil texture (0 - 15 cm)	Loam	-	-	-	Sandy clay loam	-	-	-	Clay	-	-	-	Clay loam	-	-	-
Soil pH (1:1, soil:water)	5.02 - 5.86	-	-	-	4.74 - 5.73	-	-	-	4.98 - 5.46	-	-	-	4.76 - 5.34	-	-	-
Soil EC ($mScm^{-1}$, 1:1, soil:water)	0.05 - 0.13	-	-	-	0.04 - 0.18	-	-	-	0.04 - 0.10	-	-	-	0.05 - 0.12	-	-	-
Soil OM ($g\ kg^{-1}$)	11.73 - 20.17	-	●	-	7.12 - 20.92	●	●	-	12.25 - 20.35	-	●	-	13.29 - 22.38	-	●	-
Total N ($g\ kg^{-1}$)	0.64 - 1.15	●	●	-	0.67 - 1.68	●	-	-	0.92 - 2.08	●	●	-	0.82 - 3.73	●	●	●
Available P ($mg\ kg^{-1}$)	10.29 - 220.31	●	●	●	23.86 - 128.42	-	●	●	2.78 - 6.45	●	●	-	4.24 - 13.25	●	●	-
Available S ($mg\ kg^{-1}$)	14.99 - 68.12	-	-	-	11.63 - 30.19	-	-	-	11.64 - 40.25	-	-	-	15.45 - 59.03	-	-	-
Exchangeable Ca ($cmol_C kg^{-1}$)	0.09 - 0.25	●	-	-	0.08 - 0.20	●	-	-	0.06 - 0.18	●	-	-	0.06 - 0.18	●	-	-

Table 1 (*continued*)

Soil Properties	Soil Fertility Level															
	Experimental Site No.1 (Upland Areas)				Experimental Site No.2 (Upland Areas)				Experimental Site No.3 (Lowland Areas)				Experimental Site No.4 (Lowland Areas)			
	Soil Analysis Result[1/]	Low	Medium	High	Soil Analysis Result[1/]	Low	Medium	High	Soil Analysis Result[1/]	Low	Medium	High	Soil Analysis Result[1/]	Low	Medium	High
Exchangeable Mg ($cmol_c kg^{-1}$)	0.10 - 5.39	●	●	-	1.37 - 2.64	-	●	-	1.61 - 3.88	-	●	-	1.17 - 4.50	-	●	-
Exchangeable K ($cmol_c kg^{-1}$)	0.13 - 1.24	-	●	●	0.62 - 1.21	-	-	●	0.42 - 1.01	-	-	●	0.30 - 1.16	-	-	●
Exchangeable Na ($cmol_c kg^{-1}$)	0.008 - 0.09	-	-	-	0.01 - 0.06	-	-	-	0.03 - 0.10	-	-	-	0.04 - 0.12	-	-	-
Extractable Fe (mg kg^{-1})	59.74 - 141.28	-	-	●	44.92 - 100.71	-	-	●	55.74 - 115.02	-	-	●	64.78 - 189.60	-	-	●
Extractable Mn (mg kg^{-1})	15.30 - 48.76	-	-	●	17.93 - 139.05	-	-	●	54.28 - 218.38	-	-	●	19.38 - 62.04	-	-	
Extractable Cu (mg kg^{-1})	0.34 - 3.14	●	●	●	1.11 - 3.02	-	-	●	1.02 - 1.51	-	●	●	1.00 - 2.09	-	-	●
Extractable Zn (mg kg^{-1})	0.36 - 2.68	●	●	●	0.69 - 2.03	-	-	●	0.39 - 0.72	-	●	●	0.47 - 1.16	-	●	●
Soil fertility level (overview)		●	●	-		●	●	-		●	●	-		●	●	-

Note. [1/] Average values of soil physical and chemical properties (0 - 15 cm in depth) under the rubber tree shade during the APD

Changes in Plant Nutrient Content in Soils During APD

Upland rubber plantations: N demand increased from the 2nd through the 4th-6th month ALF, then decreased during the 8th-10th month ALF. Phosphorus, K, S and Fe demand was low during the 2nd-4th month ALF, increased during the 6th-8th month ALF, then decreased at the 10th month ALF. Calcium, Mg and Zn demand was low at the 2nd month ALF, increased at the 4th month ALF, decreased during the 6th-8th month ALF, then increased at the 10th month ALF. Sodium demand was high during the 2nd-4th month ALF, decreased at the 6th month ALF, then increased during the 8th-10th month ALF. Manganese demand was high at the 2nd month ALF, decreased at the 4th month ALF, increased at the 6th month ALF, decreased at the 8th month ALF, then increased at the 10th month ALF. Copper demand remained low during the 2nd-8th months of ALF, increasing at the 10th month of ALF (Figure 3 and Table 2).

Lowland rubber plantations: N demand was low during the 2nd-4th month of ALF, increased at the 6th month of ALF, then decreased during the 8th-10th month of ALF. Phosphorus, K, Mg and Mn demand was low during the 2nd-4th month of ALF, increased during the 6th-8th month of ALF, then decreased at the 10th month of ALF. Calcium demand was high at the 2nd month of ALF, continued increasing through the 4th-8th month of ALF, then decreased at the 10th month of ALF. Sodium demand was low at the 2nd month of ALF, increased at the 4th month of ALF, decreased at the 6th month of ALF, then increased during the 8th-10th month of ALF. Sulfur demand was high at the 2nd month of ALF, decreased at the 4th month of ALF, increased at the 6th month of ALF, then decreased during the 8th-10th month of ALF. Copper and Zn demand was high during the 2nd-6th months ALF, decreased in the 8th month ALF, then increased at the 10th month ALF. Iron demand was low at the 2nd month ALF, increased during the 4th-6th month ALF, then decreased during the 8th-10th month ALF (Figure 4 and Table 2).

Acidic soil conditions (pH <5.5) in experimental sites may inhibit microbial OM decomposition while promoting dissolution of Al and Mn to potentially toxic levels (Department of Soil Science, 2001). In highly acidic conditions, Fe^{3+}, Al^{3+} and hydrous oxides of Fe, Al and Mn form insoluble compounds with soluble P, reducing P absorption and translocation (Moncharoen, 2002). Similarly, Poowarodom (2001) reported low K in durian orchards in eastern Thailand due to acidic conditions, coarse texture, and heavy rainfall causing K leaching, applicable to other nutrients. This explains reduced nutrient accumulation in rubber leaves, particularly in upland plantations. Adjusting soil pH to ≥5.5 with lime or dolomite enhances nutrient solubility and availability (Department of Soil Science, 2001) and promotes microbial decomposition of OM, thereby increasing soil nutrient content for rubber cultivation.

Table 2
The overview of plant nutrient requirements from soils and leaves for rubber growth during ADP

Time[1/]	Plant Nutrient Requirement from Soils[2/]		Plant Nutrient Requirement from Leaves[2/]		Plant Nutrient Requirement from Soils and Leaves[2/]	
Month	**Upland Areas**	**Lowland Areas**	**Upland Areas**	**Lowland Areas**	**Upland Areas**	**Lowland Areas**
2	N Na	Ca N P Cu Zn	Ca Na B S Mn	Ca Na B S Mn	Na	Ca
4	N K	Cu Na Fe Zn	P S Fe	P S Fe	K	Fe
6	Mn N K S	K S Mn N Fe	N Cu Fe Zn	N Cu Fe Zn	N S	N Fe
8	Fe N K S P Cu	Na P K Mn Cu	P K Cu Zn	P K Cu Zn	K Cu	P K Cu
10	Ca Mg Zn P K Na Cu	Mg K Cu Zn	Mg K P Mn	Mg K P Mn	P K Mg Cu Zn	K Mg

Note. When the amount of plant nutrients in the soil is lowest, rubber trees require more plant nutrients from the soil for growth than at other times
[1/] = Age of rubber leaves ALF (months)
[2/] = Overview of nutrient requirements in both experimental sites

Seasonal flooding in lowland rubber plantations creates physiological constraints that severely limit nutrient uptake despite adequate or elevated soil nutrient levels. Brief periods of waterlogging (2-5 days) induce root hypoxia, shifting metabolism to anaerobic respiration, which produces toxic metabolites and impairs energy-dependent cation transport (Ezin et al., 2010; Pezeshki, 2001). Recovery requires 7-14 days, but recurring flooding every 2-3 weeks creates continuous stress. Root architecture differs fundamentally between locations: upland trees develop deep tap roots (>150 cm) while lowland trees face subsurface compaction from former paddy plow pans at 20-35 cm depth, restricting roots to shallow zones and reducing biomass by 30-40% (Division of Soil Survey and Classification, 1987; Carr, 2012). Nutrient deficiencies were evident-Ca (<10 g kg^{-1}), Mg (<2.5 g kg^{-1}), and P fixation by Fe/Al oxides at pH 4.5-5.5. Elevated Fe (37-82 mg kg^{-1}) and Mn (465-1,091 mg kg^{-1}) remained within sufficiency ranges, indicating physiological requirement rather than toxicity (Foy, 1984; Sahrawat, 2005). However, high Mn:Fe ratios (6.8:1) suggest subclinical metabolic inefficiencies and the induction of Zn/Cu deficiencies. Temporal patterns reveal critical Ca/Mg deficiency windows during early-season flooding when trees require these nutrients for cell wall synthesis, necessitating synchronised fertilisation strategies.

Plant Nutrients in Leaves of Pre-Tapping Rubber Trees in the Upland Area (Site no.1)

The study found that the amounts of plant nutrients in rubber leaves differed significantly ($p < .01$), except for B and Fe, which showed no significant difference ($p < .05$) (Figure 5). During the 2nd month ALF: The highest plant nutrients were total K, Na and Zn = 26.43, 0.0833 and 0.0556 g kg^{-1}, respectively) (Figure 5C, 5F and 5L) whereas the lowest plant nutrients were total Ca and S = 10.09 and 3.30 g kg^{-1}, respectively) Figure 5D and 5G). During the 4th month ALF, the highest plant nutrient was absent, whereas the lowest plant nutrient was total B (32.06 mg kg^{-1}) (Figure 5H). During the 6th month of ALF. The highest plant nutrient was total Mn = 0.0718 g kg^{-1} (Figure 5J), while the lowest plant nutrients were total N and Fe = 2.51 and 0.0653 g kg^{-1}, respectively (Figure 5A and 5I). During 8th month ALF: The highest plant nutrients were total N, P, Ca, Mg, S and Fe = 37.41, 3.67, 18.15, 4.04, 5.03, 67.51 and 0.0841 g kg^{-1}, respectively and total B = 67.51 mg kg^{-1} (Figure 5A, 5B, 5D, 5E, 5G, 5H and 5I) whereas the lowest plant nutrient was total Cu = 0.0072 g kg^{-1} (Figure 5K). During 10th month ALF: The highest plant nutrient was total Cu = 0.0109 g kg^{-1} (Figure 5K) while the lowest plant nutrients were total P, K, Mg, Na, Mn and Zn = 2.51, 0.39, 1.36, 0.0195, 0.2366 and 0.0240 g kg^{-1}, respectively (Figure 5B, 5C, 5E, 5F, 5J and 5L).

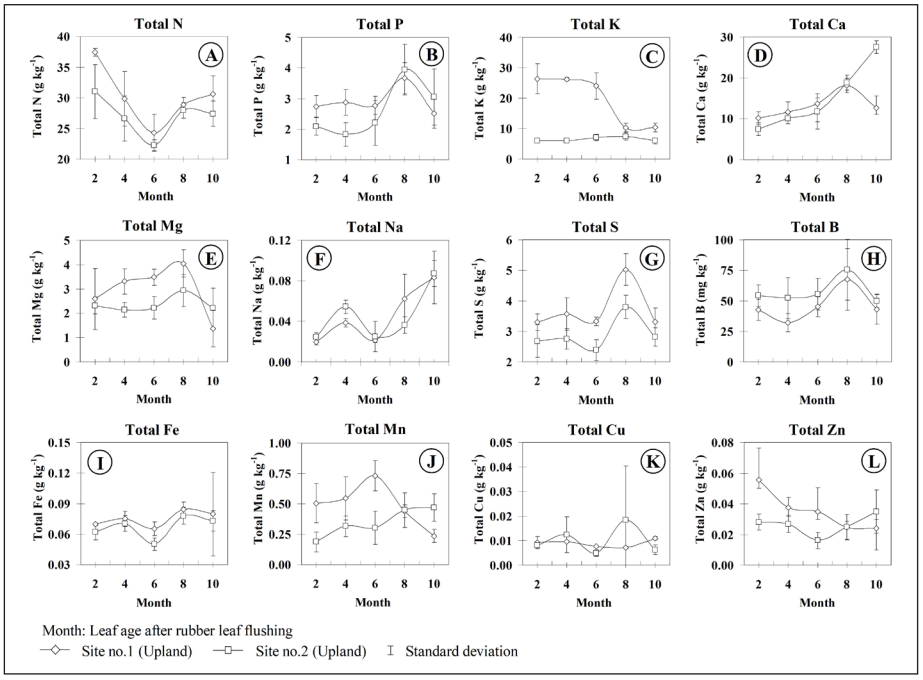

Figure 5. Plant nutrients accumulated in rubber leaves during APD in upland areas: (A) = Total N, (B) = Total P, (C) = Total K, (D) = Total Ca, (E) = Total Mg, (F) = Total Na, (G) = Total S, (H) = Total B, (I) = Total Fe, (J) = Total Mn, (K) = Total Cu and (L) = Total Zn

Plant Nutrients in Leaves of Pre-Tapping Rubber Trees in the Upland Area (Site no.2)

The results of the study found that the amounts of plant nutrients in rubber leaves showed significant differences ($p<.01$), except for total K, Mg, B and Cu, which showed no significant difference ($p<.05$), and total Zn showed no significant difference ($p<.05$) (Figure 5). During the 2nd month of ALF, the highest plant nutrient was total N = 31.04 g kg^{-1} (Figure 5A), whereas the lowest plant nutrients were total Ca, Na and Mn = 7.46, 0.0245 and 0.1880 g kg^{-1}, respectively) (Figure 5D, 5F and 5J). During the 4th month ALF: No plant nutrient was the highest, whereas the lowest plant nutrient was total P = 1.83 g kg^{-1} (Figure 5B). During the 6th month ALF: The highest plant nutrient was absent, while the lowest plant nutrients were total N, S, Fe, Cu and Zn = 22.27, 2.39, 0.0502, 0.0049, and 0.0611 g kg^{-1}, respectively (Figure 5A, 5G, 5I, 5K and 5L). During the 8th month ALF: The highest plant nutrients were total P, K, S, Fe and Cu = 3.94, 7.50, 3.80, 0.0781 and 0.0183 g kg^{-1} and total B = 75.38 mg kg^{-1} (Figure 5B, 5C, 5G, 5H, 5I and 5K), while the lowest plant nutrient was absent. During the 10th month ALF: The highest plant nutrients were total Ca, Na, Mn and Zn = 27.52, 0.0872, 0.4472 and 0.0349 g kg^{-1}, respectively (Figure 5D, 5F, 5J and 5L), whereas the lowest plant nutrients were total K = 5.99 g kg^{-1} and total B = 49.99 mg kg^{-1} (Figure 5C and 5H).

Plant Nutrients in Leaves of Pre-Tapping Rubber Trees in the Lowland Area (Site no.3)

The results of the study found that the amounts of plant nutrients in rubber leaves showed significant differences ($p<.01$ and $p<.05$), except for total N, Mg, B, Fe and Mn, which showed no significant differences ($p<.05$) (Figure 6). During the 2nd month ALF: The highest plant nutrient was total Fe = 0.0823 g kg^{-1} (Figure 6I), while the lowest plant nutrients were total Ca, Na and S = 8.76, 0.0245 and 3.32 g $kg^{-1,}$ respectively, with total B = 27.50 g kg^{-1} (Figure 6D, 6F, 6G and 6H). During the 4th month ALF: The highest plant nutrients were total P, K and Cu = 2.29, 25.83 and 0.0250 g kg^{-1}, respectively (Figure 6B, 6C and 6K). The lowest plant nutrient was total Fe = 0.0660 g kg^{-1} (Figure 6I). During the 6th month ALF: The highest plant nutrients were total B = 54.53 mg kg^{-1}, total Mn and Zn = 0.8067 and 0.0461 g kg^{-1}, respectively (Figure 6H, 6J and 6L). The lowest plant nutrients were total N and Cu (22.31 and 0.0080 g kg^{-1}, respectively) (Figure 6A and 6K). During the 8th month of ALF, the highest plant nutrients were total N, Mg and S = 27.17, 3.12 and 4.31 g kg^{-1}, respectively (Figure 6A, 6E, and 6G), whereas the lowest plant nutrients were total K and Zn = 7.89 and 0.0461 g kg^{-1}, respectively) (Figure 6C and 6L). During the 10th month ALF: The highest plant nutrients were total Ca and Na = 20.85 and 0.1833 g kg^{-1}, respectively) (Figure 6D and 6F) while the lowest plant nutrients were total P, Mg and Mn = 1.86, 2.30 and 0.4928 g kg^{-1}, respectively) (Figure 6B, 6E and 6J).

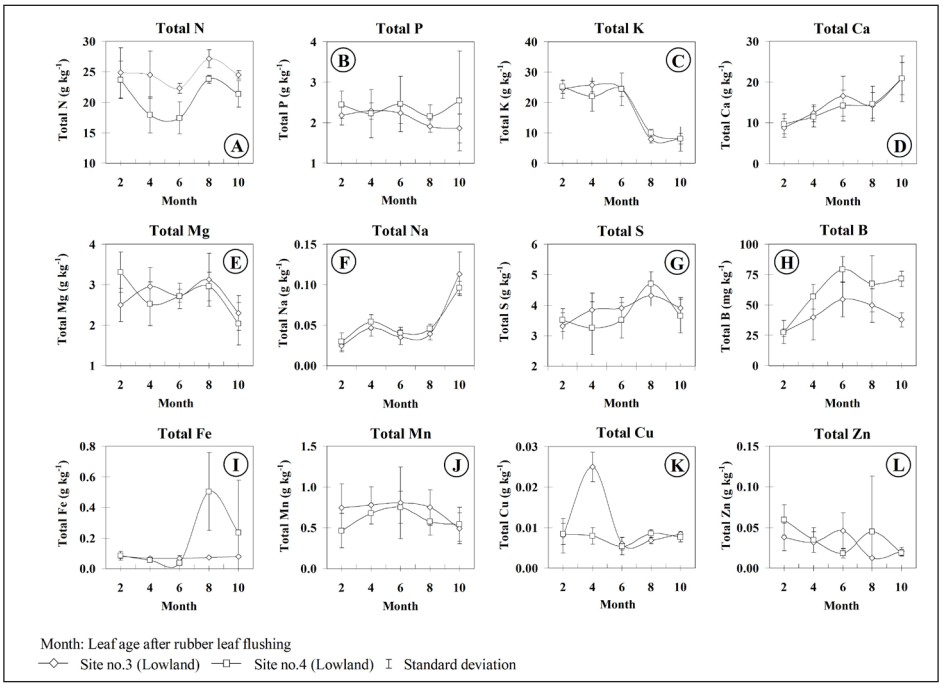

Figure 6. Plant nutrients accumulated in rubber leaves during APD in lowland areas: (A) = Total N, (B) = Total P, (C) = Total K, (D) = Total Ca, (E) = Total Mg, (F) = Total Na, (G) = Total S, (H) = Total B, (I) = Total Fe, (J) = Total Mn, (K) = Total Cu and (L) = Total Zn

Plant Nutrients in Leaves of Pre-Tapping Rubber Trees in the Lowland Area (Site no.4)

The results of the study found that the amounts of plant nutrients in rubber leaves showed significant differences ($p<.01$), except for total P, Mn, Cu and Zn, which showed no significant differences ($p<.05$) (Figure 6). During the 2nd month ALF: The highest plant nutrients were total K, Mg and Zn = 25.18, 3.31 and 0.0595 g kg^{-1}, respectively (Figure 6C, 6E and 6L) whereas the lowest plant nutrients were total Ca, Na and Mn = 4.74, 0.0290 and 0.4645 g kg^{-1}, respectively and total B = 27.17 mg kg^{-1} (Figure 6D, 6F, 6H and 6J). During the 4th month of ALF, no highest plant nutrient was observed, while the lowest plant nutrient was total S = 3.25 g kg^{-1} (Figure 6G). During the 6th month ALF: The highest plant nutrients were total B = 79.26 mg kg^{-1}, total Mn = 0.7495 g kg^{-1} (Figure 6H and 6J) while the lowest plant nutrients were total N, Fe, Cu, and Zn = 17.41, 0.0374, 0.0054 and 0.0183 g kg^{-1}, respectively (Figure 6A, 6I, 6K and 6L). During the 8th month ALF: The highest plant nutrients were total N, S, Fe and Cu = 23.79, 4.70, 0.5030, and 0.0085 g kg^{-1}, respectively (Figure 6A, 6G, 6I and 6K), whereas the lowest plant nutrient was total P = 2.16 g kg^{-1} (Figure 6B). During the 10th month ALF: The highest plant nutrients were total P, Ca and Na = 2.54, 20.84 and 0.0962 g kg^{-1}, respectively (Figure 6B, 6D and 6F) while the lowest plant nutrients were total K and Mg = 8.11 and 2.03 g kg^{-1}, respectively (Figure 6C and 6E).

The Status of Plant Nutrients in Rubber Leaves Affecting Rubber Tree Growth

Plant nutrients accumulated in rubber leaves from both upland and lowland areas were classified as medium to low (Table 3). Nutrient concentrations aligned with Suchartkul's (2011) findings for RRIM 600 rubber in southern Thailand (Chumphon, Surat Thani, Nakhon Si Thammarat): N, P, K, Ca, Mg, S = 22.00-35.10, 1.60-2.90, 7.20-14.60, 5.60-19.40, 1.80-4.00, 1.10-3.70 g kg^{-1}; Fe, Mn, Cu, Zn, B = 64.00-151.00, 142.00-574.00, 8.00-14.00, 19.00-61.00, 11.00-85.00 mg kg^{-1}, respectively. Values also corresponded with Yingjajaval and Bangjan's (2006) analysis of 4-month-old RRIM 600 leaves: N, P, K, Ca, Mg = 28.69, 1.91, 8.47, 8.81, 3.70 g kg^{-1}, respectively.

Changes in Plant Nutrient Content in Leaves During APD

Upland rubber plantations: Nitrogen and Zn demand were low during the 2nd-4th month ALF, increased at the 6th month ALF, then decreased during the 8th-10th months ALF. Phosphorus, Ca and Mg demand were high at the 2nd month ALF, decreased during the 4th-6th month ALF, then increased during the 8th-10th month ALF. Potassium demand was low during the 2nd-6th month ALF, then increased during the 8th-10th month ALF. Sodium demand was high at the 2nd month ALF, decreased at the 4th month ALF, increased at the 6th month ALF, then decreased during the 8th-10th month ALF. Sulfur, Fe and Cu demand

was high at the 2nd month ALF, decreased at the 4th month ALF, increased at the 6th month ALF, decreased at the 8th month ALF, then increased at the 10th month ALF. Boron demand was low at the 2nd month ALF, increased at the 4th month ALF, decreased during the 6th-8th month ALF, then increased at the 10th month ALF. Manganese demand was high at the 2nd month ALF, decreased during the 4th-6th month ALF, then increased during the 8th-10th month ALF (Figure 5 and Table 2).

Lowland rubber plantations: Nitrogen, P, K, Mg and Zn demand was low during the 2nd-4th month ALF, increased at the 6th month ALF, decreased at the 8th month ALF, then increased at the 10th month ALF. Calcium demand was high at the 2nd month ALF, decreased during the 4th-6th month ALF, increased at the 8th month ALF, then decreased at the 10th month ALF. Sulfur demand was high during the 2nd-4th month ALF, decreased during the 6th-8th month ALF, then increased at the 10th month ALF. Boron and Mn demand was high at the 2nd month ALF, decreased during the 4th-6th month ALF, then increased during the 8th-10th month ALF. Iron demand was high during the 2nd-6th month ALF, decreased at the 8th month ALF, then increased at the 10th month ALF. Sodium and Cu demand were high at the 2nd month ALF, decreased at the 4th month ALF, increased at the 6th month ALF, then decreased during the 8th-10th month ALF (Figure 6 and Table 2).

Relationship between Plant Nutrients in the Soil and Leaf During APD

Upland areas: Rubber trees demonstrated high Na demand from soil and leaves at the 2nd month ALF; K at the 4th month ALF; N and S at the 6th month ALF; K and Cu at the 8th month ALF; P, K, Mg, Cu and Zn at the 10th month ALF (Figure 3, 4, 5 and 6 and Table 2). Lowland areas: High Ca demand occurred at the 2nd month ALF; Fe at the 4th month ALF; N and Fe at the 6th month ALF; P, K and Cu at the 8th month ALF; K and Mg at the 10th month ALF (Figures 3, 4, 5 and 6 and Table 2).

Nutrient demand patterns differed fundamentally between locations due to distinct soil-plant-environment interactions. Upland sites showed high K demand during the 4th, 8th, and 10th months of ALF, coinciding with rapid canopy expansion, which requires K for stomatal regulation, enzyme activation, and osmotic adjustment (Marschner, 2012; Priyadarshan, 2017). Conversely, lowland sites exhibited sustained Ca demand from the 2nd-8th month ALF, reflecting dual roles in cell wall synthesis and root membrane stability under periodic anaerobic stress. Low exch.Ca (2.16-4.50 $cmol_c kg^{-1}$) created supply-demand imbalances, maintaining deficient leaf concentrations (4.74-20.85 g kg^{-1}) throughout the season. Acidic conditions (pH = 4.47-5.86) influenced nutrient availability location-specifically: uplands maintained active microbial cycling, while lowlands experienced oscillating redox conditions that alternately mobilised Fe^{2+}/Mn^{2+} during waterlogging and precipitated oxides upon reoxidation, creating temporal fluctuations in availability.

Table 3
Shows the results of evaluating the status of plant nutrients accumulated in rubber leaves that are appropriate for the growth of rubber trees

Plant Nutrients	Plant Nutrient Levels in Leaves															
	Experimental Site No.1 (Upland Areas)				Experimental Site No.2 (Upland Areas)				Experimental Site No.3 (Lowland Areas)				Experimental Site No.4 (Lowland Areas)			
	Leaves Analysis Result[1/]	Low	Medium	High	Leaves analysis result[1/]	Low	Medium	High	Leaves analysis result[1/]	Low	Medium	High	Leaves analysis result[1/]	Low	Medium	High
Total N (g kg^{-1})	25.25 - 35.67	●	●	-	23.04 - 32.65	●	●	-	19.47 - 29.17	●	-	-	14.67 - 21.38	●	-	-
Total P (g kg^{-1})	2.47 - 3.55	-	●	●	1.48 - 2.46	●	●	-	2.05 - 2.55	-	●	●	1.63 - 3.05	●	●	●
Total K (g kg^{-1})	25.77 - 26.75	-	-	●	5.95 - 6.54	●	-	-	22.37 - 28.35	-	-	●	14.87 - 26.85	-	●	●
Total Ca (g kg^{-1})	9.24 - 15.45	-	-	●	8.34 - 11.17		-	●	10.67 - 15.67	-	-		9.23 - 15.33	-	-	●
Total Mg (g kg^{-1})	2.47 - 3.85	-	●	●	1.75 - 2.27	●	●	-	2.16 - 3.43	-	●	●	1.57 - 2.86	●	●	●
Total Na (g kg^{-1})	0.0327 - 0.0427	-	-	-	0.0455 - 0.0604	-	-	-	0.0375 - 0.0577	-	-	-	0.0428 - 0.0677	-	-	-
Total S (g kg^{-1})	3.08 - 4.32	-	-	●	2.54 - 3.25	-	-	●	3.27 - 4.65	-	-	●	2.06 - 4.73	-	●	●
Total B (mg kg^{-1})	24.86 - 39.72	-	-	●	38.15 - 70.79	-	-	●	26.47 - 60.79	-	-		47.70 - 67.89	-	-	●
Total Fe (g kg^{-1})	0.0655 - 0.0863	-	●	●	0.0598 - 0.0798	-	●	-	0.0525 - 0.0713	●	●	-	0.0444 - 0.0743	●	●	-

Table 3 (*continued*)

Plant Nutrients	Plant Nutrient Levels in Leaves															
	Experimental Site No.1 (Upland Areas)				Experimental Site No.2 (Upland Areas)				Experimental Site No.3 (Lowland Areas)				Experimental Site No.4 (Lowland Areas)			
	Leaves Analysis Result[1/]	Low	Medium	High	Leaves analysis result[1/]	Low	Medium	High	Leaves analysis result[1/]	Low	Medium	High	Leaves analysis result[1/]	Low	Medium	High
Total Mn (g kg^{-1})	0.3636 - 0.7718	-	-	●	0.2285 - 0.4406	-	-	●	0.4783 - 1.0913	-	-		0.5226 - 0.8176	-	-	●
Total Cu (g kg^{-1})	0.0091 - 0.0100	●	●	-	0.0084 - 0.0255	●	●	●	0.0215 - 0.0300	-	-	●	0.0053 - 0.0103	●	●	-
Total Zn (g kg^{-1})	0.0283 - 0.0444	-	-	●	0.0198 - 0.0347	-	●	●	0.0155 - 0.0512	●	●	●	0.0233 - 0.0612	-	-	●
Plant nutrient status in leaves (overview)		-	●	●		●	●	-		-	-	●		-	-	●

Note. [1/] Range of average plant nutrient levels in rubber leaves aged 4 months, ALF, which was an appropriate time for collecting rubber leaf samples to analyse general plant nutrient content

Guidelines for Increasing Plant Nutrient Content for Rubber Trees

Results (Table 2) establish nutrient management guidelines throughout APD: (1) Upland plantations: Increase Na at 2nd month ALF; K at 4th month ALF; N and S at 6th month ALF; K and Cu during 8th-10th month ALF; P, Mg and Zn at 10th month ALF. (2) Lowland plantations: Increase Ca at 2nd month ALF; Fe during 4th-6th month ALF; N at 6th month ALF; P and Cu at 8th month ALF; K during 8th-10th month ALF; Mg at 10th month ALF.

Site-specific fertilisation must address physiological constraints beyond soil test values. Upland plantations require elevated K applications (118 g K_2O tree^{-1}) split across growth flushes and supplemental S (20 g tree^{-1}) for weathered Ultisols (Havlin et al., 2014). Lowland strategies necessitate pre-season liming (500-1,000 g $CaMg(CO_3)_2$ tree^{-1}) to raise pH ≥5.5, improving Ca/Mg availability (Brady & Weil, 2016), with early $Ca(NO_3)_2$ (300 g tree^{-1}) addressing hypoxia-induced deficiency and chelated Fe (20 g tree^{-1}) overcoming oxide fixation (Marschner, 2012). Elevated K rates (130 g K_2O tree^{-1}, 30% above upland) compensate for leaching losses under saturated conditions (Dobermann & Fairhurst, 2000).

CONCLUSION

Pre-tapping upland rubber plantations require higher Na from soil and leaves at 2nd month ALF; K at 4th month ALF; N and S at 6th month ALF; K and Cu at 8th month ALF; P, K, Mg, Cu and Zn at 10th month ALF compared to other periods. Pre-tapping lowland plantations require higher Ca at the 2nd month ALF; Fe at the 4th month ALF; N and Fe at the 6th month ALF; P, K and Cu at the 8th month ALF; K and Mg at the 10th month ALF compared to other periods. Characterising nutrient accumulation and relationships in soil and leaves throughout APD provides fundamental information for determining appropriate nutrient management strategies. This enables rubber trees to receive sufficient nutrients, in both type and quantity, for optimal growth and production.

ACKNOWLEDGEMENT

The authors wish to acknowledge the financial support provided by Prince of Songkla University, Research Project No. AGR540591S.

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