On surface soil and subsoil acidity in natural and managed land-use systems of humid tropics of Peninsular India.

K.M. Nair[1], K.S. Anil Kumar[1], M. Lalitha[1]*, Shivanand[1], S.C. Ramesh Kumar[1], S. Srinivas[1], Arti Koyal[1], S. Parvathy[1], K. Sujatha[1], C. Thamban[2], Jeena Mathew[2], K.P. Chandran[2], Abdul Haris[2], V. Krishnakumar[2], V. Srinivasan[3], Jessy[4], James Jacob[4], J.S. Nagaraj[5], Maria Violet D'Souza[5], Y. Raghuramulu[5], R. Hegde[1], and S.K. Singh[1],

[1]*Regional Centre, ICAR-National Bureau of Soil Survey and Land Use Planning, Hebbal, Bangalore, India 560 024*

[2]*ICAR-Central Plantation Crops Research Institute, Kasaragod, Kerala, India 671 124*

[3]*ICAR-Indian Institute of Spices Research, Kozhikkode, Kerala, India 673 012*

[4]*Rubber Research Institute of India, Kottayam, Kerala*

[5]*Coffee Research Institute, Chikmagalur, Karnataka*

* Corresponding author

Lalitha. M.

Scientist

ICAR - National Bureau of Soil Survey and Land Use Planning, Bangalore 560024, Karnataka, India

Email: mslalit@yahoo.co.in

Phone number: +919611790471

Abstract

Natural forests and managed plantations constitute the largest land-use systems in humid tropics of south-western parts of Peninsular India comprising the Western Ghats and coastal plain. Soils therein are naturally acid and the acidity is enhanced in managed land-use systems through inputs of chemical fertilizers. Plant nutrient deficiencies and mineral toxicities constrain crop production in acid soils. Surface soil and subsoil acidity in forest, coffee, rubber and coconut land use systems were evaluated. The spatial pattern of surface soil and subsoil acidity pointed to low intensity of acidification in Malnad region of Karnataka, moderate acidity in northern Kerala and strong acidity in southern Kerala. Among the land-use systems investigated, soils under natural forest and coffee plantations were only slightly acid in surface soil and subsoil whereas rubber- and coconut-growing soils were strongly acid. Both natural and managed land-use systems, however, had strongly acid reaction in surface soil and subsoil in southern Kerala. Biomass production and crop yields are constrained in strongly acid soil by toxic levels of Al on soil exchange complex [>0.5 cmol (+) kg^{-1} soil] and depletion of basic cations of calcium, magnesium and potassium (base saturation less than 50 per cent or Al saturation more than 50 per cent). Surface soil acidity can be ameliorated by incorporating liming materials into surface soils. Where subsoil acidity is also involved gypsum too should be incorporated. In humid climate partial solubility of gypsum permits movement of calcium into the subsoil layers wherein calcium replaces the aluminium on exchange complex and the sulphate radical precipitates the aluminium by formation of aluminium sulphate.

Key words: Humid tropics, **s**oil acidity**, s**ubsoil acidity, base saturation, aluminium saturation

Introduction

Acid soils globally cover large areas in the cold, humid northern belt of the world and hot, humid tropics[1]. Soils of around 30 per cent of the world's arable lands are acid[1-3]. In India also 30 per cent of the total cultivable area has acid soils, mainly distributed in the humid regions of south-western and north-eastern parts of the country and in the Himalayas[4]. Soils of the humid tropics are naturally acid, albeit moderately. High rainfall, leaching of bases, mineralization of organic matter, external inputs of acid-forming chemical fertilizers and inappropriate agriculture practices are the major reasons for soil acidification and its intensification[5-7]. Acid soils are constraining environments for plants and macro- and micro-organisms inhabiting it. Poor soil fertility and productivity of acid soils is due to combination of mineral toxicities (aluminium and manganese) and deficiencies (phosphorus, potassium, calcium, magnesium, zinc, boron etc.). Surface soil acidity and its effect on crop production were recognized centuries ago[8]. Recognition of subsoil acidity and its consequences, however, is quite recent, dating back just five decades[9,10].

Subsoil acidity refers to acidification below the plough layer, in general below 20 cm. It is one among the many soil-related constraints in hot, humid, tropical climatic regions. Subsoil acidity cause significant yield reduction in tropical acid soils because of high content of soluble Al and Mn or low plant-available calcium[11], inhibiting physiological and biological activities[7,12], root development[13] and uptake of nutrients such as P, Ca, Mg, K and Mo[14,15] as well as water[16,17]. It is the main chemical impediment for most deep rooted and perennial crops which require uptake of nutrients and water from subsoil layers[18].

This paper reports on surface and subsoil acidity with focus later, on natural and managed land-use systems of tropical, hot, humid region of south-western India and discusses the nature of soil acidity and its possible consequences on crop production.

Materials and methods

South-western Peninsular India comprising the Western Ghats and western coastal plain in the states of Tamil Nadu, Kerala and Karnataka (Fig. 1) experience tropical hot humid climate[19]. Forests and plantations of rubber, coffee and coconut are major land-use systems in the region. Soil-quality monitoring sites (SQMS) were established for these land-use systems[20,21]. At each site soil profiles were excavated, studied for morphology[22] and sampled for laboratory investigations.

Horizon-wise soil samples were analysed for physical and chemical properties following standard procedures. Soils were classified as per Soil Taxonomy[22]. Soil reaction (pH in water, $pH_{(w)}$ and in 0.01 M $CaCl_2$, $pH_{(Ca)}$) and electrical conductivity (EC) were estimated by potentiometric and conductometric methods, respectively[23]. Particle size distribution in the fine earth (<2 mm) was determined by sieving and use of International pipette[24]. Exchangeable bases were extracted by neutral normal ammonium acetate[25] and determined by atomic absorption spectrophotometry. Exchangeable hydrogen and aluminium were determined by extraction with 1*N* KCl[23] followed by titration with standard alkali. Base saturation and aluminium saturation were calculated as

Base saturation (%) = (Total bases/CEC)*100

Aluminium saturation (%) = [Extr. Al/(Exch. Ca+Mg+K+Na+ extr. Al)]*100

Where, exch. Ca, Mg, K, Na, total bases, CEC, extr. Al were in cmol (+) kg^{-1} soil.

From among the large data set (from 183 SQMS) soil analytical data pertaining to 12 SQMS representing the four land use systems are presented to describe the soil qualities in the study area and the nature of surface soil and subsoil acidity (table 1 and 2). However, the entire data on SQM's for the four land-use systems were used for assessing the variability of soil acidity across the land-use systems and assessment of its spatial variability.

Results

Soil qualities in the study area

The soils of the study area, formed under the humid tropical climate, are deeply weathered, leached and depleted of bases. These low-activity-clay soils are deep, welldrained, strongly acid, and low in basic cations and per cent base saturation. These soils with subsoil horizons of illuvial clay belong to Ultisol order of Soil Taxonomy[22]. However, the coastal sandy soils belong to Entisol order (table 2). The classification of the soil into different taxa at the family level of Taxonomy reflects the variability in organic matter content, distribution of illuvial clay in subsoil layers, activity of clay, presence or absence of plinthite, clay mineralogy, temperature regime and particle- size class. These soils have kaolinite, goethite, gibbsite and hydroxyl-interlayered vermiculites as major minerals in their clay fraction[26]. The physical and chemical properties of soils relevant to the subject of this paper are presented in table 2.

The texture of the soil is generally loam in surface layers and clay in subsoil layers due to illuviation of clay into subsoil layers. Soil structure is weak subangualr blocky in surface layers and moderate to strong subangular blocky in subsoil layers. Varying proportion of gravel and plinthite occur in the laterite soils of the study area, except in the soils of highland plateau and Malnad region (hilly terrain of Karnataka, east of Western Ghats).

Electrical conductivity of the soils was extremely low in surface soils and subsoils (0.01 to 0.64 dS m^{-1}), indicating negligible level of ionisable salts under the intense leaching environment of high rainfall and freely draining soils. Organic carbon content of the soils is generally high, especially in surface layers. Plantation systems of rubber and coffee with high biomass production and near zero tillage did not result in any significant decline in soil organic matter levels compared to forest soils. However, intercropped and tilled lands of coconut plantations have comparatively low levels of soil organic carbon. Soil organic carbon levels were highest in surface soils, but declined gradually with depth. Forest, coffee and rubber plantation soils had fairly high levels of organic carbon even to a depth of 50 cm below the surface (Fig. 2).

Soil reaction governs many chemical and biological properties of soil responsible for ensuring availability of plant nutrients, macro- and microbial abundance and activity, rate of decomposition of organic matter and accumulation or decomposition of toxic materials. The $pH_{(w)}$ of surface soils ranged from 4.08 to 6.0 with mean value of 5.30 and the $pH_{(Ca)}$ ranged from 4.04 to 5.6 with mean value of 4.64. Soil pH both in water and $CaCl_2$ declined considerably in subsoil layers with mean values falling to 5.0 and 4.4, respectively (Fig. 2). The pH values indicate very strong acid reaction of the soils.

The most commonly used measure of subsoil acidity is the estimate of exchangeable acidity (exch. H^+ and Al^{3+}) extracted with 1*N* KCl[27], in particular extractable Al, since aluminium toxicity is considered the most important plant-growth limiting factor in strongly acid soils. In highly weathered tropical soils, alumino-silicate minerals, both primary and secondary, and Al oxides (gibbsite) constitute a practically inexhaustible source of Al and their large specific surface area facilitates the formation of soluble and exchangeable Al. Since the Al in general exists in combination with hydroxyl, the solubility of Al in the compounds increase in proportion to H^+ ion concentration ($AlOH + H \rightarrow Al + H_2O$).

Exchangeable hydrogen was negligible in both surface soil and subsoil layers with mean values of 0.22 and 0.30 cmol (+) kg^{-1} soil. However, mean exchangeable aluminium in surface soil and subsoil was 0.56 and 1.12 cmol (+) kg^{-1} soil. Exchangeable Al was higher in the subsoil roughly corresponding to decline in pH, exchangeable bases and base saturation (table 2). Aluminium saturation of exchange complex increased in the subsoil layers with mean of 44 per cent (Fig.2).

Cation exchange capacity (CEC) of the surface soil layers ranged from 2.12 to 19.6 cmol (+) kg^{-1} soil with mean value of 11.21 cmol (+) kg^{-1} soil. In subsoils the CEC ranged from 2.08 to 16.76 cmol (+) kg^{-1} soil with mean value of 7.79 cmol (+) kg^{-1} soil. The low CEC of the soils is a consequence of the dominance of low activity clay mineral kaolinite. The relatively higher CEC in surface soils and a few immediate subsoil layers (table 2) is the contribution from organic colloids.

Calcium is the dominant basic cation on the exchange followed by magnesium and very little of potassium and sodium. Mean exchangeable Ca, Mg, K and Na of surface soils were 3.81, 1.07, 0.33 and 0.06 cmol (+) kg^{-1} soil respectively. The basic cations declined in the subsoil layers with mean values of 1.03, 0.57, 0.16 and 0.06 cmol (+) kg^{-1} soil for Ca, Mg, K, and Na, respectively. The mean base saturation as per cent of total exchange capacity for surface soils was 42 and for subsoils 25 (Fig.2).

Land use systems and soil acidity

For evaluating the intensity of surface soil and subsoil acidity the large data set comprising 29 SQMS for natural forests, 40 for coffee plantations, 100 for rubber plantations and 8 for coconut plantations was analysed. The variability in soil reaction, extractable aluminium, exchangeable calcium and magnesium, base saturation and aluminium saturation of soil exchange complex is presented in table 3. Plot of point data in a map of the study area (Fig. 1) presents the spatial patterns of the intensity of subsoil acidity, measured as extractable aluminium.

Discussion and conclusions

Significant differences were discernible in the nature and intensity of soil acidity and related soil qualities between the natural and managed land use systems investigated. They are discussed in detail for each land use system in the following sections.

Natural forests

The existence of lush evergreen forests in the highly weathered, base-depleted, impoverished soils of humid tropics rests on the very efficient recycling of plant nutrients by deep rooted trees, its preservation in the organic matter rich surface soils and rapid turnover by macro-and micro-organisms[28, 29]. The nutrients released by decomposition of organic matter is rapidly trapped and absorbed by the fine mat of roots of tropical plant species, against the downward movement with water. Generally, surface soils of natural forests in tropics are relatively rich in organic carbon, bases and are only mildly acid. The content of organic carbon and basic cations decreases down the soil profiles and the subsoils are often strongly acid and low in basic cations (Fig. 2 to 5). The analysis of data set of 29 soil profiles from forested lands in the study area returned mean surface soil $pH_{(w)}$ of 5.67 (range: 4.59 to 6.00) and subsoil $pH_{(w)}$ 5.50 (range: 3.60 to 6.70). The content of exchangeable bases (Ca, Mg, K and Na), sum of exchangeable bases, and base saturation were lower in subsoil (table 3 and Fig. 3). However, the exchangeable Al and Al saturation of exchange complex increased in the subsoil layers.

Coffee Land Use System

Coffee was introduced to India in 1670 and first large plantation was established in 1840 in Chickmagalur. At present, plantations cover 3,03,000 ha in Karnataka and Kerala together. Coffee is grown under shade in India. The plantations, mainly established in forested lands, involved clearing the undergrowth alone with most large trees retained. Except during the initial years, soil disturbance is minimal and zero tillage is practised in plantations. Despite the heavy input of acid-producing fertilizers, regular application of lime and dolomite has kept at bay the acidification of surface soils in the coffee plantations. However, carbonate liming materials have very little effect on subsoil acidity due to their very low solubility. The analysis of data set of 46 soil profiles from coffee plantations in the study area returned mean surface soil $pH_{(w)}$ of 5.86 (range: 4.74 to 7.51) and for subsoil $pH_{(w)}$ 5.50 (range: 4.3 to 7.2). The content of exchangeable bases, and exchangeable Al and Al saturation followed a trend similar to soils of natural forests.

Spatial pattern of subsoil acidity (Fig. 1) presented negligible variability in coffee plantations, except in a few instances. It is apparent that conversion of natural forests to managed coffee plantations did not result in any significant increase in subsoil acidity. The external inputs of plant nutrients and amelioration of acidity generated by acid-forming fertilisers by liming kept at bay the depletion of subsoil bases and acidification of surface soils and subsoils.

Rubber Land Use System

Rubber (*Hevea brasiliensis*) was introduced to south India in 1879 and the first commercial plantation was established in Thattekkad in Kerala. The initial plantations established till 1950's were on lands cleared from forests. However, the small holder plantations established thereafter were mainly on lands converted from other uses. Rubber plantations, unlike in the case of coffee, entailed complete clearance of forest or other plant species. For the entire life cycle of around 40 years, the plantations are monocrop of rubber, except for initial three years of the crop when annual crops like banana and pineapple are intercropped. Rubber plantations are essentially closed systems with external inputs limited to annual chemical fertilizer inputs and outgo, just around 2000 to 3000 kg of dry rubber. Zero tillage is the norm and there is practically no soil erosion from rubber plantations. The significant difference from coffee plantation management is the absence of liming to ameliorate the soil acidity. This stemmed from the strong belief that rubber is tolerant to acidity and Al.

The analysis of data set of 100 soil profiles from rubber plantations in the study area returned mean surface soil $pH_{(w)}$ of 5.11 (range: 4.16 to 6.50) and subsoil $pH_{(w)}$ 5.16 (range: 3.94 to 5.88) with surface soils strongly acid in reaction and subsoils extremely acid. The levels of organic carbon and exchangeable bases were lower in the subsoil soil layers. Al saturation was high in the subsoil layers. Conversion of forests or other cropped lands to rubber plantations resulted in strong acidification of soils and high levels of KCl-extractable Al, both in surface soils and subsoils. Strong acidification in surface soils and subsoils in rubber plantations is a consequence of external inputs of acid producing nitrogenous fertilizers and negation of liming and input of calcium and magnesium.

Coconut Land Use System

Small holder-coconut plantation is a major land-use system in midlands and coastal plains west of highland plateaus of Western Ghats. The plantations are either pure stands of palm, mixed with other perennials and annuals or in homesteads. The decline of agriculture as the primary means of livelihood in the region[30] has led to neglect of palms in small-holder coconut plantations. Agronomic management and external inputs of plant nutrients for the palm have practically ceased. So also the liming the acid soils. The observed strong acidification of soils (mean surface soil pH of 5.45 and mean subsoil pH of 5.53), low content of basic cations (mean total bases in surface soil 1.88 and 2.00 in subsoil) and high Al saturation of exchange complex (mean Al saturation 39 % surface soil and 21 % subsoil) is primarily due to neglect of liming for coconut and intercrops.

Spatial patterns in intensity of subsoil acidity

Classified data set on the intensity of subsoil Al saturation for all the SQMS, natural and managed land use systems, was plotted on a map of the study area (Fig. 1). The plot revealed significant regional variability of subsoil acidity. Subsoil Al in the Malanad region of Karanataka comprising Shimoga, Chickmagalur, Kodagu and Hassan districts was practically zero or very slight if at all. The area north of Ernakulam district to Udupi district and highlands of Wayanad plateau had a fair mix of soils with negligible, slight and strong subsoil acidity, with the last mentioned class mainly under rubber plantations. In the southern region comprising all districts south of Thrissur most observation points recorded strong subsoil aluminium saturation. It is worth mentioning here that in the south not only managed land use systems had strong subsoil acidity but also natural forests (Table 3 and Fig. 5). All the forest soils sampled south of Thrissur district in Kerala State (including Western Ghat High lands) were strongly acidic in both surface and subsoil acidity. The subsoil KCl-extractable aluminum often exceeded 0.5 cmol (+) kg^{-1} soil and Al saturation above 50 per cent for all land use systems in the southern region (Fig. 5).

Consequences of soil acidification

Acid soils are stressed environment for plant growth. They constrain plant growth by impairing plant availability of nutrients[31], microbial processes responsible for organic matter decomposition and nitrogen fixation[32-33], and activity of macro-fauna such as earthworms[34].

Subsoil acidity, in addition, is complicated by the presence of Al in soil solution and its effect on plant growth[35,36]. Al in surface soils seldom becomes toxic to plants due to its chelation by organic matter[37]. Al toxicity in subsoils results in root deformation and inhibits elongation of main axis and lateral roots[38-41]. Aluminium inhibits Ca and Mg uptake by blocking Ca+ channels in the plasma membrane[42] and by blocking sites of transport protein[43].

Net effect of root injury is inefficient uptake of nutrients and water. Plant roots do not proliferate into subsoil layers with high soluble aluminium. Inability of plants to absorb water from deeper soil layers becomes critical during the annual dry period of 3 to 6 months in the studied area.

Amelioration of soil acidity

Amelioration of soil acidity by liming is an important agronomic management for crop production all over the world. History of liming to ameliorate soil acidity dates back to the 19th century[44,45] and during 20th century liming of acid soils became a common practice and lime rate recommendations an integral part of soil-testing services. Acidity and Al toxicity in surface soil can be ameliorated through liming: incorporating liming materials such as ground lime stone (calcite: $CaCO_3$), burnt lime (CaO) or dolomite ($CaCO_3.MgCO_3$) into soil by tillage. Ca and Mg carbonates react with H^+ ions formed from hydrolysis of Al^{3+} and exchangeable aluminium[46].

The carbonates of Ca and Mg incorporated into surface soil, however, have little effect on subsoil acidity because of the low solubility of the materials and consequent low mobility[47]. Subsoil incorporation of lime by deep ploughing or using specialized equipment[48, 49] is not a feasible option, especially in plantations. Surface applied gypsum (a partially soluble salt) on the other hand moves down the soil in the leaching regime of humid environment and in the process increases labile Ca levels and decreases the Al in subsoil layers [9,10,47,50]. Ameliorative effect of gypsum is from one or more of the following mechanisms: (i) more labile calcium in subsoil (ii) formation of Al sulphates and precipitation[51] and (iii) "self liming" through ligand exchange of SO_4 for OH^+ on sesquioxides. The decrease in Al and corresponding increase in Ca in subsoil layers by gypsum treatment promote root penetration into subsoil layers and enable plants to extract nutrients and water previously beyond their reach. This is particularly advantageous in humid tropics with annual dry season.

Gypsum application rates around 5 tonnes per hectare have been found to be effective in Brazilian Oxisols. The residual effect of a single application was reported to be lasting for 4-6 years[52]. However, this rate was found insufficient for less intensively weathered, but equally acid, Ultisols of South Africa[53, 54]. Ultisols differ from Oxisols in containing greater absolute amounts of exchangeable Al and potentially active Al (Table 2) associated with mixed layer clay mineralogy[55]. Replenishment of Al^{3+} from this exchangeable source is responsible for the high lime and gypsum requirement of Ultisols, often in the range of 5 to 10 tonnes per hectare for lime and 10 to 15 tonnes per hectare for gypsum[53].

Conclusions

Soil acidity (both surface soil and subsoil) is pervasive in natural and managed land use systems of humid tropical southern India. In natural forest ecosystem, subsoil acidity is of serious concern only in land areas south of Thrissur district in Kerala. Tree plantations established in forests of this region can be affected by subsoil aluminium and deficiency of calcium and magnesium. The managed land use systems, however, have absolute requirement of regular amelioration of surface soil and subsoil acidity. The appropriate strategy for simultaneous amelioration of surface and subsoil acidity is incorporation of ground limestone and gypsum to surface soil. It is desirable to use dolomite limestone containing Ca and Mg as heavy loading of Ca through lime and gypsum inputs is likely to deplete surface soil reserve of Mg and affect plant growth. Again, for best plant effect in terms of biomass production and economic crop yields amelioration of soil acidity should be followed up with optimum plant nutrient inputs.

References

1. Von Uexkull, H. R. and E. Mutert, Global extent, development and economic impact of acid soils. *Plant and Soil,* 1995, **171**, 1-5.
2. Van Wambeke, A., Formation, distribution and consequences of acid soils in agricultural development. In: Proceedings of Workshop on Plant Adaptation to Mineral Stress in Problem Soils. Wright, M.J. and S.A. Ferrari (eds.) Spec. Publ. Cornell Univ., Agric. Exp. Stn., Ithaca, NY, 1976, pp.15-24.
3. Eswaran, H.,. Soil and site characterization for soil-based research network. In: Soil Management under humid conditions in Asia (ASIALAND). Bangok, IBSRAM, 1987, 169.
4. Maji, A. K., Obi Reddy, G. P. and Meshram, S., Acid soil map of India. Annual Report 2008. NBSS&LUP, Nagpur, India, 2008.

5. Hede, A. R., Skovmand, B. and Lopez-Cesati, J., Acid soil and aluminium activity toxicity, In: M.P. Reynolds, J.J. Ortiz-Monasterio, and A. Mchab (eds). Application of physiology in wheat breeding. International Maize and Wheat Improvement Center, 2001, pp. 172-182.
6. Rengel, Z., Uptake of aluminium by plant cells. *New Phytol*, 1996, **134**, 389-406.
7. Mora, M. L., Alfaro, M. A., Jarvis, S. S., Demanet, R. and Cartes, P., Soil aluminium availability in Andisols of Southern Chile and its effect on forage production and animal metabolism. *Soil Use and Management*., 2006, **22**, 95-101.
8. Adams, F., Soil Acidity and Liming. 2nd Edn., Am. Soc. Agron., *Crop Sci. Soc. Am. and Soil Sci. Soc. Am., Madison*, Wisconsin, USA, 1984.
9. Sumner, M. E., Aluminium toxicity – growth limiting factor in some Natal sands. *Proc. S. Afr. Su. Technol. Assoc*., 1970, **44**, 1-6.
10. Reeve, N.G., and M.E. Sumner, Amelioration of subsoil acidity in Natal Oxisols by leaching of surface applied amendments. *Agrochemophysica*, 2006, **4**, 1-6.
11. Clark, R. B., Physiological aspects of calcium, magnesium and molybdenum deficiencies in plants. In *Soil Acidity and liming*. F Adams (ed) Agron. Monograph, ASA, CSSA and SSSA, Madison, WI., 1984, **12**, 99.
12. Kumar Roy, A., Sharma, A. and Talukder, G., Some aspects of aluminium toxicity in plants. *Bot. Rev.*, 1988, **54**, 145-178.
13. Panda, S. K., Singha, L. B., Khan, M. H., Does aluminium phytotoxicity induce oxidative stress in greengram (Vigna radiata). *J. Plant Physiol*., 2003, **29**, 77 – 86.
14. Poschenrieder, C., Gunse, B., Corrales, I. and Barcelo, J., A glance into aluminium toxicity and resistance in plants. *Sci. Total Environ*., 2008, **400**, 356-368.
15. Fouche, P. S. and du Sautoy, N., Influence of surface applied lime and gypsum on subsoil acidity, extractable calcium and nutrient accumulation in Avacoado (*Persea Americana Mill.*), South African Avocado Grower's Association Yearbook, 1995, **18,** 12-16.
16. Blue, W. G. and Dantzman, C. L., Soil chemistry and root development in acid soils. *Soil Crop Sci. Fla. Proc*., 1976, **36**, 9-15.
17. Rechcigl, J. E., Reneau, R. R. JR. and Starner, D. E., Effect of subsurface amendments and irrigation on alfalfa growth. *Agron. J.*, 1985 a, **77**, 72-75.
18. Raji, B., Improving the root environment in the subsurface. In: Prochnow LI *et al*. (eds) Boas Practicas para USO Eficiente de Fertilizantes, International Plant Nutrition Institute (IPNI), 2010, pp. 349-382.

19. Nair, K.M., Anil Kumar, K.S., Srinivas, S., Sujatha, K., Venkatesh, D.H., Naidu, L.G.K., Dipak Sarkar and Rajasekharan, P., Agro-ecology of Kerala. NBSS Publ. 1038, National Bureau of Soil Survey and land Use Planning, Nagpur, India, 2011.

20. Anil Kumar, K.S., Nair, K.M., Ramesh Kumar, S.C., Srinivas, S., Ramamurthy, V., Sunil P. Maske, Jessy, M.D., Rajendra Hegde, James Jacob and S.K. Singh,· Soil Quality Monitoring Sites (SQMS) for Traditional Rubber-growing Areas of South India, NBSS Publ. No., National Bureau of Soil Survey and Land Use Planning, Nagpur, India, 2016.

21. Nair, K.M., Anil Kumar, K.S., Srinivas, S., Nagaraj, J.S., Violet D'Souza, M.,Raghuramulu,Y., Rajendra Hegde, and Singh, S.K., Soil Quality Monitoring Sites (SQMS) for Traditional Coffee-growing Areas of India, NBSS Publ. No., National Bureau of Soil Survey and Land Use Planning, Nagpur, India, 2016.

22. Soil survey Staff, Soil Taxonomy: *A Basic System of Soil classification for Making and Interpreting Soil Surveys*. Second Edition United States Department of Agriculture-National Resources Conservation Services, Agriculture Handbook, 436, US Government Printing Office, Washington DC, USA, 1999.
23. Jackson, M. L., *Soil chemical analysis*. Prentice Hall Of India (Pvt) Ltd., New Delhi, 1973.
24. Piper, C. S., *Soil and Plant Analysis*, Hans publishers, Bombay, India, 2002.
25. Sparks, *Methods of Soil Analysis Part-II: Chemical Methods*, Soil Sci. America, USA, 1996.
26. Chandran, P., Ray, S.K., Bhattacharyya, T., Srivastava, P, Krishnan, P. and pal, D.K., Laterite soils of Kerala, India: their mineralogy, genesis and taxonomy. *Australian Journal of Soil Research*, 2005, **43**, 839-852.
27. Sposito, G., The environmental chemistry of aluminum. Florida, CRC Press, Inc, 2000.
28. Herrera, R., Jordan, C.F., Klinge, H. and Medina, E., Amazon ecosystems. Thei structure and functioning with particular emphasis on nutrients. Intersciencia. 1978, **3(4)**, 223-231.
29. Herrera, R., Jordan, C.F., Medina, E. and Klinge, H., How human activities disturb nutrient cycles of a tropical rainforest in Amazonia. *Ambio.*, 1981, **10(2- 3)**, 109-114.

30. Kannan, K.P., Agricultural development in an emerging non-agrarian regional economy: Kerala's challenges. Economic and Political Weekly XLVI, 2011, **9**, 64-70.
31. Kemmit, S.J., D. Wright, K.W.T. Goulding, and D.L. Jones, pH regulation of carbon and nitrogen dynamics in two agricultural soils. *Soil Biol. Biochem*., 2006, **38**, 898-911.
32. Rousk, J., P.C. Brooks and E. Baath, Contrasting soil pH effects on fungal and bacterial growth suggest functional redundancy in carbon mineralization. *Appl. Envron. Microbiol*., 2009, **75 (6)**: 1589-1596.
33. Bru, D., A. Ramette, N.P.A. Saby, S. Dequidt, L. Ranjard, C. Jolivet, D. Arrouays. Determinants of the distribution of nitrogen-cycling microbial communities at the landscape scale. *The ISME Journal*, 2011, **5**, 532-542.
34. Lavelle, P., A. Chauvel and C. Fragoso. Faunal activity in acid soils. In. R.A. Date *et al*., (eds.) Plant Soil Interactions at Low pH. Kluwer Academic Publishers. The Netherlands, 1955, 201-211.
35. Adams, F., Nutrient importance and constraints in acid soils. *J. Plant Nutri*., 1981, **444**, 81-88.
36. Nair, K. M. and Chamuah, G. S., Exchangeable aluminium in soils of Meghalaya and management of Al^{3+} related productivity constraints. *J. Indian Soc. Soil Sci.*, 1993, **41**, 331-334.
37. Bloom, P. R., M.B. McBride, and R.M. Weaver, Aluminium organic matter interactions in acid soils: salt-extractable aluminiun. *Soil Sci. Soc. Amer. J.,* 1979, **43**, 813-815.
38. Koltz, F. and W.J. Hortz, Genotype differences in aluminium tolerance of soybean (*Glycine max. L.*) as affected by ammonium and nitrate nitrogen nutrition. J. Plant Physio., 1988,**132**, 702-707.
39. Foy, C.D., R.L. Chaney, and M.C. White, The physiology of metal toxicity in plants. *Ann. Rev. Plant Physio*., 1978, **29,** 511-566.
40. Foy, C.D., Physiological effects of hydrogen, aluminium and manganese toxicities in acid soil. In: Soil Acidity and Liming. Adams, F. (ed.) American Soc. of Agronomy, Inc., Madison, WI., 1984, pp. 57-97.
41. Marchner, H., Mechanisms of adaption of plants to acid soils. *Plant Soil*, 1991, **134,** 1-24.

42. Huang, J. W., J.E. Shaff, Grunes, D.L. and Kochian, L.V., Aluminium effects on calcium fluxes at the root apex of aluminium tolerant and aluminium sensitive wheat cultivars. *Plant physiology*, 1992, **98**, 230-237.
43. Rengel, Z. and D.L. Robinson, Aluminium effects on growth and macronutrient uptake by annual ryegrass. *Agron. J.*, 1989, **81,** 208-215.
44. Thomas, G.W., Historical developments in soil chemistry: Ion exchange. *Soil Sci. Soc. Am. J.*, 1977, **41**, 230-238.
45. Coleman, N.T., E.J. Kamprath and S. B. Weed, Liming. *Adv. Agron*., 1959, 475-522.
46. Thomas G.W. and Hargrove, The chemistry of soil acidity. In Soil Acidity and Liming. Adams. F. (ed) American Society of Agronomy Inc., Madison, WI., 1984, pp. 3-56.
47. Shainberg, I., M.E. Sumner, W.P. Miller, M.P.W. Farina, M.A. Pavan and M.V. Fey, Use of gypsum on soils: A review. *Adv. Soil Sci.*, 1989m, **9,** 1-111.
48. Farina, M.P.W. and P. Channon, Acid subsoil amelioration, 1. A comparison of several mechanical procedures. *Soil Sci. Soc. Am. J*., 1988, **52**, 169-175.
49. Jayawardane, N.S., H.D. Barrs, W.A. Muirhead, J. Blackwell, E. Murray, and G. Kirchof, Lime slotting technique to ameliorate subsoil acidity in clay soil: II Effect on medic root growth, water retention and yield. *Aust. J. Soil Res*., 1995, **33**, 443-459.
50. Richey, K.D., D.M.G. Souza, E. Lobato and O. Correa, Calcium leaching to increase rooting depth in Brazilian Savanna Oxisol. *Agron. J.*, 1980,**72**, 41-44.
51. Pavan, M.A., F.T. Bingham, and P.F. Pratt, Redistribution of exchangeable calcium, magnesium and aluminium following lime or gypsum application to Brazilian Oxisol. *J. Soil Sci. Soc. Am*., 1984, **48**, 33-38.
52. Ritchy, K.D., C.M. Feldhake, R.B. Clark, and D.M.G. Sousa, Improved water and nutrient uptake from subsurface layers of gypsum amended soils. In Agricultural utilization of urban and industrial by products. ASA Spec. Publ. 58. ASA, Madison, WI., 1995, pp.157-181.
53. Farina, M.P.W., Management of subsoil acidity in environments outside humid tropics. In A.C. Moniz et al (ed) Plant-soil interactions at low pH: Sustainable agriculture and forestry production. Brazilian Soil Sci. Soc., Campinas, Brazil, 1997, pp.179-190.

54. Farina, M.P.W., P. Channon, and G.R. Thibaud, A comparison of strategies for ameliorating subsoil acidity. I. Long term growth effects. *Soil Sci. Soc. Am. J.*, 2000, **64**, 646-651.
55. Juo, A.S.R. and E.J. Kamprath, Copper chloride as an extractant for estimating potentially reactive aluminium pools in acid soils. *Soil Sci. Soc. Am. J.*, 1979, **43**, 35.

Table 1. Locations and site characteristics of representative soils of four land use systems.

Pedon number	Districts	Latitude (N)	Longitude (E)	Slope (%)	Elevation above MSL (m)	Rainfall (mm)	Land use
P1	Chickmagalur	13° 21′ 35.1″	75° 25′ 28.0″	15-25	805	2500	Forest
P2	Ernakulam	10º 06' 32.5"	76º 29' 59.0"	1-3	25	3178	Forest
P3	Trivandrum	08º 25' 23.7"	77º 06' 37.7"	5-10	52	1658	Forest
P4	Chickmagalur	13º 22' 41.0"	75º 15' 53.1"	1-5	695	2500	Coffee
P5	Wayanad	11° 44′ 03.1″	75° 51′ 00.0″	15-25	779	3777	Coffee
P6	Idukki	09º 36' 43.8"	77º 08' 54.6"	10-15	909	4342	Coffee
P7	Udupi	13º 24' 23.6"	74º 46' 04.2"	3-5	38	3000	Rubber
P8	Wayanad	11º 04' 28.2"	75º 56' 54.3"	10-15	773	4182	Rubber
P9	Kottayam	09º 34' 34.4"	76º 34' 02.0"	10-15	30	3095	Rubber
P10	Kannur	12º 04' 55.2"	75º 15' 20.3"	1-3	24	3669	Coconut
P11	Alappuzha	09º 12' 49.7"	76º 31' 47.6"	1-3	1	2313	Coconut
P12	Kollam	08º 49' 33.6"	76º 44' 35.0"	3-5	15	2358	Coconut

Table 2: Physical and chemical properties of selected profiles

Depth (cm)	Hori-zon	Clay content	Textrl class	O.C., %	pH		Exchangeable bases					Extractable acidity			CEC, pH7	Base sat., % (CEC 7.0)	Al sat.,%
												1.0 *N*KCl		$BaCl_2$-TEA			
					(1:2.5) Water	(1:5) 0.01 *M* $CaCl_2$	Ca	Mg	K	Na	Tot.	H^+	Al^{3+}				
							cmol (+) kg^{-1} soil										
P1: Forest soils of Chickmagalur(CCRI/NBSS/P01): Fine, kaolinitic, Typic Paleustolls																	
0-11	A11	27.29	scl	4.40	6.0	5.6	8.76	3.85	0.50	0.04	13.16	0.45	0.00	16.20	15.03	88	0
11-31	Bt1	41.81	sc	2.10	6.0	5.3	3.96	1.94	0.37	0.06	6.33	0.38	0.00	11.30	9.00	70	0
31-54	Bt2	43.37	sc	1.21	6.0	5.3	2.54	1.88	0.28	0.05	4.74	0.33	0.00	9.80	6.39	74	0
54-78	Bt3	44.93	sc	0.58	5.9	5.2	1.74	1.93	0.22	0.04	3.94	0.43	0.00	6.68	4.50	87	0
78-97	Bt4	51.76	c	0.32	5.4	4.9	1.52	1.96	0.19	0.07	3.75	0.35	0.00	7.35	4.68	80	0
97-123	Bt5	50.47	c	0.26	5.5	5.1	1.76	1.89	0.21	0.05	3.91	0.40	0.00	7.35	4.77	82	0
P2: Forest soils of Ernakulam (RRII/NBSS/P110): Clayey, kaolinitic, Typic Kandiustults																	
0-15	A	27.81	scl	1.87	4.59	4.04	1.42	0.41	0.17	0.05	2.04	0.28	0.80	10.78	6.53	31	28
15-33	Bt1	50.75	c	0.72	4.63	4.08	0.55	0.26	0.14	0.05	1.00	0.35	1.43	14.21	6.34	16	59
33-61	Bt2	52.11	c	0.56	4.55	4.07	0.30	0.32	0.11	0.03	0.76	0.30	1.10	9.80	5.47	14	59
61-93	Bt3	53.34	c	0.40	4.70	4.19	0.17	0.59	0.08	0.04	0.88	0.18	0.55	8.33	5.28	17	38
93-128	Bt4	52.38	c	0.26	4.87	4.24	0.13	0.60	0.10	0.05	0.89	0.15	0.38	7.84	5.57	16	30
P3: Forest soils of Trivendrum(RRII/NBSS/P114): Loamy, kaolinitic, Typic Kandiustults																	
0-19	A	22.32	scl	1.18	5.18	4.64	0.77	0.43	0.19	0.01	1.41	0.18	0.00	3.92	2.88	49	0
19-38	AB	19.91	sl	0.67	4.56	3.91	0.19	0.17	0.07	0.01	0.43	0.38	0.85	3.92	3.46	12	66
38-59	Bt1	25.08	scl	0.35	4.57	3.90	0.18	0.15	0.06	0.01	0.40	0.25	0.90	5.39	3.26	12	69
59-80	Bt2	33.93	scl	0.35	4.66	3.95	0.40	0.20	0.09	0.02	0.71	0.33	1.10	4.90	4.13	17	61
80-107	Bt3	46.40	c	0.31	4.67	3.90	0.10	0.28	0.09	0.02	0.48	0.30	1.53	5.88	3.94	12	76
P4: Coffee growing soils of Chickmagalur(CCRI/NBSS/04) (Malanad): Clayey, Kaolinitic, Ustic Palehumults																	
0-11	Ap	42.36	c	3.77	5.60	5.20	11.48	2.96	0.49	0.05	14.98	0.15	0.00	17.50	16.02	94	0
11-28	Bt1	50.11	c	2.30	5.80	5.60	5.77	2.71	0.43	0.07	8.98	0.15	0.00	15.00	12.42	72	0
28-49	Bt2	54.79	c	1.29	5.20	4.80	2.65	1.80	0.32	0.03	4.80	0.35	0.33	14.50	9.99	48	6
49-90	Bt3	62.23	c	0.76	5.00	4.40	1.37	1.40	0.20	0.03	3.01	0.53	1.48	15.50	9.45	32	33
90-132	Bt4	61.67	c	0.74	4.90	4.40	1.12	1.30	0.15	0.04	2.61	0.58	1.65	15.00	9.72	27	39

Continued………

Depth (cm)	Hori-zon	Clay content	Textrl class	O.C., %	pH (1:2.5) Water	pH (1:5) 0.01 *M* $CaCl_2$	Exchangeable bases Ca	Mg	K	Na	Tot.	Extractable acidity 1.0 *N*KCl H^+	Al^{3+}	$BaCl_2$-TEA	CEC, pH7	Base sat., % (CEC 7.0)	Al sat.,%
								cmol (+) kg^{-1} soil									
P5: Coffee growing soils of Wayanad(CCRI/NBSS/P28): Clayey, kaolinitic, Ustic Haplohumults																	
0-20	Ap	42.41	c	2.44	5.5	4.8	3.55	0.50	0.32	0.04	4.40	0.29	0.58	9.50	14.36	31	11.56
20-52	Bt1	52.55	c	1.96	5.4	4.6	2.33	0.41	0.19	0.07	3.00	0.27	0.95	7.35	11.74	26	24.06
52-84	Bt2	53.23	c	1.52	5.1	4.4	1.88	0.27	0.12	0.05	2.32	0.29	2.38	13.50	9.85	24	50.59
84-120	Bt3	49.89	c	1.07	5.0	4.4	1.70	0.23	0.12	0.05	1.24	0.26	1.93	17.50	7.95	16	60.82
P6: Coffee growing soils of Idukki (CCRI/NBSS/46): Clayey, mixed, Ustic Palehumults																	
0-20	Ap	39.16	cl	3.17	5.20	4.40	7.76	1.37	0.87	0.10	10.10	0.29	0.58	20.10	19.60	52	5
20-32	Bt1	47.50	c	2.47	4.30	3.90	2.30	0.72	0.78	0.19	3.99	0.63	4.01	24.50	16.76	24	50
32-54	Bt2	45.44	c	1.97	4.60	3.80	1.03	0.30	0.60	0.11	2.04	0.45	3.88	20.60	13.03	16	66
54-83	Bt3	46.82	c	1.02	4.40	4.00	0.48	0.22	0.24	0.02	0.96	0.44	3.43	15.20	11.17	9	78
83-109	Bt4	43.80	c	0.65	4.50	4.10	0.48	0.27	0.39	0.09	1.22	0.39	3.50	12.70	12.05	10	74
P7: Rubber growing soils of Udupi (RRII/NBSS/P13): Clayey, kaolinitic, Typic Kanhaplustults																	
0-10	Ap	41.16	c	3.25	5.73	5.14	3.99	1.92	0.35	0.09	6.35	0.11	0.00	27.00	12.20	52	0
10-38	Bt1	54.00	c	0.71	5.25	4.51	0.55	0.60	0.05	0.07	1.26	0.33	0.00	23.00	8.00	16	0
38-59	Bt2	54.68	c	0.37	5.21	4.41	0.25	0.44	0.02	0.05	0.76	0.44	0.02	21.00	6.40	12	3
59-79	Bt3	55.74	c	0.32	5.16	4.34	0.10	0.36	0.02	0.05	0.53	0.33	0.44	17.00	6.30	8	45
79-113	Bt4	42.20	c	0.21	5.22	4.34	0.06	0.36	0.03	0.04	0.49	0.25	0.56	21.00	6.20	8	54
P8: Rubber growing soils of Wayanad (RRII/NBSS/P34): Clayey, kaolinitic, Ustic Palehumults																	
0-23	Ap	59.61	c	3.24	5.54	4.65	4.29	0.40	0.62	0.09	5.41	0.04	0.44	19.00	17.30	31	8
23-44	Bt1	63.41	c	2.92	4.83	4.19	0.73	0.12	0.20	0.07	1.12	0.05	2.11	26.00	16.19	7	65
44-67	Bt2	63.14	c	1.50	4.90	4.20	0.57	0.14	0.20	0.09	1.00	0.03	1.67	22.00	12.33	8	63
67-96	Bt3	69.97	c	0.97	4.88	4.27	0.40	0.11	0.32	0.01	0.84	0.19	1.13	22.00	11.68	7	57
96-139	Bt4	72.41	c	0.78	4.83	4.27	0.14	0.08	0.37	0.07	0.66	0.15	0.29	23.00	11.59	6	30
P9: Rubber growing soils of Kottayam (RRII/NBSS/P40): Clayey, kaolinitic, Ustic Kanhaplohumults																	
0-12	Ap	41.92	c	5.19	4.08	4.05	0.11	0.10	0.22	0.06	0.48	0.02	2.62	20.00	13.50	4	85
12-31	Bt1	58.91	c	2.66	4.30	4.16	0.02	0.08	0.10	0.06	0.26	0.02	2.35	17.00	12.42	2	90
31-52	Bt2	55.99	c	1.40	4.38	4.12	0.09	0.08	0.07	0.04	0.27	0.07	2.08	15.00	8.37	3	89
52-73	Bt3	51.07	c	1.01	4.38	4.12	0.03	0.06	0.05	0.01	0.14	0.04	2.01	14.00	7.73	2	93
73-95	Bt4	54.85	c	0.77	4.38	4.07	0.18	0.04	0.07	0.09	0.37	0.09	1.96	13.00	6.99	5	84
95-118	BC	49.82	c	0.56	4.36	4.09	0.11	0.05	0.01	0.03	0.19	0.13	1.57	17.00	6.16	3	90

Continued……

Depth (cm)	Hori-zon	Clay content	Textrl class	O.C., %	pH		Exchangeable bases					Extractable acidity			CEC, pH7	Base sat., % (CEC 7.0)	Al sat.,%
												1.0 *N*KCl		$BaCl_2$-TEA			
					(1:2.5) Water	(1:5) 0.01 *M* $CaCl_2$	Ca	Mg	K	Na	Tot.	H^+	Al^{3+}				
							cmol (+) kg^{-1} soil										
P10: Coconut growing soils of Kannur (Coco-P02): Clayey-skeletal, Kaolinitic, Plinthic Palehumults																	
0-20	Ap	30.36	scl	2.09	5.48	4.48	2.80	0.65	0.18	0.06	3.70	0.15	0.63	18.50	11.13	33	14
21-46	Bt1	40.56	c	1.26	5.41	4.38	1.42	0.22	0.10	0.04	1.79	0.33	1.15	17.50	9.84	18	39
47-71	Bt2	51.68	c	0.99	5.38	4.36	1.58	0.14	0.09	0.05	1.85	0.25	1.45	16.50	10.30	18	44
72-103	Bt3	50.49	c	0.78	5.41	4.35	1.27	0.15	0.08	0.04	1.54	0.28	1.23	16.00	9.48	16	44
P11: Coconut growing soils of Alappuzha (Coco-P07): Mixed, Aquic Ustipsamments																	
0-17	Ap	3.48	s	0.32	5.55	4.40	0.47	0.10	0.03	0.03	0.63	0.43	0.10	5.00	2.12	30	14
18-36	AC	4.08	s	0.29	5.46	4.46	0.44	0.09	0.02	0.04	0.59	0.38	0.30	7.00	2.08	28	34
37-62	C1	2.91	s	0.32	5.43	4.41	0.13	0.01	0.02	0.04	0.19	0.33	0.45	4.00	2.12	9	70
63-95	C2	2.93	s	0.67	5.42	4.49	0.07	0.00	0.01	0.04	0.11	0.35	0.53	8.00	2.39	5	82
P12: Coconut growing soils of Kollam (Coco-P05) Fine-loamy, kaolinitic, Typic Plinthustults																	
0-22	Ap	20.75	scl	0.70	5.18	4.26	0.29	0.11	0.02	0.04	0.46	0.25	1.00	9.00	3.86	12	69
23-40	Bt1	33.93	scl	0.55	5.19	4.39	0.67	0.17	0.05	0.05	0.94	0.30	0.80	8.50	4.60	20	46
41-66	Bt2	33.26	scl	0.54	5.02	4.28	0.60	0.15	0.07	0.08	0.90	0.38	0.93	9.00	5.06	18	51
67-102	Bt3	33.82	scl	0.37	5.28	4.38	0.53	0.13	0.04	0.30	0.99	0.15	0.65	9.50	4.32	23	40

Table 3. Mean values and range of soil acidity, exchangeable bases, extractable aluminium, basic cation and aluminium saturation in different land use systems

Soil Layer	Forest			Coffee			Rubber			Coconut		
	Mean	Range		Mean	Range		Mean	Range		Mean	Range	
		Min	Max		Min	Max		Min	Max		Min	Max
$pH_{(w)}$												
Surface soil	5.67	4.59	6.00	5.86	4.74	7.51	5.11	4.16	6.50	5.45	4.66	6.40
Sub soils	5.50	3.60	6.70	5.50	4.30	7.20	5.16	3.94	5.88	5.53	4.88	6.00
$pH_{(Ca)}$												
Surface soil	5.08	4.04	6.00	5.43	4.27	7.02	4.53	3.88	6.02	4.62	4.14	5.80
Sub soils	4.70	3.60	5.80	5.10	3.80	6.40	4.88	3.94	5.88	4.70	4.28	6.0
O.C., %												
Surface soil	3.13	1.18	8.75	2.63	1.05	4.57	2.95	0.99	5.63	1.27	0.70	2.09
Sub soils	0.85	0.15	4.08	0.85	0.07	3.94	1.02	0.02	4.18	0.67	0.33	1.4
Exchangeable Calcium, cmol (+) kg^{-1} soil												
Surface soil	5.76	0.34	27.20	7.74	1.66	16.25	2.27	0.00	13.55	1.48	0.29	3.00
Sub soils	2.15	0.08	17.73	3.43	0.14	17.87	1.31	0.01	7.62	1.49	0.31	3.00
Exchangeable Magnesium, cmol (+) kg^{-1} soil												
Surface soil	2.61	0.37	4.67	1.44	0.12	7.01	0.86	0.01	5.27	0.40	0.11	1.00
Sub soils	1.39	0.08	4.71	1.28	0.05	15.74	0.65	0.00	6.76	0.51	0.11	1.20
KCl extractable Al., cmol (+) kg^{-1} soil												
Surface soil	0.19	0.00	1.08	0.09	0.00	0.58	0.79	0.00	2.62	0.86	0.00	1.90
Sub soils	0.62	0.00	13.43	0.36	0.00	4.01	0.62	0.00	2.79	0.46	0.00	1.45
BS, % (CEC 7)												
Surface soil	61	5	100	71	29	100	30	2	100	33	11	98
Sub soils	41	5	100	52	6	100	26	1	100	43	11	98
Al. Saturation, %												
Surface soil	4	0	28	2	14	0	32	0	91	39	0	69
Sub soils	21	0	91	11	0	78	33	0	94	21	0	52

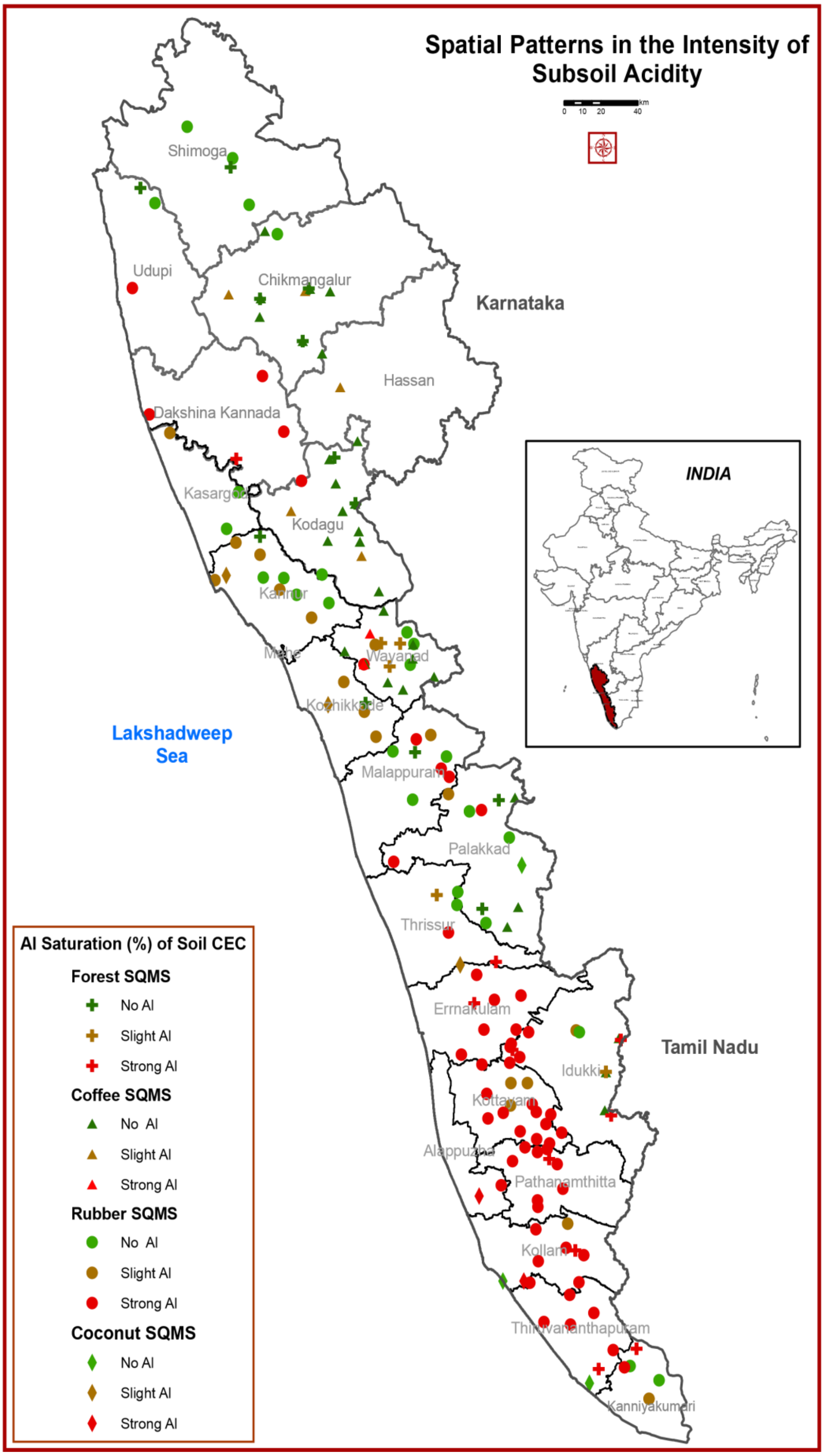

Fig. 1. Study area, SQMS and intensity of Al saturation of cation exchange capacity of soils (slight: <50%; Strong: >50% saturation)

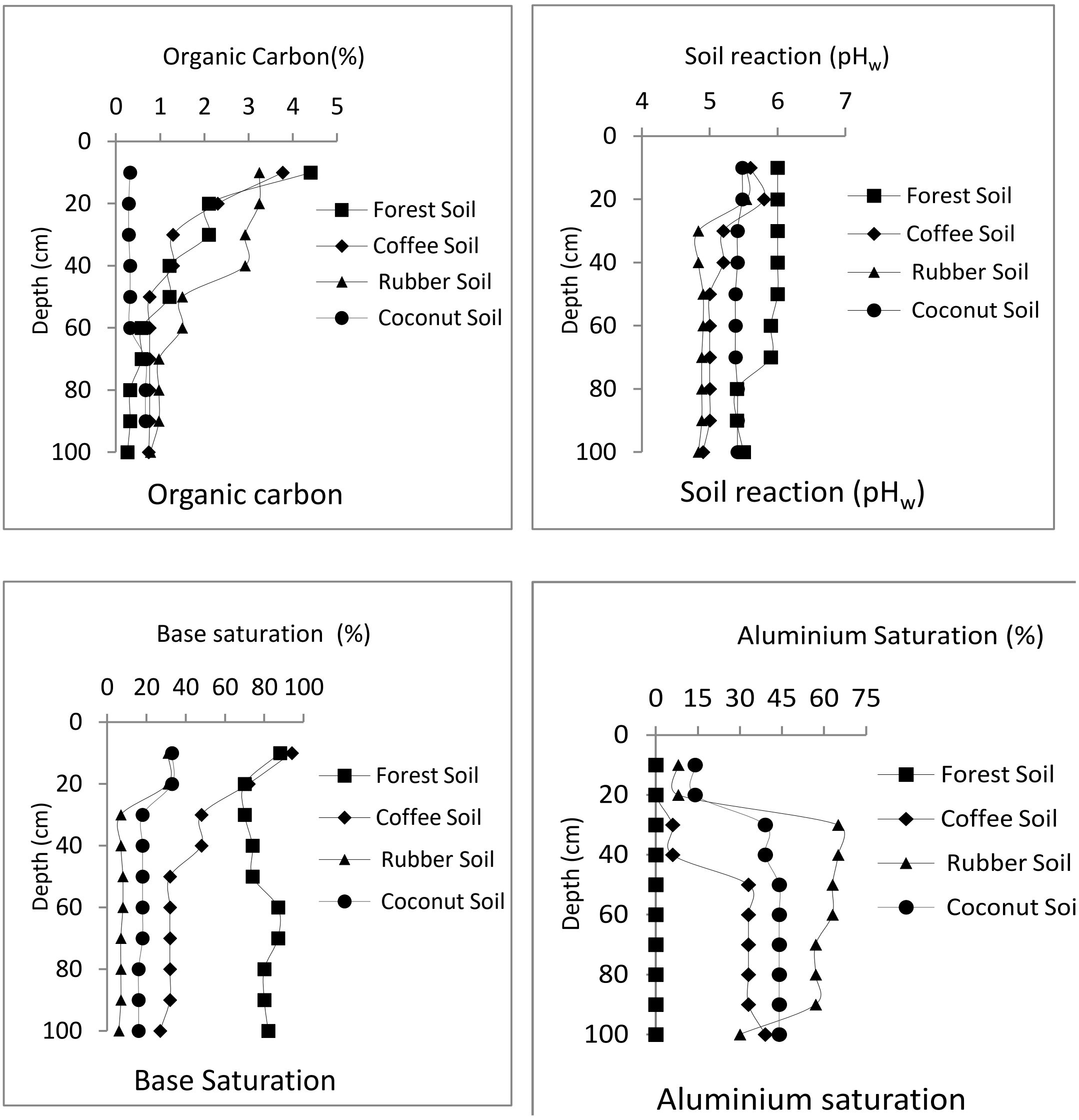

Fig. 2. Depth-wise distribution of soil properties in natural and managed land use systems.

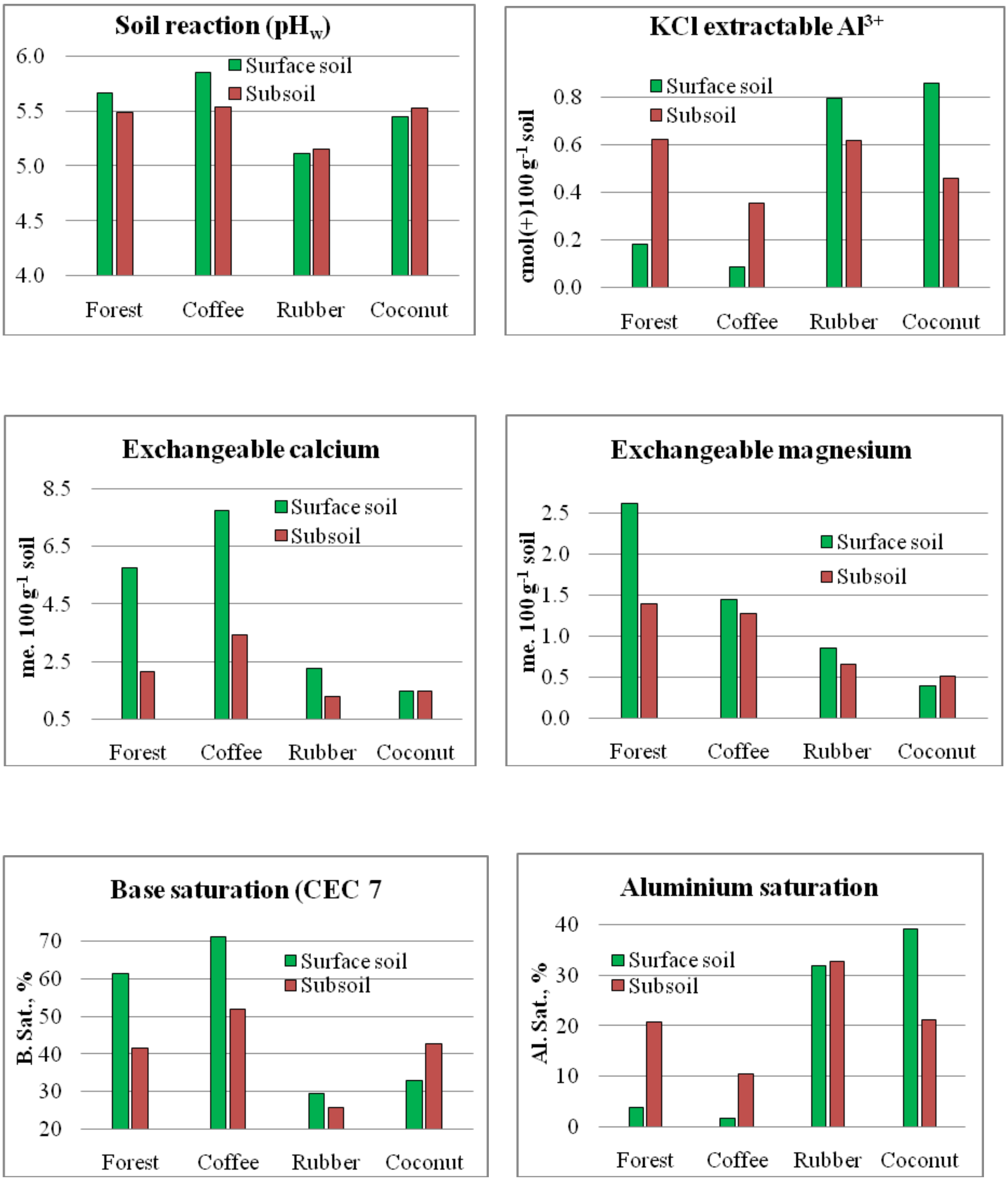

Fig. 3: Variability of soil pH, extr. Al, exch. Ca and Mg, base saturation and Al saturation in natural and managed land use systems of South India.

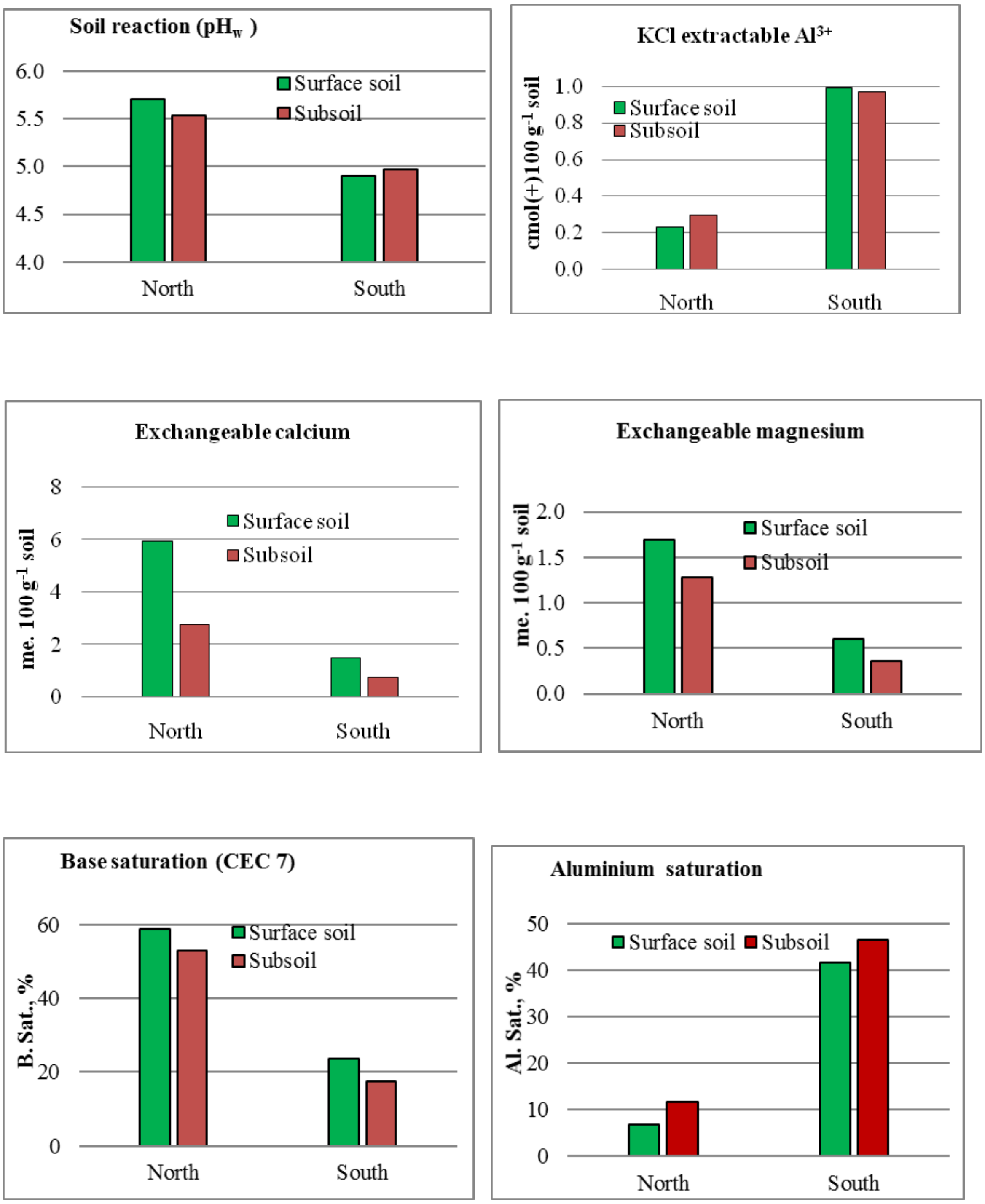

Fig. 4: Regional variability of soil pH, extr. Al, exch. Ca and Mg, base saturation and Al saturation

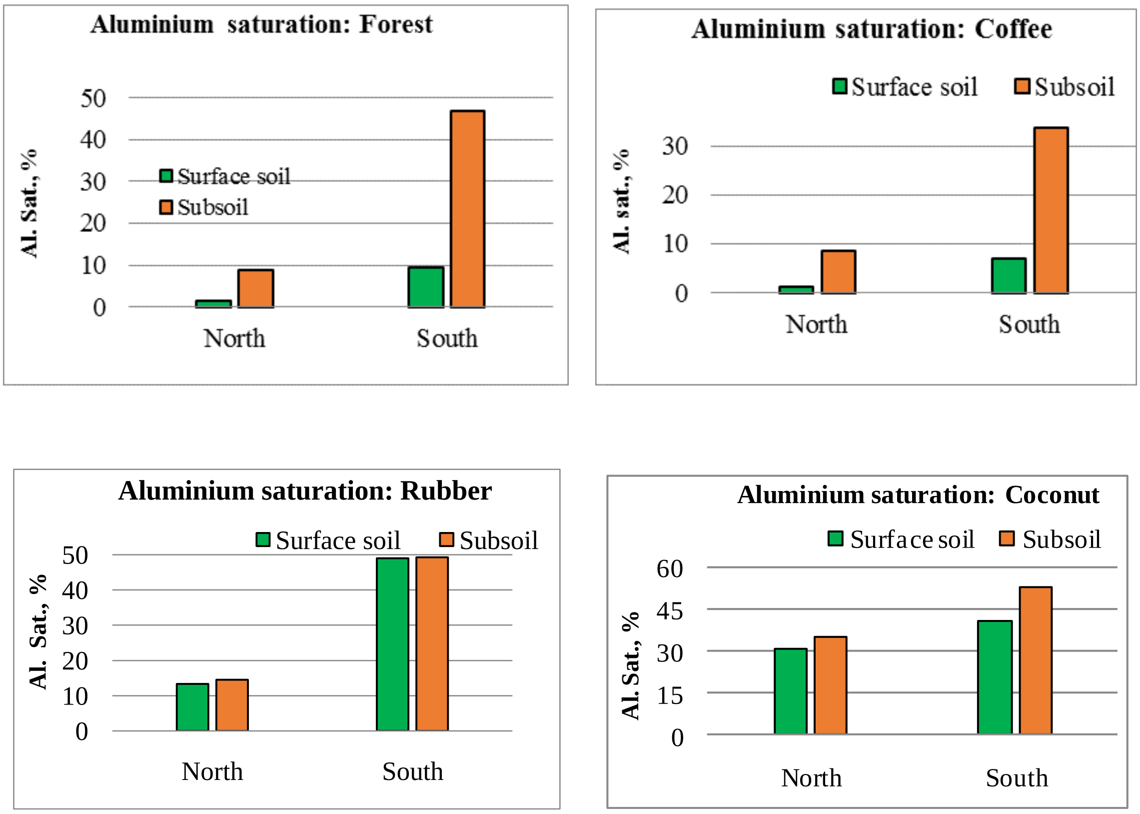

Fig. 5: Mean aluminium saturation surface and subsoils in natural and managed land use systems of northern and southern regions in the study area.