Surface soil and subsoil acidity in natural and managed land-use systems in the humid tropics of Peninsular India

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Natural forests and managed plantations constitute the largest land-use systems in the humid tropics of southwestern parts of Peninsular India comprising the Western Ghats and coastal plain. Soils therein are naturally acidic 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 was 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 studied, soils under natural forests and coffee plantations were only slightly acidic in surface soil and subsoil, whereas rubber- and coconut-growing soils were strongly acidic. Both natural and managed land-use systems, however, had strongly acid reaction in surface soil and subsoil in southern Kerala. Biomass production and crop yield are constrained in strongly acid soil by toxic levels of aluminium (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% or Al saturation more than 50%). Surface soil acidity can be ameliorated by incorporating liming materials into surface soils. In case of subsoil acidity gypsum too should be incorporated. Under humid climate partial solubility of gypsum permits movement of calcium into the subsoil layers, wherein calcium replaces the aluminium on exchange complex and sulphate radical precipitates the aluminium by formation of aluminium sulphate.

Keywords: Base saturation, humid tropics, land-use systems, surface soil and subsoil acidity.

GLOBALLY acid soils cover large areas in the cold, humid northern belt and the hot, humid tropics[1]. Soils in around 30% of the world's arable lands are acidic[1–3]. In India, 30% of the total cultivable area has acid soil, mainly distributed in the humid regions of southwestern and northeastern parts of the country and in the Himalayas[4]. Soils of the humid tropics are naturally acidic, 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 them. Poor soil fertility and productivity of acid soils is due to a 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 are well known for several centuries[8]. Recognition of subsoil acidity and its consequences, however, is quite recent, dating back to 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 causes 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].

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This article discusses surface and subsoil acidity with a focus on natural and managed land-use systems of tropical, hot, humid region of southwestern India, as well as the possible consequences of soil acidity on crop production.

Materials and methods

Southwestern Peninsular India comprising the Western Ghats and western coastal plain in the states of Tamil Nadu, Kerala and Karnataka (Figure 1) experiences 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 examination.

Horizon-wise soil samples were analysed for physical and chemical properties following standard procedures. Soils were classified according to the 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 (ref. 23) followed by titration with standard alkali. Base saturation and aluminium saturation were calculated as follows:

$$\text{Base saturation (\%)} = (\text{Total bases/CEC}) \times 100,$$

$$\text{Aluminium saturation (\%)} = [\text{extracted Al}/(\text{exchangeable Ca} + \text{Mg} + \text{K} + \text{Na} + \text{extracted Al})] \times 100,$$

where exchange Ca, Mg, K, Na, total bases, CEC and extractable Al are in c mol (+) kg^{-1} soil.

From among the large dataset (183 SQMS) soil analytical data pertaining to 12 SQMS representing the four land-use systems are presented to describe soil quality in the study area and surface soil and subsoil acidity (Tables 1 and 2). The entire data on SQMs for the four land-use systems were used for assessing the variability of soil acidity across these systems as well as spatial variability.

Results and discussion

Soil quality in the study area

Soils of the study area, formed under humid tropical climate, are deeply weathered, leached and depleted of bases. These low-activity clay soils are deep, well-drained, strongly acidic, 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). Classification of the soil into different taxa at the family level reflects 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]. Table 2 presents the physical and chemical properties of the soils.

The texture of the soil is generally loam in surface layers and clay in subsoil layers due to illuviation of clay

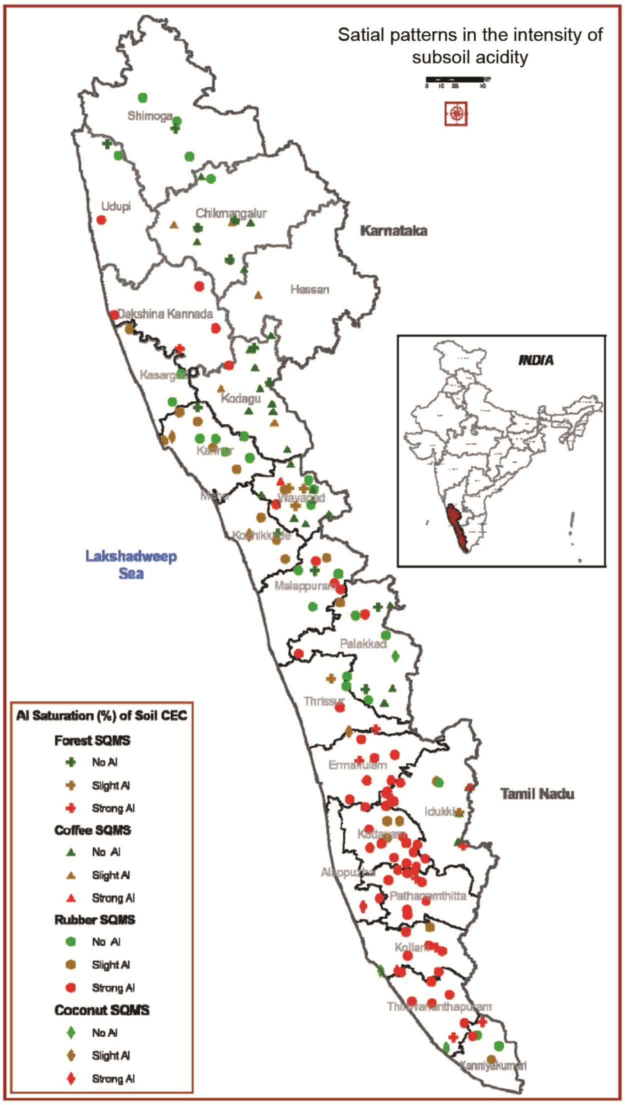

Figure 1. Study area, soil-quality monitoring sites (183 pedon locations) and intensity of Al saturation of cation exchange capacity of soils (slight: <50%; strong: >50% saturation).

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

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

into subsoil layers. Soil structure is weak subangular blocky in surface layers and moderate to strong subangular blocky in subsoil layers. Varying proportions of gravel and plinthite are found in the laterite soils of the study area, except in the soils of highland plateau and Malnad region (hilly terrain of Karnataka, east of the Western Ghats).

Electrical conductivity was extremely low in surface soils and subsoils (0.01–0.64 dS m^{-1}), indicating negligible level of ionizable salts under the intense leaching environment of high rainfall and freely draining soils. Organic carbon content of the soils was generally high, especially in the 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 level compared to forest soils. However, intercropped and tilled lands of coconut plantations had 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 at a depth of 50 cm below the surface (Figure 2).

Soil reaction governs many of its chemical and biological properties 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 a mean value of 5.30 and $pH_{(Ca)}$ 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 (Figure 2). The pH values indicate very strong acidic reaction of the soils.

The most commonly used measure of subsoil acidity is the estimation of exchangeable acidity (exch. H^+ and Al^{3+}) extracted with 1 N KCl (ref. 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 Al in general exists in combination with hydroxyl, the solubility of Al in the compounds increases 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 respectively. However, mean exchangeable aluminium in surface soil and subsoil was 0.56 and 1.12 cmol (+) kg^{-1} soil respectively. 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 a mean of 44% (Figure 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 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 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 a 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 was 3.81, 1.07, 0.33 and 0.06 cmol (+) kg^{-1} soil respectively. The basic cations declined in the subsoil layers with mean value 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 (Figure 2).

Land-use systems and soil acidity

To evaluate the intensity of surface soil and subsoil acidity, the large dataset comprising 29 SQMS for natural forests,

Table 2. Physical and chemical properties of selected profiles

Depth (cm)	Horizon	Clay content	Textrl class	OC (%)	pH (1 : 2.5) Water	pH (1 : 5) 0.01 M $CaCl_2$	Exchangeable bases Ca	Mg	K	Na	Tot.	Extractable acidity 1.0 NKCl H^+	Al^{3+}	$BaCl_2$–TEA	CEC, pH 7	Base sat. (%) (CEC 7.0)	Al sat. (%)
							cmol (+) kg^{-1} soil										
P1: Forest soils of Chikmagalur (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 Thiruvananthapuram (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 Chikmagalur (CCRI/NBSS/04) (Malnad): 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
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

(*Contd*)

Table 2. (*Contd*)

Depth (cm)	Horizon	Clay content	Textrl class	OC (%)	pH (1 : 2.5) Water	pH (1 : 5) 0.01 M $CaCl_2$	Ca	Mg	K	Na	Tot.	1.0 NKCl H^+	1.0 NKCl Al^{3+}	$BaCl_2$–TEA	CEC, pH 7	Base sat. (%) (CEC 7.0)	Al sat. (%)
							cmol (+) kg^{-1} soil										
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
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

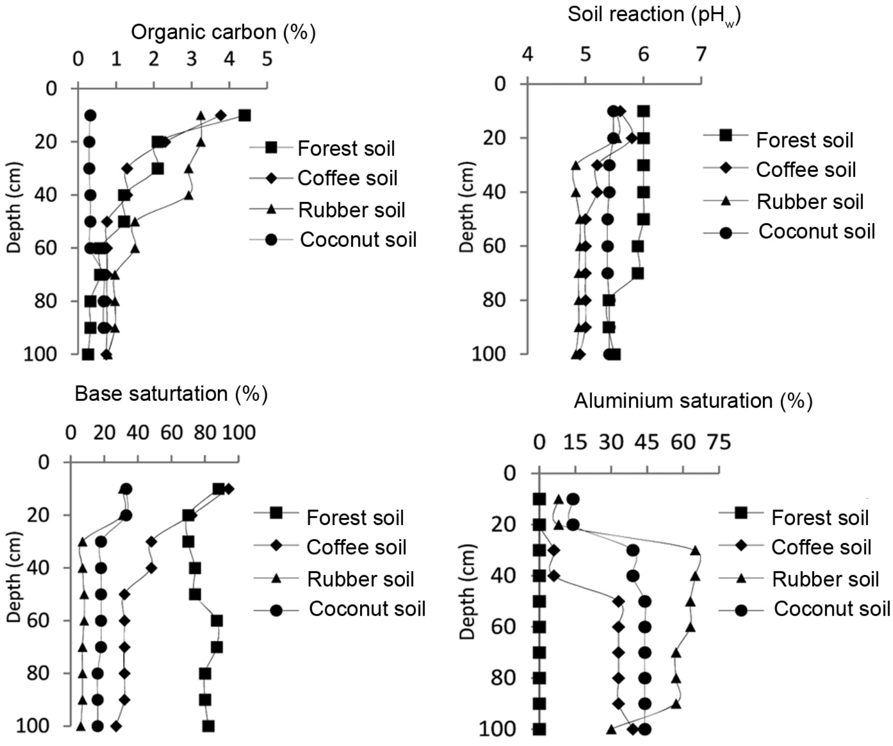

Figure 2. Depth-wise distribution of soil properties in natural and managed land-use systems.

40 for coffee plantations, 100 for rubber plantations and 8 for coconut plantations was analysed. Table 3 presents variability in soil reaction, extractable aluminium, exchangeable calcium and magnesium, base saturation and aluminium saturation of soil exchange complex. Plot of point data in a map of the study area (Figure 1) presents the spatial patterns of intensity of subsoil acidity, measured as extractable aluminium.

Significant differences were discernible in the nature and intensity of soil acidity and related soil quality between the natural and managed land-use systems examined. 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 the humid tropics is due to the efficient recycling of plant nutrients by deep-rooted trees, their 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 are 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 the tropics are relatively rich in organic carbon, bases and are only mildly acidic. The content of organic carbon and basic cations decreases down the soil profiles and the subsoils are often strongly acidic and low in basic cations (Figures 2–5). Analysis of the dataset of 29 soil profiles from forest lands in the study area provided mean surface soil $pH_{(w)}$ of 5.67 (range: 4.59–6.00) and subsoil $pH_{(w)}$ of 5.50 (range: 3.60–6.70). The content of exchangeable bases (Ca, Mg, K and Na), sum of exchangeable bases and base saturation were lower in the subsoil (Table 3 and Figure 3). However, 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 the first large plantation was established in 1840 in Chikmagalur. At present, plantations cover 303,000 ha in Karnataka and Kerala together. Coffee is grown under shade in India. The plantations, mainly established in forested lands, involve 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 prevented the acidification of surface soils in coffee plantations. However, carbonate liming materials have very little effect on subsoil acidity due to their very low solubility. Analysis of the dataset of 46 soil profiles from coffee plantations in the study area provided mean

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

	Forest			Coffee			Rubber			Coconut		
		Range			Range			Range			Range	
Soil layer	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum
$pH_{(w)}$												
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
Subsoil	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
Subsoil	4.70	3.60	5.80	5.10	3.80	6.40	4.88	3.94	5.88	4.70	4.28	6.0
OC (%)												
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
Subsoil	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
Subsoil	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
Subsoil	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
Subsoil	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
Subsoil	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
Subsoil	21	0	91	11	0	78	33	0	94	21	0	52

surface soil $pH_{(w)}$ of 5.86 (range: 4.74–7.51) and subsoil $pH_{(w)}$ of 5.50 (range: 4.3–7.2). 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 (Figure 1) showed 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 fertilizers by liming prevented 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, Kerala. The initial plantations established till 1950s 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 monocrops 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 of 750 kg and outgo of around 2000–3000 kg per hectare 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 soil acidity. This stems from the strong belief that rubber is tolerant to acidity and Al.

Analysis of the dataset of 100 soil profiles from rubber plantations in the study area provided mean surface soil $pH_{(w)}$ of 5.11 (range: 4.16–6.50) and subsoil $pH_{(w)}$ of 5.16 (range: 3.94–5.88) with surface soils strongly acidic in reaction and subsoils extremely acidic. The levels of organic carbon and exchangeable bases were lower in the subsoil layers. Al saturation was also high in the subsoil layers. Conversion of forests or other cropped lands to rubber plantations resulted in strong acidification of soils

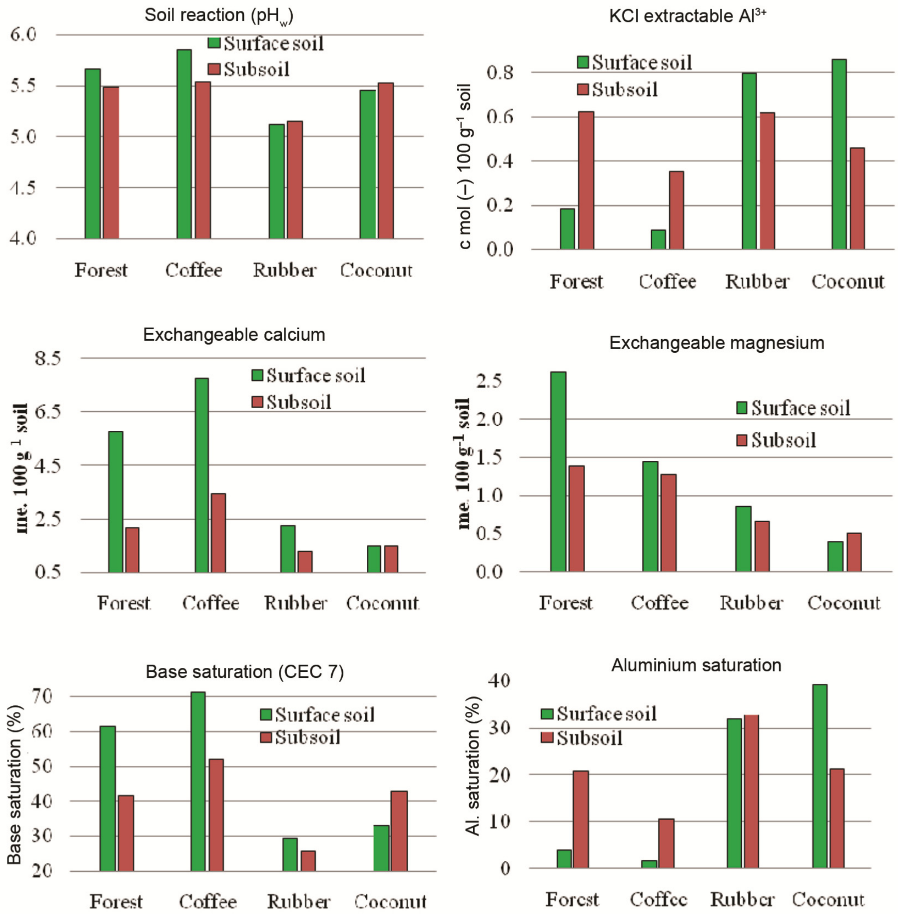

Figure 3. Variability of soil pH, extractable Al, exchange Ca and Mg, base saturation and Al saturation in natural and managed land-use systems of South India.

and high levels of KCl-extractable Al, both in surface soil and subsoil. Strong acidification in surface soil and subsoil in rubber plantations is a consequence of external inputs of acid-producing nitrogenous fertilizers, and no liming and no calcium and magnesium inputs.

Coconut land-use system

Small-holder coconut plantation is a major land-use system in the midlands and coastal plains west of highland plateaus of the Western Ghats. The plantations are 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 has led to neglect of palms in small-holder coconut plantations[30]. Agronomic management and external inputs of plant nutrients for the palm have practically ceased. So also the liming of 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 in subsoil 2.00) and high Al saturation of exchange complex (mean Al saturation of 39% in surface soil and 21% in subsoil) are primarily due to lack of liming for coconut and intercrops.

Spatial patterns in intensity of subsoil acidity

Classified dataset 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 (Figure 1). The plot revealed significant regional variability of subsoil acidity. Subsoil Al in the Malnad region of Karanataka comprising Shimoga, Chikmagalur, 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 Figure 5). All the forest soils sampled south of Thrissur district,

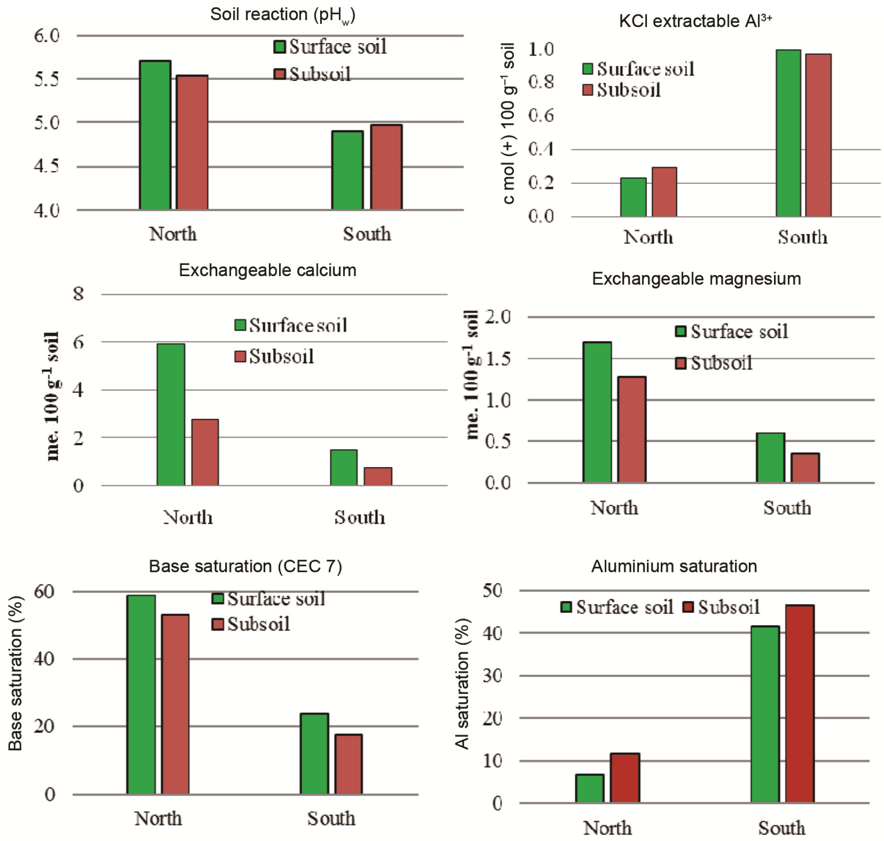

Figure 4. Regional variability of soil pH, extractable Al, exchange Ca and Mg, base saturation and Al saturation.

Kerala (including the Western Ghats highlands) were strongly acidic for both surface soil and subsoil. The subsoil KCl-extractable aluminum often exceeded 0.5 cmol (+) kg^{-1} soil and Al saturation was above 50% for all land-use systems in the southern region (Figure 5).

Consequences of soil acidification

Acid soils are stressed environment for plant growth. They constrain plant growth by impairing the 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 3–6 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]. During the 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 limestone (calcite: $CaCO_3$), burnt lime (CaO) or dolomite ($CaCO_3 \cdot MgCO_3$) 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 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. On the other hand surface-applied gypsum (a partially soluble salt) moves down the soil in the leaching regime of humid environment, and in the process increases labile Ca levels and decreases Al in subsoil layers[9,10,47,50]. Ameliorative effect of gypsum is due to 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.

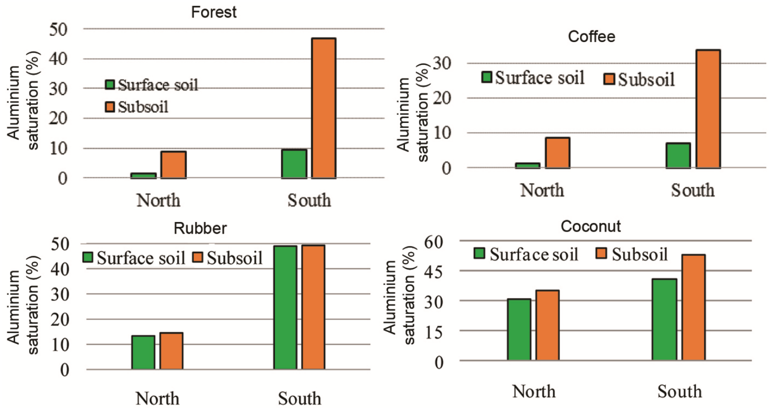

Figure 5. Mean aluminium saturation surface soil and subsoil in natural and managed land-use systems of northern and southern regions in the study area.

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 better extract nutrients and water. This is particularly advantageous in humid tropics with annual dry season.

Gypsum application rate of 5 tonnes/ha has been found to be effective in Brazilian Oxisols. The residual effect of a single application was reported to last for 4–6 years[52]. However, this rate was found insufficient for less intensively weathered, but equally acidic, 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 5–10 tonnes/ha for lime and 10–15 tonnes/ha for gypsum[53].

Conclusion

Soil acidity (both surface soil and subsoil) is pervasive in natural and managed land-use systems of the 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 are 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 effects in terms of biomass production and economic crop yields, amelioration of soil acidity should be followed by optimum plant nutrient inputs.

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