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Characterization and classification of soils on topo-sequence of Laterite landscape in tropical ecosystem of Goa

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Abstract
Five typical pedons representing major laterite landscape in tropical ecosystem of Goa *viz*., flat topped hills, escarpments, conical hills, undulating hills and colluvial low lands under varying land use were studied for their morphological characteristics, physical and chemical properties, soil genesis and taxonomy. The soils were moderately to strongly acidic in reaction, very shallow to deep in depth Texture of the soils varied from gravelly sandy clay loam to gravelly clay loam on hills, while it varies from sandy loam to clay loam in undulating and colluvial low lands. The clay content, bulk density, AWC, organic carbon, cation exchange capacity, base saturation and exchangeable hydrogen and aluminium in the sols were ranged from 12.0 to 50.8 per cent, 1.37 to 1.53 Mg m^{-3}, 1.2 to 11.4 cm m^{-1}, 0.1 to 3.3 per cent, 3.9 to 12.4 cmol (p+) kg^{-1}, 21.9 to 66.5 per cent, 0.1 to 0.3 cmol (p+) kg^{-1} and 0.0 to 0.9 cmol (p+) kg^{-1} respectively. The soils had isohyperthermic temperature regime and ustic soil moisture regime. The soils were grouped under three soil orders *viz*., Entisols, Inceptisols and Alfisols and further classified into four families *viz*., Lithic Ustorthents, Lithic Haplustepts, Dystric Haplustepts and Kanhaplic Haplustalfs.

Keywords: Characterization, classification, landscape

Introduction
Soil is the vital natural resource for the survival of life on the earth and its assessment is the prerequisite for the determination of productivity of soil and the sustainability of the ecosystem. It is well recognised that ferruginous soils are formed under humid tropical climate due to leaching of bases and release of iron and its coating on soil surfaces. Although ferruginous soils are formed under humid tropical conditions for millions of years, they vary in their physical and chemical characteristics. A considerable work has been done with respect to ferruginous soils of southern and western region of the country, but a very few information is available with respect to ferruginous soils of Goa (Govindarajan *et al*., 1974; Singh *et al*., 1998) [6, 19]. The ferruginous soils in general, have low fertility status, they support good vegetation (Chandran *et al*., 2004) [3]. Hence, the present study was undertaken to characterize and classify the dominant ferruginous soils of Goa

Materials and methods
The state of Goa is located between 14º 53′ 47″ to 15º 47′ 59″ N latitudes and 73º 40′ 54″ to 74º 20′ 11″ E longitudes with an area of 3702 km^2 (Fig. 1). It accounts for about 1 per cent of the total geographical area of the country. Mandovi, Zuari, Terekhol, Chapora and Betul are the main rivers in the state. Goa lies about 450 kms to the north of Malabar where Buchanan first recognised and named laterite (Pascoe, 1965) [13]. Major portion of Goa on the west coast of India is overlain by a thick mantle of laterite. Goa, being in the tropical zone and near the Arabian Sea, has a warm and humid climate for most of the year with mean annual temperature of 27.8°C. The mean maximum and minimum temperature are recorded in the month of May (30.2°C) and January (26.4°C). The soil temperature regime is hence iso-hyperthermic (Sehgal and Mandal, 1994) [16]. The south west monsoon yields a total annual precipitation of about 2910.5 mm from June to October. The maximum rainfall is in the month of June (828.8 mm). The relative humidity, in general varies from 89 to 67 per cent. The state

of Goa belongs to AER 19 defined as Western Ghats and Coastal plains; Hot humid and per humid ecoregion with red & lateritic and Alluvium derived soils with LGP of 210 to 270 days or more (Mandal *et. al.*, 2016) [12]. This has further classified into 19.2 and 19.3 AESR (unpublished data). At the physiography level Goa state is the part of Ghats which were divided into two sub-physiographic units namely Central Sahyadri/Western Ghats (Hw) and the west coasts (Pw). Central Sahyadri/Western Ghats was divided into two broad landscape 1) granite, and granite-gneiss, and 2) Quartzite-schistose landscape. Konkan Coast was divided into 1) Dissected hilly laterite and 2) Fluvio-littoral landscape. Basalt was considered as broad landform in South Deccan Plateau (Harindranath *et al.*, 1999) [7]. Most of Goa's soil cover is made up of laterites which are rich in ferric aluminium oxides and reddish in colour. The soil is rich in minerals and humus, thus conducive for plantation. The natural vegetation consists of trees, shrubs, hurbs, climbers, sedges and grasses like neem (*Azadiracta indica)*, babul (*Acacia spp.*), bamboo (*Bobax alba*), khair (*Acacia catechu),* lantana (*Lantana camara)*, mango (*Mangifera indica*), teak (*Tectona grandis*), jack fruit (*Artocarpus heterophyllus*) etc.

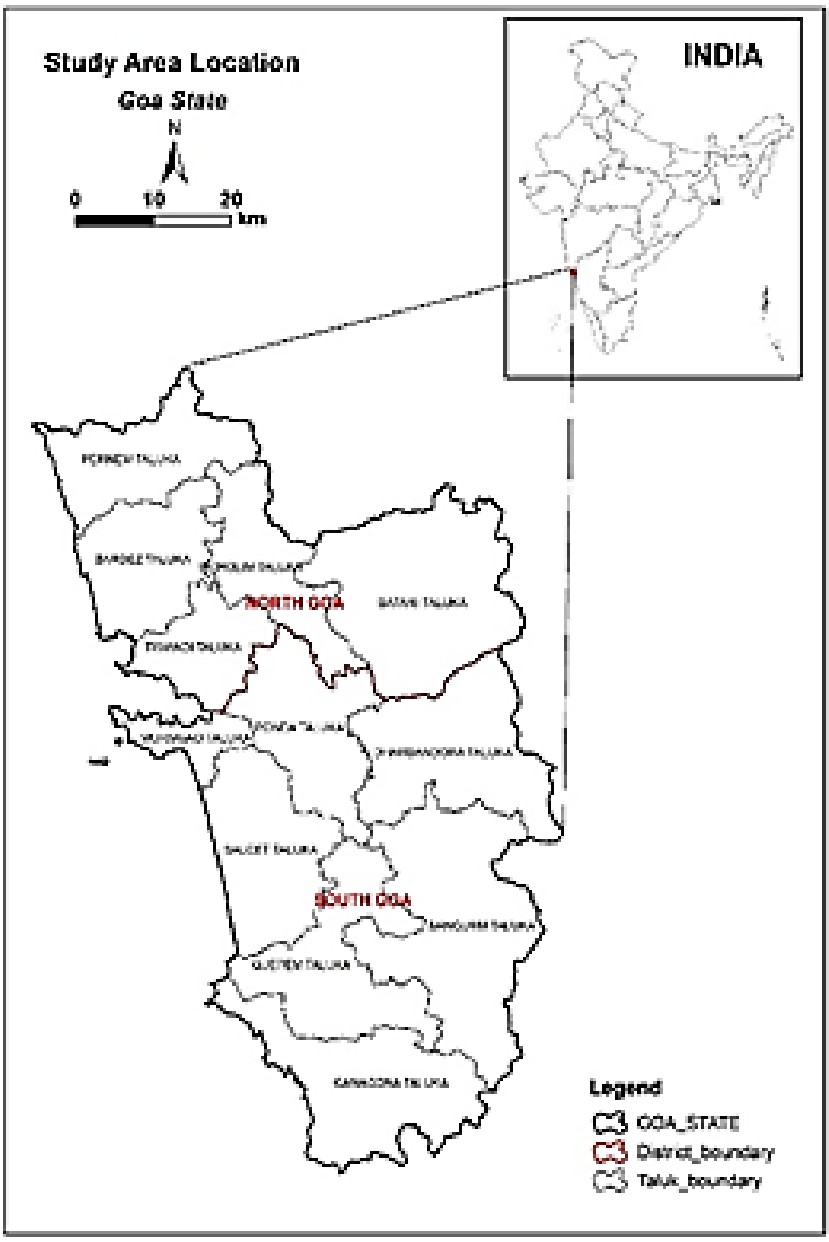

Fig 1: Location of the study area

High resolution remote sensing data IRS-P6 LISS-IV of 5.8 meter resolution, Cartosat-1 DEM of 10 meter resolution (year: 2014-15) and public domain data (i.e. online Google earth imagery) were used for the study. The land resource inventory was conducted using base map on 1:10000 scale A detailed traverse of the area was made to identify the major landforms. Five representative pedons from each landform in a topo-sequence dominantly occurring on laterite landscape in the state have been selected for the study (Table 1 and Fig. 2).

The soils of Pedon 1, 2, 3, 4 and 5 were representative of flat topped hills, escarpments, conical hills, undulating lands and colluvial low lands respectively. The soils were studied for their various morphological properties (Table 2) as per USDA Soil Survey Manual (Soil Survey Staff, 2000) [21]. Horizon wise soil samples were collected and analysed for important physical and chemical properties using standard procedures (Jackson 1973) [8]. The soils were classified taxonomically (Soil Survey Staff, 2006) [22].

Table 1: Site characteristics of pedons

Pedon	Landform	Slope (%)	Erosion	Drainage	Surface stoniness (%)	Present Land use
P1	Flat topped hills	3-5	Severe	Well	10-15	Grazing land
P2	Escarpments	8-15	Severe	Well	40-45	Moderately dense forest
P3	Conical hills	3-8	Moderate	Well	30-40	Thin forest
P4	Undulating lands	3-8	Moderate	Well	5-10	Coconut & Cashew Plantation
P5	Colluvial low lands	0-1	Slight	Well	5-10	Paddy & Coconut crop

Results and discussion

Soil morphology

The soils were very shallow to deep, well drained with severely to slightly eroded. The soils had gray colour in the range of 7.5YR to 10YR hue except the soils on escarpments which has redder hue ranging from 2.5YR to 5YR (Table 2). The similar colour complexation was also reported by Singh *et. al.* (1998) [19] at the elevated topography while working in the soils of Goa. High rainfall and high temperature with well to excessive drainage conditions on the laterite landscape were favourable for desilication and ferritization which is probably one of the reasons for redder hue at the escarpments. Further, rapid runoff and oxidative pedo-environment attributing to the redder hue (James *et. al.*, 1996 [9]; Singh *et. al.*, 1998 [19]) on the hill ranges. The dark matrix colour was due to the presence of high organic matter content in the surface horizons (Tripathi et al., 2006) [25].

Texture of the soils on flat topped hill was sandy loam (Pedon 1), gravelly sandy clay to gravelly clay on escarpment (Pedon 2) and gravelly sandy clay loam on conical hill (Pedon 3) while in undulating and colluvial low lands it varied from sandy loam to clay loam (pedon 4 & 5). The variation might be due to topography, in-situ weathering and translocation of clay by eluviation and age of the soils (Sireesha and Naidu 2013) [20]. Further it is observed that gravel content of soils decreased down the slope. The structure of the surface soils was weak, fine to medium sub-angular blocky and in the sub-surface soils it was weak to moderate, medium, sub angular blocky. In the sub-surface, dominantly coarse strong sub-angular blocky structure breaking to medium moderate sub-angular blocky structure was associated with the soils of redder hue. This is ascribed to the higher content of free iron oxides which could be acted as cementing agent for striking expression of soil structure in the pedo-environment of Goa. The sub-angular blocky structure attributed to the presence of higher quantities of clay fraction (Sharma *et. al.*, 2004) [18]. The consistency of soils on hills had soft to slightly hard, friable, non to slightly sticky and non to slightly plastic whereas soils on undulating and colluvial low lands had friable, slightly sticky and slightly plastic. Pedon 5 on colluvial low lands exhibited argillic (Bt) sub-surface diagnostic horizon with patchy thin clay cutans, while, Pedon 2 and 3 and 4 on escarpments, conical hills and undulating lands respectively exhibited cambic (Bw) sub-surface diagnostic horizon. However, pedon 1 on flat topped hills showed no diagnostic horizon. All the pedons showed clear and smooth boundaries in surface as well as sub-surface horizons in general. The soil depth-landform relationship holds well from flat topped hills to colluvial low land (Fig. 1). Thus, the soil depth over the landscape is found to be the function of landform and land uses.

Physical characteristics

The data pertaining to particle size analysis revealed that the clay content varied from 9.2 to 50.8 per cent (Table 3). Increase in clay content with depth might be due to downward translocation of finer particles from the surface layers. The decreasing in clay content with depth in pedon 4 of undulating lands might be due to *in-situ* weathering in this pedon. Silt content ranged from 0.4 to 29.0 per cent. Silt content, in general, exhibited an irregular trend with depth in pedon 4 and 5, which might be due to variation in weathering of parent material or in-situ formation (Satish Kumar and Naidu 2012) [15]. The sand content ranged from 30.2 to 85.3 per cent. Higher sand content was observed in surface horizons than those of sub-surface, which was opposite to clay content and was due to surface impoverishment of finer particles by runoff water (Surekha *et al.*, 1997) [23]. The variation in the soil texture from flat topped hills to colluvial low lands could be explained on the basis of established soil-landform relationship illustrating coarser soils on the high slopes and finer in the undulating and colluvial low lands (Fig. 1).

The bulk density varied from 1.37 to 1.53 Mg m^{-3} which might be due to the coarse texture and in some cases higher sand content. It is increases with depth, might be due to compaction of finer particles in deeper layers caused by the over-head weight of the surface layers (Thangasamy *et al.*, 2005) [24]. The low bulk density in surface layers may be due to cultivation, high organic matter and biotic activities (Vara Prasad Rao *et al.*, 2008) [26]. The lateritic soils are low in bulk density (1.33 to 1.56 Mgm^{-3}) as compared to the coastal soils of Maharashtra (1.51 to 1.60 Mgm^{-3}) (Kharche, 1996) [11]. The AWC of different pedons varied from 1.1 to 11.4 cm m^{-1}. These variations were due to the difference in depth, clay, silt, sand and organic carbon content. The low AWC in soils was due to high sand and less clay content as evident by negative correlation (r = -0.88**) between AWC and sand content. Study of AWC down the depth in the soil profile revealed that mean AWC was increased with increased clay content. Thus, AWC were the true reflections of geological formations and the topography explained the variations within the landscape.

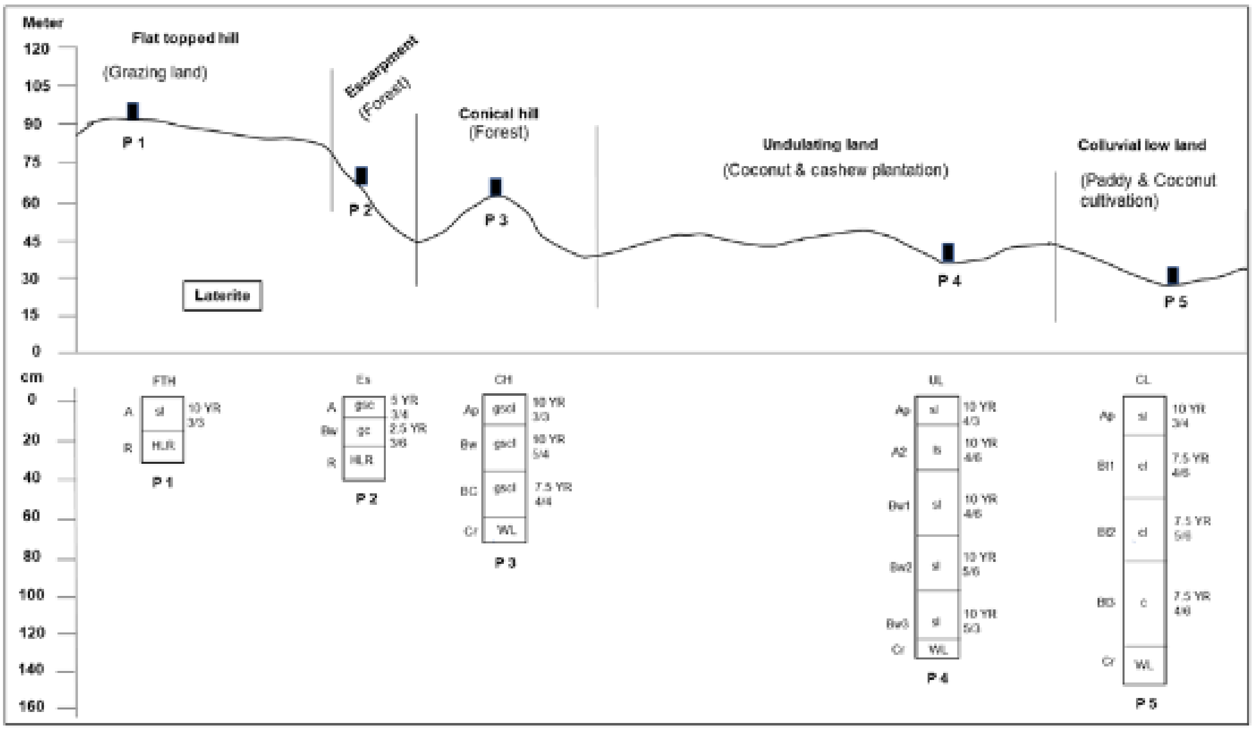

Fig 2: Soils on laterite landscape

Table 2: Morphological Characteristics of the soils

Horizon	Depth (cm)	Boundary		Matrix colour		Texture	Structure	Consistence				Porosity		Cutans			Roots		Nodules (Conir)	
		D	T	D	M			D	M	S	P	S	Q	Ty	Th	Q	S	Q	S	Q
Pedon 1: Loamy, mixed, isohyperthermic, Lithic Ustorthents																				
A	0-18	a	s	10YR 4/3	10YR 3/3	sl	m1sbk	s	fr	so	po	f	m	-	-	-	vf	m	-	-
R	18+	Hard laterite rock																		
Pedon 2: Clayey-skeletal, mixed, isohyperthermic, Lithic Haplustepts																				
A	0-11	c	s	5YR 4/4	5YR 3/4	gsc	f1sbk	sh	fr	s	p	vf	m	-	-	-	vf	m	-	-
Bw	11-30	a	s		2.5YR 3/6	gc	m2sbk	sh	fr	s	p	vf	m	-	-	-	vf	c	-	-
R	30+	Hard laterite rock																		
Pedon 3: Loamy-skeletal, mixed, isohyperthermic, Dystric Haplustepts																				
A	0-15	c	s	10YR 4/4	10YR 3/3	gscl	m2sbk	sh	fr	so	po	m	m	-	-	-	f	m	-	-
Bw	15-39	c	s	-	10YR 5/4	gscl	m2sbk	sh	fr	s	p	f	c	-	-	-	f	c	-	-
BC	39-65	c	w	-	7.5YR 4/4	gcl	m2sbk	sh	fr	s	p	f	c	-	-	-	f	f	-	-
Cr	65+	Weathered laterite material																		
Pedon 4: Coarse loamy, mixed, isohyperthermic, Dystric Haplustepts																				
Ap	0-12	g	s	10YR 4/3	10YR 4/3	sl	m1sbk	s	fr	ss	ps	f, m	c	-	-	-	vf, f	m	-	-
A2	12-38	c	s	-	10YR 4/6	ls	f1gr	l	fr	so	po	f	m	-	-	-	vf, f	c	-	-
Bw1	38-59	c	s	-	10YR 4/6	sl	m1sbk	s	fr	ss	ps	vf	m	-	-	-	vf	f	-	-
Bw2	59-88	c	s	-	10YR 5/6	sl	m1sbk	s	fr	ss	ps	vf	m	-	-	-	vf	c	-	-
Bw3	88-127	c	s	-	10YR 5/3	sl	m2sbk	h	fr	ss	ps	vf	c	-	-	-	vf	f	-	-
Cr	127+	Weathered laterite material																		
Pedon 5: Fine loamy, mixed, isohyperthermic, Kanhaplic Haplustalfs																				
Ap	0-19	c	s	10YR 4/6	10YR 3/4	sl	m1sbk	s	vfr	so	po	f	c	T	tn	p	vf, m	c	f	f
Bt1	19-45	g	s	-	7.5YR 4/6	cl	m2sbk	-	fr	ss	ps	f	m	T	tn	p	vf, m	c	f	f
Bt2	45-79	c	s	-	7.5YR 5/6	cl	m2sbk	-	fr	ss	p	f	m	T	tn	p	vf, f	m	f	f
Bt3	79-130	g	s	-	7.5YR 4/6	c	m2sbk	-	fr	s	p	f	m	T	tn	p	vf, f	m	f	f
Cr	130+	Weathered laterite material																		

Table 3: Physical characteristics of the soils

Horizon	Depth (cm)	Coarse fragments (>2.0 mm) (%)	Particle size class and diameter (mm)			Bulk density (Mg m^{-3})	AWC (%)	AWC (cm m^{-1})
			Sand (2.0-0.05) (%)	Silt (0.05-0.002) (%)	Clay (<0.002) (%)			
Pedon 1: Loamy, Lithic Ustorthents								
A	0-18	10	78.4	12.4	9.2	1.52	4.2	1.1
R	18+	Hard laterite rock						
Pedon 2: Clayey-skeletal, Lithic Haplustepts								
A	0-11	40	53.5	5.7	40.8	1.42	8.7	3.9
Bw	11-30	50	38.5	10.7	50.8	1.45	9.1	
R	30+	Hard laterite rock						
Pedon 3: Loamy-skeletal, Dystrict Haplustepts								
A	0-15	40	63.1	15.7	21.2	1.39	7.4	7.6
Bw	15-39	50	58.4	16.4	25.2	1.40	8.0	
BC	39-65	60	43.1	26.2	30.7	1.43	8.9	
Cr	65+	Weathered laterite						
Pedon 4: Coarse loamy, Dystric Haplustepts								

Ap	0-12	-	83.1	0.4	16.5	1.51	6.0	8.6
A2	12-38	-	85.3	0.7	14.0	1.53	4.4	
Bw1	38-59	-	81.2	6.8	12.0	1.52	5.6	
Bw2	59-88	-	79.0	7.7	13.3	1.52	6.6	
Bw3	88-127	-	81.4	6.4	12.2	1.53	5.9	
Cr	127+	Weathered laterite						
Pedon 5: Fine loamy, Kanhaplic Haplustalfs								
Ap	0-19	10	55.4	29.0	15.7	1.38	6.8	11.4
Bt1	19-45	10	44.8	28.1	27.2	1.37	8.0	
Bt2	45-79	5	38.3	27.7	34.0	1.39	8.3	
Bt3	79-130	5	30.2	28.9	40.9	1.41	8.8	
Cr	130+	Weathered laterite						

Chemical characteristics

The soils were moderately to strongly acidic, occasionally slightly acidic in nature with pH varying from 5.2 to 6.4 (Table 4). Mean pH values at the surface and sub-surface were 5.8 (in the confidence interval of 5.2 to 6.4) and 5.7 (in the confidence interval of 5.3 to 6.2). This wide variation was attributed to the nature of the parent material, leaching, and exchangeable sodium (Shalima Devi and Anil Kumar 2010) [17]. Acidic pH, 5.0 to 6.5 was noted in laterites (Preethi, 1996) [14]. The Ə pH is the difference of KCl and water pH. Mean Ə pH vales were -1.1 (with range of -1.0 to -1.2) at the surface and -1.2 (with range of -0.9 to -1.4) in the sub-surface. The Ə pH with large negative value (> -0.5) indicated a high negative surface charge density in these soils. The electrical conductivity (EC) of soils varied from 0.02 to 0.05 dS m^{-1}. The low EC in these soils was due to leaching of soluble salts by percolating water. Soil Organic carbon content in these soils ranged from 0.1 to 3.3 per cent and decreased with depth in almost all the pedons. SOC was varied in the confidence interval of 0.5 to 3.3 per cent at the surface and 0.1 to 2.5 per cent in the sub-surface with mean of 1.5 and 0.9 per cent respectively. This is attributed to the addition of plant residues and farmyard manure to surface horizons than in the lower horizons (Ashok Kumar and Jagdish Prasad 2010) [2]. The higher values on the hills both at the surface and sub-surface was ascribed to the protected plantations. The high organic carbon in Goa reported by Anil Kumar *et al.* (2011) [1].

The CEC in the pedon varied from 3.9 to 12.4 cmol(p+)kg^{-1} soil which corresponds to clay and organic carbon content and type of clay mineral present in these soils. The mean value of CEC at the surface and sub-surface was 9.0 cmol(p+)kg^{-1} (in the confidence interval of 6.6 to 12.4 cmol(p+)kg^{-1}) and 6.5 cmol(p+)kg^{-1} (in the confidence interval of 3.9 to 11.6 cmol(p+)kg^{-1} respectively. CEC was low in red and lateritic soils (Jose, 1993) [10] with low CEC/clay ratio (0.20 to 0.30) (Eswaran *et al.,* 1992) [5]. Exchangeable bases in the pedons were in the order of Ca^{2+}>Mg^{2+}>Na^{+}>K^{+} on the exchange complex with slightly reverse order in Na^{+} and K^{+} (K^{+} > Na^{+}) in pedon 2 and Ca^{2+} being the dominant cation on the exchange complex. The base saturation varied from 21.9 to 66.5 per cent. The mean value of surface and sub-surface was 38.9 (in the confidence interval of 21.9 to 66.5 per cent) and 43.7 per cent (in the confidence interval of 27.1 to 63.9 per cent) respectively. Mean base saturation percentage corroborates with the findings of Anil Kumar *et. al.* (2011) [1] reported for the soils of Talaulim watershed of North Goa. The exchangeable hydrogen and aluminium in the soil ranges from 0.1 to 0.7 and 0.0 to 0.9 cmol(p+)kg^{-1} respectively. Mean exchangeable hydrogen was 0.2 cmol(p+)kg^{-1} in the surface and sub-surface soils. Similarly mean exchangeable aluminium was 0.4 and 0.3 cmol(p+)kg^{-1} in the surface and sub-surface soils respectively.

Diagnostic horizons

Argillic horizon

The sub-surface layer in the soils of pedon P5, (Table 3) were more than 15 cm thick and had clay content of more than 1.2 times higher from the overlying horizons together with the thin patchy argillans were characterized as argillic horizons (Table 2) Apart from the clay content, these were hold higher available water capacity. These horizons are indicated with the symbol of Bt.

Cambic horizons

The sub-surface layers in the soils of the pedon 2, 3 & 4 have either higher clay content or organic carbon or redder hue, darker chroma and value or signature of structural alterations in terms fine to medium, moderate sub-angular blocky structure than the underlying horizons were grouped with cambic horizon. These horizons are indicated by the symbol Bw.

Table 4: Chemical characteristics of the soils

Hori-zon	Depth (cm)	pH (1:2.5)		EC (1:2.5) (dS m^{-1})	OC (%)	Exchangeable bases				CEC	BS	Acidity	
		H_2O	1*N* KCl			Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}		1 *N* NH_4OAc	Ex. H	Ex. Al
						cmol(p^{+}) kg^{-1}					(%)	cmol(p^{+}) kg^{-1}	
Pedon 1: Loamy, Lithic Ustorthents													
A	0-18	5.7	4.5	0.03	1.8	1.24	0.79	0.14	0.12	9.2	24.9	0.17	0.44
R	18+	Hard laterite rock											
Pedon 2: Clayey-skeletal, Lithic Haplustepts													
A	0-11	6.4	5.2	0.02	1.1	1.87	0.92	0.12	0.18	7.3	42.3	0.20	0.76
Bw	11-30	5.5	4.3	0.05	1.2	0.86	1.05	0.15	0.16	8.2	27.1	0.28	0.92
R	30+	Hard laterite rock											
Pedon 3: Loamy-skeletal, Dystrict Haplustepts													
A	0-15	5.3	4.2	0.04	3.3	3.02	1.32	0.17	0.13	12.4	37.4	0.22	0.09
Bw	15-39	5.5	4.4	0.02	2.5	2.76	1.24	0.16	0.11	11.6	36.8	0.31	0.26
BC	39-65	6.0	4.7	0.02	1.2	2.35	1.19	0.14	0.07	10.8	34.7	0.20	0.12
Cr	65+	Weathered laterite											
Pedon 4: Coarse loamy, Dystric Haplustepts													
Ap	0-12	5.2	4.0	0.04	1.6	2.80	1.42	0.14	0.16	6.8	66.5	0.07	0.28
A2	12-38	5.3	4.4	0.03	1.0	0.86	0.34	0.09	0.06	4.6	29.3	0.09	0.32

Bw1	38-59	6.2	4.8	0.05	0.2	1.21	0.76	0.08	0.05	4.5	46.7	0.08	0.29
Bw2	59-88	5.3	4.2	0.06	0.2	1.32	0.84	0.1	0.08	3.9	60.0	0.08	0.30
Bw3	88-127	5.5	4.3	0.03	0.1	1.48	0.89	0.13	0.12	4.1	63.9	0.09	0.31
Cr	127+	Weathered laterite											
Pedon 5: Fine loamy, Kanhaplic Haplustalfs													
Ap	0-19	5.6	4.6	0.05	1.2	1.07	0.2	0.11	0.09	6.6	26.3	0.12	0.43
Bt1	19-45	5.4	4.2	0.05	1.2	1.85	0.52	0.12	0.07	5.5	40.5	0.06	0.00
Bt2	45-79	5.5	4.2	0.02	1.2	2.14	0.72	0.12	0.04	5.5	46.3	0.05	0.00
Bt3	79-130	5.7	4.4	0.02	0.1	2.68	1.20	0.11	0.04	5.8	51.8	0.01	0.00
Cr	130+	Weathered laterite											

Soil forming processes

Geological formations and the prevailing climatic conditions were played the decisive role in the development of soils. The soils on the laterite landscape subjected to the process of desilication and ferritization in the prevailing humid climate conditions characterized with high rainfall and high temperature. The climatic conditions were favourable for alkaline weathering which is suitable for removal of silica and accumulation of iron and alumina oxides (Duchaufour, 1982) [4]. However, continuous leaching of bases in the situation of high rainfall leads to the development of moderately to strongly acidic soils.

Further, shallow to moderately shallow soils on the hills and deep soils in the colluvial low land with the signature eluviation and illuviation suggested topography had a role in the genesis of soils of laterite landscape. Shallow soils on the hills were the resultant of moderate to severe erosion of surficial matter (Table 2) and their subsequent deposition on the stable landscape, manifested as deep soils in the colluvial low land. An increase of 1.2 times clay in the sub-surface horizons with thin patchy argillans on these landscapes indicated that these landforms were good enough to support elluvial and illuvial processes (Table 2). Thus developed illuvial sub-surface horizons hold higher nutrient, base saturation and moisture (Table 3 & 4) than overlying horizons. This suggests illuvial horizons prepared the base for arresting leachates of elluvial horizons, perhaps one of the reasons for supporting deep rooted plantation crops.

Soil correlation

In the present study, we have attempted to correlate the typifying pedons with the existing soil series (Harindrnath *et al.*, 1999) [7] based on colour, depth, surface and sub-surface texture and the sequence of diagnostic horizons.

Deep, well drained soils with sandy loam surface and clay loam to clay sub-surface soils (Pedon 5) with 10 YR 3/4 colour at the surface was correlated with Batim series**,** whereas other deep, well drained soils with sandy loam surface and sub-surface (Pedon 4) were grouped with Chapora series. Moderately shallow, well drained soils with gravelly sandy clay loam surface and gravelly sandy clay loam to clay loam sub-surface (Pedon 3) were correlated with Padi series. Further shallow, well drained soils with gravelly sandy clay surface and gravelly clayey sub-surface (Pedon 2) were grouped with Verna series. Traversing further on the landscape, very shallow, well drained soils with sandy loam surface on the rocky sub-surface (Pedon 1) were branded with Dabolim series.

Soil classification

Based on the morphological, physical and chemical properties, the typifying pedons were classified according to soil taxonomy (Soil Survey Staff 2006) [22] into the order Entisols, Inceptisols and Alfisols. Pedon 1 on flat topped hills do not have any sub-surface diagnostic horizons, loamy particle size class and lithic contact within 50 cm, was classified as loamy, mixed, iso-hyperthermic family of Lithic Ustorthents sub-group of Entisol. Pedon 2 on escarpments exhibited cambic sub-surface horizon, clayey-skeletal particle size class, lithic contact within 50 cm and base saturation was less than 60 per cent, were classified as clayey-skeletal, mixed, iso-hyperthermic family of Lithic Haplustepts sub-group of Inceptisol soil order. Pedon 3 on conical hills exhibited cambic sub-surface horizon, loamy-skeletal particle size class and base saturation was less than 60 per cent, were grouped with loamy-skeletal mixed iso-hyperthermic family of Dystric Haplustepts sub-group of Inceptisol soil order. Pedon 4 on undulating lands exhibited cambic sub-surface horizon, coarse loamy particle size class and base saturation was less than 60 per cent, were grouped with coarse loamy, mixed iso-hyperthermic family of Dystric Haplustepts sub-group of Inceptisol soil order. Whereas pedon 5 at the colluvial low land exhibited argillic sub-surface diagnostic horizon, fine loamy particle size class, base saturation was more than 35 per cent and CEC was less than 24 cmol(p+)kg^{-1}, were classified as a member of fine loamy, mixed, isohyperthermic family of Kanhaplic Haplustalfs sub-group of Alfisol soil order (Table 4).

Conclusions

Based on the results, it is concluded that the ferruginous soils in tropical region of Goa in a topo-sequence were very shallow to deep, moderately to strongly acidic in rection, medium to high in organic carbon content, low in CEC and exchange complex was dominated by Ca^{2+} followed by Mg^{2+}, Na^{+} and K^{+} ions in general. The soils were classified as Lithic Ustorthents, Lithic Haplustepts, Dystrict Haplustepts and Kanhaplic Haplustalfs. Furthermore, the soil depth-landform relationship holds well from flat topped hills to colluvial low land. Thus, the soil depth over the landscape is found to be the function of landform and land uses.

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