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Pedogenic processes and soil–landform relationships for identification of yield-limiting soil properties

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Abstract. Knowledge of soil–landform relationships helps in understanding the dominant pedogenic processes causing variations in soil properties within and between landforms. In this study, we investigated how major pedogenic processes in three landform positions of the semi-arid Deccan Plateau (India) have led to current plant yield-limiting soil properties. For this, we characterised 26 pedons from three landforms – piedmont, alluvial plain and valley – and performed factor analysis on the dataset. As the frequency distribution of the dataset was highly skewed for most of the soil properties, landform-wise partition and log-transformation were performed before studying soil variability within landforms. Results indicated that two factors explained 56, 71 and 64% of variability in soil properties in piedmonts, alluvial plains and valleys, respectively. The major soils in lower piedmonts (*Typic Haplustalfs* and *Typic Rhodustalfs*) were spatially associated with Vertisols (*Sodic Haplusterts*) occurring in alluvial plains and valleys. The soil properties in alluvial plains and valleys (*Vertic Haplustepts*, *Sodic Haplusterts* and *Typic Ustifluvents*) were modified due to regressive pedogenic processes. These soils were characterised by high pH (8.5–9.8), exchangeable sodium percentage (16.5–46.6) and poor saturated hydraulic conductivity (<1 cm h^{-1}). Subsoil sodicity induced by the presence of pedogenic calcium carbonate impaired the hydraulic conductivity. Subsoil sodicity and poor saturated hydraulic conductivity were identified as major yield-limiting soil properties. The relationships found between specific soil properties, surface and subsurface horizons, and position in the landscape helped to determine the dominant pedogenic processes and how these influenced current soil properties and their effects on crop yield.

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Introduction

Soils vary in their properties within and between landforms (Gessler *et al*. 2000) due to pedogenic processes operating over different periods of time (Abdelfattah 2013; Świtoniak 2014). The magnitude of variation is influenced by climate, topography and vegetation (Hall 1983; Yaalon 1983). The spatial variation of soil properties such as organic matter, clay content, pH and water retention capacity is caused by pedogenic processes which are influenced by hydrological and temperature regimes modified by topography (Pilesjő *et al*. 2005; Florinsky 2012). The intensity of different pedogenic processes varies with landforms. Specific processes like calcification, salinisation and sodification are dominant in arid and semi-arid environments (Abdelfattah 2013). In soils of Indian semi-arid tropical (SAT) environments, major pedogenic processes are associated with the turnover of organic matter, formation of pedogenic calcium carbonate (PC), illuviation of clay particles and development of subsoil sodicity (Pal *et al*. 2012, 2013, 2014).

The interaction between soil properties in different landforms is influenced by soil-forming processes (Kravchenko and Bullock 2000) and results in modification of soil properties that directly or indirectly influence crop performance (Marques da Silva and Silva 2008). Assessment of variation in soil properties will help to understand the interactions between them in a specific landform. Modern statistical techniques such as factor, principal component and cluster analyses can be used to study soil variability (Sielaff and Einax 2007). The statistical analysis of any dataset is influenced by its frequency distribution. In natural systems like soils, the normal distribution is not always the case due to skewness of data caused by heterogeneity, especially with increased scale of observations (Seyfried and Wilcox 1995). Logarithms, square root transformation and Box–Cox technique are some of the methods widely used to transform skewed data before statistical analysis. Factor analysis is a technique that reduces the dimensions of data without losing vital information and identifies significant variables in a dataset (Shukla *et al*. 2006). Moreover, the variation between surface and subsurface properties can be assessed from factor plots and it could be used for ascertaining pedogenic processes (Momtaz *et al*. 2009). In the present study, factor analysis was used to study the soil variability and relationships between soil properties in each landform.

The Deccan Plateau covers an area of 0.42 million km^2 in central and southern India and is characterised by SAT climate. Rainfed agriculture is predominant in this region and the soils are prone to natural degradation due to high evapotranspiration, low rainfall, high temperature and PC formation (Pal *et al*. 2000). The presence of PC is particularly important in the Vertisols of this region – *Typic Haplusterts* and *Sodic Haplusterts* (Soil Survey Staff 2014) – and its formation has been considered responsible for the enrichment of magnesium (Mg) and sodium (Na) at exchange sites and the associated increase in soil pH (Balpande *et al*. 1996; Pal *et al*. 2006). Through these processes, soils have become sodic, which has led to a loss of structure and a low saturated hydraulic conductivity (sHC) (<2 cm h^{-1}) and thus impaired plant growth. Other soils common in the Deccan Plateau are specific Alfisols, such as *Typic Haplustalfs* and *Typic Rhodustalfs*, and Inceptisols, such as *Typic Haplustepts* and *Vertic Haplustepts*. These soils generally have low cation exchange capacity (CEC), base saturation (BS) in the range of 35–45% and overall poor fertility. Hence, crop productivity in such SAT soils under rainfed farming systems remains low (Pal *et al*. 2014). These soils need optimum management to sustain crop production by minimising the limitations caused by unfavourable soil properties. Studies on the influence of pedological variables on crop yield are limited (Ayoubi *et al*. 2009; Juhos *et al*. 2015). Kadu *et al*. (2003) identified sHC as the limiting factor in SAT Vertisols causing 50% reduction in cotton yield in central India. Knowledge of the relationships between soil properties in a specific landform may help determine the dominant pedogenic processes of these soils and provide an opportunity to manage them better and improve crop performance. The objectives of the present study were (i) to study the variation in soil properties in three different landforms occurring in the SAT Deccan Plateau region of India, (ii) to establish relationships between soil properties and pedogenic processes and (iii) to identify soil limitations for crop yield.

Materials and methods

The study area is located within 16°35′13″–16°44′31″N and 78°07′37″–78°18′36″E in Mahabubnagar district, Telangana, India and covers an area of 21 560 ha. Elevation is in the range of 434–662 m (WGS 84 datum) above mean sea level. The climate is SAT with mean annual temperature of 33°C. The mean annual rainfall varies within 450–550 mm. The study area qualifies for *hyperthermic* and *ustic* soil temperature and moisture regimes, respectively (Soil Survey Staff 2003). The soils occur mainly on three types of geological formations: peninsular gneissic complex, younger granites and basaltic alluvium. The natural vegetation comprises acacia (*Acacia nilotica* L'Her.), ber (*Zizipus jujuba* Mill.), palas (*Butea monosperma* L.) and tamarind (*Tamarindus indica* L.). Major crops grown are cotton (*Gossypium hirsutum* L.), maize (*Zea mays* L.) and pigeon pea (*Cajanus cajan* L.) mostly under rainfed conditions.

Indian Remote Sensing Satellite (IRS-P6) and high-resolution Linear Image Self Scanning (LISS-IV) image (November 2014) and Cartosat-1 stereo pairs were used to extract a digital elevation model with 10-m resolution. False colour composite was generated from different band combinations of satellite data (Sahu *et al*. 2014) and identification of landforms was carried out using terrain attributes and visual image interpretation techniques. The landforms piedmonts (9899 ha), alluvial plains (4262 ha) and valleys (5021 ha) were identified and delineated in ArcGIS 10 (Fig. 1). To study soil properties, six transects, all from a higher to lower elevation were selected. A total of 26 soil pedons were studied from selected transects occurring in piedmonts (11), alluvial plains (8) and valleys (7). The lengths of transects were 596–2264 m (Fig. 2). The slope varied within 3–8, 0–1 and 0–3% in piedmonts, alluvial plains and valleys, respectively. The pedons were studied for their morphological characteristics in the field and 117 horizon-wise samples were collected from all pedons, air-dried, sieved through a 2-mm sieve, processed and analysed in the laboratory.

Particle size analysis was performed by hydrometer method (Gee and Bauder 1986), bulk density (BD) by core method (Blake and Hartge 1986) and sHC by constant head method (Klute and Dirksen 1986). Soil pH was measured with 1 : 2 soil/water ratio (Whitney 1998). Organic

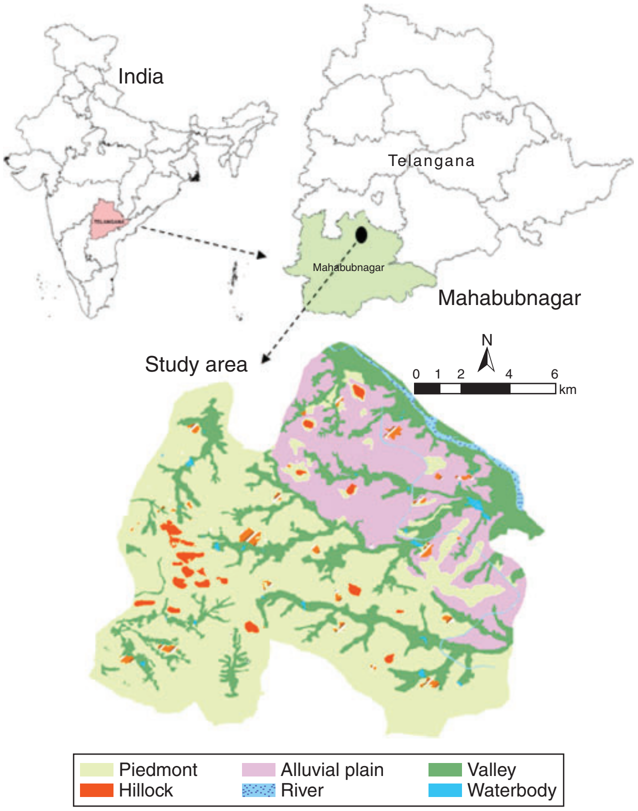

Fig. 1. Location of study area and major delineated landforms.

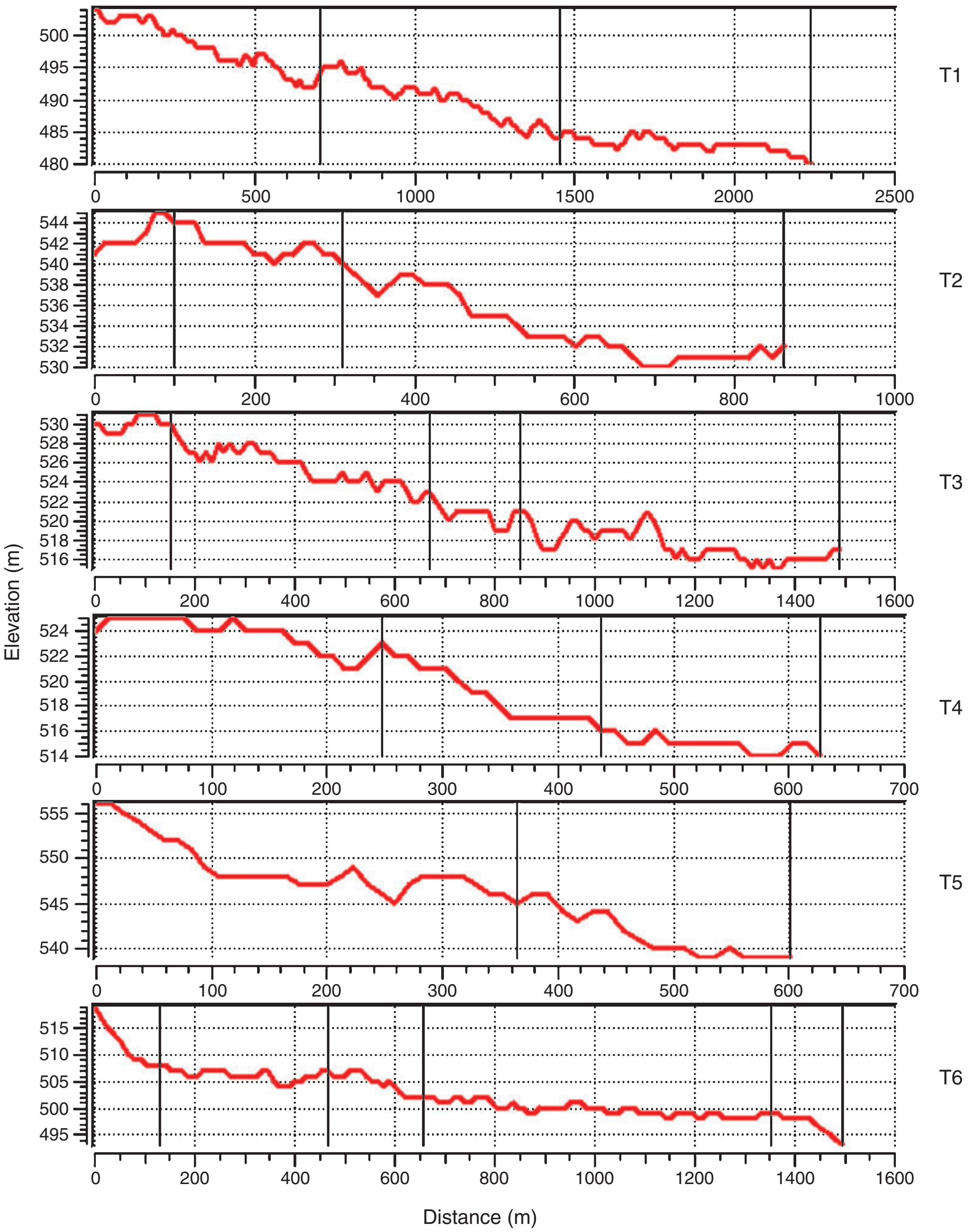

Fig. 2. Selected transects (T1–T6) showing the length and slope gradient. The transects were identified in six different locations and the soil profiles were studied from higher elevation to lower elevation.

carbon (OC) was determined by the method of Walkley and Black (1934). Calcium carbonate ($CaCO_3$) equivalent (%) was determined by the method described by Piper (1966) in which hydrochloric acid (HCl) was added to soil and the unreacted HCl in the suspension determined by titrating with sodium hydroxide. CEC and exchangeable cations were estimated using 1 N ammonium acetate (buffered at pH 7.0) by standard procedures (Schollenberger and Simon 1945; Sumner and Miller 1996). BS was estimated as the ratio of total exchangeable bases to CEC. Exchangeable sodium percentage (ESP) and exchangeable magnesium percentage (EMP) were estimated as the ratio of exchangeable Na and Mg to CEC, respectively. Available nitrogen (N) was estimated by alkaline permanganate method (Subbiah and Asija 1956). Available phosphorus (P) was extracted with 0.5 N sodium bicarbonate (Olsen *et al.* 1954) and determined by ascorbic acid colourimetric method (Watanabe and Olsen 1965). Available potassium (K) was determined by the method of Schollenberger and Simon (1945). The soils were classified as *Lithic Ustorthents* and *Typic Haplustepts* (upper piedmont), *Typic Haplustalfs* and *Typic Rhodustalfs* (lower piedmont), *Vertic Haplustepts* and *Sodic Haplusterts* (alluvial plain and valley) and *Typic Ustifluvents* (alluvial plain) according to soil taxonomy (Soil Survey Staff 2014). The average yield data of cotton, maize and pigeon pea pertaining to each soil type were computed from village level yield data of crops (period of 2008–15) obtained from the Department of Agriculture, Government of Telangana, Hyderabad.

Descriptive statistics, frequency distribution, log-transformation of data and factor analysis were carried out using STATISTICA (version 10.0) software (StatSoft Inc.). Landform-wise stratified data were used to study the distribution of soil properties within landform and their interactions. The log-transformed data of soil horizons were coded with a, b, c, d, e and f in order of increasing depth to differentiate surface and subsurface soil properties and used for factor analysis. The first two factors explained a substantial percentage of the total variance of data and were used for interpretation.

Results and discussion

Soil variability

The soil variability was assessed using the coefficient of variation (CV) for the combined dataset from all landforms. The criteria proposed by Wilding (1985) were used to classify the soil properties into classes of most (CV > 35%), moderate (CV = 15–35%) and least (CV < 15%) variable. Silt, clay, sHC, CaCO$_3$, OC, CEC, ESP and EMP were the most variable properties, whereas BD and pH were the least variable for the non-transformed data (Table 1). The log-transformation of data modified the variability of soil properties, and so only ESP (CV 56%) was classed as most variable. Silt, clay, BD, CaCO$_3$, CEC and EMP were moderately variable; and sand, pH and BS were the least variable properties.

Frequency distribution of soil properties

Normal distributions were observed only for sand, silt and clay for non-transformed data. Log-transformation improved the frequency distribution for pH, CaCO$_3$, OC and EMP (Table 1). The landform-wise stratification of data also improved the distribution of pH, CaCO$_3$, CEC and ESP in alluvial plains and of BD, pH and BS in the valleys for non-transformed data (Appendix 1). Log-transformation of landform-wise stratified data improved distribution for all properties except BD in piedmonts and for sand, silt, pH, CaCO$_3$, OC and BS in alluvial plains (Appendix 2). The high heterogeneity of soils across landforms could be the reason for non-normal distribution of soil properties. Log-transformation reduced the skewness and improved the accuracy of statistical analysis and interpretation.

Distribution of soil properties in landforms

The relationship between soil properties within specific landforms was interpreted using the factor analysis results. In piedmonts, two factors explained 56% of the variability. High correlations were observed between sand and BD; pH and BS; and CaCO$_3$ and EMP (Fig. 3*a*). In soils with low pH, the clay content was negatively correlated with ESP due to leaching of Na$^+$ and dominance of Ca^{2+} and Mg^{2+} in the exchange complex. There were two groups of soil properties (Fig. 3*b*): group 1 composed of surface soil properties with high OC and sHC and

Table 1. Descriptive statistics for combined data of soil properties from all landforms

BD, bulk density; sHC, saturated hydraulic conductivity; OC, organic carbon; CEC, cation exchange capacity; BS, base saturation; ESP, exchangeable sodium percentage; EMP, exchangeable magnesium percentage; s.d., standard deviation; CV, coefficient of variation; ns, non-significant; **, significant at 0.01 level

Properties	Mean	Median	Min.	Max.	Variance	s.d.	CV	Skewness
Sand (%)	61.59	60.70	39.50	88.60	132.26	11.50	18.67	0.32ns
log sand	1.78	1.78	1.60	1.95	0.01	0.08	4.56	–0.03ns
Silt (%)	9.05	9.10	1.00	18.20	17.50	4.18	46.22	–0.13ns
log silt	0.89	0.96	0.00	1.26	0.08	0.29	32.80	–1.52ns
Clay (%)	29.36	30.90	4.60	52.40	120.36	10.97	37.37	–0.37ns
log clay	1.43	1.49	0.66	1.72	0.05	0.22	15.14	–1.44ns
BD (Mg m^{-3})	1.48	1.41	1.24	1.99	0.04	0.19	12.75	0.92**
log BD	0.17	0.15	0.09	0.30	0.00	0.05	31.59	0.74**
sHC (cm h^{-1})	1.73	0.11	0.00	15.85	12.94	3.60	208.33	2.73**
log sHC	0.18	0.03	0.00	0.52	0.01	0.05	53.55	0.27**
pH	8.32	8.73	5.75	9.76	1.37	1.17	14.10	–0.77**
log pH	0.92	0.94	0.76	0.99	0.00	0.07	7.18	–0.95ns
CaCO$_3$ (%)	5.91	5.39	2.43	23.89	8.31	2.88	48.75	3.35**
log CaCO$_3$	0.73	0.73	0.39	1.38	0.03	0.17	23.63	0.46ns
OC (%)	0.48	0.45	0.08	1.66	0.07	0.27	57.30	1.69**
log OC	–0.39	–0.35	–1.10	0.22	0.07	0.26	–66.11	–0.62ns
CEC (cmol(p+) kg^{-1})	17.89	16.40	2.59	40.20	135.58	11.64	65.09	0.49**
log CEC	1.14	1.21	0.41	1.60	0.12	0.34	30.24	–0.47**
BS (%)	76.14	83.80	27.66	120.93	677.89	26.04	34.20	–0.30**
log BS	1.85	1.92	1.44	2.08	0.03	0.17	9.34	–0.75**
ESP	16.25	15.43	0.61	46.66	150.64	12.27	75.54	0.24**
log ESP	0.98	1.19	–0.21	1.67	0.30	0.55	56.28	–0.75**
EMP	16.33	15.49	4.00	31.44	56.93	7.55	46.19	0.12**
log EMP	1.16	1.19	0.60	1.50	0.06	0.24	20.45	–0.64ns

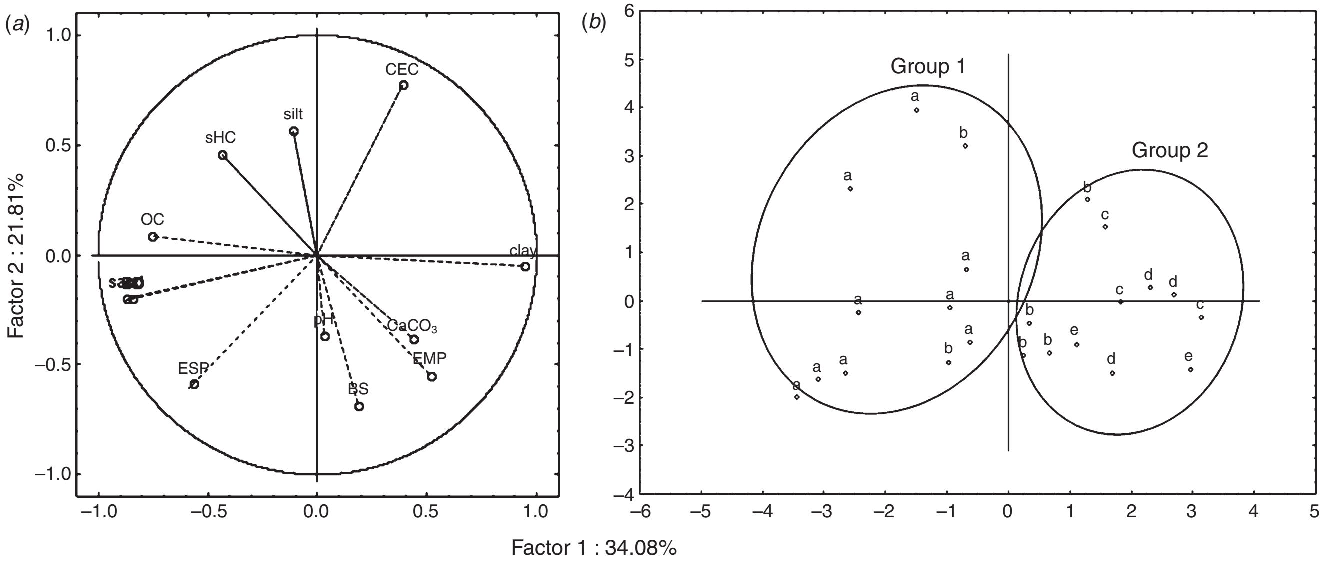

Fig. 3. Results of factor analysis for the piedmont landform showing the (*a*) relationship between soil properties and (*b*) distribution of surface (group 1) and subsurface soil sample (group 2) values in the factor plot. BD, bulk density; BS, base saturation; CEC, cation exchange capacity; ESP, exchangeable sodium percentage; EMP, exchangeable magnesium percentage; sHC, saturated hydraulic conductivity; OC, organic carbon.

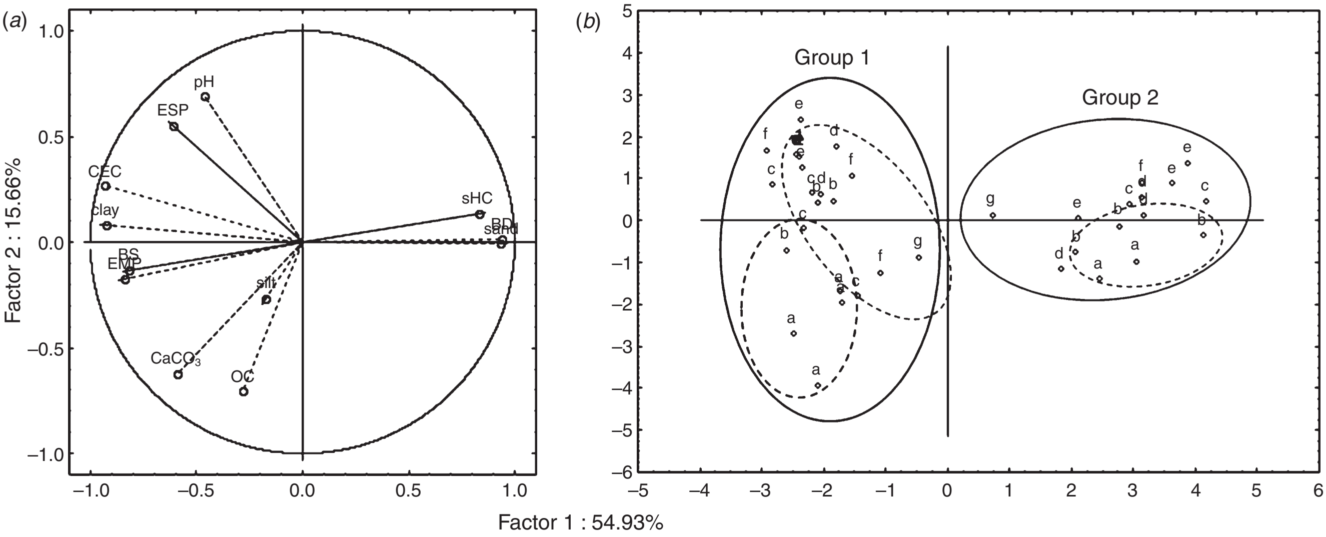

Fig. 4. Results of factor analysis for the alluvial plain landform showing the (*a*) relationship between soil properties and (*b*) distribution of surface (group 1) and subsurface soil sample (subsurface) values in the factor plot. The subgroups within groups 1 and 2 indicate the variation of soil properties within horizons. BD, bulk density; BS, base saturation; CEC, cation exchange capacity; ESP, exchangeable sodium percentage; EMP, exchangeable magnesium percentage; sHC, saturated hydraulic conductivity; OC, organic carbon.

group 2 composed of subsurface soil properties with high clay, $CaCO_3$, BS and CEC.

In alluvial plains, two factors explained 71% of the variability. High positive correlations were observed between sand, BD and sHC; and BS and EMP (Fig. 4*a*). Moderate correlations were observed between $CaCO_3$, silt and OC content and these properties were negatively related to sHC. ESP was positively correlated with pH, CEC and clay. The distribution of soil properties resulted in soils clustered into two major groups (Fig. 4*b*): group 1 comprised soils with irregular distribution of soil properties in both surface and subsurface layers and group 2 comprised subsurface soils with high pH (8.6–9.1), clay content (31.4–39.5%), ESP (11.4–22.3) and $CaCO_3$ (5.8–11.1%).

In valleys, two factors explained 64% of the variability (Fig. 5*a*). Positive relationships were observed between CEC and clay; $CaCO_3$ and ESP; and sHC, OC and BD. Soil pH, $CaCO_3$ and ESP were negatively related with OC and sHC. The grouping (Fig. 5*b*) of soil properties suggested that surface properties (group 1) differed from subsurface properties (group 2). The surface soils had a high content of OC (0.75–1.66%), as expected, and high sHC (4.5 cm h^{-1}); whereas subsurface soils had high clay (33.0–52.4%), pH (9.1–9.4), $CaCO_3$ (7.8–10.2%), ESP (19.4–46.6) and EMP (16.5–26.4). Factor analysis of the three landforms suggested that sHC was influenced by BD, ESP and EMP. From these results, we inferred that impairment of soil

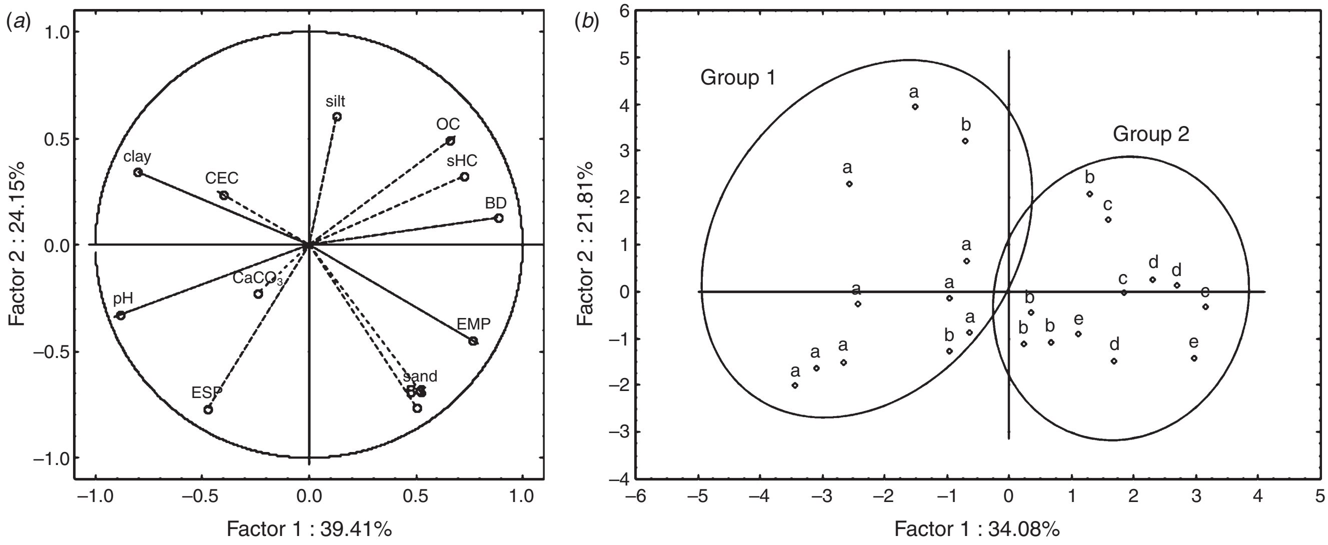

Fig. 5. Results of factor analysis for the valley landform showing the (*a*) relationship between soil properties and (*b*) distribution of surface (group 1) and subsurface soil sample (group 2) values in the factor plot. BD, bulk density; BS, base saturation; CEC, cation exchange capacity; ESP, exchangeable sodium percentage; EMP, exchangeable magnesium percentage; sHC, saturated hydraulic conductivity; OC, organic carbon.

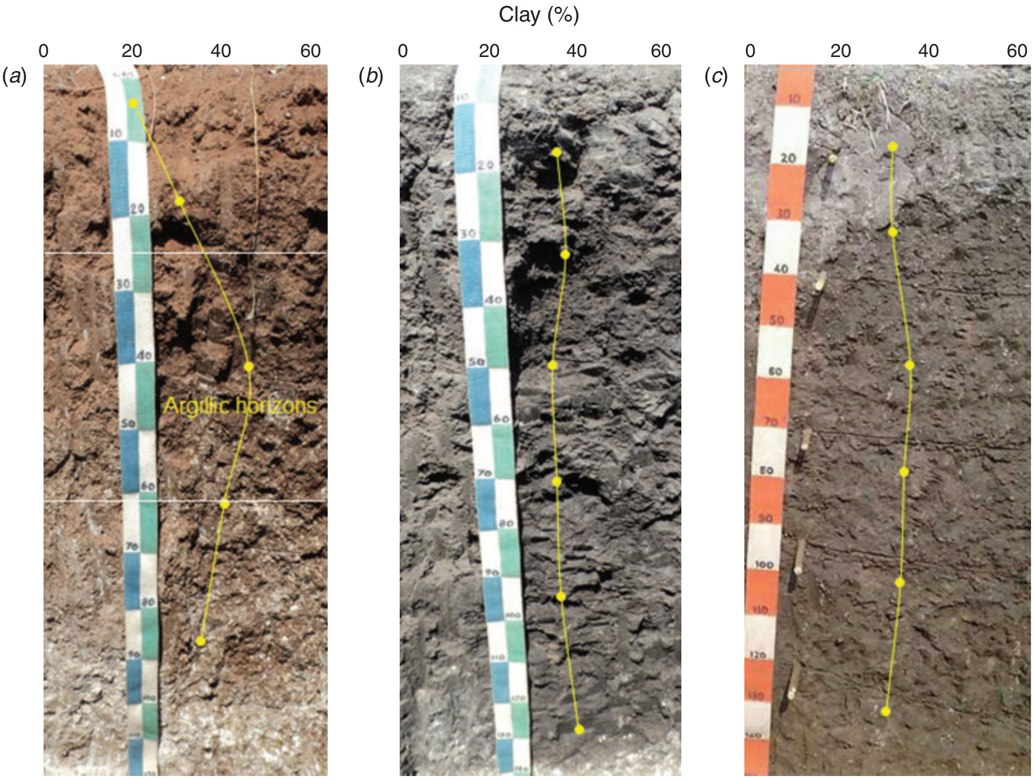

Fig. 6. Typical pedons of major soils with depth distribution of clay content: (*a*) *Typic Haplustalfs* (piedmont); (*b*) *Sodic Haplusterts* (alluvial plain); and (*c*) *Vertic Haplustepts* (valley).

hydraulic conductivity was caused by both physical (BD) and chemical properties (ESP and EMP).

Pedogenic processes and soil–landform relationship

The soils in the piedmont upslope were classified as *Lithic Ustorthents* and *Typic Haplustepts*, which were shallow with depths of 20–50 cm (Appendix 3). Profile development was restricted due to continuous erosion caused by surficial downslope movement of water. These soils were poor in OC (<0.5%) and available nutrients (119–209, 11.4–19.0 and 88–141 kg ha^{-1} of N, P and K, respectively). The downslope soils were classified as *Typic Haplustalfs* and *Typic Rhodustalfs*. These soils were deep and slightly acidic (pH 5.6–6.2), with BS < 50% and a high clay content in B (argillic) horizons (Fig. 6*a*). Recent clay mineralogical studies on similar soils indicate the dominant presence of clay kaolin (not a discrete kaolinite mineral but a 0.7-nm mineral interstratified with hydroxy-interlayered smectites) (Bhattacharyya *et al*. 1997; Chandran *et al*. 2005; Pal *et al*. 2014). The surficial flow resulted in shallow upslope soils (<50 cm) and the eroded materials were deposited downslope, resulting in deep soils. Thus, the variability in soils of piedmonts was due to the movement of water and its re-distribution in the landscape (Hall 1983). The present SAT Alfisols were truncated soil profiles – evident from the upward depth distribution of clay in the solum, a sharp decline in the Ap horizon and thick argillic horizons immediately beneath the Ap horizon (Fig. 6*a*). These Alfisols experienced prolonged weathering in the humid tropical climate of the Upper Cretaceous to Plio-Pleistocene. The Plio-Pleistocene was a transition period when the climate became drier with the rising of the Western Ghats. As a result, the upper layers of these Alfisols formed in the preceding humid tropical climate were truncated by multiple arid erosional cycles (Pal *et al*. 2014). Such modification in the geomorphic surface is also evident from the presence of broken argillans in the solum (Pal *et al*. 2014).

The soils of alluvial plains (*Sodic Haplusterts* and *Typic Ustifluvents*) varied to a great extent due to different pedogenic processes. *Fluvents* are anisotropic (Hall 1983) with irregular deposition of materials. For example, there was respective irregular depth distributions of clay, OC and $CaCO_3$ (%) in soils of alluvial plains (Fig. 7*a–c*). Such irregular distribution of soil properties could be attributed to mass movement, periodic flooding and deposition of multiple sources of materials (Huggett 1975, 1976). These soils have a polygenetic history (Presley *et al*. 2010) with red soils buried under soils developed from basaltic parent material possibly during the humid–arid transition period of the Plio-Pleistocene (Pal and Deshpande 1987; Pal *et al*. 2012).

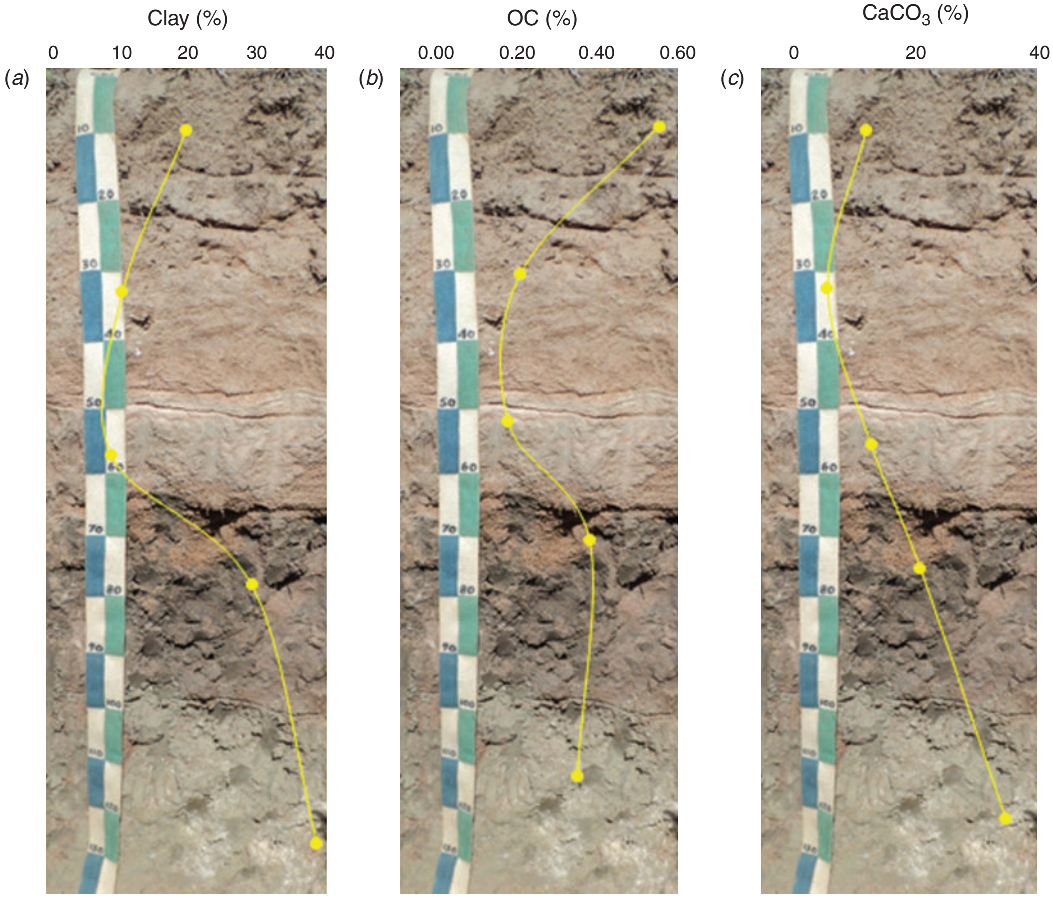

Fig. 7. Pedon representing *Typic Ustifluvents* in alluvial plains showing irregular distribution of (*a*) clay, (*b*) organic carbon (OC) and (*c*) $CaCO_3$.

Table 2. Yield of crops and their relationship with exchangeable sodium percentage and saturated hydraulic conductivity

Numbers in parentheses show standard deviation of crop yield, *n* value (cotton = 21, maize = 16 and pigeon pea = 24).*, Significant at 0.05 level; A, correlation coefficient between ESP and yield; B, correlation coefficient between sHC and yield

Soil	Cotton			Maize			Pigeon pea		
	Yield (kg/ha)	A	B	Yield (kg/ha)	A	B	Yield (kg/ha)	A	B
Typic Haplustalfs	392 (±41)	0.23	0.18	1368 (±141)	0.31	0.24	518 (±39)	0.20	0.31
Typic Rhodustalfs	354 (±38)	0.32	0.45	1255 (±125)	0.19	0.33	450 (±46)	0.27	0.33
Typic Ustifluvents	138 (±18)	–0.58*	0.22	277 (±35)	–0.61*	0.70*	169 (±29)	–0.53*	0.21
Vertic Haplustepts	310 (±40)	–0.61*	0.58*	659 (±52)	–0.49*	0.55*	346 (±48)	–0.75*	0.60*
Sodic Haplusterts	192 (±22)	–0.71*	0.77*	611 (±44)	–0.62*	0.54*	285 (±28)	–0.49*	0.59*

Although the smectitic parent material from the weathering Deccan basalt was deposited in the lower piedmont plains, valleys and micro-depressions during the previous humid climate, the SAT Vertisols were developed in such alluvium during the dry climate of the Holocene period (Fig. 6*b*) (Pal *et al.* 2001, 2006, 2012). The spatial association of the Vertisols with red soils (*Typic Haplusalfs* and *Typic Rhodustalfs*) could be explained through the landscape reduction process as suggested for both humid tropical (Bhattacharyya *et al.* 1993; Beckmann *et al.* 1974) and SAT Vertisols (Pal *et al.* 2012). The formation of Vertisols could be due to flooding of micro-low positions with surface water during brief high-intensity showers that led to wetting and drying cycles. In the initial stages of soil formation, smectite-rich products of weathering were deposited in micro-depressions. Over time, these sites gradually flattened, and internal drainage dominated over surface runoff. The red soils of the present and past humid tropical climate continued to weather, forming kaolin (smectite–kaolinite interstratified minerals). In contrast, Vertisols continued to exist even in the humid tropical climate due to continuous supply of calcium (Ca)-rich zeolite minerals. Because the period of the humid tropical climate ended during the Plio-Pleistocene transition (Pal *et al.* 1989), both smectite and kaolin in SAT Vertisols were preserved to the present (Pal *et al.* 2012). The SAT climate restricted further leaching in Vertisols and caused calcareousness and increased pH and ESP in the subsoils (Pal *et al.* 2012) as regressive pedogenic processes (Pal *et al.* 2013). The soils of valleys are classified as *Vertic Haplustepts* and *Sodic Haplusterts* (Fig. 6*c*) and their formation in SAT climate was explained above. The sodic *Haplusterts* are less intensively cultivated but could be a vibrant agricultural cropping system as they have high BS due to the presence of Ca-zeolites (Bhattacharyya *et al.* 1993, 1999; Pal *et al.* 2006, 2012).

Crop yield limiting factors

Crop yields in *Typic Haplustalfs* and *Typic Rhodustalfs* were comparatively higher than other soils (Table 2). The productivity of cotton, maize and pigeon pea were lowest in *Typic Ustifluvents*. In general, crop yield decreased in the order of *Haplustalfs* > *Rhodustalfs* > *Haplustepts* > *Haplusterts* > *Ustifulvents*. However, the reason for the low crop productivity varied among the soils. *Sodic Haplusterts* and *Vertic Haplustepts* had high clay content (31.4–52.4%) and were alkaline (pH 8.7–9.8) in reaction. The low yield of crops in these soils could be attributed to high ESP and poor sHC (<1 cm h^{-1}).

Typic Ustifluvents have sandy horizons occurring at different depths, hence, root anchoring support and water holding capacity are limiting factors for deep-rooted crops like cotton, maize and pigeon pea. Moreover, these sandy layers (Fig. 7) facilitate the leaching of nutrients along with percolating water and their deposition beyond the root zone, which deprives the crops of nutrients and causes poor plant growth and yield. This fact is supported by the low contents of available nutrients (6.2–87.8, 9.9–15.5 and 52.4–122.3 kg ha^{-1} of N, P and K, respectively) in these soils.

Conclusions

This study was an attempt to understand the interactions between soil properties influenced by dominant pedogenic processes and their effect on crop yield in major landforms of the SAT regions of India. The results suggested that the interaction between water movement and soil materials and their translocation and re-distribution varied in different landforms. The horizon-wise distribution of soil properties in each landform helped to identify the major soil-forming processes that produced heterogeneous soils, suggesting their implications on landscape evolution and soil development. Moreover, subsoil sodicity and poor saturated hydraulic conductivity were identified as the pedological variables limiting crop yield in the study area. Therefore, suitable land management interventions are essential to raise and sustain crop productivity.

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Appendix 1. Frequency distribution of soil properties (non-transformed) in different landforms

BD, bulk density; sHC, saturated hydraulic conductivity; OC, organic carbon; CEC, cation exchange capacity; BS, base saturation; ESP, exchangeable sodium percentage; EMP, exchangeable magnesium percentage; s.d., standard deviation; CV, coefficient of variation; ns, non-significant; **, significant at 0.01 level

Properties	Landform	Mean	Median	Variance	s.d.	CV	Skewness
Sand	Piedmont	61.60	64.10	81.91	9.05	14.69	–0.16**
	Alluvial plain	62.54	57.59	209.55	14.48	23.15	0.22**
	Valley	59.44	60.10	36.32	6.03	10.14	–0.62$^{\text{ns}}$
Silt	Piedmont	7.01	6.00	15.63	3.95	56.37	0.37**
	Alluvial plain	9.41	8.80	14.57	3.82	40.55	–0.27**
	Valley	11.16	12.20	17.98	4.24	37.99	–0.77**
Clay	Piedmont	31.39	30.40	78.39	8.85	28.21	–0.02**
	Alluvial plain	28.04	33.90	191.79	13.85	49.38	–0.20**
	Valley	29.39	30.30	20.80	4.56	15.52	–0.77ns
BD	Piedmont	1.49	1.57	0.02	0.15	10.28	–0.18**
	Alluvial plain	1.52	1.37	0.05	0.23	15.33	0.67**
	Valley	1.40	1.40	0.00	0.07	4.77	0.05ns
sHC	Piedmont	0.97	0.50	1.93	1.39	142.75	2.14**
	Alluvial plain	2.96	0.09	22.90	4.79	161.62	1.71**
	Valley	0.03	0.00	0.00	0.06	187.92	2.01**
pH	Piedmont	6.77	6.66	0.46	0.68	10.00	0.23**
	Alluvial plain	8.87	8.87	0.24	0.49	5.56	0.11ns
	Valley	9.29	9.35	0.13	0.37	3.94	–0.65ns
$CaCO_3$	Piedmont	3.67	3.51	0.53	0.73	19.90	0.13**
	Alluvial plain	6.10	6.17	1.68	1.30	21.24	0.03ns
	Valley	8.71	8.80	20.16	4.49	51.58	2.69**
OC	Piedmont	0.55	0.56	0.03	0.18	32.26	0.22**
	Alluvial plain	0.43	0.35	0.07	0.26	59.88	2.05**
	Valley	0.48	0.45	0.15	0.39	81.85	1.83**
CEC	Piedmont	10.46	10.70	12.00	3.46	33.12	–0.35ns
	Alluvial plain	20.78	18.85	224.27	14.98	72.08	0.01ns
	Valley	22.07	21.75	4.68	2.16	9.80	0.48**
BS (%)	Piedmont	54.32	56.10	220.45	14.85	27.33	0.67**
	Alluvial plain	80.14	85.18	688.56	26.24	32.74	–0.75**
	Valley	98.50	100.66	112.67	10.61	10.78	–0.67ns
ESP	Piedmont	2.01	1.61	1.47	1.21	60.23	1.06**
	Alluvial plain	21.14	20.67	110.40	10.51	49.69	0.42ns
	Valley	25.69	26.21	20.03	4.48	17.42	0.05**
EMP	Piedmont	11.32	11.63	9.83	3.14	27.69	0.94ns
	Alluvial plain	16.94	19.62	73.40	8.57	50.58	–0.20**
	Valley	22.18	21.27	19.30	4.39	19.80	0.61**

Appendix 2. Frequency distribution of soil properties (log-transformed) in different landforms

BD, bulk density; sHC, saturated hydraulic conductivity; OC, organic carbon; CEC, cation exchange capacity; BS, base saturation; ESP, exchangeable sodium percentage; EMP, exchangeable magnesium percentage; s.d., standard deviation; CV, coefficient of variation; ns, non-significant; **, significant at 0.01 level

Properties	Landform	Mean	Median	Variance	s.d.	CV	Skewness
log sand	Piedmont	1.78	1.81	0.00	0.07	3.67	–0.36ns
	Alluvial plain	1.78	1.76	0.01	0.10	5.69	–0.03ns
	Valley	1.77	1.78	0.00	0.05	2.58	–0.84ns
log silt	Piedmont	0.76	0.78	0.09	0.30	38.67	–0.68ns
	Alluvial plain	0.92	0.94	0.07	0.27	28.98	–2.10ns
	Valley	0.99	1.09	0.09	0.29	29.80	–2.78ns
log clay	Piedmont	1.48	1.48	0.02	0.13	8.84	–0.44ns
	Alluvial plain	1.37	1.53	0.08	0.28	20.62	–0.87**
	Valley	1.46	1.48	0.01	0.07	4.97	–1.05ns
log BD	Piedmont	0.17	0.20	0.00	0.05	26.60	–0.27**
	Alluvial plain	0.18	0.14	0.00	0.06	36.42	0.57**
	Valley	0.14	0.14	0.00	0.02	14.35	–0.05ns
log sHC	Piedmont	–0.39	–0.30	0.36	0.60	–153.78	0.27ns
	Alluvial plain	0.95	0.95	0.00	0.02	2.55	0.02ns
	Valley	0.18	0.03	0.01	0.05	53.55	0.27**
log pH	Piedmont	0.83	0.82	0.00	0.04	5.22	0.12ns
	Alluvial plain	–0.88	–0.48	1.20	1.10	–124.87	–0.46ns
	Valley	0.97	0.97	0.00	0.02	1.79	–0.71ns
log $CaCO_3$	Piedmont	0.56	0.55	0.01	0.09	15.74	–0.10ns
	Alluvial plain	0.78	0.79	0.01	0.10	12.33	–0.35ns
	Valley	0.90	0.94	0.03	0.19	20.57	0.45**
log OC	Piedmont	–0.29	–0.25	0.02	0.16	–54.49	–0.84ns
	Alluvial plain	–0.43	–0.46	0.05	0.23	–54.54	–0.15ns
	Valley	–0.46	–0.35	0.14	0.38	–82.43	–0.29**
log CEC	Piedmont	0.99	1.03	0.03	0.18	17.71	–1.17ns
	Alluvial plain	1.14	1.28	0.20	0.44	38.87	–0.39**
	Valley	1.34	1.34	0.00	0.04	3.13	0.36ns
log BS	Piedmont	1.72	1.75	0.01	0.12	6.80	0.10ns
	Alluvial plain	1.87	1.93	0.03	0.18	9.67	–1.24ns
	Valley	1.99	2.00	0.00	0.05	2.46	–0.96ns
log ESP	Piedmont	0.23	0.21	0.07	0.26	111.62	0.13ns
	Alluvial plain	1.26	1.32	0.06	0.25	19.60	–0.61**
	Valley	1.40	1.42	0.01	0.08	5.55	–0.45ns
log EMP	Piedmont	1.04	1.07	0.01	0.12	11.25	0.13ns
	Alluvial plain	1.15	1.29	0.08	0.29	24.93	–0.75**
	Valley	1.34	1.33	0.01	0.08	6.29	0.25ns

Appendix 3. Soil morphology of representative pedons from three landforms

f, fine; f c, fine common; f f, fine few; f m, fine medium; vf f, very fine few; T m c, Argillan, moderate, continuous; T Tk c, Argillan, thick, continuous; T tn p, Argillan, thin, patchy

Depth (cm)	Horizon	Colour	Texture	Structure	Gravel (%)	Cutans	Roots	Effervescence
Upper piedmont 1 – Loamy, skeletal, mixed, hyperthermic, Lithic Ustorthents								
0–17	Ap	Brown (7.5YR4/3)	Gravelly sandy clay loam	Subangular blocky	28	–	vf f	Nil
Upper piedmont 2 – Loamy, mixed, hyperthermic, Typic Haplustepts								
0–18	Ap	Dark brown (7.5YR3/2)	Gravelly sandy clay loam	Subangular blocky	22	–	f f	Slight
18–52	B	Dark brown (7.5YR3/3)	Gravelly sandy clayloam	Subangular blocky	18	–	f f	Slight
Lower piedmont 1 – Fine loamy, mixed, hyperthermic, Typic Rhodustalfs								
0–13	Ap	Dark brown (7.5 YR3/2)	Sandy clay loam	Subangular blocky	3	–	f c	Nil
13–37	Bt1	Reddish brown (5YR4/3)	Sandy clay	Subangular blocky	2.5	T tn p	f c	Slight
37–70	Bt2	Dark red (2.5YR3/6)	Sandy clay	Subangular blocky	3.5	T m c	f f	Slight
70–89	Bt3	Dark red (2.5YR3/6)	Sandy clay	Subangular blocky	5	T tk c	–	Slight
89–120	Bt4	Dark red (2.5YR3/6)	Sandy clay	Subangular blocky	5	T tk c	–	Slight
Alluvial plain 1 – Fine loamy, mixed, hyperthermic, Vertic Haplustepts								
0–18	Ap	Dark grey (10YR4/1)	Sandy clay loam	Subangular blocky	2	–	f c	Strong
18–38	Bw1	Dark grey (10YR4/1)	Sandy clay loam	Subangular blocky	<1	–	f c	Strong
38–69	Bw2	Dark grey (10YR4/1)	Sandy clay loam	Subangular blocky	<1	–	–	Violent
69–94	Bw3	Dark grey (10YR4/1)	Sandy clay loam	Subangular blocky	<1	–	–	Violent
94–122	Bw4	Dark greyish brown (10YR4/2)	Sandy clay loam	Subangular blocky	<1	–	–	Violent
122–151	Bw5	Brown (10YR5/3)	Sandy clay loam	Subangular blocky	<1	–	–	Violent
Valley – Fine, smectitic, hyperthermic, Sodic Haplusterts								
0–20	Ap	Dark grey (10YR4/1)	Clay	Subangular blocky	<1	–	f c	Violent
20–43	Bw1	Very dark greyish brown (10YR3/2)	Clay	Subangular blocky	<1	–	f c	Violent
43–68	Bw2	Very dark grey (10YR3/1)	Clay	Subangular blocky	<1	–	vf f	Violent
68–94	Bss1	Very dark grey (10YR3/1)	Clay	Angular blocky	<1	–	–	Violent
94–131	Bss2	Very dark grey (10YR3/1)	Clay	Angular blocky	<1	–	–	Violent
131–155	Bss3	Dark grey (10YR4/1)	Clay	Angular blocky	<1	–	–	Violent
Alluvial plain 2 – Fine loamy, mixed, hyperthermic, Typic Ustifluvents								
0–9	Ap	Brown (10YR4/3)	Sandy clay loam	Subangular blocky	5	–	f m	Strong
9–19	2A1	Dark yellowish brown (10YR4/4)	Sandy clay loam	Subangular blocky	7	–	vf f	Strong
19–33	2A2	Dark yellowish brown (10YR4/4)	Sandy loam	Subangular blocky	2.5	–	–	Strong
33–72	3A1	Greyish brown (10YR5/2)	Sandy loam	Subangular blocky	1	–	–	Strong
72–88	3A2	Brown (10YR5/3)	Loamy sand	Single grain	–	–	–	Strong
88–118	3A3	Brown (10YR5/3)	Loamy sand	Single grain	–	–	–	Strong
118–160+	B	Dark grey (10YR4/1)	Sandy clay loam	Subangular blocky	–	–	–	Violent