

Sand and clay mineralogy of sal forest soils of the Doon Siwalik Himalayas

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The petromineralogical characterization of the soil was carried out for the 12 soil profiles exposed in the *Shorea robusta* dominated forests of the Siwalik forest division, Dehradun. The quartz was observed as the dominating light mineral fraction (64–80%) in all the profiles studied. Biotite, hornblende, zircon, tourmaline, rutile and opaques comprising of iron minerals constituted the heavy mineral fraction (20%). The mineralogy of both the sand and clay fractions revealed a mixed mineralogy. The clay minerals in the order of their dominance were vermiculite, illite, kaolinite and mixed layer minerals. The presence of vermiculite and illite in appreciable quantities indicates that these were synthesized from the K-rich soil solution, as orthoclase and micas were present in significant quantities in the sand minerals. The mineral suites identified in the study shows that the geological, climatological and topographical factors of the region collectively played a dominant role in their formation and transformation. After critical appraisal of the results, it may be deduced that the mineralogical composition, physicochemical properties and total elemental analysis of the soils do not show any deficiency of the bases and other plant nutrients in general. The inherent fertility of the soil is good as indicated by the sand and clay mineralogy of the soil and the biotite and feldspar together with the mica is an important source of nutrients for the vegetation in the soils of the Doon valley.

1. Introduction

The soil mineralogy and weathering stages are two important phenomena governing host of physico-chemical soil characteristics and thereof having a central role in the management of the (semi-) natural forested ecosystems (Maheshwari and Samra 1984; Raina *et al* 1994). The knowledge of the minerals and their transformations help in understanding the distribution of forest types and their biogeochemistry. It is of great aid in formulating and adopting the success of the necessary silvicultural practices. The forests being of much longer

duration greatly depend on the nutrient bearing minerals in the soil for the continuous and adequate supply for their opportune growth and optimum production. The minerals, more specifically clay minerals, endow soils with unique surface charge chemistry and reactivity. This provides chemical homeostasis to the terrestrial biogeochemical cycles eventually influencing forest growth and regeneration. The nutrients adsorbed on the surface of negatively charged clay minerals are removed from the clay colloids by plant uptake and resultant immobilization, leaching and harvesting regimes. Eventually, the soil complexes are replenished with

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the base cations and other nutrients by weathering and transformation of primary and secondary minerals, apart from atmospheric deposition and biological cycling; collectively maintaining the long-term mass balances of the nutrients in the forested ecosystems.

The comprehension of the mineralogy is fundamental to both the conventional approach of proper understanding and the assessment of weathering, pedogenesis, soil management and potentiality for different uses and modern approach of acid deposition and terrestrial acidification load assessment of the ecosystems (critical loads), global climate change (direct negative feedback relationship between increasing atmospheric CO₂ levels and weathering of Ca-bearing silicate minerals) and harvesting regime concurring with nutrient sustainability in forested ecosystems. For the reasons discussed above, basic properties of the soils and their importance of specialized silvicultural operations for sustainable forest and nutrient management necessitate accurate identification, characterization and knowledge of the soil mineralogical constitution. Therefore, much significance has been attached to the evaluation of mineral reserves in the soils (Yadav and Chand 1967; Singhal *et al* 1982; Banerjee *et al* 1989). It is for this reason that forestry scientists are concerned with the identification of minerals, largely as direct and indirect sources of the plant nutrients; sustained supply of which to the forests, especially for the unfertilized ones, depends on the mineral assemblages that build up the soil. Paramount importance of the mineralogical studies in the forestry is thus clear and merit greater attention in the form of intensified characterization efforts of these most active soil fractions in relation to the natural vegetations in the soil investigations.

The mineralogical studies of the forest soils have not been prioritized in the Indian forestry. Even when it is illustrated that the nature and amount of minerals are largely responsible for the sustained supply of basic cations and anions which eventually influence the buffering capacities of the soils; two factors that are necessary for conditioning the forest growth and productivity are cation exchange capacity (CEC) and base saturation percentage (BSP). Although several mineralogical studies are available in literature from the different soil types of India, very few mineralogical studies have been documented from the forested ecosystems (Dhar and Jha 1980; Dhar *et al* 1988; Raina *et al* 2000), and that too providing very limited information in relation to the forest nutrition. Keeping these points in view, the present study was initiated to learn the mineralogical composition of the soils of the Doon valley forests supporting the mosaics of

Shorea robusta Gaertn. f. (sal). This study will provide information for the sal growing regions and also helps in characterizing the soil mineralogical make-up in relation to the growth and development of the species essential for sustainable forest management.

2. Material and methods

2.1 Study area

The Doon valley is located in the Siwalik Himalayas, lying between latitudes 29°55' and 30°30' N and longitudes 77°35' and 78°24' E. It is about 20 km wide and 80 km long saucer-shaped valley with a geographical area of ca. 2100 km². The valley is longitudinal, intermontane, synclinally depressed bouldery (Thakur and Pandey 2004; Kumar *et al* 2007) filled with coarse clastic fan – Doon gravel of late Pleistocene and Holocene (Puri 1950). The valley is uniformly oriented in the NW–SE direction, with the Lesser Himalayas in the northeast and the Siwalik ranges in the southwest. The two major hydrologic basins of the valley are the Ganga in the southeast with the Song and Suswa as its main tributaries and the Yamuna in the northwest with the river Asan as its main tributary.

The Doon valley falls under the sub-tropical to temperate climate due to its variable elevation. The meteorological data (from the two stations operating in the region, FRI and CSWCRTI) of the last 75 years showed that the average maximum temperature for the Doon valley was 27.65°C and the average minimum temperature was 13.8°C, with average maxima in June (40.00°C) and average minima in January (1.80°C). The area received an average annual rainfall of 2025.43 mm (figure 1). The region receives most of the annual rainfall during June to September, the maximum rainfall occurring in July and August. The soil moisture is usually udic with a thermic to a hyperthermic soil temperature regime according to the Soil Survey Staff (1998).

Geomorphologically, the landforms in the valley are formed due to differential erosion, deposition and tectonic activity varied in time and space. Several workers have described the geomorphology (Medlicoot 1864; Nossin 1971; Nakata 1972) and the lithostratigraphy (Thakur 1995; Thakur and Pandey 2004) of the Doon valley in the past. The present study was initiated in the sal forests developed on the post-Siwalik Doon gravels (older Doon gravel, younger Doon gravel and alluvium) of late Pleistocene to Recent age (Singh *et al* 2001) originating from the erosional action of the rivers and streams. Of the three geological units, the younger

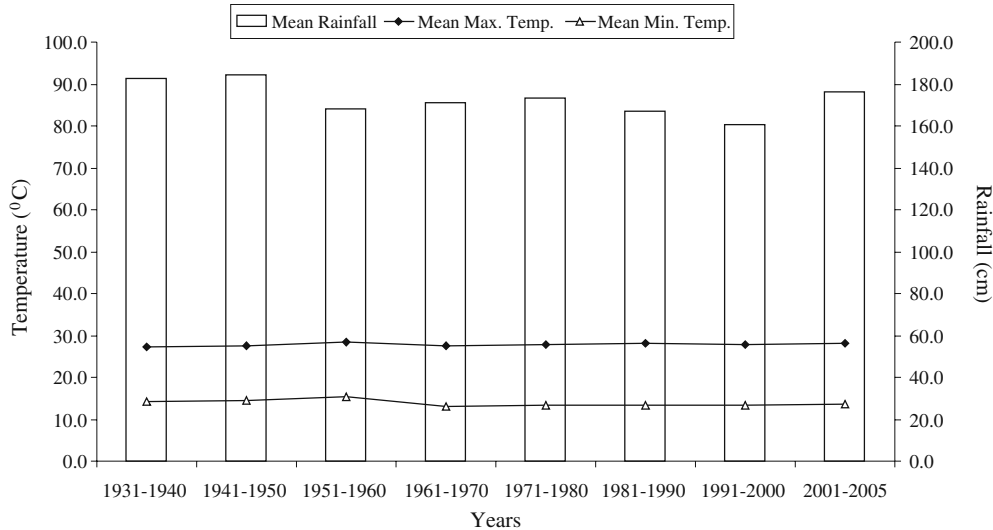


Figure 1. Ombrothermic graph of the Doon valley for the last 75 years (FRI, meteorology).

Doon gravels occupy the central and a major part of the valley. They occur in the form of large fans, formed by the reworking of the oldest Doon gravels, also known as the principal Doon fans (Bartarya 1995). A poorly sorted mixture of clay, sand and very large boulders characterize this region. In addition to this, the soft sandstones and the quartzite boulders and pebbles are intermixed with the alluvial and colluvial deposits (Sharma *et al* 1989). The alluvium consists of very fine clay and partly sand.

The soils of the Doon Siwalik were developed on the deep alluvial deposits with parent material derived from the Doon alluvium. It consists of accumulated beds of clays, boulders, pebbles and sand with the admixture of water-borne small to big size stones in the subsoil in varying proportions (Singhal *et al* 1982; Yadav *et al* 1973). This alluvium was deposited by the multilateral, multi-braided channel system. All the study sites investigated in the present study were heavily forested with the northern tropical moist deciduous forest having an admixture of a variety of species in the four-tier structure (top canopy, middle strata, understory shrub and herb strata) with *S. robusta* as the predominant species. The study was carried out within the four forest ranges – Barkot, Thano, Lachhiwala and Asarori (table 1 and figure 2). The vegetation around each profile was enumerated by laying quadrats, a summary of which is presented in table 2 and the details were reported elsewhere (Gautam *et al* 2006; Gautam 2007).

2.2 Methodology

Twelve soil profiles were exposed in the study area representing the study sites in the four for-

est ranges. Representative soil samples were collected from all the horizons for the physicochemical analysis (Black 1965). Air-dried soil samples were separated from the sand, silt and clay fractions following gravity sedimentation. They were initially treated with HCl and H₂O₂ (6% and then 30%) to remove the carbonates and the organic matter respectively and finally treated with (NaPO₃)₆ before dispersion by ultrasonic shaking. Fine sand fractions (0.25–0.05 mm) were treated with oxalic acid to remove the iron coatings. Prior to mounting on the glass slides using canada balsam, fine sand fractions were further fractionated and separated using the standard procedure into light and heavy fractions using bromoform (sp. gravity 2.82 mgm⁻³). Finally, for the qualitative and quantitative estimation of the lighter and heavier minerals, mounted slides were studied under the Leitz Labour Lux Pol II petrological microscope (Cady 1965).

The clay fractions were separated from the bulk samples by the settling technique (Hardy and Tucker 1988). The free iron oxides were removed following Mehra and Jackson (1960). Thereafter, separated clay suspensions (<2 μm) were treated with K and Mg acetate in order to isolate the peaks of the individual clay minerals. Subsequently, the clay suspensions were placed on the glass slides and allowed to dry to get the oriented clay minerals. Further, two more pre-treatments were employed for the complete elucidation of the clay minerals involved in discriminating the expanding and non-expanding minerals by the ethylene glycol solvation and the heat treatments (550°C for 2 h) to distinguish the otherwise similar and overlapping peaks of vermiculite, chlorite and kaolinite. The clay mineralogical compositions were established from the

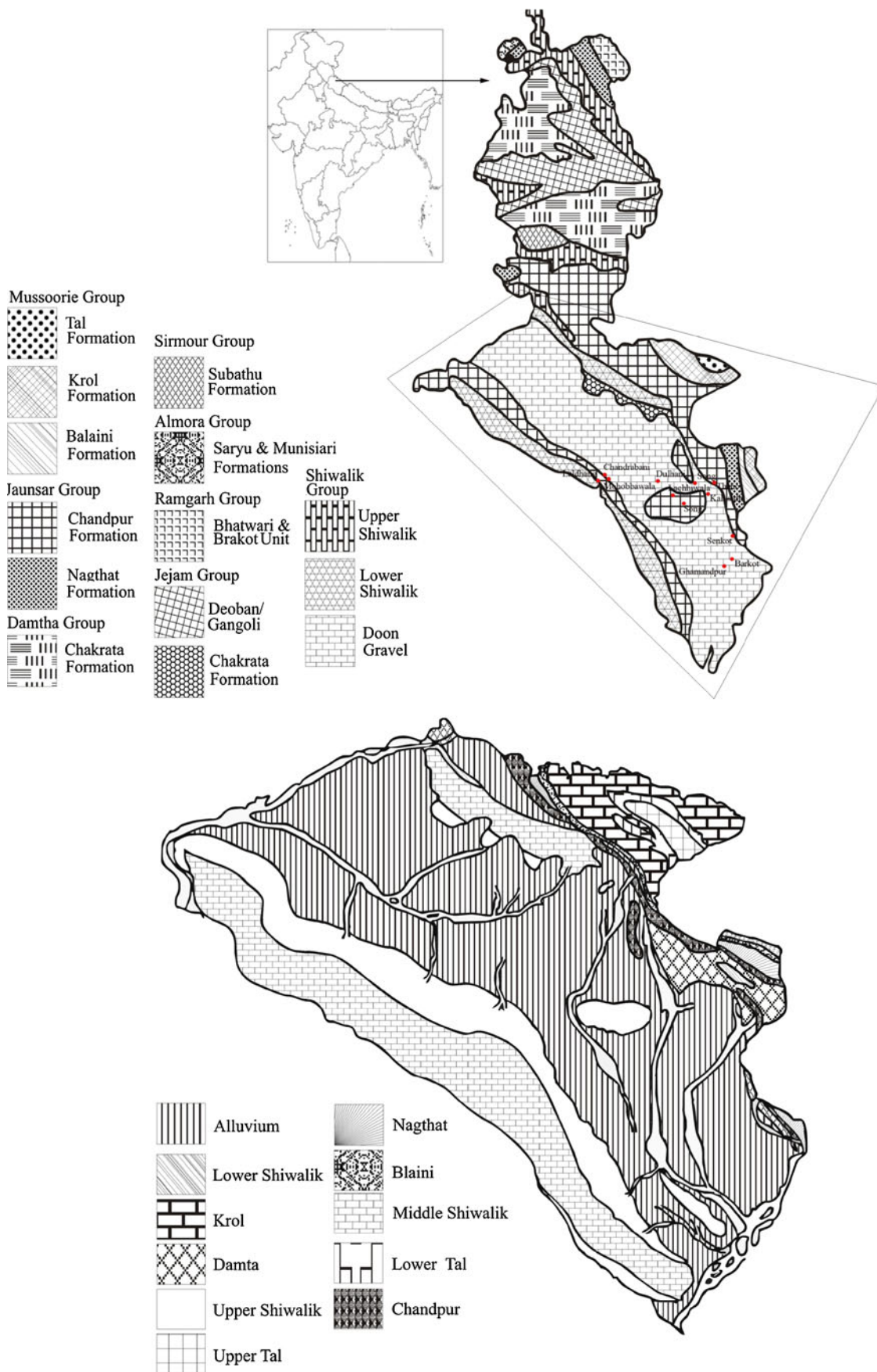


Figure 2. Geological location map of the Doon Valley. Points showing the study sites within *Shorea robusta* dominated forests. Barkot, Thano, Lachhiwala and Asarori are the four forest ranges chosen in the present study.

Table 1. Site characteristics for the 12 sites under the *Shorea robusta* forests in Doon valley.

Forest range	Sites (blocks)	Point coordinates	Elevation (m)	Physiography	Land use
Barkot	Senkot	E 78° 13'55.3" and N 30° 09'40.9"	524	Valley bottom	Forest
	Barkot	E 78° 13'18.4" and N 30° 09'52.9"	439	Valley bottom	
	Ghamandpur	E 78° 13'44.6" and N 30° 07'20.0"	447	Valley bottom	
Thano	Thano	E 78° 11'39.5" and N 30° 14'51.3"	735	Valley bottom	Forest
	Kalusidh	E 78° 10'54.9" and N 30° 13'45.0"	638	Valley bottom	
	Lambirao	E 78° 10'48.3" and N 30° 14'16.6"	663	Valley bottom	
Lachhiwala	Song	E 78° 07'56.0" and N 30° 12'48.9"	524	Valley bottom	Forest
	Lachhiwala	E 78° 06'38.6" and N 30° 13'37.2"	596	Valley bottom	
	Dulhani	E 78° 04'45.6" and N 30° 14'58.6"	664	Valley bottom	
Asarori	Mohabbawala	E 78° 58'41.8" and N 30° 15'22.6"	617	Valley bottom	Forest
	Chandrabani	E 78° 58'36.8" and N 30° 15'24.9"	620	Valley bottom	
	Laldhang	E 78° 57'55.0" and N 30° 15'12.8"	710	Valley bottom	

peak positions obtained by diffraction using a PANalytical XPert Pro X-ray diffractometer with Cu K α operating at 45 kV and 40 mA (λ 1.54443 Å) at a step size of 0.02° 2θ and a scan speed of 1° 2θ /min and scanned from 1–40° 2θ .

The clay minerals were identified following Brown and Brindley (1980), Moore and Reynolds (1997) and Wilson (1987). The relative percentages of the individual clay minerals were semi-quantitatively estimated based on the I_{001} peak (Deepthy and Balakrishnan 2005). The peaks used for the semi-quantification are 14 Å of the vermiculite, 7.1 Å of the kaolinite and 10 Å of the illite (clay mica). Among Mg and K-treated samples, the strongest peaks were selected for the relative percentage calculations of the clay mineral of interest. For geochemical analysis of the soil, <2 mm air-dried fractions were crushed and pulverized into a very fine powder form from which powder-pressed pellets were prepared using polyvinyl alcohol. The analysis was made with the wavelength dispersive SRS-300 sequential XRF spectrometer, Siemens at the Wadia Institute of Himalayan Geology, Dehradun. All the other parameters undertaken in the study were performed employing the standard methods.

3. Results

3.1 Soil characteristics

3.1.1 Morphological characteristics

The solum of the Doon valley is of variable depth, medium to deep, depending upon the physiography and relief. The thickness of the non-calcareous solum was 90–130+. In all the profiles studied the structure of the upper horizons (A_0/A_1 – A_2)

were medium moderate granular, which changes to medium moderate blocky down the profile, with plenty of fine roots. The highest concentrations of the fine to medium root systems were noticed in the B-horizon in comparison to the epipedon and the C-horizon. The hard and compact C-horizon is the reason behind the less abundance and restricted penetration of the roots. In Barkot, lower horizon had a platy structure. The profile characteristic consistencies were usually non-sticky friable but moist in the epipedon, which changed from a sticky friable to a sticky firm at the lower depths, ascribable to the fair amount of clay contents. In the Senkot, Ghamandpur, Barkot and Laldhang, lower horizons were sticky, firm, compact and moderately hard. Contradistinctive were dry, non-sticky and loose to friable in consistence with the sloping ground profiles of the Thano, Song and Dulhani. The soil profiles studied on the hill slopes were shallow with weakly developed horizons, especially B-horizon, with obscured boundaries and were very bouldery. These are most certainly developed on the relatively younger sediments brought down and deposited by the erosion from the Himalayan foreland. The stoniness and the size of the pebbles, gravels, cobbles and boulders of varying sizes increased with the depth of the profiles. These surfaces being at the lower topographic position are subjected to the periodic sedimentation and thus represent an unstable part of the landscape. Hence, both the soil development and the sedimentation go hand in hand, interrupting one another (Jassal *et al* 2000). Furthermore, because of the gradient, soils at these sites suffer from erosion during the rains, thus exhibiting limited profile development. The presence of the gravels and the stones in the sub-surface of these solums effectively reduces the volume of the soil that cascades into the diminished nutrient and water retention capacity compared to

the counterpart solum exposed on the flat terrain. In comparison, profiles on the flat terrain (valley bottom) or gentle slopes were comparatively well developed and moister. These profiles developed on the alluvium derived from the Himalayan Foreland showed prominent, about 40–70 cm thick, moist argillic B-horizon free from stones at the lower depth.

The absence of A_{00} , inconspicuous or superficial A_0 and thin A_1 and A_2 horizons noticed in all the profiles examined apparently shows high microbial activity operating within these forests. All the same, a high disturbance regime of these forests is also one of the salient reasons for the minuscule presence of the upper organic horizons. Because of the relatively higher stability due to moderate gradient and linear to concave configuration of the land surface, the valley basin profiles experienced uninterrupted leaching and illuviation of the mobile soil constituents in the solum. These surfaces thus represented better-developed soils, showing relatively deep soil profile with the mollic epipedon and the argillic sub-surface horizons. The colour of the soil was usually dark brown at the surface due to the incorporation of the organic matter, which changed to pale brown in the middle of the solum, which again changed to yellowish/greyish brown and then to brown/dark brown towards the end of the profile. Except the upper B-horizon, the colour of the rest of the B-horizon was brown to dark brown with diffused or wavy boundaries. The colour of the C-horizon was also dark brown and the conditions were moist in most of the profiles, except the shallow profiles of the Lachhiwala and Song, where it was light brown. The brown to dark brown B-horizons were characterized by a distinct increase in the fine-grained material and illuvial concentration of the clayey material. A thick dark brown eluviated sub-surface horizon shows the possible migration of the clay contents and the organic matter within the profile. The mottling was seen in the lower horizons, generally more noticeable in the upper B-horizon (dark black spots), but completely absent from the profiles studied on slopes. The soil within the forested region remains moist for most part of the year. It is because of the diminished evaporation from the forest floor owing to appreciable tree density (table 2) and high total canopy cover provided by the (co-)dominant trees, ground vegetation and accumulation of litter and organic mass on the forest floor.

3.1.2 Physiochemical characteristics

The physical and chemical properties of the soils are given in table 3. The percentage value of the size fraction varied from 54.41% to 71.95% for sand; 7.51% to 21.14% for clay and 9.18%

Table 2. Site characteristics for the 12 sites of Doon valley.

Forest range	Sites (blocks)	Species	Density of sal (trees/ha)	Dominant vegetation (Sal)			Moisture						
				Avg. DBH (cm)	Avg. height (m)	Total basal area (m ² /ha)	Density (tree/ha)	Organic matter	Plant litter	Surface	Sub-surface		
Barkot	Senkot Barkot	Sal, Syzygium	947	36.21	25.68	11.01	357	Little	High	Compact	Moderately	Moist	
		Sal, Syzygium, Terminalia	1330	36.05	30.02	12.45	407	Heavy	Moderate	Compact	Moderately	Moist	
Thano	Ghamandpur	Sal, Terminalia	1067	26.19	22.39	4.8	283	Little	Moderate	Moderate	Compact	Moderately dry	Moist
		Pure Sal	460	29.79	28.06	10.53	430	Moderate	Moderate	Loose friable	Moist	Moist	
		Sal, Syzygium	1083	32.24	22.85	12.68	607	Moderate	High	Compact	Moderately	Moderately	
		Sal, Litsea, Ehertia, Miltia	567	34.25	24.60	8.57	310	Moderate	High	Compact	Moderately	Moist	
Lachhiwala	Song	Syzygium, Sal, Terminalia	527	39.20	22.34	4.46	123	Moderate	High	Loose friable	Moderately dry	Moist	
		Sal, Syzygium	1167	26.98	24.75	8.06	470	Moderate	High	Compact	Moderately	Moist	
Asarori	Lachhiwala Dulhani	Sal, Syzygium	583	34.94	24.27	11.88	413	Moderate	High	Loose friable	Moderately	Moist	
		Sal, Syzygium	870	25.71	21.91	11.39	860	Moderate	Moderate	Compact	Moderately dry	Moist	
Asarori	Mohabbawala Chandrabani Laldhang	Sal, Syzygium	653	28.48	22.93	9.87	517	Moderate	High	Compact	Moderately dry	Moist	
		Sal, Ehertia	700	30.07	23.16	7.10	333	High	High	Compact	Moist	Moist	

Table 3. Physical and chemical properties of soil in various study sites. Values in parenthesis are standard deviation.

Blocks/sites	Texture (%)			pH (H ₂ O)	Bulk density (gm/cm ³)	Porosity (%)	Exchangeable cations (Cmol (p+) kg ⁻¹)				Exch. Ca:Mg	BS (%)	Tot. N (%)	Avg. N (%)	Org. C (%)	Org. matter (%)	C:N
	Sand	Clay	Silt				CEC	Ca	Mg	K							
Senkot	67.93 (±2.51)	18.91 (±7.72)	13.00 (±1.00)	6.13 (±0.31)	1.34 (±0.06)	39.52 (±3.53)	11.70 (±0.40)	5.25 (±0.10)	3.88 (±0.33)	0.51 (±0.01)	1.36 (±0.14)	82.43 (±3.00)	0.12 (±0.02)	0.02 (±0.01)	1.80 (±0.40)	3.10 (±0.69)	15.32 (±1.22)
Barkot	64.56 (±1.98)	21.14 (±5.24)	14.15 (±3.55)	5.64 (±0.04)	1.20 (±0.06)	39.07 (±4.09)	15.47 (±0.95)	5.47 (±0.42)	3.75 (±0.42)	0.46 (±0.04)	1.47 (±0.14)	62.61 (±0.72)	0.11 (±0.01)	0.02 (±0.01)	1.82 (±0.44)	3.14 (±0.76)	16.95 (±3.37)
Ghamandpur	65.91 (±2.19)	20.54 (±6.33)	13.30 (±2.28)	5.34 (±0.34)	1.34 (±0.05)	34.79 (±1.83)	18.10 (±0.62)	4.75 (±0.25)	3.93 (±0.62)	0.42 (±0.01)	1.22 (±0.16)	50.4 (±0.06)	0.08 (±0.01)	0.03 (±0.01)	1.45 (±0.15)	2.50 (±0.26)	20.12 (±6.87)
Kalusidh	59.73 (±1.87)	18.21 (±8.64)	21.66 (±1.35)	5.50 (±0.34)	1.20 (±0.09)	43.16 (±1.04)	18.37 (±0.06)	4.82 (±0.12)	2.79 (±0.46)	0.52 (±0.00)	1.75 (±0.28)	44.28 (±2.92)	0.19 (±0.05)	0.02 (±0.01)	1.69 (±0.20)	2.92 (±0.34)	9.23 (±3.02)
Thano	54.41 (±1.51)	17.70 (±7.21)	27.43 (±0.77)	5.63 (±0.78)	1.21 (±0.05)	42.79 (±3.41)	16.30 (±0.40)	5.58 (±0.14)	3.33 (±0.44)	0.53 (±0.02)	1.69 (±0.22)	58.02 (±3.83)	0.10 (±0.01)	0.01 (±0.01)	1.62 (±0.30)	2.79 (±0.52)	15.64 (±1.86)
Lambidhar	56.95 (±2.08)	19.55 (±4.59)	23.16 (±1.37)	6.21 (±0.08)	1.17 (±0.02)	43.74 (±0.76)	13.32 (±1.87)	5.28 (±0.06)	4.23 (±0.28)	0.67 (±0.02)	1.25 (±0.07)	77.88 (±9.10)	0.11 (±0.02)	0.02 (±0.01)	1.74 (±0.32)	2.99 (±0.55)	16.41 (±2.99)
Song	65.62 (±2.53)	20.45 (±6.61)	13.71 (±1.92)	6.46 (±0.13)	1.14 (±0.10)	50.60 (±3.72)	14.03 (±0.35)	5.38 (±0.34)	4.38 (±0.15)	0.53 (±0.04)	1.23 (±0.08)	73.43 (±4.41)	0.16 (±0.05)	0.02 (±0.01)	1.80 (±0.25)	3.10 (±0.43)	11.48 (±2.54)
Lachhiwala	57.50 (±0.86)	23.95 (±8.85)	18.02 (±1.96)	6.38 (±0.30)	1.20 (±0.02)	47.25 (±0.79)	14.40 (±0.78)	5.12 (±0.75)	3.96 (±0.17)	0.49 (±0.05)	1.29 (±0.20)	66.7 (±8.42)	0.10 (±0.05)	0.02 (±0.01)	1.45 (±0.49)	2.49 (±0.84)	15.03 (±1.90)
Dulhani	62.04 (±1.75)	17.51 (±7.15)	20.27 (±1.12)	5.85 (±0.12)	1.21 (±0.03)	41.07 (±3.09)	11.97 (±3.11)	3.96 (±0.26)	4.02 (±0.67)	0.61 (±0.29)	1.00 (±0.15)	73.97 (±12.81)	0.11 (±0.03)	0.02 (±0.01)	1.89 (±0.64)	3.25 (±1.11)	17.05 (±1.10)
Mohhabawala	69.53 (±1.62)	19.40 (±8.22)	10.84 (±2.15)	5.53 (±0.06)	1.26 (±0.05)	42.01 (±4.81)	10.30 (±0.90)	3.97 (±0.39)	3.45 (±0.29)	0.47 (±0.11)	1.15 (±0.09)	76.87 (±7.63)	0.12 (±0.04)	0.02 (±0.01)	1.51 (±0.53)	2.60 (±0.91)	14.46 (±1.11)
Chandrabani	71.95 (±1.15)	18.74 (±5.58)	9.18 (±0.54)	5.60 (±0.14)	1.29 (±0.02)	43.09 (±2.70)	14.60 (±0.56)	5.23 (±0.27)	3.99 (±0.75)	0.59 (±0.04)	1.35 (±0.29)	67.35 (±6.88)	0.12 (±0.02)	0.02 (±0.01)	1.48 (±0.23)	2.55 (±0.40)	13.00 (±3.63)
Laldhang	68.08 (±1.10)	19.82 (±9.11)	11.92 (±3.97)	5.96 (±0.05)	1.30 (±0.02)	39.11 (±2.11)	15.63 (±0.65)	4.42 (±0.23)	4.03 (±0.22)	0.61 (±0.02)	1.10 (±0.04)	57.95 (±2.62)	0.14 (±0.03)	0.02 (±0.01)	2.17 (±0.91)	3.74 (±1.57)	15.09 (±4.61)

Table 4. Mineralogical composition of sand light and heavy mineral fractions.

Sites	Depth	Q	OF	PF	M	Q/ F	Q/ M
		% by weight of total light sand fractions					
Barkot	0-9	70.3	7.0	6.4	16.3	5.3	4.3
	9-27	70.2	8.3	6.2	15.3	4.8	4.6
	27-89	68.4	9.5	7.1	15.0	4.1	4.6
	89-160	67.6	10.4	5.4	17.6	4.3	3.8
Senkot	0-11	73.4	9.4	7.3	9.9	4.4	7.4
	11-19	74.5	10.5	5.0	10.0	4.8	7.5
	29-92	71.6	10.5	5.9	12.0	4.4	5.9
	92-157	66.6	9.4	8.1	15.9	3.8	4.2
Ghamandpur	0-12	72.6	8.4	9.2	9.8	4.1	7.4
	12-32	66.6	11.2	5.3	16.9	4.0	3.9
	32-101	70.1	10.5	7.3	12.1	3.9	5.7
	101-130	65.1	11.4	7.1	16.4	3.5	3.9
	130-162	64.3	10.5	8.0	17.2	3.5	3.7
Kalusidh	0-4	80.2	6.3	4.1	9.4	7.7	8.5
	4-26	79.1	6.8	4.3	8.4	6.8	9.4
	26-47	76.2	5.3	5.3	13.2	7.1	5.7
	47-93	77.4	6.3	3.4	12.9	7.9	6.0
	93+	75.3	7.3	5.3	12.1	5.9	6.2
Thano	1-3.5	78.6	8.5	4.3	8.7	6.2	9.0
	3.5-19	79.7	7.3	4.1	8.9	6.9	8.9
	19-58	76.5	5.2	4.6	13.7	7.8	5.6
	58-88	74.3	6.5	4.3	14.9	6.9	4.9
	88-115	76.3	7.4	4.7	11.6	6.3	6.5
	115+	70.4	6.3	5.1	18.2	6.2	3.9
Lambirao	0-5	78.2	6.5	3.7	8.9	7.7	8.8
	5-21	78.1	8.4	3.9	8.1	6.3	9.6
	21-51	76.6	5.0	5.7	12.2	7.1	6.3
	51-97	72.4	6.3	4.8	11.9	6.5	6.1
	97-118	74.1	7.4	5.2	12.1	5.9	6.1
	118+	72.7	6.3	5.2	16.3	6.2	4.5
Song	0-5	81.2	5.3	5.2	9.7	7.5	8.3
	5-28	78.1	6.2	5.6	8.6	6.7	9.1
	28-46	77.2	7.4	4.2	12.2	6.7	6.3
	46-95	77.4	5.3	4.6	13.2	7.8	5.9
	95+	76.3	7.4	5.0	12.7	6.2	6.0
Lachhiwala	1-8	78.5	6.5	6.1	8.9	6.2	8.8
	8-35	77.6	8.4	5.0	9.0	5.8	8.6
	35-110	79.3	7.3	4.2	9.2	6.9	8.6
	110-140	80.4	6.4	4.3	8.9	7.5	9.0
Lakshmansidh	0-2	72.6	8.6	5.9	12.9	5.0	5.6
	2-6	68.4	9.5	7.2	15.9	4.1	4.3
	6-12	71.5	6.5	5.2	16.8	6.1	4.2
	12-92.5	73.5	8.4	5.1	13.0	5.4	5.7
	92.5	75.5	7.4	5.2	11.9	6.0	6.3
Mohabbawala	0-2	70.5	9.5	5.0	15.0	4.9	4.7
	2-37	71.6	8.5	4.2	15.8	5.7	4.5
	37-90	68.9	7.6	5.7	17.7	5.1	3.9
	90+	67.6	6.7	4.8	20.9	5.9	3.2
Chandrabani	0-3	74.5	7.5	8.1	9.9	4.8	7.5
	3-35	70.6	7.4	9.3	12.7	4.2	5.5
	35-86	72.3	6.8	7.6	13.1	4.9	5.5
	86+	71.4	8.9	6.9	13.1	4.6	5.5
Laldhang	0-6	69.6	8.8	5.8	15.8	4.7	4.4
	6-24	70.1	7.7	6.1	16.1	5.1	4.4
	24-73	68.4	9.5	5.0	17.1	4.7	4.0
	73-138	71.6	7.5	5.1	15.8	5.7	4.5
	138+	67.6	9.5	5.2	17.7	4.6	3.8

Note -: absent; Q: quartz; OF: orthoclase feldspar; PF: plagioclase feldspar; M: mica; CM: chloritized mica; C: chlorite; B: biotite; H: hornblende; Z: zircon; T: tourmaline; R: rutile; Opq: opaque minerals; G: garnet; UN: unidentified minerals.

Opq	B	CM	C	G	Z	T	R	H	UN	Z/B	R/B	G/B
% by weight of total heavy sand fractions												
20.5	20.2	7.6	14.6	2.0	2.8	2.5	1.5	5.0	23.0	0.1	0.0	0.1
18.5	16.4	7.8	20.3	2.5	2.0	3.8	2.9	3.6	22.0	0.1	0.2	0.1
17.6	17.6	6.8	21.4	–	2.5	3.2	1.5	4.6	25.0	0.1	0.0	0.0
16.4	19.8	6.2	20.9	1.5	2.4	3.0	2.5	5.5	22.0	0.1	0.1	0.0
21.6	19.3	5.6	16.6	1.9	3.0	3.5	1.0	4.5	23.0	0.1	0.0	0.1
20.8	20.0	4.6	22.0	0.2	2.5	2.2	0.5	4.0	23.0	0.1	0.0	0.0
19.5	15.4	5.8	22.3	1.5	2.0	3.8	2.9	4.6	22.0	0.1	0.2	0.1
18.4	18.8	7.2	19.9	–	2.4	4.0	2.0	6.5	21.0	0.1	0.1	0.0
21.0	19.9	5.3	16.9	1.9	3.1	3.4	0.9	4.6	23.0	0.1	0.0	0.1
21.8	20.0	3.6	22.0	0.2	2.7	2.0	0.5	5.0	22.0	0.1	0.0	0.0
20.0	14.9	6.5	21.6	–	3.0	3.7	2.0	5.6	23.0	0.2	0.1	0.0
18.6	17.6	5.8	23.4	–	3.5	2.2	1.5	4.4	23.0	0.2	0.1	0.0
17.4	19.0	8.0	18.9	1.5	2.4	4.1	2.0	5.5	21.0	0.1	0.1	0.0
25.8	20.5	4.8	19.0	1.0	2.6	4.1	–	2.1	20.0	0.1	0.0	0.0
24.0	13.7	5.8	19.8	0.8	1.2	3.3	2.0	4.3	25.0	0.1	0.1	0.0
24.2	21.7	3.3	23.2	2.1	3.3	4.0	–	3.1	15.0	0.1	0.0	0.1
24.5	13.6	6.1	24.9	1.9	2.9	4.5	–	4.5	17.0	0.2	0.0	0.1
26.0	13.2	5.6	22.0	–	3.1	4.9	1.5	5.5	18.0	0.2	0.1	0.0
24.8	21.5	4.8	19.0	0.9	2.5	4.9	–	1.1	21.0	0.1	0.0	0.0
23.0	20.9	3.8	22.2	2.0	2.9	4.4	1.1	1.5	18.0	0.1	0.0	0.1
25.8	12.1	7.8	17.9	0.8	0.9	4.1	0.9	4.3	25.0	0.1	0.0	0.0
23.1	19.9	4.8	23.5	1.9	3.3	3.8	–	3.1	17.0	0.1	0.0	0.1
24.5	13.6	7.1	23.9	1.7	2.8	4.3	–	4.5	18.0	0.2	0.0	0.1
26.6	12.6	7.6	20.0	–	2.9	4.8	–	5.5	20.0	0.2	0.0	0.0
23.8	21.5	4.5	19.8	1.1	2.7	4.4	–	2.1	20.0	0.1	0.0	0.0
24.4	14.1	5.9	18.7	0.9	1.7	4.5	1.8	4.3	24.0	0.1	0.1	0.0
25.1	17.7	4.4	25.3	2.2	3.2	4.2	0.9	3.1	14.0	0.2	0.0	0.1
23.5	13.9	7.3	23.8	1.5	2.7	3.8	0.9	4.7	18.0	0.2	0.0	0.1
25.8	14.2	6.1	22.1	0.9	2.4	4.2	1.3	5.2	18.0	0.1	0.1	0.0
26.1	13.2	5.1	22.3	–	3.3	4.3	1.3	5.3	19.0	0.2	0.1	0.0
21.3	18.5	4.8	22.6	2.3	3.6	4.1	1.2	1.5	20.0	0.2	0.0	0.1
24.9	13.0	6.6	19.1	1.9	0.9	3.5	1.9	4.3	24.0	0.1	0.1	0.1
27.3	11.0	7.6	17.1	2.9	0.9	3.5	–	4.3	25.0	0.1	0.1	0.1
21.1	18.9	4.8	23.5	2.0	3.5	3.9	0.1	3.1	19.0	0.2	0.0	0.1
24.6	11.6	7.6	20.0	–	3.1	4.9	1.6	5.5	21.0	0.2	0.1	0.0
25.9	12.0	7.6	18.1	1.9	1.9	2.5	1.9	4.3	24.0	0.1	0.1	0.1
27.2	10.7	6.2	15.1	2.0	1.9	3.5	2.5	5.5	25.0	0.1	0.2	0.2
24.9	13.0	6.6	19.1	1.9	0.9	3.5	1.9	4.3	24.0	0.1	0.1	0.1
27.3	11.0	7.6	17.1	2.9	0.9	3.5	–	4.3	25.0	0.1	0.0	0.2
22.8	20.5	4.8	19.0	1.0	2.6	5.0	0.1	1.1	23.0	0.1	0.0	0.0
21.0	19.9	3.8	22.2	2.0	3.1	4.5	1.2	1.0	21.0	0.1	0.1	0.1
23.8	11.1	7.8	17.9	0.9	1.1	4.2	1.1	5.3	27.0	0.1	0.1	0.1
21.1	18.9	4.8	23.5	2.0	3.5	3.9	0.1	3.1	19.0	0.2	0.0	0.1
24.6	11.6	7.6	20.0	–	3.1	4.9	1.6	5.5	21.0	0.2	0.1	0.0
21.8	19.7	5.5	18.9	1.0	0.9	3.1	0.3	2.2	28.0	0.0	0.0	0.0
22.7	20.8	4.9	19.9	0.9	–	2.1	0.0	1.9	28.0	0.0	0.0	0.0
20.1	17.6	5.0	20.1	–	1.1	4.0	0.0	2.4	40.0	0.1	0.0	0.0
23.6	17.0	6.7	21.5	0.8	1.5	3.9	–	1.8	24.0	0.2	0.0	0.0
19.7	20.1	6.7	17.7	1.8	–	3.6	1.5	2.4	28.0	0.0	0.0	0.1
20.0	18.7	5.9	18.6	1.6	1.5	2.8	0.7	1.7	29.0	0.1	0.0	0.1
18.8	19.7	4.7	16.5	0.9	1.1	2.9	0.0	1.5	34.0	0.1	0.0	0.0
21.1	16.4	5.4	18.4	1.0	–	3.0	0.1	1.8	43.0	0.0	0.0	0.0
19.3	19.0	4.5	19.3	2.0	1.6	3.3	–	2.6	28.0	0.1	0.0	0.1
17.5	17.5	4.9	16.5	1.8	1.1	2.7	1.1	2.4	35.0	0.1	0.0	0.1
20.6	18.3	5.0	17.4	1.6	–	2.6	–	1.9	33.0	0.0	0.0	0.1
21.1	16.3	6.7	18.9	–	–	2.7	1.0	2.0	31.0	–	0.0	0.0
23.4	15.0	6.9	21.4	–	0.8	2.9	0.9	1.8	27.0	0.1	0.0	0.0

to 27.43% for the silt. The texture classes were either loamy sand (Senkot and Chandrabani) or sandy loam (Barkot, Ghamandpur, Kalusidh, Thano, Lambidhar, Song, Lachhiwala, Dulhani, Mohhabawala and Laldhang). In general, the top soils were relatively coarse textured, being sandy loam, compared to the sub-soils, which were loamy sand, where clay contents increased gradually with depth. The bulk density from the various study sites showed fine-textured soil surface, except in the Thano, Song and Dhulhani where the soil surface was coarse textured. Table 3 indicates maximum porosity percentage in Song (50.60%) and minimum porosity percentage in Ghamandpur (34.79%).

The $\text{pH}_{\text{H}_2\text{O}}$ specify that the soil of all the sites were moderately acidic, ranging from 5.34 (Ghamandpur) to 6.46 (Song). The critical appraisal of table 3 show maximum CEC present in the soil of the Kalusidh ($18.37 \text{ Cmol (p+) kg}^{-1}$) closely followed by Ghamandpur ($18.10 \text{ Cmol (p+) kg}^{-1}$), and minimum in the Lambidhar ($9.97 \text{ Cmol (p+) kg}^{-1}$). Among exchangeable cations the Ca^{2+} was in the range between $5.58 \text{ Cmol (p+) kg}^{-1}$ (Thano) and $3.96 \text{ Cmol (p+) kg}^{-1}$ (Dulhani); Mg^{2+} between $4.38 \text{ Cmol (p+) kg}^{-1}$ (Song) and $2.79 \text{ Cmol (p+) kg}^{-1}$ (Kalusidh) and K^+ between $0.67 \text{ Cmol (p+) kg}^{-1}$ (Lambidhar) and $0.42 \text{ Cmol (p+) kg}^{-1}$ (Ghamandpur). The BSP at the Senkot was as high as 82.43%, whereas in the Kalusidh it was just 44.28%. The Doon soils have appreciable quantity of OM, varying between 2.49 (Lachhiwala) and 3.74 (Laldhang). The organic carbon (OC) was highest in Laldhang (2.17%) and lowest in Ghamandpur and Lachhiwala (both having 1.45% OC). Within the profiles surface horizons contain a higher amount of OC and nitrogen (N) compared to the sub-surface horizons. The minimum and the maximum total nitrogen (tot. N) was noticed in the Ghamandpur (0.08%) and Kalusidh (0.19%), respectively. Whereas, the available nitrogen varied between 0.01 (Thano) and 0.02–0.03 (in the rest of the sites). The C:N ratio for the 12 sites ranged from 9.23 in Kalusidh to 20.12 in Ghamandpur.

3.2 Sand mineralogy

The light minerals constituted more than 80% of the total fine sand fractions. Different minerals identified in the light fractions were quartz, feldspars (plagioclase and orthoclase) and mica (muscovite). The quartz was dominantly present in all the profiles, contributing 64–80% towards the light mineral fractions (table 4). The grains were generally rounded to sub-rounded, containing cracks, having iron coatings and usually

showed a wavy pattern with the striations. The feldspars were the other abundant group of minerals; accounting for 9 to 18.5% of the total light fractions. The orthoclase feldspar was invariably higher (5–11.4%) than the plagioclase feldspar (3.4–9.2%). The plagioclase feldspar crystals were clear and free from fracture, inclusion and showed multiple twinning, whereas the orthoclase feldspars were highly fragmental because of their physico-chemical instability. The altered and weathered grains exhibited pitted appearance on the surface. Some grains appeared clouded due to ferruginous coating. The mica (muscovite) is also present in considerable proportions as the light mineral fractions due to its inheritance from the parent material.

The samples from all the analysed profiles show moderate diversity within the heavy mineral assemblages, consisting mainly of opaques, biotite, chlorite, chloritized mica and relatively minor percentages of hornblende, tourmaline, zircon, rutile and garnet. Heavy minerals constitute 20% of the minerals. Opaque minerals comprised 16–27% of the total heavy mineral fractions followed by biotite, viz., 11–22%. Opaque minerals dominated the heavy mineral fractions – a group name of iron bearing minerals like ilmenite, hematite and magnetite. Biotite was present in all profiles in appreciable amount and its distribution decreased with depth. Calcite constituting 14–25% of the total heavy mineral fractions was commonly present in all soil profiles and its contents increased with depth. The mineralogical examination of heavy fraction shows the presence of ultra stable zircon and rutile, the most resistant mineral in small quantities in all the horizons of the profiles. Hornblende was present in minor amounts, viz., 1–6.5% and its distribution was almost uniform throughout the profile. Tourmaline was present in small quantities and even in traces, does not indicate any alteration due to its most resistant nature and it acts as an inherent ingredient of soils. The presence of garnet in much less quantities could have possibly been derived from metamorphic source. In general, the distribution of heavy mineral fractions in the soils seemed to be a function of nature of the parent materials. Different weathering ratios like zircon/biotite, rutile/biotite and garnet/biotite show some possible trend of weathering, particularly with respect to heavy minerals.

3.3 X-ray diffraction analysis

The 14 \AA peak, which disappears on heating the sample to 550°C showed the presence of the vermiculite. The minerals had a characteristic 14 \AA d -spacing under both the Mg and K saturation which

confirmed that it corresponds to the non-swelling type vermiculite. The 2.37–2.45 Å peaks also indicated the presence of the vermiculite. The reduction of the 14 Å peak intensity reflections on the K-saturation showed the presence of a small amount of chloritized vermiculite. A slight shift of the 14 Å to 14.5–14.7 Å on glycolation and complete absence or inconspicuous peak of the 14 Å intensity after heat treatment to 550°C substantiated the presence of the vermiculite. The presence of the first-order peak at 9.98–10.1 Å and the strong and sharp second- and third-order peaks at 4.98–5 Å and 3.33–3.35 Å, respectively in all the profiles studied indicated a universal presence of the illite in all the profiles, with more or less uniform distribution throughout the profile. The sharpness of the peak intensities in all the samples suggests that the illite is one of the dominant clay minerals. The basal (001) peak at 7.1 Å indicated the presence of the kaolinite together with the (002) and subsequent peaks at 3.54 and 2.28 Å, respectively. Although, peaks remained unaffected after glycerol treatment, peaks disappeared on heating the sample up to 550°C. This is attributed to the loss of crystalline characteristics of the kaolinite. No exact reflection and the poorly defined diffraction area between 14.0 Å and 10/9.98 Å might be due to the presence of the illite/mica-vermiculite disordered mixed layer mineral that collapses to the 10 Å when samples were heated to 550°C, but remain on glycolation. These mixed layers seem to have been formed as a result of weathering of the biotite. The presence of free quartz in the clays was evident from the 4.21 to 4.26 Å peaks. In some of the samples, 3.2 Å peak showed the presence of feldspar as another non-clay accessory mineral (Moore and Reynolds 1997).

4. Discussion

4.1 Physicochemical properties

The Doon sal forest soils were characterized by high exchangeable Ca^{2+} , Mg^{2+} , OC, OM and a fair amount of N. Owing to high OM and a fair presence of the clay and clay colloids, these soils in the first instance show good fertility status, with adequate supply of Ca^{2+} , Mg^{2+} except K^{+} , which otherwise show diminishing availability. The BSP of the exchange complex is high owing to the presence of cations where exchangeable Ca^{2+} is sufficiently high, especially in the surface layers on account of intensive turn-over of this element through leaf-litter, despite its low total presence in the soil.

According to Meiwes *et al* (1986) and Ulrich (1991), soils of the Doon sal forests with pH 6.5–

5.0 lie in the silicate buffer range showing adequate nutrients supply and reduced cation losses in the leaching. Moderate clay contents offer appreciable surface area to hold the dissolved ions thus restricting the loss of ions from leaching. The ratio of CEC (by NH_4OAc at pH 7) to clay > 0.60 showed that these soils lie in the superactive class. The lesser exchangeable K^{+} (0.49–0.67 Cmol (p+) kg^{-1}) compared to its total counterpart (1.45–4.11%) indicated the presence of the unweathered primary minerals containing this element in the soil. The A-horizon in all the profiles showed higher CEC and exchangeable cations, particularly Ca^{2+} , compared to the subsequent horizons, which is obvious by the presence of a fairly high OM in the epipedon compared to the lower horizons. Much higher exchangeable Ca:Mg ratio was noticed in the upper horizons compared to the lower horizons. This shows that a large quantity of the litter turnover has a definite role in the replenishment of the base cations and in the development of the soil.

The BSP showed that the soils of the Doon valley lies in the buffer range of 50–80%, with the absence of the carbonate minerals. Parenthetically it indicates moderate to high fraction of the base cations at the exchange sites and the presence of relatively high content of slow weathering minerals. Most of the buffering that was provided to the soil comes from the two ions, viz., Ca^{2+} and Mg^{2+} . Appreciable BSP signifies a definite role of photorecycling in the replenishment and recycling of the base cations in the soils inclusive of the intrinsic soil forming processes – weathering and atmospheric deposition. This is ascribed to the gradual accretion and decomposition of the leaf litter. The buffering capacity within the soil was provided by the cation exchange between the soil solution and the surface of the minerals and the OM. The OM on the surface and within the surface horizon was in humified stage indicating the conduciveness of the microenvironment for the humification. The total annual litter-fall in the Doon sal forest ranges from 760 $\text{kg}^{-1}\text{ha}^{-1}\text{yr}^{-1}$ (Gautam 2007) to 5608 $\text{kg}^{-1}\text{ha}^{-1}\text{yr}^{-1}$ (Kukreti 2002). Nevertheless, a thin layer of the litter and a small A-horizon indicate the degree of rapidity and intensity of the decomposition, mineralization, humification and humus formation. Typical physiography with two distinct climatological conditions, tropical humid in the summer to somewhat temperate humid in the winter, facilitate that mineralization and humification go alongside as a major soil forming process within the Doon valley. Because of the variable elevation in the Doon valley, humification rather than mineralization is assumed to have a slightly greater role in the soil formation despite it falling under the tropics (Singhal *et al* 1976;

Singhal and Sharma 1979, 1983; Ghosh *et al* 1980). The multi-tier forest habitat has a high net productivity. This supports high organic productivity due to continuous addition of the leaf litter, enriching the soil with OM, which is evidently the reason for the higher OC. The presence of OM directly influences the OC. Therefore, the highest and the lowest values were the same as were in the case of OM. The high C:N ratio shows faster decomposition of the OM under the climatological and edaphic conditions prevalent within these forests, with low levels of N in the soils and thus very low or negligible N-leaching.

4.2 Sand minerals and weathering and depositional environment

The soils of the study area were developed on the alluvium brought down by the rivers from the Himalayas. There seems to be a relation between the geological history of the sedimentary material and the type of clay mineral assemblages present. There is an axiomatic relationship between the soil substrate, pedogenic history and the suites of the clay mineral present.

The mineralogy of these profiles and the rounded to sub-rounded grains indicate that the materials have travelled a long distance before getting deposited (Dhar *et al* 1988; Purohit *et al* 1993) in the Doon valley. The Doon valley is bounded by the Lesser Himalayas in the northeast and by Siwalik hills in the southwest. Hence, their source lies in the rocks of these formations (Chandel and Singh 2000; Thakur and Pandey 2004). Besides, the Doon valley is a watershed bounded by the Ganga in the east and Yamuna in the west with many tributaries that traverse the valley longitudinally and several seasonal streams (*rau*). Hence sediments in the Dehradun were deposited by multilateral, multiple braided channel system having high rate of aggradation and high avulsion frequency (Kumar *et al* 2003). The rock system through which these rivers and their tributaries flow is bouldery conglomerate inter-bedded with variable thickened bands of ferruginous clay and of sandstone of the upper Siwalik or tertiary age, which towards the northern side of the valley consist of quartzite and schists overlain by the large scree deposits. And so, the minerals of the fine sand fractions are partly due to the mineralogy of the rock systems of the tract across which the rivers are flowing and partly due to the deposition of the sediments.

The relatively high quartz within the surface horizons than in the underlying horizons could be due to more surface weathering and their development from the parent materials derived from

the Himalayas or their inheritance from reworked sediments (Pettijohn 1984). The observation gained further support from the decreasing quartz/feldspar ratios with the depth in all the pedons. The light and heavy mineral suites of these profiles indicate that the soil minerals that are fast to weather through the geochemical weathering and are a potential source of the plant nutrients (feldspar, micas, biotite, hornblende, etc.) are less in proportion than the minerals which are resistant to weathering and are stable (quartz, garnet, tourmaline, zircon, etc.). The appraisal of light and heavy sand mineral fractions deduced that in comparison of quartz apparently other minerals are present in less significant proportions. The abundance of quartz indicates minimal modification of sediments by transport and chemical weathering. Both the feldspar and mica occur in appreciable amounts, which are presumably due to slow geochemical weathering of these minerals under the prevailing conditions of high precipitation and altitude and the acidic content of the soil. The relative distribution of feldspars within the profiles is mainly influenced by variations in the parent materials and the weathering activity. The high percentage of mica at the bottom and lower percentage at the top within the profiles indicate intense weathering at the surface. It is also evident from the greater quartz/mica ratio at the surface horizon compared to the sub-surface horizons. Calcite, being the most weatherable mineral and in large quantities at the sub-surface horizon coupled with the relatively faster decomposition indicates its enrichment at the sub-surface horizon due to leaching. Biotite being the weatherable mineral altered more readily to chloritized mica (also vermiculite in clay) which remained almost constant throughout the soil pedons. The higher percentage of Opq in the heavy mineral fractions is interesting. In all the profiles studied, the higher concentration of Opq was noticed within the sub-surface horizons in comparison to the surface horizon. This indicates greater weathering in the sub-surface of the pedon. Deviation to this trend was noticed within the profiles of Barkot. Increasing percentage of the Opq with the depth in all the profiles may be due to the pedogenic processes of decomposition, leaching at the surface and enrichment and synthesis along with the braunification and rubification at the bottom horizon. Their presence at the surface and sub-surface horizons indicates movement of water inside the profile (Raina *et al* 1998). When adjudged separately from that of other minerals, the high percentage of the opaques together with the other ultra-stable minerals, i.e., tourmaline and zircon indicates the high intensity of weathering. With increase in the weathering

intensities, the unstable and weatherable minerals in the soil complex undergo alteration and their concentration start diminishing with simultaneous increase in the opaques and other weathering resistant minerals. On the contrary, per cent of light weatherable minerals in good amounts in the soil profiles are not in agreement with the above-stated fact of intense weathering, depicting that soils are relatively at their moderate stage of development. The presence of mica, feldspar, biotite and hornblende in the sand and the dominance of vermiculite and mica-illite in clay fractions (discussed in the preceding section) indicate that the parent materials have not yet been weathered fully and the soil formation subsequently has not reached maturity (Sahu and Dash 1991). An appreciably good amount of mica, feldspar, biotite and chlorite show slow geochemical weathering that these minerals are subjected to, which otherwise seems counterintuitive under the climatic conditions existing within the valley.

On the whole distribution of the heavy mineral fractions in the soils seemed to be a function of the nature of parent materials. These heavy minerals can survive several transportational, depositional and erosional cycles and are accompanied in the sediments which can also survive several such attrition cycles. It is, therefore, most likely that the fractions of heavy mineral assemblage depicting intense weathering owe their origin from either the already weathered sediments of metamorphic and igneous rocks and reworked sediments, source area of which exist in the Lesser Himalayas, supposedly deposited during Middle Miocene to Late Pleistocene period of Quaternary, both early and late and/or these being chemically inert, ultra stable minerals such as zircon, rutile and tourmaline are most likely to survive post-depositionally in relatively good percentages and are commonly found in soils. All the profiles lie in the foothills of Siwaliks in the south and that of Lesser Himalayas in the north and hence their source lies in the rocks of these formations. A number of studies state the role of alluvial-fluvial-colluvial depositional conditions in sediment enrichments of the Doon valley (Nossin 1971; Nakata 1972; Kumar and Ghosh 1991; Kumar *et al* 2003; Suresh *et al* 2004). Lithostratigraphy of Dehradun shows that the various geological units of the valley belongs to recent alluvium, which occupy a major share of the Doon valley to Late Pliocene to Middle Miocene Siwaliks, hard and soft sandstones interbedded with mudstones, boulders and conglomerates and pretertiary (Lesser Himalaya) sandstones, quartzites, slates and phyllites (Thakur 1995). Garnet, tourmaline, hornblende are constituents of the Siwalik group of rocks (Wadia 1966; Raju and Dehadrai

1962) and fluvial sediments of the Siwaliks are composed dominantly of quartz, feldspar, micaeous minerals, and non-opaques, zircon, rutile, tourmaline (Kumar *et al* 2003; Suresh *et al* 2004). Almost identical mineralogy of rock formation of the Lesser Himalayas in the north of the Dehradun valley (Raina *et al* 2000; Husain 2006) and in the fine sand fractions has been noticed (Raina *et al* 1998). The matching mineralogy appeared from the alluvium of the present soils underpin that mineralogy of these profiles is from the inheritance of material, mainly from reworked sediments, low to high grade metamorphic rocks and also from the igneous rocks (Maheswari *et al* 1981). Also, it is evident from the sub-rounded to rounded morphology of the minerals that they are transported and deposited through the alluvial and fluvial systems from various source terrains of Siwaliks and Lesser Himalayas dominated by quartzites, gneisses, phyllite, shale and slate. Despite the varied sources the fine sand is dominated by 60–80% of quartz with noticeable feldspar and mica. These features suggest that sediments of different origin, which are the parent material of the soils, undergo mixing and subsequent homogenization during more than one cycle of transportation and deposition.

The occurrence of mixed mineralogy depicting weatherable, moderately stable and ultra stable minerals describing heterogeneity in weathering intensities help us to conclude that in these soils which are developed on the alluvium, it reflects the differences of the provenance material rather than that of pedogenic processes. To sum up, minerals reflect geogenic origin rather than pedogenetic and a relatively undersized soil forming pedological history which supposedly has taken place after the sediments have been deposited. This interpretation can be substantiated from the sub-rounded to rounded grains of minerals illustrating transportation.

4.3 Clay minerals and weathering environment

The clays from all the four forest ranges, representing the alluvium, is a mixture of identical clay mineral suites – vermiculite, illite, kaolinite and mixed layer mineral with a very small proportion of accessory non-clay free quartz and feldspar (figure 3). The semiquantitative analysis of the clay minerals showed the abundance of clay minerals in the order of vermiculite, illite, kaolinite, mixed minerals with quartz and feldspar as accessory minerals (table 5). The results of the present study are in agreement with the previous studies from other sal ecosystems indicating a similar array of clay minerals together with sand minerals in the soil (table 6).

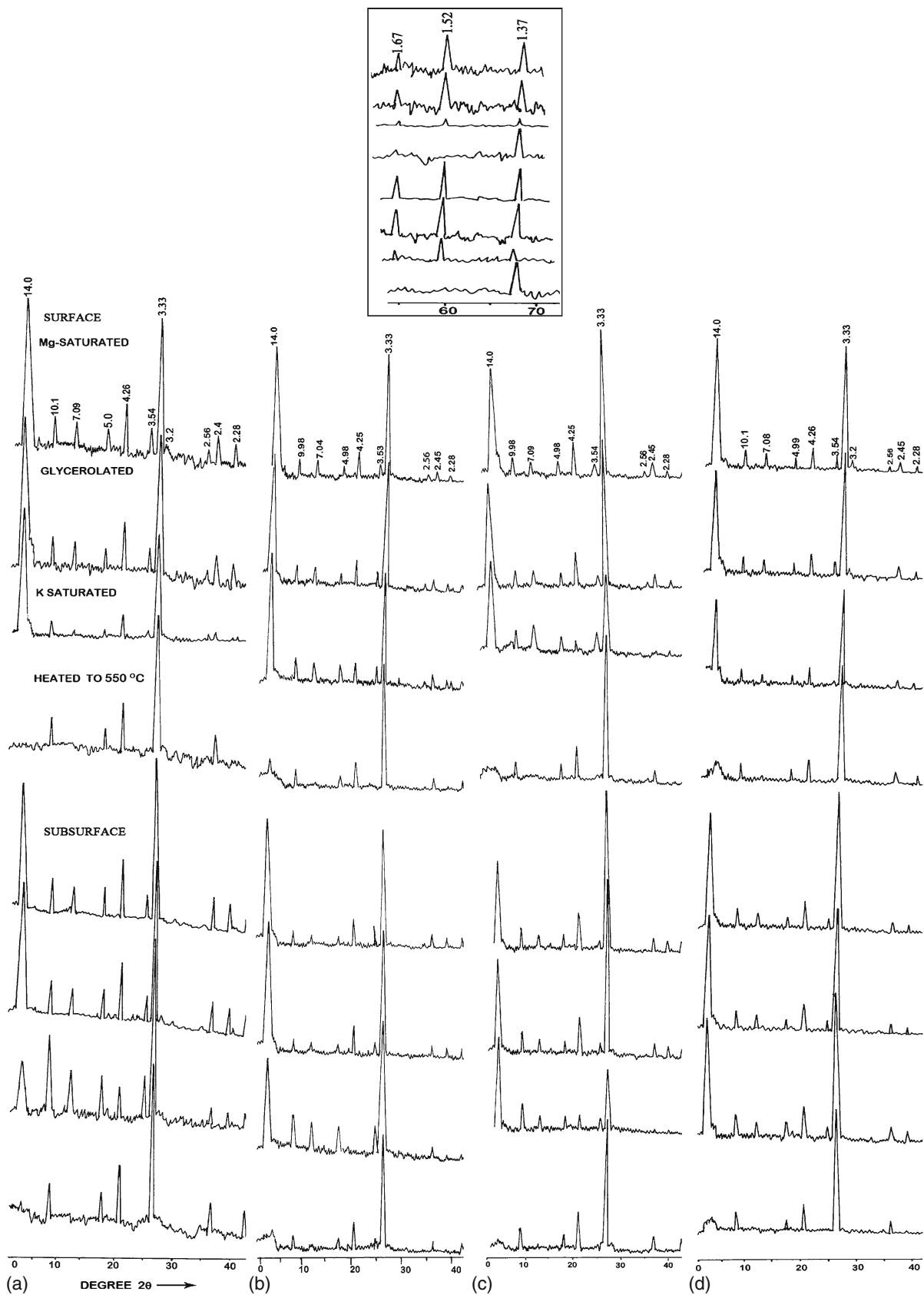


Figure 3. X-ray diffractogram of surface and sub-surface clay fractions of (a) Barkot, (b) Thano, (c) Lachhiwala, and (d) Asarori forest ranges of the Doon Valley. In the inset is shown the prominent (0 6 0) order peak of illite showing dioctahedral nature of illite.

Table 5. Relative semi-quantitative clay (%) mineralogical information.

Site	Layer	Clay minerals (%)				Non-clay accessory minerals	
		Ver	Ill	Ka	MX	Qtz	Feld
Barkot	Surface layer	52	25.0	12.0	3.0	7.0	1
	Sub-surface layer	48	29.0	13.0	2.0	8.0	Tr
Thano	Surface layer	53	21.5	16.5	1.5	7.0	0.5
	Sub-surface layer	47	24.0	21.0	2.0	6.0	Tr
Lacchiwala	Surface layer	55	22.0	14.0	2.0	7.0	Tr
	Sub-surface layer	53	23.0	15.5	2.0	6.5	Tr
Asarori	Surface layer	53	25.0	13.0	3.0	6.0	Tr
	Sub-surface layer	49	25.5	17.0	2.0	5.5	1

Ver: vermiculite; Ill: illite; Ka: kaolinite; MX: mixed layer mineral; Qtz: quartz; Feld: feldspar; Tr: traces.

No major differences in the peak intensities of the surface and sub-surface diffractograms showed a uniform distribution of the clay mineral suites throughout the profile. This may be due to the uniform climatic conditions and the source (parent rock as well as deposition environment and mechanisms) in the study area. Two basic physico-chemical conditions, which could have aided the formation of clay minerals in the Doon environment, are water-rock interactions and those of the weathering and precipitation (Velde 1992). This is evident from the (sub-)tropical to temperate climatic conditions prevalent in the valley with the summer temperature touching $>40^{\circ}\text{C}$ together with good drainage conditions and appreciable OM accumulation. High rainfall results in higher water/rock ratio, which lowers the Si^{4+} ion concentration, as well as the metals/ H^{+} ratio and enhances chemical weathering, thus favouring the formation of the kaolinite directly from the silicate minerals. On the contrary, the water/rock ratio decreases with low rainfall, as a result of which Si^{4+} ion concentration and metals/ H^{+} ratio comes into equilibrium with the rock. Under this condition $\text{K}^{+}/\text{H}^{+}$, $\text{Na}^{+}/\text{H}^{+}$, $\text{Ca}^{2+}/\text{H}^{+}$ and $\text{Mg}^{2+}/\text{H}^{+}$ ratios increase, favouring alternation of the biotite (and muscovite) to clay-mica/illite (Grim 1968). The formation of the mixed layer minerals is attributed to the moderately warm and humid conditions prevalent in the Siwaliks. In the moderately warm and humid conditions degradation of the biotite proceeds mainly by the vermiculitization with non-ordered mixed layer illite-vermiculite formation (Lisitsa and Tikhonov 1969).

The presence of vermiculite in the soil owes its origin to the weathering of the biotite, which is present in an appreciable amount in the sand fraction. The narrow, sharp and centered 10 \AA peak shows well crystallinity of illite (WCI) (Meunier and Velde 2004) with large crystal size and large diffraction domains and the absence of interstratifications with other clay minerals (Weaver 1961;

Grim 1968). The high intensity of 3.3 \AA peak as compared to 10.1 \AA reveals the polymorphic mica (Samra 1982). The presence of illite in the clay fraction can be ascribed to appreciable amount of the mica in the sand. Further peaks remained unaffected by the glycerol treatment or by heating the sample to 550°C , thereby confirming that the degree of hydration of the mica was not much. A slight discrepancy of 10 to 9.98 \AA in the peak position for sub-surface samples point out that the illite might have undergone degradation (Samra 1982). A strong 4.98 \AA (002) peak and (060) peak at the 1.50 – 1.53 \AA show dioctahedral nature of the illite. This is further corroborated by the intensity ratios $I_{(001)}/I_{(002)} \leq 4$ (Graff-Petersen 1961). The kaolinite is an important weathering product and a common constituent in most soils of low latitudes (Dixon 1989), formed by the *in-situ* chemical weathering of the underlying rocks and from colluvial materials derived from highly weathered profiles (Varajao *et al* 2001). The kaolinite might have been developed by the *in-situ* weathering of the feldspars after deposition in warm and humid climate prevalent in the Doon valley. The presence of vermiculite in appreciable amounts compared to the other clay minerals, particularly kaolinite shows that the soils under the Doon sal is in the intermediate stage of weathering. However, pedogenic transformation and alteration of the minerals have taken place in the soil. The lack of swelling upon glycolation excludes the presence of expandable clay minerals within the mixed layer minerals. No part of the 10 \AA peak moves toward 14 \AA after glycolation, but 14 \AA is still observed and this may be due to the vermiculite. A sharp and symmetrical peak shows that the mixed layer minerals are not present in appreciable amounts and there was very little weathering after the deposition.

The transformation and alteration of minerals into other minerals is assumed to have followed the sequence of biotite/mica \rightarrow illite \rightarrow mixed layer

Table 6. Comparative mineralogical studies with other sal forested ecosystem.

Area	Climate	Light mineral	Heavy	Clay minerals	References
Dehradun, Uttarakhand	Subtropical				Maheshwari and Samra (1984)
(a) Shahmansur		Q, F, M, Ce	OM, Ky, T, Z, E	I, S, K, ML	
(b) Chilawali		Q, F, M	OM, Ky, T, Z, E, G, H	I, S, K, ML	
(c) Dudhli		Q, F, Ce, M	OM, T, Z, Ky	I, V, C, K, ML	Banerjee et al (1988*, 1989†)
South Kheri, Uttar Pradesh	Subtropical	*Q, M	*C, OM, T, Z, G, H, E	†K, Ge, Gi, IMM	Raina et al (1998)
Dehradun, Uttarakhand	Subtropical			—	
(a) Mahipur		Q, F, M	OM, B, C, CM, Z, G, H		
(b) Ladpur		Q, M, F	OM, B, C, CM, H, T, Z		
(c) Rajpur		Q, M, F	OM, B, C, CM, H, T, Z		
Haldwani, Uttarakhand	Subtropical	—	—	I, PM, V, C	Samra (1982)
(a) Guljapani				I, PM, V	
(b) Sunmanthapla				I, PM, K	
(c) Gunia Rao				I, PM, K	
(d) Naghan				I, K, CH, Q, V	Husain (2006)
Mussourie, Uttarakhand	Temperate	—	—	V, I, K, ML	Present study
Doon Valley, Uttarakhand	Subtropical	Q, F, M	OM, B, C, CM, Z, G, H		

Note. Q: quartz, M: mica, F: feldspar, OM: opaque minerals, Ce: chert, B: biotite, CM: chloritized mica, C: calcite, G: garnet, Z: zircon, T: tourmaline, R: rutile, H: hornblende, E: epidote, I: illite, PM: polymorphic mica, Ge: geothite, V: vermiculite, K: kaolinite, IMM: integrated micaceous minerals, Ky: kyanite, S: smectite, ML: mixed layer minerals.

minerals → vermiculite → kaolinite, under comparatively wet moisture regime and slight acidic conditions. However, direct transformation/alteration of feldspar → kaolinite (Eswaran and Bin 1978); biotite/mica → kaolinite or orthoclase (K-feldspar) → illite cannot be ruled out. The presence of biotite in the sand shows that the vermiculite is the weathering product of the biotite, formation of which is favoured by good drainage conditions and strong leaching environment; conditions that are apparently present in the soil environment of the sal forests. Though the effects of vegetation on the alteration and neo-synthesis of the minerals are difficult to separate from that of the climate, the presence of high OC, OM and high organic acids (Singhal et al 1976; Sharma 1982; Singhal and Sharma 1983), wet moisture regime, high leaching rates, high transpiration loss rates, high floristic diversity and root biomass suggest that the natural vegetation has a definite role in defining the clay mineralogy of the sal forested regions, actively and/or passively. The natural vegetation might have interacted with the biotite or mica and is responsible for the alteration or neo-synthesis of the vermiculite and/or kaolinite.

Hence, the humid, warm and cold alternating climates with the high summer as well as winter rainfall in the region are the major factors which favoured the formation of the existing clay mineral in the soils of the Doon valley. In association with the geological (capacity factor), climatological and topographical factors (intensity factor), water/rock ratio, i.e., the amount of rainfall, are probably the most important in determining the type of clay minerals present in the soils of the Doon valley, where floristic diversity together with the temperature help to determine the direction of the alteration.

4.4 Forest nutrition and total elemental analysis

The presence of weatherable minerals, which are precursor primary minerals for the clay minerals in a fairly good amount, reflects a good inherent fertility of the soil dominated by the sal. It is also true that despite the preponderance of the quartz in the mineral suite together with the low-level of other weatherable minerals, growth, development and regeneration of the sal and its associate species under the existing soil conditions do not appear to have been hampered or impaired.

To know the current productivity of the soil total elemental analysis was carried out. Table 7 shows the average total elemental composition for the soil fractions (<2 mm) of the horizons derived from the Doon valley sal forests and reveal that the major constituent of the soil was silica, SiO₂ >60%. The higher percentage of SiO₂ noticed in the

surface horizons shows a more siliceous surface horizons compared to the sub-surface horizons, except in Chandrabani where SiO_2 percentage increases with depth. Among sesquioxides, Al_2O_3 (6.78–18.62%) was more than Fe_2O_3 (2.78–7.28%) and showed increasing trend with depth of the profile. The computation of I_{002}/I_{001} ratios for the illite, which is ≥ 3 , showed that the illite is Al-rich (Esquevin 1969; Jackson 1977). This is probably the reason for higher quantities of Al_2O_3 in the soil. The quantities of Fe_2O_3 observed within the profile demonstrate leaching of iron from the A-horizon and its subsequent deposition in the B-horizon, indicating podsolization, which otherwise seem paradoxical for the Doon valley. The distribution of Al_2O_3 within the profile confirms podsolization as one of the processes of soil formation, though feeble (Yadav 1963). The total bases ranged between 3.5 and 6.5%, in the order of $\text{K}_2\text{O} > \text{MgO} > \text{Na}_2\text{O} > \text{CaO}$. Among alkaline earth metals, MgO was more in proportion compared to CaO; former content varied from 0.90–2.44% and the latter was in the range of 0.03–1.21%. In addition, CaO was least abundant among the basic elements of the soils. The low percentage of CaO in the soil is because of the probable accelerated loss in leaching to lower depth and the absence of pyroxenes and amphiboles from the soil, though plagioclase feldspar was present in the soil. Higher MgO is because of its less solubility and mobility, hence less leaching losses. The comparison of CaO with NaO reveals that the rate of disappearance of calcic plagioclases was more than the sodic plagioclases, as the former is less resistant to weathering than the latter. Although, the input of Ca to the Doon valley from the Krol formation, i.e., limestone, phosphorite and phyllite is very high, well-drained soil (table 3) promotes accelerated leaching which in due course of time leads to the depletion of Ca from the soil (Purhoit *et al* 1993). Among alkalis, presence of high percentage of K_2O (1.45–4.11%) is attributed to high proportion of K minerals – mica (biotite) and feldspar. Among the micas, trioctahedral mica and biotite release a sufficient quantity of K compared to the dioctahedral mica (muscovite) even at low intensity of weathering. Na_2O ranged from 0.22–0.82%. Appreciable MgO and Fe_2O_3 are because of the presence of ferromagnesian minerals – calcite, biotite, tourmaline, together with opaque minerals in the heavy sand fractions. According to Saini *et al* (1995) higher abundance of Fe_2O_3 together with MnO is attributed to secondary enrichment by the soil development process as well as a contribution from the basic volcanic rocks of the Garhwal formation. Abundance of Fe_2O_3 within the sub-surface horizon as compared to the surface horizons showed possible migration and higher mobility of

the acidic cation under prevalent leaching environment. The higher abundance of K and Al in the Doon sal forest soils suggests that the felsic sources (granitic rocks, gneisses and quartzite) from the higher Himalayan region and to some extent the Siwalik sediments played a major role in the derivation of the Doon forest soils (Saini *et al* 1995). The low quantities of P_2O_5 were noticed in the range of 0.07% (Chandrabani) to 0.19% (Thano). The low presence of phosphorus seems to be due to the low rate of release from the soil minerals and somewhat higher amounts of the organic matter (Shrikhande and Yadav 1954; Yadav 1963). The loss on ignition (LOI) was high (3.63–20.13%) in the present study area, with no definite pattern of distribution within the profiles. This may be ascribed to the high percentage of OM, as very high LOI (>15%) was observed only in the surface horizons enriched with the organic layer.

The tree stand development, long-term accumulation and immobilization of the basic cations in the woody biomass and extensive and/or intensive forest harvesting in the forests has an acidifying effect (biological acidification) on the soil, particularly in the rooting zones. This is through a permanent export of the immobilized nutrients in the biomass extraction (Olsson *et al* 1996) and after harvesting in the accelerated drainage. The degree at which the forest harvesting cause depletion of the nutrient in the soil and pursuantly contribute to the soil acidity is largely determined by the acid neutralizing capacity of the soil, which in turn is determined principally and primarily by the presence of primary minerals and parent materials. If the rate of breakdown of the minerals and base cations release plus inputs to the system is less than the depletion by the biomass uptake and drainage, then acidification is inevitable (Hodson *et al* 1997). The mass-balance, particularly, between the weathering rates of supply of the basic cations, cations and anions leaching losses and harvesting cycles controls the rate of replenishment and balance of the nutrients in the soils within the forested areas to maintain sustainability of the nutrients. To know the role of vegetation in the overall weathering and alteration of the primary mineral, studies focusing on the species-specific long-term mass balance approach are required. These studies are imperative for the long-term productivity and development of the ecosystem. Such studies are largely missing when it is known that these can help us to understand whether stochastically or deterministically different species or their association affect the alteration of the primary minerals, overall weathering regime and finally unabated supply of the nutrients to the vegetation. The mass-balance is more important on impoverished sites brought under afforestation,

Table 7. Average total elemental analysis for the soil derived from sal forests in Doon valley. Values in parenthesis are the standard deviations.

Sites		N ₂ O	MgO	K ₂ O	CaO	TiO
Barkot	Mean	0.45 (± 0.04)	1.72 (± 0.06)	2.86 (± 0.06)	0.12 (± 0.03)	0.76 (± 0.01)
	Min	0.40	1.66	2.78	0.08	0.74
	Max	0.50	1.78	2.91	0.15	0.77
Senkot	Mean	0.50 (± 0.04)	1.69 (± 0.02)	2.80 (± 0.02)	0.13 (± 0.03)	0.80 (± 0.02)
	Min	0.47	1.67	2.77	0.09	0.78
	Max	0.55	1.72	2.82	0.16	0.82
Ghamandpur	Mean	0.49 (± 0.13)	2.16 (± 0.22)	2.86 (± 0.18)	0.31 (± 0.10)	0.85 (± 0.03)
	Min	0.34	1.89	2.62	0.23	0.81
	Max	0.62	2.44	3.04	0.47	0.88
Kalusidh	Mean	0.35 (± 0.13)	1.91 (± 0.04)	3.45 (± 0.50)	0.19 (± 0.20)	0.77 (± 0.03)
	Min	0.23	1.85	2.83	0.03	0.73
	Max	0.54	1.95	4.11	0.51	0.80
Thano	Mean	0.69 (± 0.11)	1.68 (± 0.12)	3.27 (± 0.32)	0.21 (± 0.16)	0.71 (± 0.00)
	Min	0.56	1.54	3.12	0.03	0.71
	Max	0.82	1.81	3.43	0.41	0.72
Lambirao	Mean	0.42 (± 0.10)	1.90 (± 0.04)	3.34 (± 0.35)	0.32 (± 0.12)	0.80 (± 0.02)
	Min	0.28	1.85	2.91	0.13	0.77
	Max	0.57	1.95	3.76	0.51	0.83
Song	Mean	0.53 (± 0.10)	1.41 (± 0.22)	2.25 (± 0.40)	0.44 (± 0.39)	0.71 (± 0.08)
	Min	0.45	1.09	1.89	0.04	0.61
	Max	0.69	1.66	2.90	0.92	0.81
Lacchiwala	Mean	0.46 (± 0.14)	2.27 (± 0.14)	2.69 (± 0.10)	0.37 (± 0.14)	0.89 (± 0.02)
	Min	0.33	2.14	2.59	0.25	0.86
	Max	0.63	2.42	2.78	0.56	0.91
Lakshmansidh	Mean	0.44 (± 0.16)	1.28 (± 0.26)	2.01 (± 0.13)	0.51 (± 0.40)	0.65 (± 0.08)
	Min	0.22	0.90	1.85	0.06	0.54
	Max	0.61	1.46	2.14	0.96	0.73
Mohabbawala	Mean	0.41 (± 0.08)	1.23 (± 0.15)	1.73 (± 0.17)	0.13 (± 0.08)	0.58 (± 0.01)
	Min	0.33	1.01	1.55	0.07	0.56
	Max	0.52	1.32	1.89	0.23	0.59
Chandrabani	Mean	0.42 (± 0.11)	1.20 (± 0.16)	1.72 (± 0.25)	0.13 (± 0.09)	0.55 (± 0.04)
	Min	0.32	0.98	1.45	0.06	0.50
	Max	0.57	1.34	1.99	0.26	0.58
Laldhang	Mean	0.48 (± 0.09)	1.44 (± 0.14)	1.72 (± 0.09)	0.37 (± 0.48)	0.64 (± 0.03)
	Min	0.38	1.23	1.59	0.10	0.59
	Max	0.60	1.55	1.82	1.21	0.66

reforestation (secondary forests) and for old degrading forests. The initial successful development of the plantation and pursuant extraction on these sites should not be confused with the optimum supply of nutrients and that of the weathering of the primary minerals adequate enough to fill the void created by a major loss of nutrients, the reasons of which are aforementioned. The resultant permanent export of the nutrients out of the system by the indiscriminate extraction of the biomass in these very sites greater than the rate of replenishment of the nutrients by the weathering of primary minerals may create real growth limiting nutrient deficiencies.

In order to make more meaningful sustainable nutrient management within the natural forest

stands, where artificial fertilization is elusive because of spatial and temporal dimension and variability, rate of removal of the immobilized nutrients by regulating the harvesting cycles of the mature or old crop should be in balance with that of the replenishment rates of the nutrient within the stand. Also, the presence of mineral suites and weathering rates acts as a buffer against episodic acid deposition. The acidification of the terrestrial ecosystem shall ensue when the presence of a few weatherable minerals or hard to weather minerals fail to mediate the impacts of acidic deposition from the atmosphere. The impact of acid deposition can have severe repercussions on the working of the ecosystem, with changes ranging from temporary to a permanent shift in the species

MnO	Fe ₂ O ₃	Al ₂ O ₃	SiO ₂	P ₂ O ₅	LOI
0.14 (± 0.01)	6.21 (± 0.31)	15.62 (± 0.29)	62.82 (± 0.53)	0.15 (± 0.02)	8.49 (± 0.39)
0.13	5.93	15.37	62.22	0.14	8.12
0.15	6.56	16.03	63.32	0.17	9.03
0.15 (± 0.43)	6.31 (± 0.67)	15.40 (± 0.43)	63.40 (± 0.75)	0.15 (± 0.01)	8.90 (± 0.44)
0.13	5.92	14.76	62.62	0.14	8.31
0.17	6.69	16.23	64.43	0.17	9.25
0.15 (± 0.03)	6.09 (± 0.65)	15.64 (± 2.20)	62.35 (± 3.04)	0.17 (± 0.02)	10.46 (± 0.96)
0.13	5.33	12.90	58.64	0.13	9.01
0.20	6.76	18.04	65.24	0.19	11.44
0.11 (± 0.01)	5.76 (± 0.63)	16.35 (± 1.86)	61.19 (± 2.30)	0.12 (± 0.05)	8.96(± 2.72)
0.10	4.77	14.48	59.49	0.07	7.19
0.12	6.43	18.55	64.72	0.21	13.59
0.15 (± 0.02)	5.64 (± 0.57)	16.79 (± 1.27)	60.16 (± 1.17)	0.19 (± 0.03)	11.59 (± 1.42)
0.13	4.54	15.28	59.02	0.15	9.62
0.17	6.01	18.62	62.32	0.24	13.31
0.10 (± 0.00)	5.55 (± 0.69)	17.23 (± 0.76)	61.61 (± 2.59)	0.11 (± 0.02)	8.93 (± 1.62)
0.10	4.77	16.52	58.89	0.09	6.96
0.11	6.25	18.48	64.72	0.13	11.49
0.15 (± 0.06)	4.31 (± 0.32)	13.15 (± 2.77)	69.07 (± 2.30)	0.17 (± 0.09)	12.36(± 3.27)
0.08	3.92	10.03	66.41	0.07	7.92
0.25	4.56	16.21	71.97	0.31	17.03
0.14 (± 0.01)	6.29 (± 0.84)	15.82 (± 2.02)	61.58 (± 3.21)	0.16 (± 0.04)	10.03 (± 1.04)
0.13	5.56	13.54	57.87	0.11	8.99
0.16	7.28	17.67	64.63	0.19	11.47
0.14 (± 0.07)	4.18 (± 0.52)	11.92 (± 2.49)	66.71 (± 5.24)	0.12 (± 0.05)	12.67 (± 6.33)
0.05	3.51	9.62	61.84	0.06	5.42
0.21	4.59	15.31	72.76	0.16	20.13
0.09 (± 0.04)	3.74 (± 0.70)	9.62 (± 1.92)	79.12 (± 2.48)	0.08 (± 0.02)	6.12 (± 1.28)
0.06	2.86	6.89	77.13	0.06	4.60
0.15	4.43	11.05	82.67	0.10	7.40
0.09 (± 0.03)	3.27 (± 0.54)	9.17 (± 1.89)	77.05 (± 4.33)	0.07 (± 0.02)	4.49 (± 1.28)
0.06	2.78	6.78	71.56	0.05	3.63
0.14	4.03	10.82	81.97	0.09	6.40
0.10 (± 0.05)	4.16 (± 0.25)	9.96 (± 1.26)	73.61 (± 5.23)	0.09 (± 0.05)	8.43(± 5.99)
0.05	3.96	8.76	64.72	0.05	5.33
0.18	4.57	11.34	78.12	0.18	19.11

composition and other defining properties that define uniqueness of an ecosystem. On the other hand, a soil may not be sensitive to the impact of acid deposition because it contains an adequate supply of the weatherable base-rich primary minerals that in their capacity are able to effectively neutralize the incoming acidity. The mineralogy and weathering rates are therefore, crucial in determining whether a soil is sensitive to the effects of the acid deposition from the atmosphere or not. It is therefore, necessary to gain insight on weathering and alteration of the primary minerals and transformation and alteration of the clay minerals. To achieve more figurative insight on the potential of the nutrient supply to balance the rate of nutrient loss, especially through crop harvesting, which

forests and soils can sustain, with no short-term or long-term detrimental effect on growth dynamics, fundamental weathering rate studies are essential.

The knowledge of the minerals occurring in the forest ecosystem and their transformations are limited and rates of weathering of the primary minerals are completely absent. Although such studies together with other comprehensive soil studies not only help in understanding the distribution and biogeochemistry of a forested ecosystem, it will also be of great help in formulating and adopting the success of the necessary silvicultural practices, especially for the unfertilized soils. It is necessary to work out detailed mineralogical suites and calculate weathering rates concomitant to harvesting rates in various environments and

forested ecosystems inclusive of the grassland and restoration sites brought under reforestation and afforestation.

5. Conclusion

It is easily conceivable from the results that sal forested soils of this region have identical suites of mineral which is almost identical from one pedon to the other. These identical mineral assemblages which otherwise depict different weathering intensities and assign soil with different weathering stages apparently suggest the nature of alluvium which is derived from varied rocks of Lesser Himalayas and Siwaliks. The critical appraisal of the mineralogical composition, physicochemical properties and total elemental analysis of the soils does not show any deficiency of the bases and other plant nutrients in general. The inherent fertility of the soils is as good as indicated by the sand and the clay mineralogy, which provide an unrestricted potential source of the base cations. It is evident that an appreciable quantity of Ca and K-bearing minerals like feldspar, biotite muscovite and hornblende were present and these together with the clay mineral illite are the source of K^+ and Mg^{2+} in the soils of sal forests of the Dehradun. In the present study, perusal of the mineral suites, on the one hand shows the supply of cations in sal forests of the Doon valley seems to be high enough to satisfy tree growth. On the other hand, high precipitation during the growing season (avg. 1843 mm April–October) favour high and permanent loss of the elements beyond the rooting zone by leaching and/or runoff, making surface as well as sub-surface soils impoverished in the basic cations and anions. The forest management practices for the Doon valley therefore should exercise caution during whole tree harvesting, which altogether export the immobilized nutrients in the biomass and effectively restrict the loss of nutrients in runoff by providing sizeable canopy cover.

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References

- Banerjee K C, Prasad K G and Raina A K 1989 Clay minerals in the soils of south Kheri forests, Uttar Pradesh; *Indian For.* **115**(8) 555–559.
- Bartarya S K 1995 Hydrogeology and water resources of intermontane Doon valley; *J. Him. Geol.* **6**(2) 17–28.
- Black C A 1965 *Methods of Soil Analysis* (Madison: Am. Soc. Agron. Inc.).
- Brown G and Brindley G W 1980 X-ray diffraction procedures for clay mineral identification; In: *Crystal Structures of Clay Minerals and their X-ray Identification* (eds) Brindley G W and Brown G (London: Mineralogical Society) pp. 305–360.
- Cady J G 1965 Petrographic microscope technique; In: *Methods of Soil Analysis. Part I: Physical and Mineralogical Properties* (ed.) Black C A (Madison: Am. Soc. Agron. Inc.).
- Chandel R S and Singh I B 2000 Morphostratigraphy and Fan Morphology of Doon Valley; *Photonirvachak* **28**(4) 265–274.
- Deepthy R and Balakrishnan S 2005 Climatic control on clay mineral formation: Evidence from weathering profiles developed on either side of the Western Ghats; *J. Earth Syst. Sci.* **114**(5) 545–556.
- Dhar B and Jha M N 1980 Micro-mineralogy of forest soils developed on different parent rocks and their suitability afforestation; *Indian For.* **105**(2) 102–112.
- Dhar B, Jha M N and Kukretee S P 1988 Mineralogy of soils under forests in the Lesser Himalaya; *J. Ind. Soc. Soil Sci.* **36** 151–157.
- Dixon J B 1989 Kaolinite and serpentine group minerals; In: *Minerals in Soils Environments*, 2nd edn (eds) Dixon J B and Weed S B (Madison: Soil Science Society of America) pp. 357–403.
- Esquevin J 1969 Influence de la composition chimique des illites sur leur cristallinité; *Bull. Centre de Recherches de Pau (Soc. National des Ptroles d'Aquitaine)* **3** 147–153.
- Eswaran H and Bin C W 1978 A study of a deep weathering profile on granite in Peninsular Malaysia: II. Mineralogy of the clay, silt and sand fractions; *Soil Sci. Soc. Am. J.* **42** 149–153.
- Gautam M K 2007 Study of critical load of air borne sulphur and nitrogen induced acidification of the forest soils of Doon valley; PhD Thesis, Forest Research Institute, Dehradun (Uttarakhand) India.
- Gautam M K, Tripathi A K and Manhas R K 2006 Indicator species for the natural regeneration of *Shorea robusta* Gaertn. F. (sal); *Curr. Sci.* **93**(10) 1359–1361.
- Ghosh R C, Singhal R M and Sharma S D 1980 Electrophoretic fractionation and characterization of humic acids of the soils of Doon valley under Sal (*Shorea robusta*); *Indian For.* **106**(3) 205–212.
- Graff-Petersen P 1961 Lermineralogien i de limniske jurasidminter på Bornholm. Diss. Copenhagen, cited from P. Pulkkinen 2004; Mineralogy and geochemistry of the fine and the clay fractions of till in northern Finland; Department of Geosciences, Faculty of Science (Oulu, Finland: Oulu University Press).
- Grim R E 1968 *Clay mineralogy*; 2nd edn (New York: McGraw-Hill Book Co. Inc).
- Hardy R G and Tucker M E 1988 X-ray powder diffraction of sediments; In: *Techniques in Sedimentology* (ed.) Tucker M E (London: Blackwell Scientific Publications) pp. 191–228.
- Hodson M E, Langan S J and Wilson M J 1997 A critical evaluation of the use of the PROFILE model in calculating mineral weathering rates; *Water Air Soil Pollution* **98**(1/2) 79–104.

- Husain H J 2006 Lithology and soil characteristics in relation to forest vegetation of Garhwal Himalaya; PhD Thesis, Forest Research Institute, Dehradun, India.
- Jackson T A 1977 A relationship between crystallographic properties of illite and chemical properties of extractable organic matter in pre-phanerozoic and phanerozoic sediments; *Clays Clay Miner.* **25** 187–195.
- Jassal P, Sidhu P S, Sharma B D and Mukhopadhyay S S 2000 Mineralogy and geochemistry of some soils of Siwalik hills; *J. Indian Soc. Soil Sci.* **48**(1) 163–172.
- Kukreti P 2002 Nutrient Cycling Studies in Sal Forest with Special Reference to Mortality; PhD, Thesis Forest Research Institute Dehradun (Uttarakhand), India.
- Kumar R and Ghosh S K 1991 Sedimentological studies of the Upper Siwalik Boulder Conglomerate Formation of Mohand Area, Dist. Saharanpur, U.P.; *Himalayan Geol.* **2** 159–167.
- Kumar R, Ghosh S K, Mazari R K and Sangode S J 2003 Tectonic impact on the fluvial deposits of Plio-Pleistocene Himalayan foreland basin, India; *Sedim. Geol.* **158** 209–234.
- Kumar R, Suresh N, Sangode S J and Kumaravel V 2007 Evolution of the quaternary alluvial fan system in the Himalayan foreland basin: implications for tectonic and climatic decoupling; *Quatern. Int.* **159** 6–20.
- Lisitsa V D and Tikhonov S A 1969 Transformation of biotite in sod-podzol soils; *Soviet Soil Sci.* **11** 98–106.
- Maheshwari V K and Samra J S 1984 Mineralogical studies of forest soils in relation to weathering and natural vegetation; *Indian J. For.* **7**(3) 190–196.
- Maheshwari V K, Samra J S and Bagati TN 1981 Soil weathering sequences with references to mineralogy and natural vegetation; *Indian J. For.* **43**(3) 173–178.
- Medlicott H B 1864 On the geological structure and relations of the southern portions of Himalayan ranges, between the rivers Ganges and Ravee; *Geol. Surv. India Memoir.* **3** 1–212.
- Mehra O P and Jackson M 1960 Iron oxide removal from soils and clays by dithionite citrate system buffered with sodium bicarbonate; *Clays Clay Miner.* **7** 317–327.
- Meiwes K J, Khanna P K and Ulrich B 1986 Parameters for describing soil acidification and their relevance to the stability of forest ecosystems; *Forest Ecol. Manag.* **15** 161–179.
- Meunier A and Velde B 2004 *Illite: Origin, evolution and metamorphism* (New York: Springer).
- Moore D M and Reynolds R C 1997 *X-ray diffraction and identification and analysis of clay minerals*; 2nd edn (New York: Oxford University Press).
- Nakata T 1972 *Geomorphic History and Crustal Movements of the Himalayas*; Institute of Geography, Tohoku University, Sendai.
- Nossin J J 1971 Outline of the geomorphology of the Doon valley, Northern India U.P, India; *Z. Geomorph., N.F. Suppl. Bull.* **12** 19–50.
- Olsson B A, Bengtsson J and Lundkvist H 1996 Effects of different forest harvest intensities on the pools of exchangeable cations in coniferous forest soils; *Forest Ecol. Manag.* **84**(1–3) 135–147.
- Pettijohn F J 1984 *Sedimentary Rocks*; 2nd edn (New Delhi, India: CBS Publishers and Distributors).
- Puri G S 1950 Soil pH and forest communities in the Sal (*Shorea robusta*) forests of the Dehradun valley, U.P. India; *Indian For.* **76**(7) 292–303.
- Purohit K K, Rathi M S, Khanna P P, Mukherjee P K, Saini N K and Sriram V 1993 Distribution and background concentration of major elements in Doon Valley soils; *J. Him. Geol.* **4**(1) 103–110.
- Raina A K, Pharasi S C and Prasad K G 1994 Interrelationship between geology, soil and vegetation of Kanasar range in Chakrata division of Uttar Pradesh; *Indian For.* **120**(12) 1095–1103.
- Raina A K, Jha M N and Pharasi S C 1998 Fine sand mineralogy of some selected soils of Mussoorie forest division of Uttar Pradesh; *Indian For.* **124**(11) 925–931.
- Raina A K, Jha M N and Pharasi S C 2000 Sand mineralogy of some sodic soils of U.P.; *Ann. For.* **8**(2) 229–237.
- Raju A T R and Dehadrai P V 1962 Upper Siwalik sedimentation in parts of Punjab; *Quart. J. Geol. Min. Met. Soc. India* **34**(1) 1–8.
- Sahu G C and Dash S S 1991 Sand and clay mineralogy of some coastal salt affected soils of Orissa; *J. Ind. Soc. Soil Sci.* **39** 517–522.
- Saini N K, Rathi M S, Khanna P P, Mukherjee P K, Purhoit K K and Sriram V 1995 Geochemical characteristics of Doon Valley soils; *J. Him. Geol.* **6**(2) 35–45.
- Samra J S 1982 Clay mineralogical studies in relation to soil development and vegetation in Haldwani forest division of Uttar Pradesh; *Indian For.* **108**(3) 189–195.
- Sharma S D 1982 Status of organic matter in some typical soils of Doon valley with special reference to regeneration and quality of forests; Ph.D. Thesis, H N B Garhwal University Srinagar (Uttarakhand), India.
- Sharma S D, Banerjee S P, Rawat V R S, Raina A K and Singh B 1989 Present productivity of soils supporting Sal (*Shorea robusta*) in Doon valley, Uttar Pradesh; *J. Ind. Soc. Soil Sci.* **37** 539–544.
- Shrikhande J G and Yadav J S P 1954 Effect of nitrogen upon availability of phosphorus; *J. Ind. Soc. Soil Sci.* **2** 115–120.
- Singh A K, Parkash B, Mohindra R, Thomas J V and Singhvi A K 2001 Quaternary alluvial fan sedimentation in the Dehradun piggyback Basin, NW Himalaya: Tectonic and paleoclimatic implications; *Basin Res.* **13** 449–471.
- Singhal R M and Sharma S D 1979 Study of organic matter of some typical soils of Doon valley forests; *Ind. J. For.* **6**(4) 274–277.
- Singhal R M and Sharma S D 1983 Study of organic matter of some typical soils of Doon valley forests; *Ind. J. For.* **6**(4) 274–277.
- Singhal R M, Pathak T C and Banerjee S P 1976 A comparative study of some typical soils of Doon valley with reference to their organic matter; *Indian For.* **102**(10) 814–823.
- Singhal R M, Samra J S, Sharma S D, Pande P and Sharma S K 1982 Soil biosequence of a forest land of Doon Valley with reference to its vegetation; *Indian For.* **108**(4) 293–299.
- Soil Survey Staff 1998 *Soil Survey Manual* (Jodhpur, India: Scientific Publishers).
- Suresh N, Ghosh S K, Kumar R and Sangode S J 2004 Clay-mineral distribution patterns in late Neogene fluvial sediments of the Subathu sub-basin, central sector of Himalayan foreland basin: Implications for provenance and climate; *Sedim. Geol.* **163** 265–278.
- Thakur V C 1995 Geology of Dun Valley Garhwal Himalaya: Neotectonics and coeval deposition with fault propagation folds; *J. Him. Geol.* **6**(2) 1–8.
- Thakur V C and Pandey A K 2004 Late Quaternary tectonic evolution of Doon in fault bend/propagated fold system, Garhwal Sub-Himalaya; *Curr. Sci.* **87**(11) 1567–1576.
- Ulrich B 1991 Soil acidification and alkalization; In: *Soil Acidity* (eds) Ulrich B and Sumner M E (New York: Springer-Verlag) pp. 28–79.
- Varajao A F D C, Gilkes R J and Hart R D 2001 The relationships between kaolinite crystal properties and the

- origin of materials for a Brazilian kaolin deposit; *Clays Clay Miner.* **49**(1) 44–59.
- Velde B 1992 *Introduction to Clay Minerals* (New York: Chapman and Hall).
- Wadia D N 1966 *Geology of India* (New Delhi: Tata McGraw Hills Publishing Co.).
- Weaver C E 1961 Clay minerals of the Ouachita structural belt and adjacent foreland; Univ. Texas Bur. Economics Geology Publ. No. 6120, pp. 147–162.
- Wilson M J 1987 X-ray powder diffraction methods; In: *A Handbook of Determinative Methods in Clay Mineralogy* (ed.) Wilson M J (London: Blackie Academic).
- Yadav J S P 1963 Studies on soil profiles in Chakrata division of Uttar Pradesh; *Indian For.* **89**(1) 18–38.
- Yadav J S P and Chand G 1967 *Need for the mineralogical analysis of forest*; Proc. 11th Silva Conf. FRI Dehradun India.
- Yadav J S P, Banerjee S P, Badola K C and Singh K 1973 Changes in soil properties consequent upon growing eucalyptus in natural Sal area; *Ind. J. Agri. Chem.* **6**(2) 109–115.

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