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Soil formation under the influence of topography, climate and weathering in the rocky terrain of the Purulia district of West Bengal

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Abstract

The present study assesses the impact of topography and climate on soil properties and its formation in the Purulia district of West Bengal with the help of Glass Electrode, Walkley, and Black's rapid titration, and the interpolation methods in different terrains under sub-tropical climatic conditions using Landsat-8 satellite images, SRTM-DEM, soil map, geological map, land use land cover, and Soil Moisture Index (SMI), pH, and soil organic matter maps. The study reveals that the formation of soil follows a definite pattern according to the topography, parent material, and climate of the area. Undulating topography and uneven distribution of rainfall characterize the entire region. The soil of the region is residual in nature, developed from the weathering of granite gneiss. The thin soils are acidic with pH levels varying between 5 and 6.5. The present climate with a wider range of temperatures and very little rainfall throughout the area reflects varying degrees of weathering. Precipitation and temperature have a strong impact on weathering and soil formation due to chemical alteration of the parent materials that generate these soils.

Keywords: *Terrain, weathering, Glass electrode method, soil formation, soil properties.*

Introduction

Variations in soil properties are usually attributed to variations in climate and topography. The soils over time, emerge as a result of the complex interaction of many interconnected factors like climate, topography, parent material, and organisms, etc. A few centimeters of soil take hundreds of years to develop. The climate is one of the most important factors which have an impact on soil formation with significant implications for its development, structure, stability, water-holding capacity, and erosion (Phillips *et al.*, 2008). Climate and topography constitute two important factors that give a sequence of different mineralogical stages which is also related to soil-forming factors. The nature, intensity, and distribution of the weathered materials depend upon the climate and the position on a slope (Tardy *et al.*, 1973). Topography controls the breakdown of soil and alters the movement of water in the soil. Terrain characteristics of any area are determined by its topography, climate, and soil type. The relationship between weathering and the formation of soil in granitic gneiss terrain is linked with precipitation and temperature resulting in a chemical alteration of parent materials (Weinert, 1965; Stevens

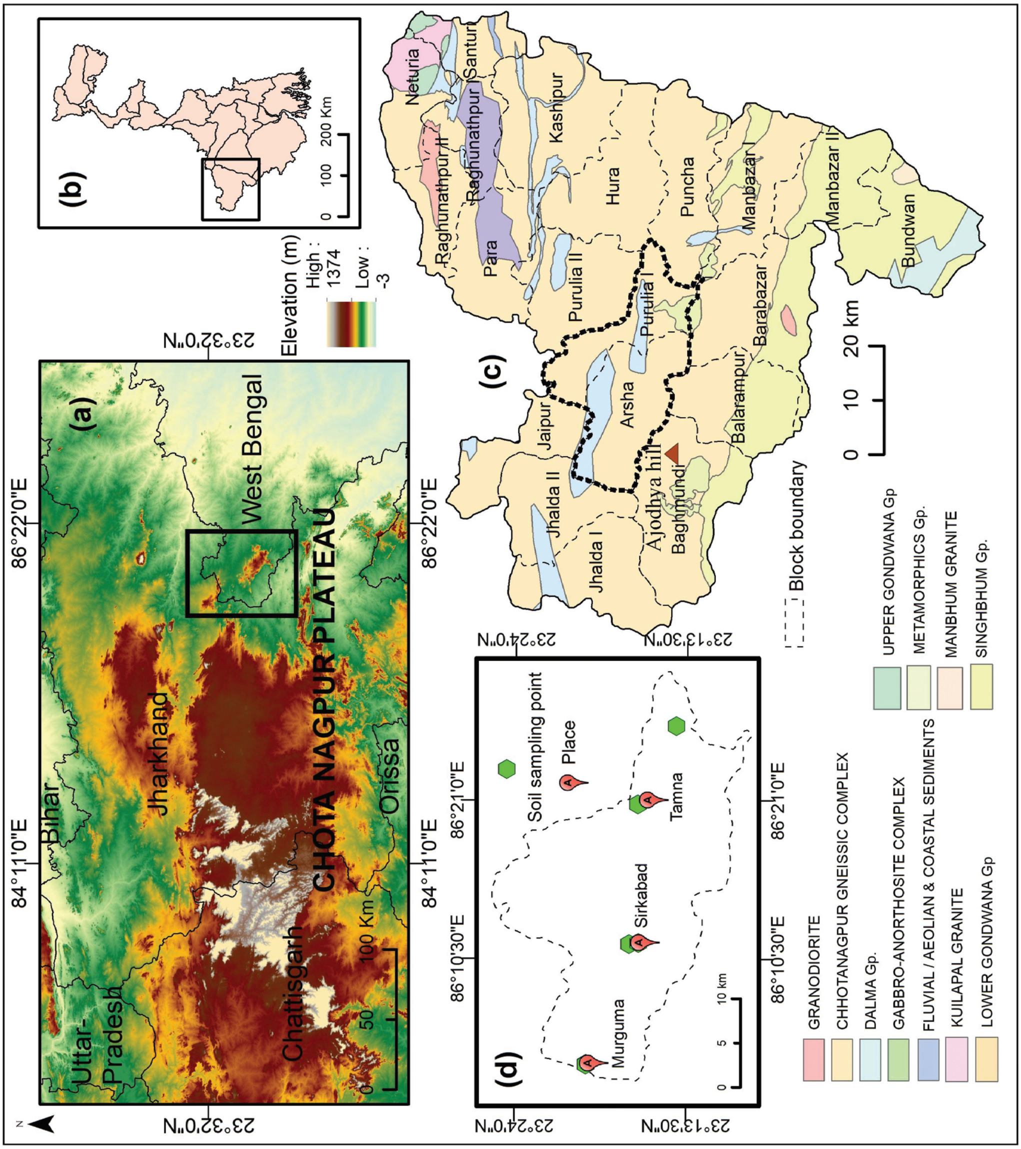

Fig. 1: (a) Purulia in its physiographic location (b) Location of Purulia district in West Bengal (c) Geological formation of the Purulia district mainly comprises Chotanagpur gneissic complex (d) Soil sampling collection point of Arsha and Purulia I block

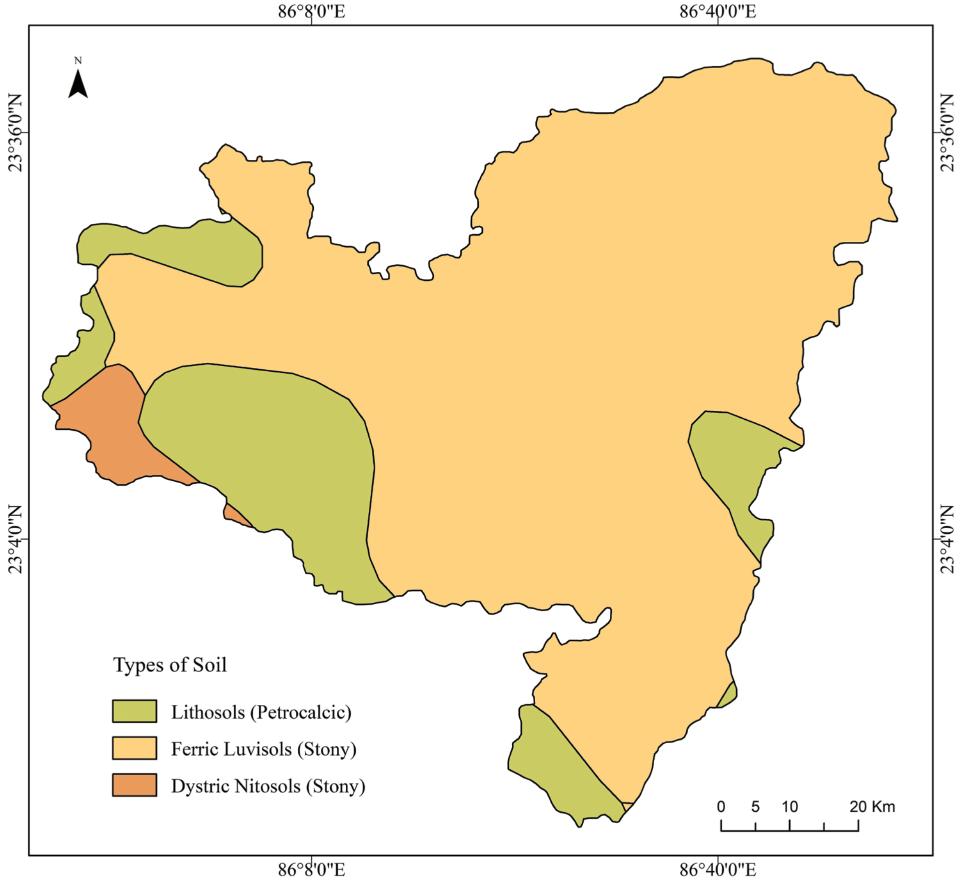

Fig. 2: FAO soil classification. Ferric Luvisols soil is dominant in the whole district of Purulia. Lithosols also known as skeletal soils and dystric nitosols soils are also seen in some parts of this district.

& Walker, 1970; Simon *et al.*, 2021; Owens & Watson, 1979). Various geomorphic factors in different climatic conditions play a significant role in determining the soil properties through the weathering process.

The soils of West Bengal greatly vary from one place to another. The soil of the western fringe of this state is unique. The westernmost district of West Bengal, Purulia is situated in the rugged topography of the Chotanagpur plateau. Pre-Cambrian to Archean granite gneiss and mica schist types rocks of the Purulia district are intensely weathered (Dolui *et al.*, 2014). Lateritic soil with a low retention capacity is a unique nature of this soil (Islam, 2018). The crystalline hard rocky terrains of the district are associated with a thin soil layer (Roy & Hazra, 2020). Purulia is abundant with rocks and minerals. It is a part of the Chotanagpur granite gneiss complex and is composed of granite, hornblende, and mica schist types of rock. Soil formation is unique, mainly driven by the weathering of rocks and minerals. Physical abrasion decreases the size of particles and therefore increases their surface area, making them more susceptible to rapid chemical reactions (Clinton & Chinago, 2020; Riebe *et al.*, 2004). Chemical weathering is also influenced by the mineralogical compositions of the parent material. A combination of physical and chemical weathering stimulates the mechanical breakdown which creates layers like the leaves of a cabbage. Rocks and minerals vary in their resistance to weathering. The sub-tropical climate with extremely high temperatures during summer and average annual precipitation (1281.89 mm) make a favourable condition for Purulia for moderate-strong physical and chemical weathering. This study is in part inspired by previous research on soil formation under the influence of weathering and mineralogical alteration, also indicating a physicochemical variation among pedological properties (Naskar *et al*, 2010; Sarkar, 2019). However, different parts of Purulia district have variable soil composition. The relationship between the pedological characteristics with topographic variation and the impact of climate on soil formation through weathering has not been identified earlier in the Purulia district. The present study addresses the following research questions: how do soil characteristics change with the topography and climatic factors? How do soil properties link with weathering and their parent rocks? This research aims to assess the impact of topographical variation and climate on soil properties. The study also intends to establish the relationship between parent rocks and soil properties through weathering. Determining the soil properties and their development process ultimately helps to manage them effectively. The sustainable use of soil and agricultural production potential largely depends on the physical properties of the soil. Understanding soil formation and its properties will help in the recognition of sites best suited for agriculture. Farmers may apply this knowledge to make choices about crop selection, irrigation strategies, and soil management practices. It enables better-informed choices on sustainable land use, soil conservation measures, and agricultural output too.

Materials and methods

Study area and field data collection

Physiographically, the Purulia district is a part of the Chotonagpur gneissic complex of the eastern India peninsula shield and the Singhbhum group of rocks (Fig. 1c). This group of rocks consists of a variety of granitic gneisses such as quartz-biotite granite gneiss (Mitra & Acharya, 2015; Acharya & Prasad, 2017). The elevation of the Purulia district ranges from 85m to 700m (Fig. 1a). The study area consists of two types of soil; mainly ferric luvisols and lithosols as per the Food and Agriculture Organization (FAO) soil classification system. Skeletal soil, also known as lithosols mainly consists of partially weathered rock fragments (Fig 2). The soil thickness is very thin due to intense erosion. According to Bhattacharya *et al* (1985), the soils of the district can be classified into 3 broad categories - Gneissic, Gondwana, and Transition soils. This region is dominated by gneissic soil, produced from gneissic rocks, and is typically sandy loam with low fertility. Purulia has a subtropical climate and is one of the most drought-prone districts in West Bengal experiencing extremely dry weather with little precipitation. The region receives rainfall from the southwest monsoon and the average annual rainfall is 1346 mm only. Undulating topography and uneven distribution of rainfall characterize the entire region. The Arsha block is at a relatively higher altitude located close to the Ajodhya hills with elevations varying from 303m to 482m. On the other hand, away from the Ayodhya hills, the Purulia I block is situated at a lower altitude, with elevation ranging between 124m and 214m. These two blocks with different elevations were selected for understanding the soil properties according to the topographic variations. Nine soil samples were collected from Murguma and Sirkabad situated in Arsha block and Tamna of Purulia I block each at different elevations and with varying slopes (Fig. 1d).

Soil sampling and laboratory method

Soil samples at 0-10 cm depth were collected in sealable plastic bags. About 150-200 grams of dried bulk samples were broken by a hammer, ground the soil samples in a mortar to reduce the rock aggregate to smaller particles, and finally, these samples were spread out in a petri dish to air dry for a week to get powder samples. The air-dried powder samples are sieved thoroughly. The physical and chemical properties of soil samples were then analyzed. To get hygroscopic moisture content in the soil, the samples were dried again in a hot air oven at a temperature of 105°C - 111°C for several hours. Soil organic matter was determined by the Walkley & Blacks wet-combustion method. The percentage of hygroscopic moisture is determined by heating the air-dry samples for three hours (SIST ISO 11464, 2006). A global digital pH meter was used for the determination of soil pH (SIST ISO 10390, 2006).

Climatic variables

For the present study, mean monthly, annual temperature, and precipitation data were collected from the India Meteorological Department (IMD), Kolkata. Descriptive statistics have been used to show the monthly variation of rainfall. The arithmetic mean is used for average monthly rainfall. Standard deviation is used for measuring the dispersion of rainfall. The standard deviation and coefficient of variation of annual rainfall were calculated to check the rainfall variability. Soil properties i.e., hygroscopic moisture, organic matter, pH value, etc. are affected by seasonal changes in climate and soil wetting-drying processes (Aksakal *et al.*, 2019) and the present study measured these factors and their variations in different topographic and climatic conditions.

Result and discussion

Soil formation and pedological characteristics

The physico-chemical properties of the soil vary due to the influence of topography. The degree of slope (Fig. 3a) and elevation in the district of Purulia are comparatively high in the Murguma of Arsha block, nearer to the Ajodhya hills. The elevation of Tamna and Sirkabad is lower. Thus, the formation of soil follows a definite pattern according to the topography. Due to the steep slope, much of the runoff moves away from Murguma resulting in low hygroscopic moisture ranging between 0.023 and 0.04 percent. The elevation of Sirkabad is lower than that of Murguma and the hygroscopic moisture is 0.04 to 0.06 percent. The percentage of hygroscopic moisture in the foothill region (Tamna) of the Ajodhya hills varies from 0.15 to 0.18 percent. Tamna is located at a lower elevation than Sirkabad.

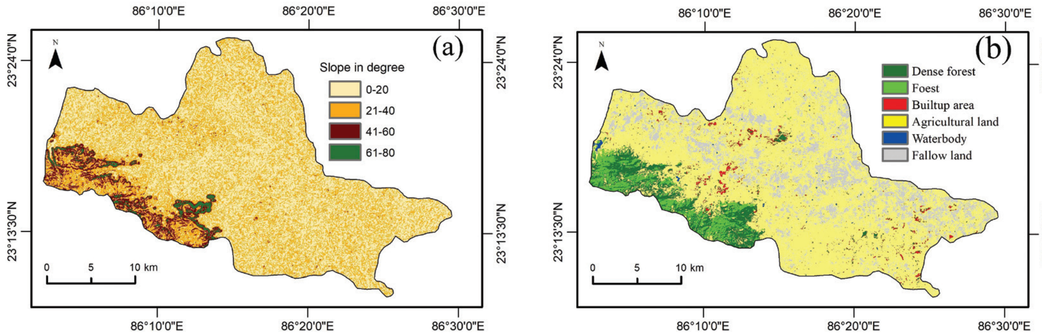

Fig. 3: Physical characteristics of Arsha and PurulialI Blok, (a) Slope (degree) and (b) Landuse and landcover (LULC)

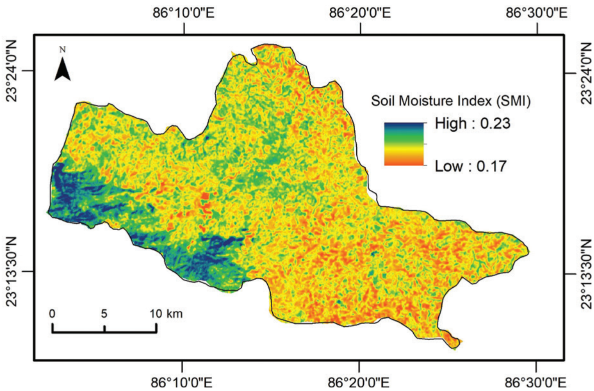

Fig. 4: Soil Moisture Index (SMI) value of Arsha and Purulia 1 block

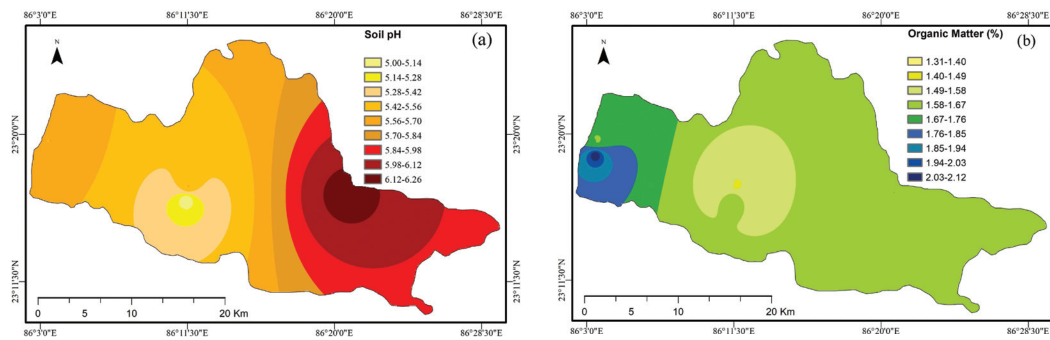

Fig. 5: (a) Variation of soil pH and (b) percentage of organic matter at the Arsha and PurulialI bloc

Table 1: Descriptive statistics of rainfall data of the Purulia district during 1997-2017 (in mm)

Year	Annual Rainfall	Mean	SD	CV (%)	Variance	Min	Max	Range
1997	1313.62	109.47	137.88	125.95	19010.31	12.07	395.37	383.3
1998	1276.55	106.38	90.78	85.34	8241.54	0	224.65	224.65
1999	1355.22	112.94	148.16	131.18	21951.35	0	410	410
2000	954.73	79.56	82.78	104.05	6853.17	0.35	197.04	196.69
2001	1001.48	83.46	91.95	110.17	8454.11	0	282.68	282.68
2002	1193.9	99.49	117.10	117.70	13711.84	0	367.75	367.75
2003	1260	105.00	102.26	97.39	10456.55	0	268	268
2004	1220	101.67	125.83	123.76	15833.33	0	392	392
2005	1079	89.92	90.92	101.11	8267.17	9	250	241
2006	1276	106.33	132.38	124.50	17525.15	0	381	381
2007	1614	134.50	187.51	139.41	35158.27	0	549	549
2008	1348	112.33	158.03	140.68	24972.24	0	425	425
2009	1024	85.33	109.83	128.71	12063.52	0	295	295
2010	798	66.50	69.29	104.20	4801.73	0	192	192
2011	1557	129.75	166.31	128.18	27658.02	0	421	421
2012	1396	116.33	139.63	120.03	19495.52	6	363	357
2013	1778.6	148.22	154.24	104.06	23791.22	0	434.6	434.6
2014	1322	110.17	128.21	116.37	16439.02	0	315.1	315.1
2015	1208.2	100.68	158.93	157.86	25259.21	0.4	563.6	563.2
2016	1368.8	114.07	165.57	145.15	27412.72	0	506.8	506.8
2017	1574.7	131.23	165.20	125.89	27290.34	0	568.2	568.2

A positive relationship is found between the elevation and organic matter content. The percentage of organic matter in the comparatively higher (303m - 392m) elevated Murguma ranges from 1.40 - 2.34 percent due to the presence of vegetation cover in contrast to 1.07 to 1.68 percent at Shirkabad and Tamna (Fig. 5b) located at lower elevation. The lateritic soil is found in the study area which is acidic in nature and deficient in organic matter. Soil properties of pH, organic matter content, and hygroscopic moisture of the soil are varied with the slope characteristics. The physicochemical attributes of the soil are influenced by land use and land cover too. In this context, the study measures lower organic matter content (1.07 - 1.68 %) of soils under cultivated land than the forest area due to the loss of organic matter by water erosion and removal of topsoil. The soil pH is low at Murguma (Fig. 5a) due to relatively higher organic matter in the surface layer of this location. The pH value of all the soil samples of the Arsha and Purulia I block ranges from 5 to 6.55. The pH value of Murguma is marginally lower than that of Shirkabad and Tamna. The study shows topography-induced variations in the physical and chemical

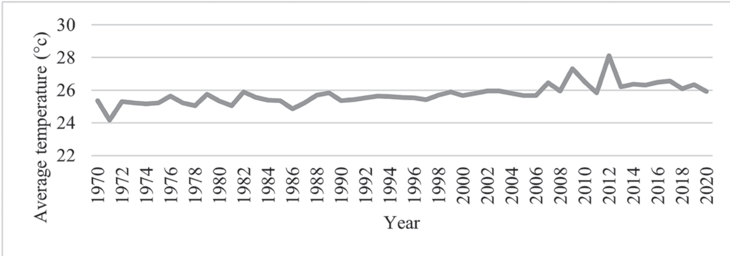

Fig. 6: Average annual temperature of Purulia District

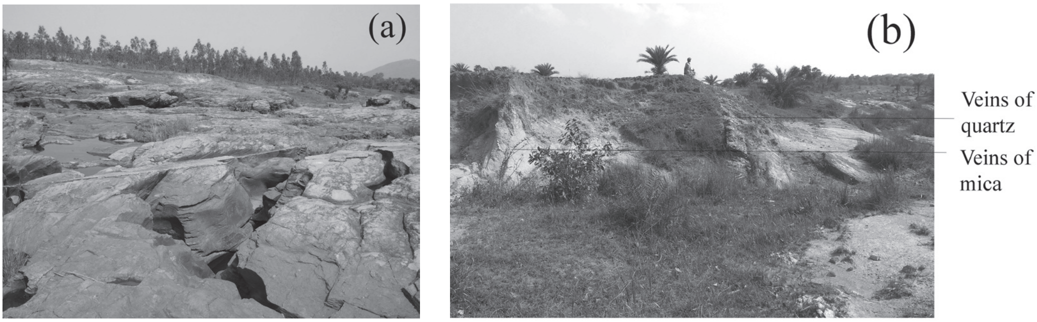

Fig. 7: (a) Physical weathering and (b) chemical weathering are seen in the same weathering crust

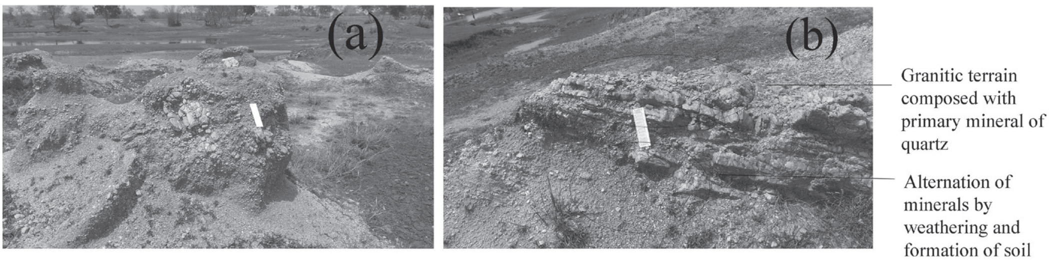

Fig. 8: (a) Mica and silica particles combine with alumina and iron to form the clay minerals. (b) Mineralogical alteration by weathering which generates soils

Fig. 9: High annual temperature range makes rocks prone to weathering, increases cleavage in the rock surface, and the mineral composition of the rock transfers into the soil

properties of the soil due to the addition of varying amounts of organic matter, pH, and hygroscopic moisture. The comparatively elevated area of Arsha block contains low pH and is relatively more acidic. In contrast, soil in Purulia I block has a higher pH value and tends to retain more water. Therefore, soils in the low-lying areas of Tamna have high hygroscopic moisture content due to better water retention capacity. Similarly, organic matter content in the elevated area (Arsha block) is usually high due to the presence of vegetation cover.

Quantifying geomorphic and climatic effects on weathering

It is clear by now that soil characteristics are mainly determined by topographic variations within a particular geological substrate. However, the soil characteristics in the study area are also influenced by climatic factors as soil formation through chemical weathering is greatly influenced by the availability of soil moisture. The rate of chemical reactions increases with temperature and tends to occur in hot sub-humid climatic regions. The earlier research (Kirkpatrick *et al*., 2014) also supported the fact that climate and weathering have a significant impact on soil properties. Purulia experienced little temperature fluctuation during 1970-2020 (Fig. 6). The highest annual average temperature was 28.12°C in the year 2012 and the lowest was 24.17°C in 1971 (Fig. 6). The sub-tropical climate with extremely high temperatures during summer with annual average precipitation of 1281.89mm creates favourable conditions for moderate-strong physical and chemical weathering. Rock fragmentation and chemical modification occur concurrently for soil formation. The basic minerals of parent rock quartz and mica schist (Fig. 7) are altered by chemical weathering to generate soil. The soil of the region is largely residual in nature due to the combined effect of high temperature and comparatively low rainfall mostly developed from granitic rocks. The monthly average rainfall (Table 1) for the last 20 years (1997 - 2017) is 1277.15 mm marked by large variations ranging from 798 mm (2010) to 1778.6 mm (2013). The standard deviation for the maximum annual rainfall was 166.31 mm. The standard deviation and the range show the high unpredictability of annual rainfall. The coefficient of variation of annual rainfall varied in the range of 85.34 - 157.86 %. Low water holding capacity and unpredictability of the rainfall results in a thin layer of the soil over much of the district. The water-holding capacity of the soil during the drought condition is low. The soil moisture index (SMI) is very low with a value close to 0 in much of Arsha and Purulia I block (Fig. 4) revealing a high soil water deficit. The evaporation rate is high due to the high temperature in summer. This high evaporation and hard rocky terrain restrict the leaching and eluviation process.

Weathering and soil formation

The role of physical weathering, alteration of minerals, and rock fragments are no less important in soil formation (Fig. 7). The characteristics of the soil are considerably dependent on the mineralogical composition of the parent rock. The alteration of primary minerals and the formation of secondary minerals take place during the process of weathering (Fig. 8b). The present climatic condition in the district with a high range of temperatures and little rainfall leads to moderate to strong intensity of weathering. Rainfall controls the moisture supply for chemical reactions and the removal of soluble constituents of the minerals. Minerals like quartz, silica, hornblende, and feldspar are found in this region. Quartz is poorly susceptible to chemical weathering and is not chemically altered. Physical weathering-induced smaller quartz grains are found in the upper layer of all weathered crusts (Fig. 8b). Quartz is disintegrated into smaller particles that form the sand and the coarse silt particles. Hornblende is ultimately weathered to form clay minerals. Soil developed from granite is a mixture of sand, feldspar, mica, and hornblende which makes it less fertile. The resistance of rock to weathering is also dependent on structural discontinuities. Variation in annual average temperature (highest 28.12°C and lowest 24.17°C) in the study area leads to a high rate of the physical weathering of the exposed rock, which in turn increases cleavages (Fig. 9) and make rocks susceptible to chemical weathering. In Fig. 8a, it is seen that the lower surface of weathering crust is soft due to the richness of mica and silica which are mixed with organic matter. Some silica particles are removed but a large proportion remains at the same place. The remaining silica particles are combined with alumina and iron and are transformed into minerals. The presence of minerals under the sub-tropical climate through chemical alteration has resulted in the formation of a weathered crust.

Conclusion

The physico-chemical properties of the soil are seen to vary with the topography in the study area. Organic matter is quite high ranging from 1.40 to 2.34 percent in the elevated area of Arsha block and this high organic matter concentration is due to the presence of forest cover. Soil moisture and soil pH also vary with variations in topography in the study area. The presence of high organic matter content results in low pH at the Arsha and Purulia 1 block. Samples from the higher elevation of Murguma show pH values ranging from 5 to 5.84. On the other hand, the pH values range from 5.85 to 6.94 at the Purulia 1 block. Apart from geomorphic factors, soil characteristics are influenced by the climate and its resultant weathering. The scarcity of rainfall is one of the responsible factors of deficit moisture in the soil. Thus, the soils of this study area are residual in nature. A wide range in temperature and very little rainfall throughout the study area is responsible for moderate to high degrees of weathering. Quartz, silica, mica schist, and feldspar are widespread in this region. The soil developed from granitic parent materials is less fertile. The physico-chemical properties of the soil are also changed on account of topographical variation. Weathering in the study area is aided by the abundance of rocks and minerals. Primary minerals are altered by chemical alteration and generate a thin layer of soil. Apart from elevation and slope, there is a scope to consider other topographical factors like aspect and drainage to understand the soil formation process in this region. Understanding the soil properties, formation, and its relationship with topography may help to take soil erosion controlling measures, identification of suitable crops, and better land use practices.

Competing interest

The authors declare that they have no conflict of interest.

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