Natural chemical degradation of soils in the Indian semi-arid tropics and remedial measures

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Most published research on soil degradation in general emphasizes the role of anthropogenic factors. Even among the natural soil degradation processes the regressive pedogenic processes that lead to the formation of $CaCO_3$ and concomitant development of subsoil sodicity and the adverse effects of palygorskite on the soils of the semi-arid tropics (SAT), have received little global attention as the natural processes of chemical degradation of soils. Studies in India during the last two decades, however, have demonstrated the important role of regressive pedogenic processes in natural degradation of major soil types in the Indian SAT regions. The present article summarizes the research on natural degradation of soils in the Indian SAT. The management practices to reclaim the degraded soils are also discussed with examples.

Keywords: $CaCO_3$ formation, regressive pedogenesis, remedial measures, SAT soils, subsoil sodicity.

Introduction

THE diversity of soils in the Indian semi-arid tropics (SAT) is demonstrated by the existence of six soil orders (Alfisols, Aridisols, Entisols, Inceptisols, Mollisols and Vertisols) out of the 12 soil orders in Soil Taxonomy[1]. The SAT environments are identified at the suborder level within the ustic moisture regime, suggesting the prevalence of dryness during a few months of the year. However, still there is enough soil moisture for potentially growing crops in the rainy season[2]. The specific definition of ustic moisture regime is based on the mean annual soil temperature, and the duration of the period in which the control section of the profile remains moist or dry[2]. By this definition, the ustic moisture regime occurs in the tropical regions, with a monsoon climate that has at least one rainy season lasting three or more months in a year[2].

Majority of the SAT soils support rain-fed agriculture with low productivity. Despite increase in food production due to the implementation of improved soil, water and nutrient management practices, many parts of the world continue to face food insecurity. About 60% of the world's population facing food insecurity resides in South Asia and sub-Saharan Africa. Most of these areas are rain-fed and there are several challenges in improving the livelihoods of the rural poor. Rain-fed areas are mostly inhabited by poor rural communities. Moreover the rain-fed agriculture in the SAT area is fragile in view of spatial and temporal variation of rainfall. Besides, the rainfall is of high intensity and during a short duration, which causes severe soil erosion, leading to physical, chemical and biological degradation of soils[1,3–5].

This basic fact has made scientists, agriculturists, environmentalists and policy makers anxious whether the soil resource base will be able to feed the expected 8.2 billion world population by 2030 (www.unpopulation.org). Soils being dynamic are able to supply nutrients, buffer acid-base reactions, absorb and degrade pathogens, detoxify and attenuate xenobiotic and inorganic compounds; and also they possess the capacity of self-restoration through the process of soil formation. Soil formation however is a slow process and a substantial amount of soil can form only over a geologic timescale. Soil misuse and extreme climatic conditions can damage such self-regulating capacity and give way to regressive pedogenesis[6], and thus might lead to the soil to regress from higher to lower usefulness and or drastically diminished productivity. Such an un-favourable endowment of soils is termed 'soil degradation'[7].

Definition, processes and factors of soil degradation

Lal *et al.*[7] defined soil degradation as 'diminution of soil quality (and thereby its current and potential productivity) and/or a reduction in its ability to be a multi-purpose resource due to both natural and human-induced causes'. Processes that lead to soil degradation include accelerated erosion, increasing wetness and poor drainage, laterization, salinization, nutrient imbalance, decline in soil organic matter and reduction in activity and species activity of soil fauna and flora[7]. Processes of soil degradation include chemical, physical and biological degradation of

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soils; and the interactions among these factors affect the capacity of a soil for self-regulation and productivity.

Factors causing soil degradation are both by natural and human-induced and enhance degradation, leading to changes in properties of soils and the attributes for their life support[7]. Although selected pedogenic processes such as laterization, hard setting, fragipan formation and claypan formation are hitherto considered as natural soil degradation processes as they lead to less desirable physical and chemical conditions, causing degradation of soils[7,8], the majority of the information on soil degradation at national[9,10], regional[11] or international level[12,13] has focused only on anthropogenic degradation. However, a few recent reports on major soil types (Indo-Gangetic Plains or IGP, red ferruginous and deep black soils) at the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP, ICAR), Nagpur, India showed that the development of sodicity and accumulation of relatively higher amounts of exchangeable Mg (EMP) than that of exchangeable Ca (ECP) in soils are also a natural process of soil degradation in the SAT climatic conditions[1,3,14–20].

Neotectonic-climate linked and mineral induced Natural Chemical Soil Degradation

In response to the global climatic event during the Quaternary, soils at many sites witnessed climatic fluctuations globally, especially in the last post-glacial period. Frequent climatic changes occurred during the Quaternary[21]. Tectonic slopes and or faults determine the courses of large rivers[22] and play a significant role in the evolution of geomorphology and soils[5]. Crustal movements also caused the change in climate from humid to semi-arid, as experienced with the formation of the Western Ghats[23]. In the endeavour by FAO's[11] to record land degradation in south Asia, the potential effects of global climatic change to cause degradation in soils were not considered. It was, however, envisaged that if adverse changes occur in some areas, then these processes will certainly constitute a most serious form of human-induced degradation of natural resources. Climate change from the humid to semi-arid did occur during the late Holocene in major parts of the Indian subcontinent[3–5]. It is quite likely, therefore, that the current aridic environment prevailing in many parts of the world, including India, might create adverse physical and chemical environment, leading to reduced productivity of soils. In addition, the impairment of soil physical properties in presence of magnesium-rich palygorskite minerals has also been observed[3,24]. Thus a new research initiative to identify the changes in soil properties in the SAT due to climate change and Mg-minerals, can help in expanding our basic knowledge in pedology and thus provide opportunity to develop relevant database[25]. Such database could be important for adapting sustainable soil management and long-range resource management strategies for many developing nations in the arid and semi-arid regions of the world, especially in the Indian subcontinent, where arid and semi-arid environments cover more than 50% of the total geographical area[1]. There is no dearth of literature on soil degradation due to anthropogenic activities[9–13]. But a precise account of factors of natural chemical degradation in major soil types of India forms a robust database for reference[3–5,25] to expand the present knowledge on natural soil degradation and to protect the livelihood of humankind.

Pedogenic processes in the SAT: cause of chemical soil degradation

The soils of the SAT regions in general are calcareous and on many occasions they are also sodic either in the subsoil or throughout the depth of soil profile[1,18]. Incidentally, all sodic soils are calcareous, but all calcareous soils are not sodic[1]. Calcareousness of soils is caused by the presence of both pedogenic and non-pedogenic $CaCO_3$, but the pedogenic formation of $CaCO_3$ (PC) is not a favourable chemical reaction for soil health because this creates unfavourable physical conditions, caused by concomitant development of exchangeable sodium per cent (ESP)[1,14,26]. The presence of pedogenic $CaCO_3$ (PC) that is distinguished from the pedorelict $CaCO_3$ (NPC) by the soil thin section studies[2], is common in major soil types of India (alluvial soils of the Indo-Gangetic plains, ferruginous soils and shrink-swell soils) (Figure 1). In the SAT environments, water loss through evapo-transpiration is considered the primary mechanism in the precipitation of PC, while temperature controls the water flow in the soil[1]. However, the development of sodicity is not realized yet in the desert soils due to their sandy textural class, ensuring better leaching of bicarbonates; and thus PC is generally observed at greater depth[1]. In the loamy and clayey textured soils, the leaching of bicarbonates is slow and thus both PC and sodicity develop in upper horizons[1]. Such pedogenetic processes are well demonstrated in the ferruginous soils (Alfisols) of southern India, which have ~30% clay, and are dominated by 2 : 1 expanding clay minerals and developed in humid tropical climate of pre-Pliocene. In these Alfisols, the formation of PC is observed due to the impact of the present day semi-arid climate, making these soils calcareous, unlike the ferruginous soils of humid tropical part of the country. The PCs in such soils are mainly concentrated as lubinites (Figure 1 *c*) that are formed only when the soil solution is supersaturated with $CaCO_3$ in the semi-arid environments[27]. Therefore, in addition to the aridity of the climate, the texture has an important role in the accumulation of carbonates in soils[28].

The accumulation of soil inorganic carbon (SIC) in terms of formation of PC in soils hitherto was considered as an undesirable natural endowment as it caused the impairment of soil productivity[1,29]. The formation of PC in the arid climate enhances the pH and also the relative abundance of Na^+ ions on soil exchange sites and in the solution; and the Na^+ ions in turn cause dispersion of the fine clay particles. The dispersed fine clays translocate in major soil types of India[3–5] as the formation of PC creates a Na^+-enriched chemical environment conducive for the deflocculation of clay particles and their subsequent movement downward. Therefore, the formation of PC and the clay illuviation are two concurrent and contemporary pedogenetic events, resulting in increase in relative proportion of sodium, causing increased sodium adsorption ratio (SAR) and ESP and pH values with depth (Figure 2). These pedogenetic processes continue to represent a pedogenic threshold during the dry climates of the Holocene[3–5]. Thus the formation of PC is a basic natural degradation process[1], induced by tectonics-climate linked events[17,25,30], which exhibits the regressive pedogenesis[6] which also immobilizes C in unavailable form.

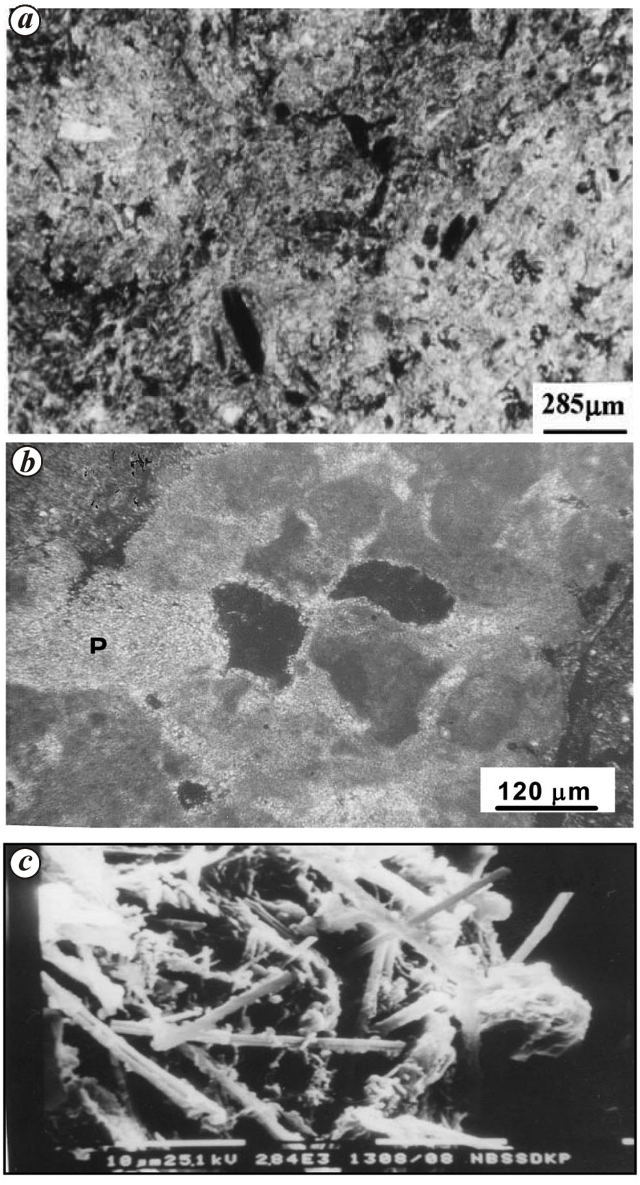

Figure 1. Representative photomicrographs of pedogenic $CaCO_3$. ***a***, Soils of the IGP (Natrustalfs); ***b***, Vertisols of central India; ***c***, Ferruginous soils of southern India (Alfisols) (adapted from Pal *et al.*[25]).

Palygorskite-induced natural chemical soil degradation

The Vertisols of dry climates of the peninsular India have poor drainage due to clay dispersion caused by exchangeable magnesium[19]. From this it follows that the saturation of Vertisols not only with Na^+ ions but also with Mg^{2+} ions blocks small pores in the soil[18]. In other words, Mg^{2+} ions are less efficient than Ca^{2+} ions at flocculating soil colloids, although the United States Salinity Laboratory[31] grouped Ca^{2+} and Mg^{2+} ions together as both these ions improve the soil structure. This action is further impaired by low ESP (>5, <15) which reduces the saturated hydraulic conductivity (sHC) to <5 mm h^{-1}, causing more than 50% reduction in cotton yield[3]. The dispersion of clay colloids and impairment of the sHC of Vertisols is generally an effect of ESP or EMP in presence or absence of soil modifiers. However, the sHC of zeolitic Vertisols of the Marathwada region of Maharashtra is reduced to less than 10 mm h^{-1}, although the soils are non-sodic (Typic Haplusterts[32]), neutral to mildly alkaline in pH, with less than 5 ESP, and EMP increasing with depth. In some pedons, the EMP is greater than ECP at depths below 50 cm. Mineralogical studies indicate that palygorskite is found mainly in the silt and coarse clay fractions[32]. Palygorskite minerals are present in both normal black and associated sodic black soils in India[32] and elsewhere[33]. Among the commonly found minerals, palygorskite contains more magnesium[34]. Neaman *et al.*[35] examined the influence of clay mineralogy on disaggregation in some palygorskite-, smectite- and kaolinite-containing soils (ESP <5) of the Jordan and Betshe'an valley in Israel. Palygorskite is the most disaggregated of the clay minerals, and its fibre is not associated with or within aggregates in soils and suspensions even when the soils are saturated with Ca^{2+} ions. Palygorskite particles thus move downward in the profile preferentially over smectite and eventually clog the soil pores[36]. Therefore, Vertisols with palygorskite content with high EMP lead to the dispersion of the clay colloids that form a 3D mesh in the soil matrix. This interaction causes drainage problems when such soils are irrigated, presenting a predicament for crop production. In view of their poor drainage conditions and loss of productivity, non-sodic Vertisols (Typic Haplusterts) with palygorskite minerals may be considered as naturally degraded soils. Soils with such characteristics also occur in other parts of the world and

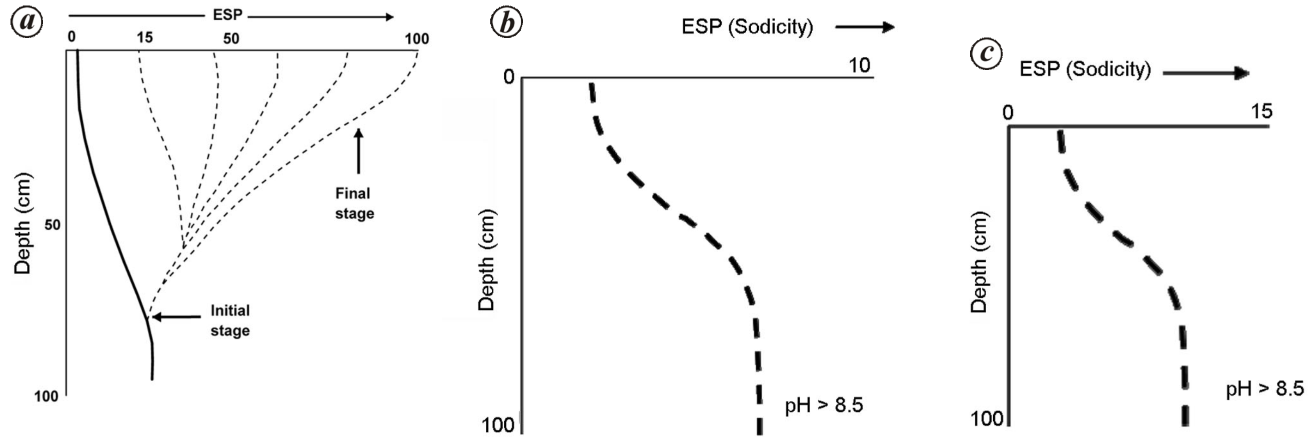

Figure 2. Illuviation of Na-clay triggered by formation of PC, causing higher ESP and pH in the sub-soils (adapted from Pal *et al.*[25]). ***a***, IGP soils; ***b***, Ferruginous soils; ***c***, Vertisols.

therefore a new initiative to classify this group of soils is warranted[3,24].

Micro topography: as factor of natural soil degradation in SAT

It is observed that the SAT soils that are calcareous have sodicity in the subsoil or throughout the soil profile. But the degree of sodicity varies in the soilscape. In the IGP and area representing ferruginous soils highly sodic soils occur at the micro-low (ML), whereas non-sodic/less sodic soils are observed in the micro-high (MH) positions (Figure 3 *a* and *b*)[17,20]. In contrast, sodic Vertisols (Sodic Haplusterts) occur in ML and non-sodic/less sodic Vertisols (Typic Haplusterts) in MH positions (Figure 3 *c*)[19]. The soils in a micro-topographical sequence have contrasting chemical characteristics. The soils at MH positions are less alkaline in the IGP and highly alkaline in SAT Vertisols areas respectively. In the IGP the micro-lows are repeatedly flooded with surface water during brief high-intensity showers, and so the soils are subject to cycles of wetting and drying. This provides a steady supply of alkalis by hydrolysis of feldspars, leading to precipitation of calcium carbonate at high pH and development of subsoil sodicity. This impairs the hydraulic properties of soils and eventually leads to the development of relatively high ESP in the subsoils. The SAT climate and topography interact to facilitate greater penetration of bicarbonate-rich water in ML than in MH positions. The sHC of the soils at ML position is almost nil in the subsurface layers due to higher amount of clay smectite and ESP. The SAT climate of the area induced precipitation of carbonates which in turn has increased Na^+ ion in the exchange complex[1]. This is common in IGP, ferruginous and black soil regions of India wherein SAT climate induces the precipitation of calcium carbonates with a concomitant development of subsoil sodicity[1,14,17,19,20].

The formation of $CaCO_3$ and illuviation of clay can be considered as the two pedogenic processes occurring simultaneously as contemporary events in the drier climates in ML position. Similar micro topographical situations in the formation of sodic and non-sodic soils on ML and MH positions respectively are observed in soils of the north-western parts of the IGP[17] and also in ferruginous soils of southern India[20]. In contrast, in swell-shrink soils of central India a reverse situation was observed; sodic soils occur in MH and non-sodic soils as ML position. Relatively higher amounts of PC and subsoil sodicity in MH Vertisols than in ML soils suggest the formation MH sodic soils which is due to relatively more aridity on MH than the ML positions[19]. Thus the development of $CaCO_3$ and sodicity in the soils of ML and MH positions may be widespread in similar SAT areas of India. The rate of formation of PC for bench mark soils in Indian IGP, black (shrink-swell) soils and red ferruginous soils of SAT has been estimated to be 129, 37.5 and 30 kg $CaCO_3$ ha^{-1} yr^{-1} respectively[2]. Although the rate of formation of carbonates in ferruginous and black SAT soils is not alarming at present, due care is needed while irrigating these soils. In view of a high rate of $CaCO_3$ formation in the drier part (SAT) of the IGP soils, immediate remedial measures are required to make them resilient.

Indices of soil degradation

The impairment of soil physical properties due to high ESP/EMP and the presence of palygorskite mineral, as judged by reduced sHC, explains the cause-effect relation for the development of natural soil chemical degradation in SAT. However, such an explanation for the degradation

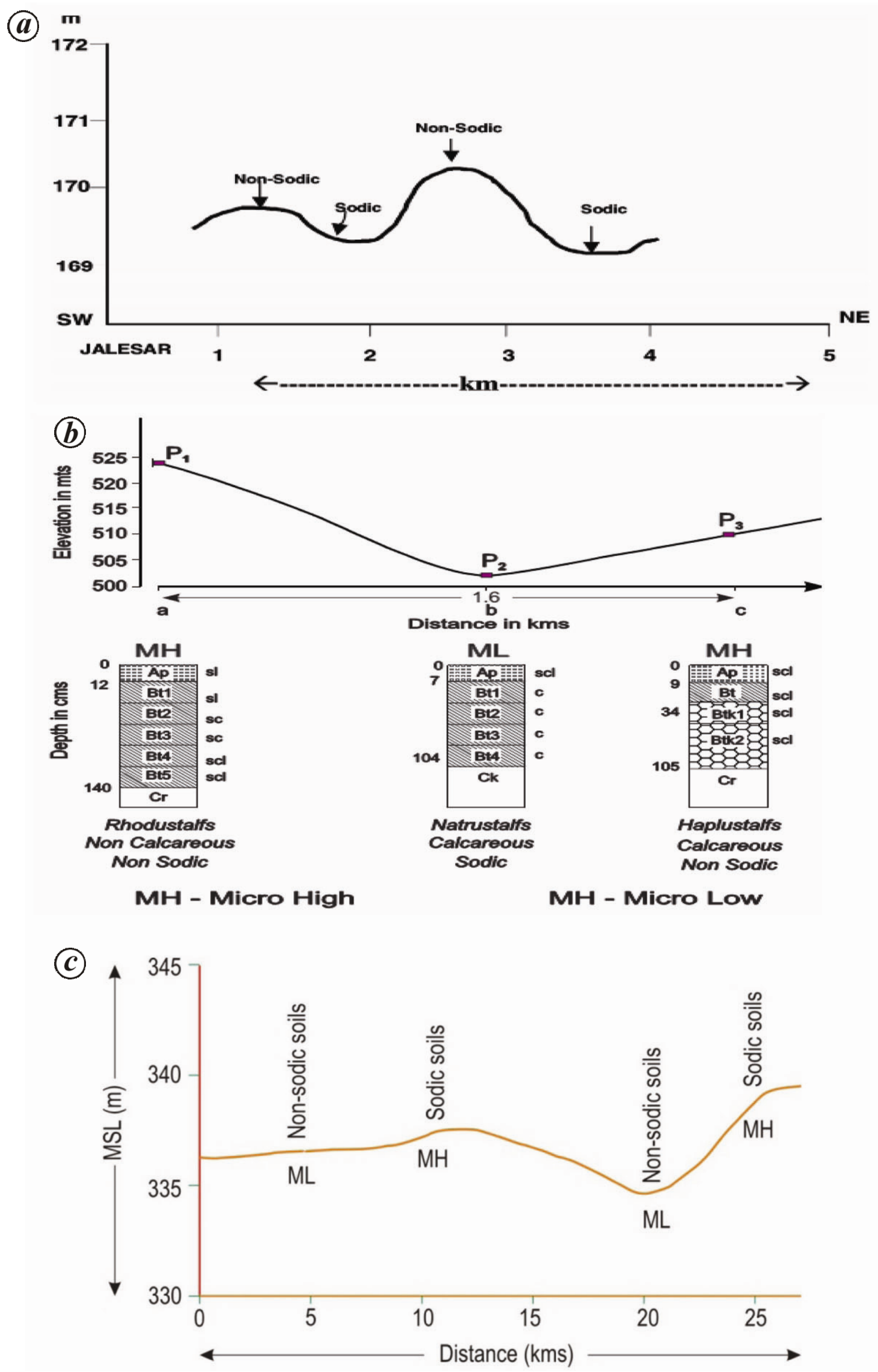

Figure 3. ***a***, NE–SW profile in Ganga–Yamuna interfluve of the IGP showing non-sodic soils on MH and sodic soils on ML sites. ***b***, Schematic diagram of the landscape representing the unique role of micro topography in the formation of non-sodic and sodic RF soils at MH and ML positions. ***c***, Juxtaposition of the occurrence of sodic and non-sodic soils (Vertisols) on MH and ML positions in black soils region (adapted from Pal *et al.*[25]).

of soils remains unconfirmed as it is not related to crop performance and yield. Also, the critical limits of these indices has not been established. Sodicity tolerance ratings of crops in loamy-textured soils of the IGP indicated that a 50% reduction in relative yield of rice and wheat was observed when soil ESP was above 50 and ~40 respectively[37]. In shrink-swell soils (Vertisols), an optimum yield of cotton can be obtained when soils are non-sodic (ESP <5) and have sHC >20 mm h^{-1}. About 50% reduction in yield occurs when soils are sodic (ESP >5) showing low sHC (<10 mm h^{-1}). However, the Ca-rich zeolitic black soils (Sodic Haplusterts) of Rajasthan and Gujarat support rainfed crops fairly well[18,38] due to favourable soil drainage (sHC >10 mm h^{-1}). Therefore, fixing a lower limit of sodicity[18] at ESP >40 for soils of the IGP[37], at ESP >5 but <15 for Indian Vertisols[39], at ESP 6 for Australian soils or at ESP >15 for all soil types[40] does not seem relevant for Vertisols[18]. In view of the impairment of the hydraulic properties of soils in SAT, a value of sHC <10 mm h^{-1} (as weighted mean in 0–100 cm depth of soil) was advocated to define sodic soils instead of using an ESP[18].

Remedial measures for degraded soils

Results obtained so far indicate that SAT soils are prone to chemical degradation showing strikingly different soil properties as compared to a normal soil. Therefore maintenance of required balance between exchangeable and water soluble Ca^{2+} ions in soil systems is a challenge for land resource managers to make these degraded soils resilient.

Predicament in identification and reclamation of sodic soils

Sodic soils in the north-western (NW) parts of the IGP show salt-efflorescence in the surface as an evidence of soil sodicity and this soil characteristic is mappable using remote sensing. However, such maps for the shrink-swell soils (Vertisols and intergrades) are not available because of the absence of salt-efflorescence in the soil surface. In addition, despite having poor hydraulic properties (<10 mm hr^{-1} even at an ESP >5 but <15) do not qualify as salt-affected soils according to the United States Salinity Laboratory criteria. The Central Soil Salinity Research Institute (ICAR), Karnal developed reclamation technology, which recommends the use of mined gypsum, followed by paddy as the first crop[37]. The full potential of this technology, however, depends upon the proper identification of nature of sodicity in all major soil types and also on the quantum of subsidy received by land holders (offered by different Govt and non-Govt organizations) of such problem soils for the procurement of the raw gypsum.

An alternative management protocol to make sodic soils resilient

Non-zeolitic and non-gypsiferous Vertisols (Sodic Haplusterts) in SAT show poor sHC (<10 mm hr^{-1}) even at ESP ≥5 <15, and have poor crop productivity, and are impoverished in organic carbon (OC) but are rich in $CaCO_3$. Such soils show enough resilience under improved management (IM) system of the International Crops Research Institute for Semi-Arid Tropics (ICRISAT)[41] that does not include any amendment like gypsum and FYM. The average grain yield of the IM system over thirty years was five times more than that in the traditional management (TM) system. Adaptation of the IM system improved physical, chemical and biological properties of soils to the extent that a poorly drained black soil (Sodic Haplusterts) can now qualify for well-drained soil (Typic Haplusterts). A continuous release of higher amount of Ca^{2+} ions during the dissolution of $CaCO_3$ (8.4 mg/100 g soil/year in 1 m deep profile) under the IM system, compared to slower rate of formation of $CaCO_3$ (0.10 mg/100 g soil/year in 1 m profile), provide enough soluble Ca^{2+} ions to replace unfavourable Na^+ ions on the soil exchange sites. Higher exchangeable Ca/Mg ratio in soils under IM system improved the sHC for better storage and release of soil water during dry spell between rains. Adequate supply of soil water helped in better crop productivity and higher OC sequestration. The improvement in Vertisols' sustainability suggests that the IM system is capable of mitigating the adverse effect of climate change[42]. This management protocol though slow as compared to gypsum-aided one, is however cost-effective and farmer-friendly. This technology is recommendable for a large scale impact on agricultural productivity[43,44]. Moreover, it opens up an interesting area of soil research that is to realize the benefit of the presence of $CaCO_3$ as a hidden treasure during the reclamation of sodic soils even with the addition of gypsum as practised in NW part of the IGP[25]. This has been detailed through C transfer model which was reported to work better in the drier part of the IGP[25].

Calcium carbonates make IGP sodic soils resilient

Following reclamation with gypsum, some sodic soils (Natrustalfs) improve in terms of their morphological, physical and chemical properties so much that these soils can now be reclassified as well-drained and OC-rich normal Alfisols (Haplustalfs). Generally, gypsum as amendment is added in relatively less amount than estimated by 'Gypsum Requirement' of highly sodic soils with ESP ~90–100 (Natrustalfs). But even with the low amount of added gypsum, sodic soils are reclaimed to show their resilience. Thus the success of this reclamation protocol is not all due to gypsum added because it does not enrich soil solution by the required amount of Ca^{2+} ions to replace Na ions on the soil exchange sites. Further, the Ca requirement to replace all exchangeable Na^+ ions is mainly through the rapid dissolution of the native pedogenic $CaCO_3$ (PC) during the growing of the rice crop under submerged conditions. The rate of dissolution of PC during 30 months' cultural practice with gypsum in Natrustalfs has been estimated to be 254 mg/100 g soil in the top 1 m of the profile. This indicates a much higher rate of dissolution (~100 mg/100 g soil/year)[25] than its rate of formation (0.86 mg/100 g soil/year) in the top 1 m soil depth[1].

Role of $CaCO_3$ as soil modifier in ensuring soil sustainability of SAT soils

After becoming non-sodic in nature through cultural practices, both IGP soils (Haplustalfs) and Vertisols (Haplusterts) have substantial stock of $CaCO_3$ (SIC) in the first 1.5 m depth, which has potential to improve the drainage, establishment of vegetation and also sequestration of OC in soils[25]. The continuance of agronomic practices of the National Agricultural Research Systems (NARS) and ICRISAT can provide the most important Ca^{2+} ions both in solution and exchange sites of soil. These resilient soils still contain nearly 2–7% $CaCO_3$. In view of the rate of its dissolution (~100 mg/100 g soil/year for IGP soils, and 21 mg/100 g soil/year for Vertisols[3,44]), it is envisaged that under improved management in the SAT environment, total dissolution of $CaCO_3$ would take a time of couple of centuries. Such chemical environment would not allow both Haplustalfs and Haplusterts to transform to any other soil order so long $CaCO_3$ would continue to act as a soil modifier[3,44]. Positive role of $CaCO_3$ in both reclamation and sequestration of OC in SAT soils may benefit maintaining the soil health of the farmlands if additional financial support through national and international initiatives including the incentives or transferable C credits under CDM is made available[45] to stake holders of sodic soils.

Conclusions

Pedogenic calcium carbonate, soil sodicity and palygorskite mineral impair the hydraulic properties of the SAT soils. The unfavourable physical property reduces the crop productivity in the SAT soils. This type of unfavourable soil health triggered by the tectonic-climate linked regressive pedogenic processes, need to be globally considered as the natural soil degradation process despite the claims of their occurrence as a result of human induced soil degradation in the SAT areas. The regressive pedogenic processes that are inherently linked to the development of natural soil degradation, expand the basic knowledge in pedology and thus it may have relevance in soils of other SAT areas of the world. The knowledge gained through the research efforts made in the Indian subcontinent explains the cause–effect relationship of the degradation and provides enough insights as to how the remedial measures are to be invented including the role of pedogenic $CaCO_3$ and geogenic Ca-zeolites as soil modifiers along with gypsum, in making naturally degraded soils resilient and healthy.

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