



Soil Resilience and Sustainability of Semi-Arid and Humid Tropical Soils of India: A Commentary*

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Introduction

Soil is a dynamic and living natural resource, which supports to produce goods and services of value to humans but not necessarily with perpetual ability against the degradative processes. It is well known that soil formation 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 self-regulating capacity and give way to regressive pedogenesis (Pal *et al.* 2013), and thus might lead to the soil to regress from higher to lower usefulness and or drastically diminished productivity. Such an unfavorable transformation of soils is termed as 'soil degradation'. However, soils do have an inherent ability to restore their life support processes if the disturbances created by anthropogenic activities are not too drastic and sudden, and mitigated with enough time is allowed for life-support processes to restore themselves. This intrinsic ability of soils to regenerate their productivity is called resilience (Szabolcs 1994). Therefore, soil resilience is the ability to bounce back or return to normal functioning, after adversity, for sustainable productive purposes.

Processes of soil degradation include chemical, physical and biological degradation of soils; and the interactions among these factors affect the capacity of a soil for self-regulation and maintaining productivity.

Historic non - resilient soil situation leading to abandoning of the site, due to man-made soil degradation has been recorded as in the collapse of Harappan civilization of the Indo-Gangetic Plains. In present times we are witnessing it in the shifting cultivation areas of North - East India, by the rapidity with which old sites are abandoned and new sites are chosen for cultivation.

A wealth of soil information has been developed by the NARS, state government departments and ISRO. Pal *et al.* (2000), Bhattacharyya *et al.* (2013) have given a comprehensive review on this subject.

I. Soil Resilience is affected by factors such as 1. Moisture related and other physical properties mediated stresses. 2. Nutrient supply related chemical stresses. 3. Toxic level of chemical elements. 4. Pollutants and contaminants through untreated sewage and industrial effluents and 5. Low Organic (carbon) matter content below a threshold level. Some examples are given below:

Soil resilience mediated through intrinsic soil properties such as textural composition and mineralogical make up are difficult to manipulate through land management practices, such as moisture stress and relieving it with longer release of applied water is dependent on moisture retention – release characteristics of the soil which again is conditioned by structure and texture of the soil. The

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scheduling of surface irrigation and design of the drip irrigation system is therefore dependent on the nature of the soil and its moisture characteristics.

Resilience of the soil after receipt of the first monsoon rains in the black soil (Karisal mann) areas of Tirunelveli district is dependent on the nature and quality of the soil. Farmers recognize and name those soils which come to easy workability and tillage operations as against those soils which turn into large clods and become amenable for tillage operations after a long time interval from the onset of monsoon rains (Mosi *et al.* 1991). Similar is the behaviour of the soils with the occurrence and its effect on seedling emergence and thawing behaviour of the soil in north India during winter months. The resilience of the soil for providing nutrient supply to plants within the range of “available soil nutrients” is moderated through the soils. The quantity intensity (Q/I) relations for P and K soil nutrients and the nature of Electro Ultra Filtration (EUF) fractions of soil K which differ between different kinds of soil and between soils of same kind, determine the behaviour of the soils for managing long term soil nutrient management and adoption of Integrated Plant Nutrient Supply System (IPNS). Soil test based IPNS strategy for prevailing crop rotation taking into account the nutrient buffer capacity of the particular soil type should be the management strategy for maintenance of soil fertility over time.

The data from plots of Long Term Fertilizer Experiments (LTFE) and Long Term Crop Rotation Experiments in the agricultural research stations provide research scope for unraveling the differential resilience characteristic of the unmanured and differentially manured plots of the soil and between different kinds of soils, in terms of soil mediated yield trends over time series of similar crop-weather seasons and the expressions of soil resilience in maintaining soil quality and yield trends.

Organic Matter in Soil

The organic matter of the soil is the life giving entity to the soil and the soil-borne flora and fauna. The Royal Commission of Agriculture (1928) concluded that the organic carbon status of Indian soils have come to an equilibrium with prevailing climatic conditions and land management practices followed.

Studies made by Jenny and Raychaudhari (1960) and analysis of LTFE data by Swarup *et al.* (2000) shows that there is depletion of soil organic matter in soils of India over time. It is recognized that only when the organic carbon content is above the threshold level its beneficial effects on soil resilience will be more pronounced and manifested. The wide spread problem of soil degradation is directly related to the lower soil organic carbon concentration in the soils of India.

The following commentary and discussion is related to the physical (soil loss due to water erosion) and natural chemical degradation caused by two extreme climatic conditions *i.e.* semi-arid (SAT) and humid tropical (HT) climates.

II. Physical and chemical degradation in Indian semi-arid tropical (SAT) soils

Physical degradation - soil erosion

Under the SAT environments, the red ferruginous (RF) soils of Indian states suffer soil loss due to erosion, and the loss is maximum in Karnataka (49%) followed by Andhra Pradesh (40%) and Tamil Nadu (20%) (ICAR-NAAS 2010), considering soil loss $> 10 \text{ t ha}^{-1} \text{ yr}^{-1}$ (using the empirical Universal Soil Loss Equation (USLE) to estimate spatial variations of soil loss factors like R, K, L, S, C and P factors) as the threshold for soil degradation. The RF soils of SAT dominantly belong to Alfisols, and the other soil orders are Inceptisols, Entisols and Mollisols (Pal *et al.* 2014). Considering the rate of soil formation in dry environments at $< .25 \text{ mm yr}^{-1}$ (Kassam *et al.* 1992), SAT Alfisols would gain soil at least $3.67 \text{ t ha}^{-1} \text{ yr}^{-1}$. However, short-term hydrological studies on small agricultural watershed on Alfisols at the ICRISAT Center, Patancheru, India indicate an average soil loss from SAT Alfisols under traditional system is around $3.84 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Pathak *et al.* 1987). On the other hand, the results from long-term study reported an annual soil loss of $4.62 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Pathak *et al.* 2013). To reduce unwarranted soil loss of the SAT Alfisols, improved system of management developed by the ICRISAT (Pathak *et al.* 1987) made Alfisols resilient as reflected by the minimized soil loss to nearly $1 \text{ t ha}^{-1} \text{ yr}^{-1}$ and simultaneously increased crop productivity compared to traditional system on a sustained manner. These results suggest that a threshold value of soil loss by water erosion as sign of degradation, need be based on pedogenesis and experimental results rather than assuming

an arbitrary value of $>10 \text{ t ha}^{-1}\text{yr}^{-1}$ to avoid unwarranted national expenditure for the current and future conservation measures (Pal *et al.* 2014).

Chemical degradation - formation of CaCO_3 and sodicity

Although selected pedogenic processes such as laterization, hard setting, fragipan formation and clay-pan formation are hitherto considered as natural soil degradation processes as they lead to less desirable physical and chemical conditions, causing degradation of soils (Hall *et al.* 1982), the majority of the information on soil degradation at national (Sehgal and Abrol 1992, 1994), regional (FAO 1994) or international level (Oldeman 1988; UNEP 1992) has focused only on degradation caused by anthropogenic activities.

In the report of FAO (1994) on land degradation in south Asia, the potential effects of global climatic change to cause degradation in soils was 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. As a matter of fact, climate change from the humid to semi-arid did occur during the late Holocene period in major parts of the Indian sub continent (Pal *et al.* 2012a, 2013; Srivastava *et al.* 2015). 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. A few recent reports on major soil types (Indo-Gangetic Plains or IGP, Red Ferruginous and Deep Black Soils) from the Indian Council of Agricultural Research-National Bureau of Soil Survey and Land Use Planning (ICAR-NBSS&LUP), Nagpur, India showed that the regressive pedogenesis (Pal *et al.* 2013) in terms of the formation of the pedogenic CaCO_3 (PC) and concomitant development of sodicity and accumulation of relatively higher amounts of exchangeable Mg (EMP) than that of exchangeable Ca (ECP) in soils, is also a natural chemical process of soil degradation in SAT climatic conditions (Balpande *et al.* 1996; Pal *et al.* 2000, 2001, 2003, 2006, 2012a; Vaidya and Pal 2002; Chandran *et al.* 2013). Such a precise account of regressive pedogenesis in terms of factors of natural chemical degradation in major soil types of India forms a robust database for reference (Pal *et al.* 2009, 2012a, 2014; Srivastava *et al.* 2015) to expand the present

knowledge on natural chemical soil degradation and to protect the livelihood of humankind.

Thus a new research initiative to identify the changes in soil properties in the SAT due to climate change can help in expanding our basic knowledge in pedology and thus provide opportunity to develop relevant database (Pal *et al.* 2009). Such a 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 (Pal *et al.* 2000).

III. Physical and chemical degradation in Indian HT (Humid Tropical) soils

Physical degradation-soil erosion

Soils under HT climate of NEH (north-eastern hills) and southern peninsular areas are most affected by water erosion, and the highest area under this category of degradation is in Nagaland (87%), followed by Meghalaya (78%), Arunachal Pradesh (73%), Assam (66%), Manipur (53%), Tripura (38%), Sikkim (37%) and Kerala (15%). These estimates were based on an assumption that soil erosion $< 10 \text{ t ha}^{-1}\text{yr}^{-1}$ generally does not significantly affect soil productivity; and the HT soils with this amount of loss were not considered degraded (ICAR-NAAS 2010). The rate of soil formation varies from $< 0.25 \text{ mm yr}^{-1}$ in dry and cold environments to $> 1.5 \text{ mm yr}^{-1}$ in humid and warm environments (Kassam *et al.* 1992). If the rate of soil formation is taken as 2.0 mm yr^{-1} for soils of HT climate, the amount of top soil formation would be around $29 \text{ t ha}^{-1}\text{yr}^{-1}$ (Bhattacharyya *et al.* 2007). This gain in soil strongly suggests that the rate of soil loss by water erosion from Ultisols, Alfisols, Mollisols and Inceptisols is not at all significant (Bhattacharyya *et al.* 2007). The pedogenetic processes in HT soils, which are not given due consideration while following the USLE for estimation of soil erosion, ensures the positive balance of soil formation, and thus mature soils (like Ultisols, Alfisols, Mollisols and clay enriched Inceptisols) on a stable landscape under HT climate is a reality. The major pedogenetic processes that are operative to give rise to these soil orders, are evident through the addition of C by litter falls and its accumulation as soil organic matter under adequate vegetation and climate,

translocation of clay particles (to form clay enriched B horizons) and transformation of 1.4 minerals to 1.4-0.7 nm mixed layer minerals which are not pure kaolinite but are kaolins with a basal spacing of around 0.7 nm (Pal *et al.* 2014). In contrast, in acidic soils (mainly Entisols) on higher slopes (ridges, scarps and terraces) under low vegetation with only shrubs and bushes, soil development is greatly hampered by the severe soil loss due to water erosion. Soil loss is also evident in other soils that have less vegetative cover. Besides proper mechanical conservation measures, such soils areas may be suitable for forestry, horticultural and plantation crops to build resilience in them (Bhattacharyya *et al.* 1998, 2007).

Chemical degradation-soil acidity

Development of acidity in soils is indeed a sign of natural chemical degradation due to profuse chemical weathering under HT climate. Acid soils of the HT climate have less soil fertility. Such soils with strong (pH < 4.5) and moderate acidity (pH 4.5–5.5) only were considered and they occupy about 6.98 m ha which is about 9.4% of the total geographical area of the country (ICAR-NAAS 2010). Soils of HT climate in the states of Kerala, Goa, Karnataka, Tamil Nadu and North Eastern Hill (NEH) areas are strong to moderately acidic Alfisols, Ultisols and Mollisols and their further weathering in HT climate would finally close at Ultisols with considerable amount of layer silicate minerals (Pal *et al.* 2014). In view of contemporary pedogenesis, it is difficult to reconcile that Ultisols would ever be weathered to reach an unproductive stage like in Oxisols with time (Pal *et al.* 2014) as envisaged by Smeck *et al.* (1983) and Lin (2011). In view of their successful use for food production for centuries would it be prudent to consider such acid soils as degraded? This warrants for a revision in the present methodology giving due recognition of their pedogenetic processes that do not drive to an unproductive stage of soils.

IV. Resilience and Sustainability of Soils

It is essential to develop through research the cause-effect relationship of the soil degradation and such basic knowledge enables the land resource managers to invent appropriate management protocols to make degraded soils resilient. At present such knowledge is available for degraded soils of both SAT and HT environments.

Resilience and sustainability of naturally degraded SAT soils

The adverse SAT climatic conditions during the Holocene induce precipitation of CaCO₃ with a concomitant development of sodicity in the subsoils of the SAT region. The subsoil sodicity impairs the saturated hydraulic conductivity (sHC) of soils, and as a result many soils of the Peninsular India suffer from loss of productivity (Pal *et al.* 2013). However, such soils show enough resilience under the improved management even when they are not endowed with soil modifiers such as Ca-zeolites and gypsum.

A management protocol to make calcareous and sodic deep black soils (Vertisols) resilient

SAT Vertisols (Sodic Haplusterts) that are not endowed with natural zeolite and gypsum, show poor saturated hydraulic conductivity (sHC) (< 10mmhr⁻¹) even at ESP < 15, and have poor crop productivity, and are impoverished in organic carbon (OC) but are rich in CaCO₃, and show enough resilience under improved management (IM) system of the ICRISAT (International Crops Research Institute for Semi-Arid Tropics) (Wani *et al.* 2003). The IM system 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 Ca²⁺ ions during the dissolution of CaCO₃ (8.4 mg/100g soil/year in 1m deep profile) under the IM system, compared to slower rate of formation of CaCO₃ (0.10 mg/100g soil/year in 1m profile), provide enough soluble Ca²⁺ 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. This management protocol though very slow as compared to gypsum-aided one, is however a cost-effective and farmer-friendly, and also helps land resource researchers to realize the benefit of the presence of CaCO₃ as a hidden treasure in making degraded soils resilient.

Calcium carbonates make IGP sodic soils resilient

When reclaimed with gypsum, some sodic soils (Natrustalfs) become resilient as reflected in their improved morphological, physical and chemical properties so much that these soils can now be reclassified as well-drained and OC-rich normal Alfisols (Haplustalfs) with remarkable enhancement in rice-wheat productivity. Generally, gypsum as amendment is added in relatively less amount than estimated by 'Gypsum Requirement' of highly sodic soils with ESP~ 90-100 (Natrustalfs) (Pal 2013). But even with the low amount of added gypsum, sodic soils are reclaimed to show their resilience. Gypsum added does not enrich soil solution by the required amount of Ca^{2+} ions to replace Na ions on the soil exchange sites. In fact, 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/100g soil in the top 1m of the profile. This indicates a much higher rate of dissolution (~ 100 mg/100g soil/year) (Pal *et al.* 2009) than its rate of formation (0.86 mg/100g soil/year) in the top 1m soil depth (Pal *et al.* 2000). The formation of PC causes the development of sodic soils (Pal *et al.* 2000) but its unique role in minimizing the cost of gypsum aided reclamation process and also making sodic soils resilient, adds to the present knowledge on resilience of degraded SAT soils of India and elsewhere.

Gypsum makes SAT Vertisols resilient

Under rain-fed situation, continuous efforts to grow cotton, pigeon pea and sorghum in Gypsic Vertisols of the SAT southern India indicate no development of sodicity (ESP < 5) in the profile despite the rapid formation of CaCO_3 , due to much faster solubility of gypsum than CaCO_3 . At present gypsum helps to mitigate the adverse effect of climate change from humid to semi-arid during the Holocene. The present sustainability of crop productivity in such soils would however be further improved by using good quality irrigation water so long gypsum remains available with time. In absence of gypsum these soils would lose sustainability as they would turn out to be sodic with poor drainage. Research on long-term experiments in calcareous Vertisols but naturally endowed with gypsum is needed, which may suggest how long an amount of gypsum would help in

sustaining the present agricultural crop productivity by mitigating the adverse effect of PC under SAT environment.

CaCO_3 as soil modifier in ensuring 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 (as soil inorganic carbon, 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 (Pal *et al.* 2009). The continuance of agronomic practices of the NARS (National Agricultural Research Systems) 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/100g soil/year for IGP soils, and 21 mg/100g soil/ year for Vertisols (Pal *et al.* 2012a, 2015), 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 (Pal *et al.* 2012a, 2015). 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 (Pal *et al.* 2015) to stake holders of sodic soils.

V. Resilience and sustainability of HT soils

Acidic Alfisols, Ultisols and Mollisols do respond to management interventions and support luxuriant forest vegetation, horticultural, cereal crops, tea, coffee and spices (Sehgal 1998), and thus contribute substantially to India's growing self-sufficiency in food production and food stocks (Chandran *et al.* 2005). In view of such reality, it would not be prudent to class them as chemically degraded soils with poor fertility. These soils do show their ability to stall the drastic chemical and mineralogical changes under intense HT climatic conditions for the last several millions of years (Pal *et al.* 2014). Questions remain how such soils are able to withstand the progressive pedogenesis in HT climate that would have otherwise made these soils to Oxisols, which are

notorious in supporting crop productivity. An explanation is provided in the following paragraph.

In soils (developed on rocks/sediments rich in feldspar, zeolites and other Ca-rich minerals) of HT climate of India, the dominance of kaolin (smectite-kaolinite or vermiculite-kaolinite mixed layer minerals) indicates that in spite of prolonged weathering for millions of years, the weathered products of Ca-rich minerals of the parent materials have not reached even the pure kaolinitic mineral stage. The formation of kaolin clay mineral suggests that the formation of acidic Alfisols, Mollisols and Ultisols, and their pedogenic threshold at this time supports the supposition that steady state may exist in soils developed over long periods of time spanning not just thousands of years (Smeck *et al.* 1983; Yaalon, 1975) but also millions of years (Bhattacharyya *et al.* 1993, 1999; Chandran *et al.* 2005). Therefore, the formation and persistence of these soils provide an example that in an open system such as the soil, the existence of a steady state seems a more useful concept than based on equilibrium in a rigorous thermodynamic sense (Smeck *et al.* 1983; Bhattacharyya *et al.* 1999, 2006; Chandran *et al.* 2005), and Jenny's state factor equation is essentially valid. This contention finds support from the current pedogenetic processes in Ultisols in NEH areas. The OC rich Ultisols have less Al-saturation in surface horizons due to the downward movement of Al as organo-metal complexes or chelates, but have higher base saturation than the sub-surface horizons due to addition of alkaline and alkaline metal cations (Pal *et al.* 2014) through litter fall (Nayak *et al.* 1996), and there is no desilication and transformation of kaolin to gibbsite.

In Ultisols, Alfisols and Mollisols of HT climate, C sequestration is relatively high as indicated by their OC concentration ranges from 1.0 to 5% (Pal *et al.* 2014)). Soils in a wet climate under forest have high OC content, sufficient to qualify as Mollisols. The OC addition to Ultisols and Alfisols has been possible as a result of, favourable soil temperature and moisture regime. It is known that 2:1 expanding clay minerals provide higher surface area for OC accumulation. But a high positive balance of OC in kaolin dominated soils clearly indicates a positive role of this mineral and other hydroxy-interlayered clay minerals because kaolin often shows a relatively high value of CEC ~30 cmol (p+) kg⁻¹ (Ray *et al.* 2001) than that

of well crystalline kaolinite. Therefore, besides the dominating effect of humid climate in cooler winter months with profuse vegetation, the soil substrate quality in terms of larger surface area is of fundamental importance in OC sequestration in soils, an important issue in maintaining soil health and sustainability (Velayutham *et al.* 2000; Pal *et al.* 2014). This has been possible due to considerable chemical reactivity of soil kaolin that helps provide an effective substrate to support agriculture and other land uses in the tropics. Soil kaolin provides the intrinsic ability to regenerate the productivity of these acid soils, thus making them resilient. Therefore, to sustain crop productivity at an enhanced level, large tracts of lands dominated by acid soils can be brought under improved soil, water and nutrient management to help meet the food needs of ever increasing Indian population and elsewhere of the tropical world (Pal *et al.* 2014; Gilkes and Prakongkep 2016).

VI. Epilogue

To make degraded soils resilient, the basic information on cause-effect relationship of soil degradation is essential. The establishment of cause-effect relationship needs to be developed on identification of basic pedogenic processes that are linked to regressive and progressive pedogenesis in SAT and HT climates, respectively. Such gain in knowledge can equip well the land resource managers to develop the innovative management protocols for making degraded soils (with and without soil modifiers), resilient and sustainable. Regressive pedogenesis in SAT soils minimizes both soluble and exchangeable Ca²⁺ ions that impair their productivity. On the other hand despite their remarkable acidity, the unique presence of kaolin in the OC-rich acidic Alfisols, Mollisols and Ultisols formed during progressive pedogenesis in HT climate makes them resilient, helps in sustaining the agricultural, horticultural and forestry activities, and also in sequestering OC and removing the myth of their poor fertility. Studies on 'Soil resilience' and 'quality soil management' for enhanced 'soil quality' and sustainable land use management practices may focus on:

1. Long term fertilizer experiments and Nutrient Buffer capacity of soils
2. Long term crop rotation experiments and bioremediation techniques
3. Soil site-crop suitability matching and development of 'soil productivity index' and 'land quality index' for crops.

4. IPNS practices for building up organic carbon content of soils to at least 1% level.

The following axiom in the 'Atharva veda', as if the ploughman speaks to the Mother Earth underlines the message of upgrading soil resilience by adopting 'quality soil management' practices:

"What of thee I dig, let that quickly grow over
Let me not hit thy vitals or thy heart"

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