Chapter 10
Summary and Concluding Remarks

Abstract The treatise of Indian and tropical soils ends with a chapter 'Summary and Concluding Remarks', which projects a concise but a precious synthesis of unique research results obtained by the soil and earth scientists on major soil types of tropical Indian environments. In the past, much valuable work has been done throughout the tropics, but it has been always difficult to manage these soils to sustain their productivity and it is more so when comprehensive knowledge on their formation remained incomplete for a long time. Soil care continues to be the main issue in national development and thus needs to be a constant research agenda in the Indian context. This is imperative since soil knowledge base becomes critical in meeting the food demand for ever increasing human population. In this task basic pedological research is required to understand some of the unresolved edaphological aspects of the tropical Indian soils to develop improved management practices. This chapter highlights the major theme areas of soils (Chaps. 2–9) that have been dealt in the perspective of the recent developments in pedology, mineralogy, taxonomy and edaphology with context of tectonics and climate change in the Indian sub-continent. The usefulness of such information in unravelling many interesting pedological, edaphological, mineralogical and taxonomical issues of soils of the country has been well established. The synthesis of research results finally transforms to state-of-art information, which may serve as guiding principles to improve and maintain soil health through adequate national recommended practices in other tropical parts of the world.

Keywords Indian tropical soils · State of art information

This treatise provides state-of-art information on recent developments in the tropical soils of India. Summary and concluding remarks of each chapter are highlighted in the following.

1. Under both irrigation and rain-fed conditions Vertisols are cultivated for various agricultural crops. In HT climatic environment, agronomic practices for growing crops under irrigation do not cause soil degradation while in SAD and AD climates crops fail but grow well in the presence of soil modifiers. Without soil

D.K. Pal, *A Treatise of Indian and Tropical Soils*,
DOI 10.1007/978-3-319-49439-5_10

modifiers, however, the soils become saline and sodic under irrigation in SAT environments and lose their productivity. On the other hand, in presence of a soil modifier like palygorskite, non-sodic Vertisols (Typic Haplusterts) have severe drainage problems, like the non-zeolitic Aridic Haplusterts, even with an ESP ≥5 but <15. Zeolitic Sodic Haplusterts have no drainage problem and are productive like Typic Haplusterts at present. The present agricultural land uses clearly underscores that even though Vertisols are relatively homogeneous major soil group; they exhibit a remarkable variability in their land use and crop productivity. This scenario calls for the attention of the edaphologists to understand the pedogenetic factors that cause the variability in their properties. A synthesis of recent developments in the pedology of Vertisols achieved through the use of high resolution micro-morphology, mineralogy, and age control data along with their geomorphic and climatic history, has created a much better understanding on the effects of pedogenetic processes due to climate change during the Holocene. The climate change has caused modifications in the soil properties in the presence or absence of Ca-zeolites, gypsum, $CaCO_3$ and palygorskite minerals.

The formation and persistence of Vertisols in the Deccan basalt areas under HT climatic conditions, provides a unique example of tropical soil formation. Such soil formation remained incomprehensible unless the role of zeolites was highlighted by the Indian soil scientists during the last two decades. Persistence of these soils in HT climate for millions of years has provided a deductive check on the inductive reasoning of the conceptual models on the formation of Vertisols in HT climate. Zeolitic Vertisols (both sodic and non-sodic by definition) are under cultivation for crops like rice and sugarcane because of the lack of prolonged waterlogging. Additionally, such soils also support winter crops. These soils under the present typical agricultural land uses are mitigating the adverse effect of Holocene climate change to aridity and also sequestering carbon from the atmosphere. Experimental results obtained on the use of zeolites (other than heulandites) as soil conditioners and slow-release fertilizers provide important clues to address the possible role of soil heulandite in minimizing the conversion NH_4^+ ions to gaseous phases of N and adsorption and desorption of major nutrients in natural soil environments. Delineation of Ca- rich zeolites in Indian soils is now available. Therefore, fresh research efforts are needed to understand the selective role of zeolites in the adsorption and desorption reactions of N, P and K. Such additional knowledge highlights an organic link between pedogenetic processes and bulk soil properties, thereby providing a better understanding of many pedological and edaphological issues related to Vertisols. The novel insights will serve as guiding principles to improve and maintain their health and quality while developing suitable management practices to enhance and sustain their productivity. As a matter of fact, much of the success of the management interventions still depends on the proper classification of Vertisols at the subgroup level, identifying the impairment of drainage in Aridic Haplusterts (ESP ≥5, <15), Typic Haplusterts (with

palygorskite) and the improvement of drainage in Sodic Haplusterts/Sodic Calciusterts with soil modifiers. The SAT Vertisols at present are less intensively cultivated because of their inherent limitations, despite that they represent a productive resource under improved management. It follows then that geographical areas dominated by Vertisols require immediate national attention for their judicious use to produce more food required for the populous Indian subcontinent and other countries in the developing world.

2. Red ferruginous (RF) soils of tropical environments belong to five taxonomic soil orders (Entisols, Inceptisols, Alfisols, Mollisols and Ultisols). This fact amply justifies a statement that tropical RF soils in India have captured wide soil diversity. The spatially associated Ultisols with acidic Alfisols and Mollisols in both zeolitic and non-zeolitic parent materials in humid tropical climatic environments provides a unique example of tropical soil formation by discounting the exiting conceptual models on tropical soils. However, this fact was not much appreciated, until the role of zeolites and other base rich parent materials was implicated in pedology and edaphology by the Indian researchers during the last two decades. In reality, these soils support multiple production systems and generally maintain positive organic carbon balance without adding significantly to greenhouse gas emissions. A synthesis of literature on the recent developments on the pedology of RF soils, including their physical, chemical, biological, mineralogical and micro-morphological properties, and their degradation status is very timely as the renaissance in soil science is already in place. The new knowledge improves the understanding as to how the parent material composition influences the formation of Alfisols, Mollisols and Ultisols in weathering environments of HT climate. This knowledge also explains how the relict Alfisols of SAT areas is polygenetic created by climate shift during the Holocene. Despite the fact that the extent of soil loss by erosion, and acidity in Ultisols, Alfisols, Mollisols and Inceptisols (with clay enriched B horizons) is generally moderate, these soils need improved nutrient, water and soil water management practices under conservation based agriculture to sustain crop productivity at an enhanced level. Pioneering research efforts have helped establish an inherent link between pedogenetic processes and bulk soil properties, and have facilitated a better comprehension of many pedological and edaphological issues related to Alfisols, Mollisols and Ultisols mainly of HT climate. The synthesis has improved the basic understanding of why the formation of Oxisols from Ultisols is an improbable genetic pathway in tropical environment of India and elsewhere in the world. There is a strong need to modify the mineralogy class of highly weathered RF soils. This treatise will help to dispel some of the myths on the formation of tropical soils and their low fertility by putting in context their characteristics and capacity to be productive. To sustain crop productivity at an enhanced level, large tracts of lands dominated by RF soils need to be brought under improved soil, water and nutrient management to help meet the food needs of ever increasing Indian population.
3. Recent research by both earth scientists and soil scientists in the IGP soils based on large number of well-presented pedons spread along the west hot arid climate

to per-humid climate in the east, have led to new perspectives on the historical development of the IGP and the soils therein. This adequately addresses the hitherto little known subtleties of pedogenesis and polygenesis due to recorded tectonic, climatic and geomorphic episodes and phenomena, and anthropogenic activities during the Holocene.

Based on degree of development, five geomorphic surfaces, QIG1 to QIG5 with soil ages 0.5 ka, 0.5–2.5 ka, 2.5–5.0 ka, 5.0–10 ka, >10 ka respectively, are mappable in the IGP and correspond to the post-incisive chronosequences that evolved in response to interplay of fluvial processes, climatic fluctuations, and neotectonics during the Holocene. The polygenetic signatures, illuvial clay pedofeatures, pedogenic carbonates, clay mineralogy, and stable isotope geochemistry, suggest the evolution of the IGP soils witnessed two humid phases (13.5–11.0 and 6.5–4.0 ka) with intervening dry climatic conditions. The pedogenic response to the neotectonics suggests upliftment of blocks caused break in the sedimentation and initiation of pedogenic activity under the prevailing climate. Episodic uplift of different blocks resulted in a sequence of soils with varying degree of development.

The IGP soils across the topographic gradient (<0.02%) with varying climate from hot-arid to per humid belong to Entisols, Inceptisols, Alfisols, and Vertisols orders. Some of the sodic soils (Natrustalfs) changed to non-sodic soils (Haplustalfs), and the Mollisols (OC enriched soils) changed to Typic Haplustalfs (less OC enriched soils) after two decades of reclamation and agriculture, respectively. Addition and depletion of OC, formation pedogenic $CaCO_3$, illuviation of clay particles and argilli-pedoturbation are the major pedogenic processes in soils of the IGP during the Holocene. The IGP soils are, in general, micaceous, but the soils with vertic characters are smectitic. The soils with micaceous and smectitic mineralogy were formed in alluviums derived from the Himalayas and Cratonic rocks, respectively.

The beginning of agricultural activity over the southwest Asia is represented by the site of Mehrgarh at 7000 BC with further dispersal eastward over the upper and middle Gangetic Plains occurred around 2000 BC. Deforestation and cultivation of the IGP for over several millenniums has influenced the regressive pedogenesis of the IGP. The rapid development of calcareousness and concomitant sub-soil sodicity in semi-arid areas as natural soil degradation process, and enhancement of the $CaCO_3$ (SIC, soil inorganic carbon) and soil bulk density due to anthropogenic activities are the two potential threats, which require appropriate management interventions for restoring and maintaining soil health for sustainable agricultural production.

Soil carbon dynamics can help in determining the pertinence of management interventions of the National Agricultural Research Systems (NARS) to raise as well as to maintain agricultural productivity of soils of the IGP. The sequestration of atmospheric CO_2 as SOC (especially in soils under rice cultivation) and SIC in the vast arid and semi-arid soils suggests that the greenhouse gas

emission from the IGP soils do not seem to contribute substantially to the global warming potential.

A better understanding of the pedology of the IGP soils and their linkage to climate change, landscape stability, and anthropogenic activity appear to be potentially useful as guideline for their management. Thus the new knowledge base has potential as a reference for critical assessment of the pedosphere for health and quality in different parts of the world and may facilitate developing a suitable management practices for the food security in the 21st century.

4. The treatise on modelling tropical soils indicates that although among the most popular models applicable in soil formation, the residua and haplosoil models have relevance to formation and persistence of Indian tropical soils, they cannot explain the existence of million years old Vertisols, Alfisols and Mollisols under humid tropical climate because these models did not consider the stability of base rich primary minerals over time. This novel understanding provides a deductive check on the inductive reasoning so far made on the formation of soils in tropical humid climate and also establishes the validity of Jenny's state factor equation in the formation of the Indian tropical soils in the intense weathering environments under HT climate.
5. Pedogenic calcium carbonate, soil sodicity and palygorskite mineral impair the hydraulic properties of the SAT soils, which reduces their crop productivity. This type of unfavourable soil health triggered by the tectonic-climate linked regressive pedogenic processes needs to be globally considered as the natural soil degradation process despite the claims of its occurrence as a result of human induced soil degradation in the SAT areas. The regressive pedogenic processes that are inherently connected to the development of natural soil degradation, expands the basic knowledge in pedology and thus it may have relevance in soils of other SAT areas of the world. 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.
6. The mineralogical research work undertaken over the last several decades on important soil/paleosols types and the sediments demonstrates that the pedogenic clay minerals of intermediate weathering stages like HIS, Sm/K, HIV, PCh and pedogenic carbonates can be very useful paleoclimatic indicators. This basic information on soil clay minerals can serve as an important tool for the soil and earth scientists and especially the paleoclimatologists to infer climate change not only of India but elsewhere of the world.
7. A thorough knowledge and appreciation of minerals in soils is critical to our understanding and use of soil. Despite our general understanding on the role of minerals in soils, it is necessary to investigate the properties of the minerals, especially clay minerals, their mixtures and surface modifications in the form that they occur in the soil. From the few examples under different agro-climatic

situations cited it is evident that unless the mineralogical description is accurate enough for the purpose intended, it would not be prudent to look for their significance in soils. With the use of high resolution mineralogy, identification and explanation of many enigmatic situations in soils can be conveniently solved. Therefore, the advanced information developed provides adequate mineralogical database that would explain discretely many unresolved issues of the nutrient management in terms of specific soil minerals in general, and clay minerals in particular and their significance in soil as a sustainable medium for plant growth.

8. Edaphology is inherently based on deep fundamental understandings of soils and thus basic pedological research in tropical soils needs to be encouraged vigorously to link some of their major unresolved edaphological aspects to develop improved management practices.
9. This exposition based on the recent advances in pedology and edaphology of the Indian tropical soils, may serve as guiding principles to improve and maintain soil health through adequate national recommended practices in other tropical parts of the world.