Soils of the Indo-Gangetic Plains: their historical perspective and management

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The Indo-Gangetic Alluvial Plains (IGP) is among the most extensive fluvial plains of the world and cover several states of the northern, central and eastern parts of India. The IGP occupies a total area of approximately 43.7 m ha and represent eight agro-ecological regions (AER) and 14 agro-ecological subregions. The area of the IGP is nearly 13% of the total geographical area of the country, and it produces about 50% of the total foodgrains to feed 40% of the population of the country. Thus the sustainability of the present cropping system and also the health of the soils demand a review on the historical development of the soils and their management that remained associated with the tectonic, climatic and geomorphic history of the IGP since it came into existence due to collision of the Indian and Chinese plates during the Middle Miocene. This review provides a state-of-the-art information on the historical development of soils of the IGP, their tectonic-climate-linked natural degradation during the Holocene, and changes in the levels of carbon in soils under agriculture (mainly rice–wheat cropping system), practised over the years. In view of the vast area of the IGP, research initiatives on benchmark soils are, however, still needed to record the subtilities in pedogenesis, especially their polygenetic history due to climate change during the Holocene. This way a historical soil–climate-crop databank may be established to help in fine-tuning the existing management interventions of the national agricultural research system and also the system-modellers in predicting future projections on the sustainability issue of the rice–wheat cropping system in the IGP.

Keywords: Climate change, historical soil development, Indo-Gangetic Plains, polygenesis, soil management interventions.

THE Indo-Gangetic Plains (IGP) ranks as one of the most extensive fluvial plains of the world. The deposit of this tract represents the last chapter of earth's history. It came into existence due to the collision of the Indian and Chinese plates during Middle Miocene[1]. The Indian plate is still moving at the rate of 2–5 cm/yr towards the north and forming the world's highest mountain range on its border. The north-south compression generated throughout the plate ensures that it is continuously under stress and provides the basic source of accumulating strain in the fractured zones[2]. The fluvial deposits and landforms of the IGP have been influenced by the stresses directed towards north and northeast. The major rivers of the IGP have changed their courses and, at present, are flowing in southeast and easterly directions with convexity towards the southeast, which is strikingly similar to the arcuate pattern of the major thrusts bordering the IGP[3]. Thus the IGP shows a series of terraces, bars and meandering scars resulting in microhigh and microlow areas on the apparently smooth topography[4,5]. The IGP is still tectonically active and the major sedimentation is taking place from large river systems of the IGP. The IGP developed mainly by the alluvium of the Indus, Yamuna, Ganga, Ramganga, Ghagra, Rapti, Gandak, Bhagirathi, Silai, Damodar, Ajay and Kosi rivers. Geophysical surveys and deep drilling by the Oil and Natural Gas Commission of India[6–8] suggest that the IGP is a vast asymmetric trough with maximum thickness of 10,000 m, that thins out to the south. The IGP covers about 43.7 m ha and represents eight agro-ecologial regions (AERs) and 14 agro-ecological subregions (AESRs; Figure 1)[9]. The nature and properties of the alluvium vary in texture from sandy to clayey, calcareous to non-calcareous and acidic to alkaline. Though the overall topographic situation remains fairly uniform with elevations of 150 m amsl in the Bengal basin, and 300 m amsl in the Punjab plain, local geomorphic variations are significant[10].

Early studies on soils

Agriculture was the mainstay of the people of ancient India. The agriculturists then were quite conscious of the nature of soils and its relation to the production of specific crops of good economic return[11,12]. Archaeological investigations along many important sites in the southern, central and western parts of the IGP suggest considerable progress from incipient agricultural activities to well-developed agricultural practices over a span of the last 10,000 years[13–18]. According to recorded information ancient India during the period 2500 BC to AD 600, a vast knowledge acquired by the then agriculturists by

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experience has become tradition, and the same has been passed on from generation to generation. However, a major part of this has been forgotten and thus has become a story of the past[11,12]. Raychaudhuri[11] indicated that scientific interest in the characteristics of the Indian soils began when the Geological Survey of India started studying the soils and the underlying strata in 1846. The earliest investigations by Voelcker[19] and Leather[20] distinguished the soils of the IGP as one of the four major soils of the country. With increasing realization of the fact that the soils are one of the greatest endowments that nature has provided to mankind, few resource-oriented surveys were carried out by the second quarter of the 20th century in the river-valley projects of some parts of the country. Later on the Crops and Soils Wing of the Board of Agriculture realized the need for more information on soils of the country for many purposes. Accordingly, the Imperial (now Indian) Council of Agricultural Research finally sponsored the All India Soil Survey Scheme in 1943. This scheme examined and collated the available soil-survey information and the related analytical data which could be suitably projected on the Soil Map of India. Its Final Report in 1953 embodied the first comprehensive work on soil survey in the whole country (British India).

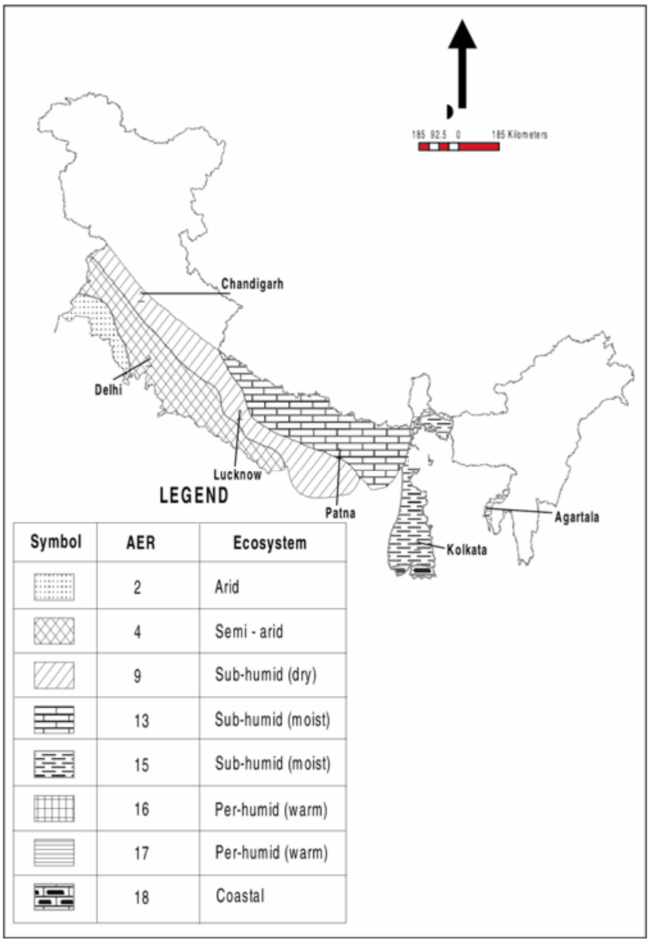


Figure 1. Location map of the Indo-Gangetic Plains (IGP), India showing agro-ecological subregions.

In spite of some limitations, this brought out valuable information and paved the way for future expansion of soil survey programmes, both at the Centre and in the States (then Provinces)[21].

Wadia and co-workers[22] mentioned that soil groups were nearly co-terminal with the boundaries of the geological outcrops. Vishwanath and Ukil[23] prepared a soil map (1943) portraying the different climatic types on the basis of N.S. quotients by adopting colour and texture as units of classification; these were correlated with four major climatic zones (arid, semi-arid, humid and perhumid). In 1954, a revised map was prepared at the Indian Agricultural Research Institute (IARI), New Delhi, on the scale 1 m = 70 miles, and it showed 20 broad soil classes. This map was revised by Raychaudhuri[24] and later on by Raychaudhuri and Govindarajan[25]. It provided the extent, distribution of different soil classes in the map, and their equivalents available in the USDA system. The Indus Valley Project was the earliest map (1970) that showed the general characteristics of northwestern Rajasthan and parts of Pakistan covered by soils of the IGP[10]. This was referred to by Wadia and co-workers[22] in their publication on the geological formation of India.

During the past five decades several workers have indicated the various soil-forming processes in soils of the IGP, such as calcification, leaching, lessivage, salinization and alkalinization, gleization and homogenization[26]. The temperature regime is hyperthermic (i.e. mean annual temperature is >22°C and the difference of mean summer and winter temperature is >6°C), but differences in precipitation (Figure 2) have contributed to the formation of a variety of soils in the plains that represent mainly three soil orders like Entisols, Inceptisols and Alfisols[26]. Recent studies indicate that the IGP is dominated by Entisols, Inceptisols, Alfisols, Mollisols and Aridisols[9,27,28]. During the last decade an integrated approach has been helpful to provide information on the tectonic, geomorphic, palaeoclimatic and historical aspects on the evolution of soils in the plains[4,5,15,29–32].

Age of the soils

In the recent past, the IGP was considered to consist of older and younger alluvia. The older alluvium marked by

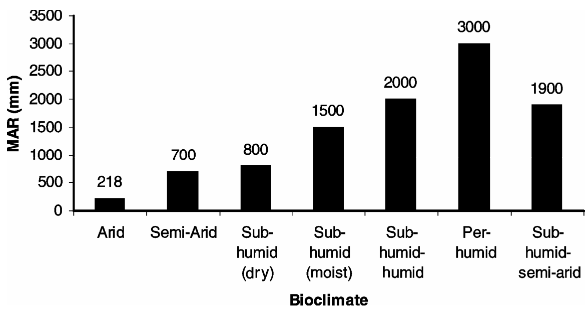


Figure 2. Distribution of mean annual rainfall (MAR) in different bioclimatic systems in the IGP.

a higher degree of pedogenesis was assigned a lower Pleistocene age[33,34] or a minimum age[35] of 120,000 yrs. Recent soil-geomorphic studies on soils of the IGP indicate the presence of more than two soil surfaces younger than 13,500 cal yrs BP[15,31,32,36]. Based on their degree of development, soils of the central and lower IGP have been grouped into several members of soil chrono-association[5,15,29,30,32].

Climatic, neotectonic and geomorphic history

Fluvial landforms and alluvial sediments in the IGP are important Quaternary continental records, which hold potential for the examination of climatic, tectonic and lithological controls over their formation[37]. In response to the global climatic event during the Quaternary, the IGP too witnessed climatic fluctuations, especially in the last post-glacial period. Frequent climatic changes occurred during the Quaternary[38]. This palaeoclimatic record has been documented from the NW and SW parts of India[39–41]. Climatic variations has also been inferred from Holocene soils[5,30,31]. A cold, arid to semi-arid climate prevailed during the Early Holocene to about 7390 cal yrs BP in the central and western parts of the IGP, favouring pedogenic calcrete development. Later a warm and humid climate set in, followed by drier conditions that continued until the present[30,31].

In the IGP pollen studies in a horseshoe indicated four phases of vegetational development corresponding to very arid, arid, semi-arid and sub-humid climatic phases during the last 8000 years[42]. An earlier study[43] on the historical records of climate and vegetation in the northern IGP by Randhawa indicated that desiccation had set in about 2000–3000 years ago. The study also pointed out that the Brij districts of the NW part of the IGP have a vegetation that is now found in deserts, were covered with a wet tropical forest of evergreen trees of Indo-Malayan affinities.

Neotectonics has played a significant role in the evolution of the geomorphology and soils of the north central[30], north western[4,5,15] and lower Gangetic plains[32]. It has determined areas of active sedimentation, microtopographical variations, pedogenesis and erosion. It led to tilting and sagging of large blocks resulting in shifting and increase in sinuosity of the rivers. Tectonic slopes/faults determined the courses of large rivers[5,15,29,30,36,37].

Pedogenesis of soils

During the early Holocene to 7390 cal yrs BP and also during the later warmer and wetter period, weathering of minerals, illuviation of clay, calcification, decalcification[5,15,30,44,45] and little addition of organic matter[44,45] and argillipedoturbation[32] have been the major pedogenic processes. These soils are enriched with fine-grained micas[45,46] (Figure 3) which weather to 2 : 1 expanding clay minerals[45–47]. However, in soils with vertic characters[48] in the lower IGP, clays rich in smectites as the first weathering product of plagioclase feldspar in the humid tropical weathering[49], were carried by rivers draining the Rajmahal Basaltic Traps in the west[50].

There are various processes that are capable of producing different types of clay minerals[51]. Among these, the formation of clay minerals during pedogenesis is the most fundamental. Precipitation, temperature and drainage are the principal controls of clay mineral formation and these factors reflect climate and relief[52]. Weathering of biotite was substantial. Preferential downward movement of weathered products of biotite (di- and trioctahedral expanding minerals) resulting in decreasing trend of clay mica is a sure test of clay illuviation, even when clay skins are absent[45]. Clay illuviation in soils of the IGP has not always resulted clay skins or, where present, in pure void argillans. Instead, 'impure clay pedofeatures' are typical in these soils (Figure 4 *a*) because of the impairment of parallel orientation of clay platelets, a specific process different from those described so far for the genesis of less-oriented void argillans[45]. The illuviation of clay particles and their subsequent accumulation in the Bt horizons of soils of the semi-arid parts of the IGP have occurred in sodic environment caused by the precipitation of soluble Ca^{2+} ions as $CaCO_3$ (Figure 4 *b* and *c*), thus discounting any role of soluble Ca^{2+} ions and the presence of $CaCO_3$ in preventing the movement and accumulation of clay particles. Thus the formation of impure clay pedofeatures and pedogenic $CaCO_3$ are two pedogenic processes occurring simultaneously in soils of the IGP as contemporary pedogenic events[53] and may act as an example of pedogenic thresholds in the semi-arid climate since the last 4000 yrs BP.

Polygenesis of soils

Although it is difficult to determine the characteristic soil minerals of different climatic zones, clay mineral assemblages of soil chrono-association of the northern and central IGP, indicate that pedogenic smectite–kaolin (Sm/K) can be considered as a potential indicator for palaeoclimatic changes, viz. arid to humid climates[29,31] during the Holocene. Subsequent studies indicate that not only the clay mineral but also the detailed micromorphological characters of clay pedofeatures and calcium carbonates can establish the polygenetic nature of the soils of the northern and central IGP[54]. During pedogenesis two major regional climatic cycles are recorded; relatively arid climates between 10,000–6500 and 3800 yrs BP, and a warm and humid climate punctuated between these aridic climate[31].

The climatic episodes reported so far are reflected in the alteration of primary and secondary soil minerals and also in the soil fabrics. Biotite weathered to trioctahedral

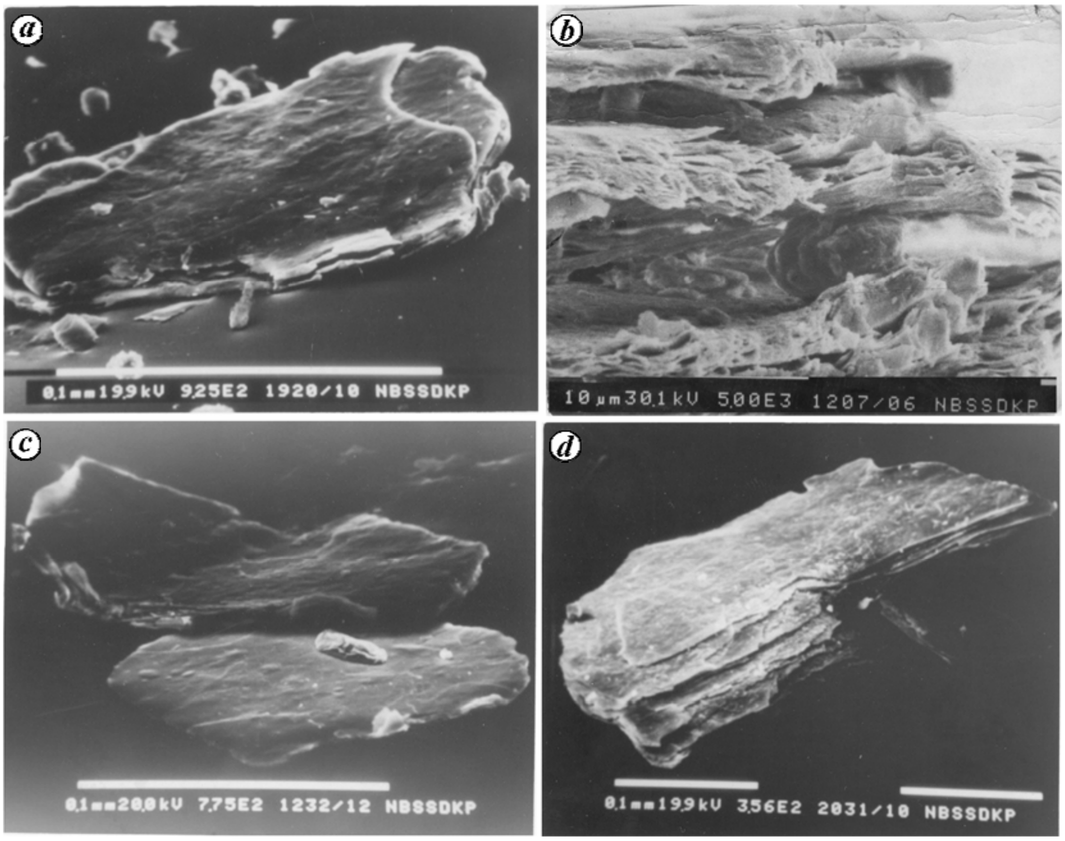


Figure 3. Representative scanning electron microscopic (SEM) photographs of sand-sized mica (biotite) in soils of semi-arid (***a***, ***b***) and sub-humid (***c***, ***d***) parts of the IGP. (Source: Division of Soil Resource Studies, NBSS&LUP (ICAR), Nagpur.)

vermiculite and smectite in the soils during arid conditions, and smectite was unstable and transformed to Sm/K during the warm and humid phase (6500–4000 yrs BP). When the humid climate terminated, vermiculite, smectite and Sm/K have been preserved to the present day. During the change in climate, the degraded, thick, illuvial clay pedofeatures record the earliest phase of pedogenesis in humid conditions (Figure 5 *a*). In the following semi-arid conditions pedogenic $CaCO_3$ was formed. The episode of pedogenic $CaCO_3$ formation was again followed by a wetter phase, in which further clay illuviation occurred. During this humid phase, the pedofeatures of earlier phases were also affected; pedogenic $CaCO_3$ was partially dissolved and reprecipitated in lower horizons (Figure 5 *b*)[54]. Development of the IGP soils during the Holocene, climatic fluctuations appears to be more important than realized hitherto. Soils older than 2500 yrs BP are relict palaeosols, but they are polygenetic because of their subsequent alterations[31,55].

Degradation of soils

The post-glacial warm period in which human civilization developed and flourished represents a short epoch which began 10,000 yrs BP. Within the present interglacial period too, thermal conditions have continued to change. It is believed that the monsoons were much stronger in the early part of the interglacial. Around 4500–3700 yrs BP, rainfall in the Indus Valley was probably much more than double the amount received now as for which both agriculture and forestry flourished[43,56]. The presence of animals in the swamps, like elephants and rhinoceros in Sind and western Punjab, is provided by the seals recovered from Mahanjodaro and Harappa, which date back to ca. 3250 BC. Sind and western Punjab are practically desert now[43]. The drought conditions that followed could have caused the end of the great Harappan civilization. According to Randhawa[43], vegetation in most parts of the IGP in the past had been forest. This has been destroyed both by biotic interference and by the resulting desiccation of the area as a result of deforestation. It is believed that aridity and desert conditions are now being created locally over the fertile IGP by ruthless cutting of forests.

Soils under arid and semi-arid parts of the IGP lack organic carbon due to high rate of decomposition. The adverse climatic conditions induce precipitation of $CaCO_3$, thereby depriving the soils of Ca^{2+} ions on the soil exchange complex with a concomitant development of sodicity in the subsoils. The subsoil sodicity impairs the hydraulic conductivity of soils. The impairment of percolative moisture regime provides an example of a soil where gains exceed losses. This self-terminating process[57] leads to the formation of sodic soils with exchangeable sodium percentage (ESP) decreasing with depth. Formation of pedogenic $CaCO_3$, a basic process initiating development of sodicity, should be considered as a basic and natural process of soil degradation[55]. $CaCO_3$ has been formed during the semi-arid climate prevailing for the last 4000 yrs BP and the rate of formation is proceeding fast. It is estimated to be 0.86 mg/100 g of soil/yr in the first 100 cm of the profile (129 kg ha^{-1} yr^{-1} for mean bulk density of 1.5 Mg m^{-3})[55].

Canal irrigation was introduced at the end of the 19th century to minimize the problem of aridity and to stabilize crop yields in the northwestern part of the IGP. This resulted in the expansion of the cultivated area. However, introduction of irrigation during the dry climate without the provision of drainage led to soil salinization and alkalinization within a few years, due to rise in the groundwater table containing high proportion of sodium relative to divalent cations and/or high residual alkalinity. In addition, the use of groundwater with high sodic hazards for irrigation has resulted in the extension of sodic soils[58,59]. However, sodic soils interspersed with non-sodic or less sodic soils occur in both canal-irrigated and unirrigated areas of the semi-arid part of the IGP. Therefore, introduction of canal irrigation in the IGP is not the only reason for the development of sodic soils. Formation of sodic soils may involve microbiological reduction of sulphate and ferric iron to form sulphide, which with CO_2 released by biological oxidation of abundant organic matter forms bicarbonate[60]. However, this was discounted by Bandopadhyay[61] for the sodic soils of the NW part of the IGP, which contain neither abundant organic matter nor

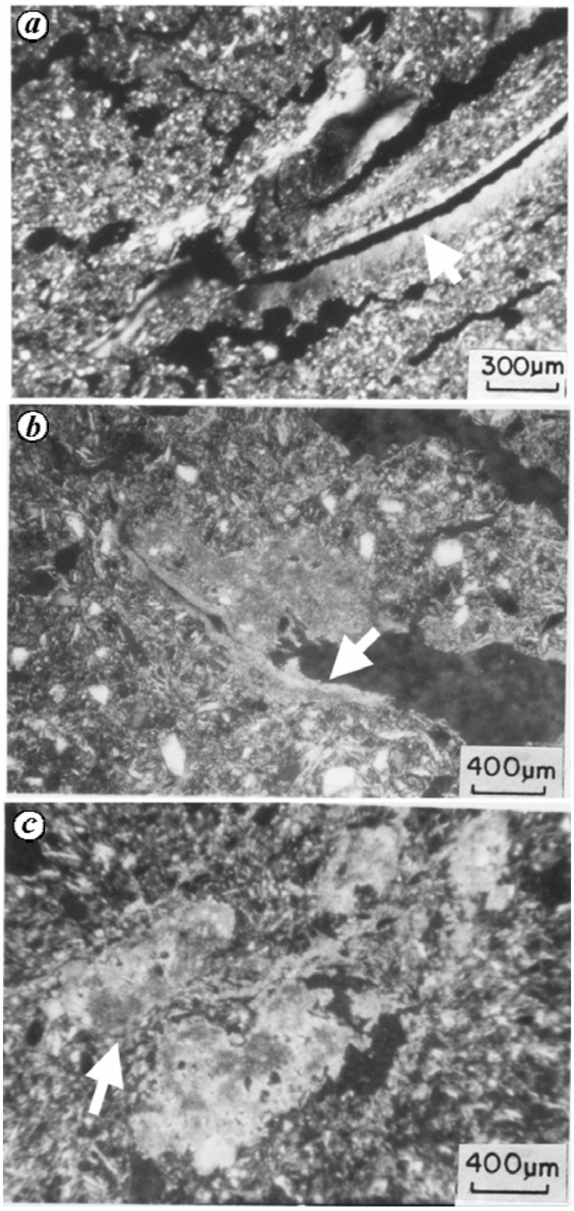


Figure 4. Representative photomicrographs in cross-polarized light of (***a***) thick, impure clay pedofeatures of Natrustalfs, (***b***) clay pedofeatures with micrite hypocoating in Typic Natrustalfs and (***c***) clay pedofeatures between two calcium carbonate nodules in Natrustalfs during the present semi-arid climate of the IGP. (Source: Division of Soil Resource Studies, NBSS&LUP (ICAR), Nagpur.)

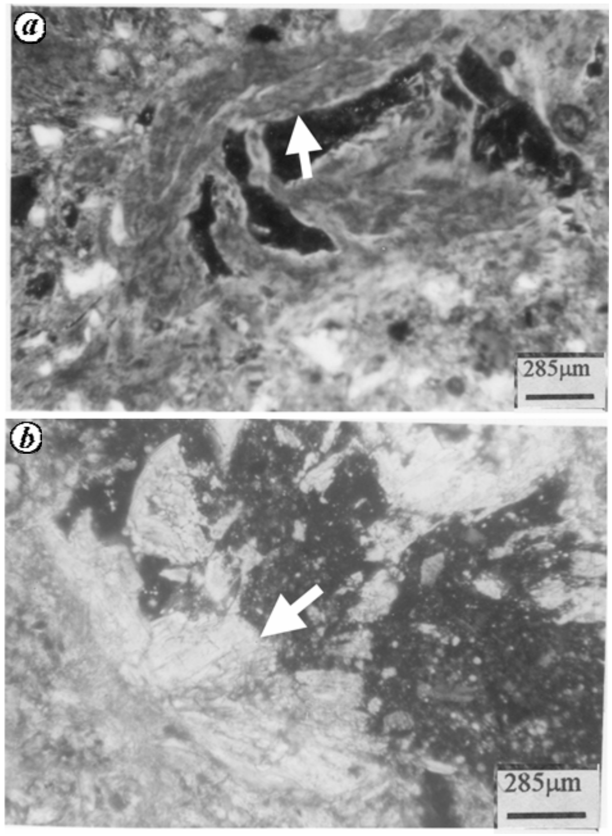


Figure 5. Representative photomicrographs in cross-polarized light of the thick, degraded, illuvial clay pedofeatures of Haplustalfs (***a***) and dissolution of pedogenic calcium carbonate of Haplustalfs (***b***) during the earlier humid climate of the IGP. (Source: Division of Soil Resource Studies, NBSS&LUP (ICAR), Nagpur.)

sufficient soluble sulphate ions. In addition, these soils generally lack permanently reducing conditions. In the NW part of the semi-arid IGP non-sodic and sodic soils occur on microhigh and highly sodic soils on microlow positions (Figure 6). Pal and co-workers[53] demonstrated that the main soil-forming processes were clay illuviation, deposition of pedogenic $CaCO_3$ and concomitant development of subsoil sodicity in these soils. The microlows 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 feldspar, leading to precipitation of $CaCO_3$ at high pH and development of subsoil sodicity. It impairs the hydraulic conductivity of soils and eventually leads to the formation of sodium-rich soils (Natrustalfs) with ESP increasing up the profile. The semi-arid climate and topography interact to facilitate greater penetration of bicarbonate-rich water in microlow than microhigh positions. Thin sections show deformational pedofeatures such as cross and reticulate striation of plasmic fabric (Figure 7 *a*), disruption of clay pedofeatures (Figure 7 *b*), carbonate nodules (Figure 7 *c*) and elongation of voids (Figure 7 *b*) as a result of tectonic activity during the Holocene. There is also supported from geodetic observations[62,63] that an area under tectonic compression undergoes horizontal movements and slow changes in height. By creating microlow and microhigh sites, the tectonic activity may also have been ultimately responsible for the formation of more and less sodic soils[4].

Management of soils

The IGP covers approximately 13% of the total geographical area of India and produces nearly 50% of the country's foodgrains to feed 40% of the total population of the country. The Mughal statistics confirm that much of the land in the IGP was under cultivation. This involved traditional mixed cropping methods. This land-use pattern continued till the middle of the 19th century. Over the last three–four decades the states of the IGP have been successful in increasing their foodgrain production, chiefly rice and wheat, by introducing high-input technologies to meet the demands of the exponentially growing population. The soils under arid climates require addition of organic matter and phosphorus but not potassium in the initial years of cultivation[64]. The strategies

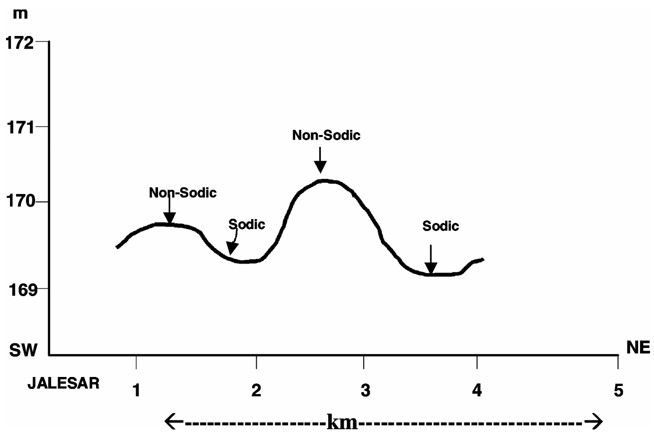


Figure 6. NE–SW profile in Ganga–Yamuna interfluve of the IGP showing non-sodic soils on microhigh and sodic soils on microlow sites. (Source: Division of Soil Resource Studies, NBSS&LUP (ICAR), Nagpur.)

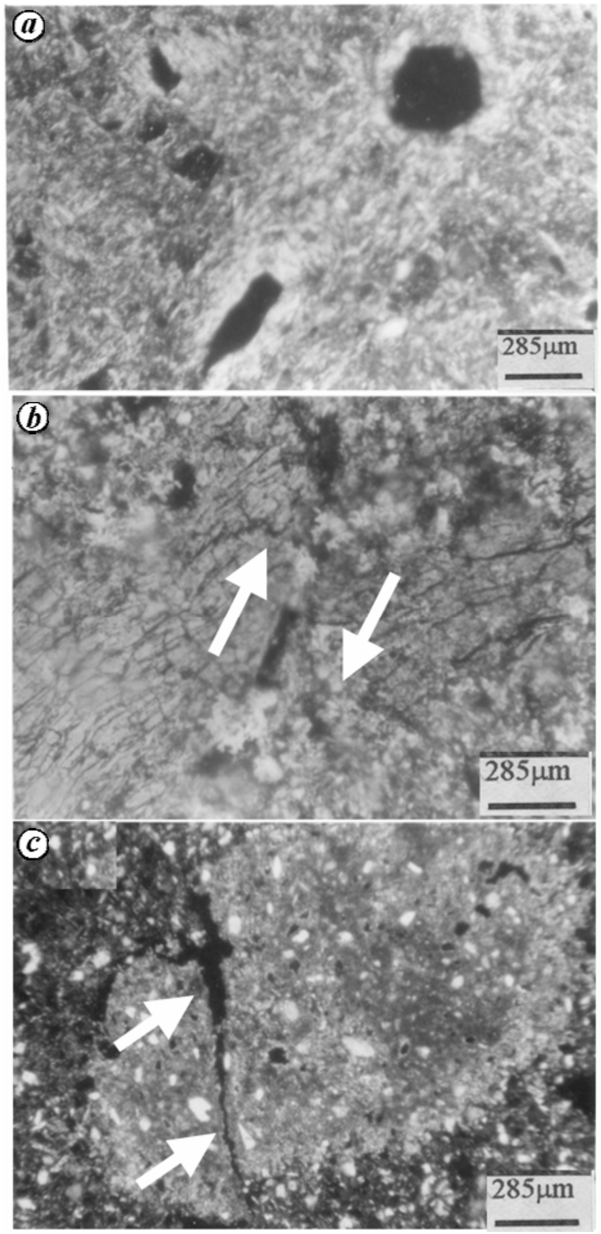


Figure 7. Representative photomicrographs in cross-polarized light of micromorphological features of Haplustalfs and Natrustalfs of the IGP. ***a***, Moderate–strong cross-striated b-fabric. ***b***, Fragmentation and displaced clay pedofeatures and formation of elongated rough voids. ***c***, Fragmented and displaced nodule of calcium carbonate. (Source: Division of Soil Resource Studies, NBSS&LUP (ICAR), Nagpur.)

and measures adopted to achieve this success included, among others, (i) the spread of high-yielding varieties, (ii) expansion of irrigated area, (iii) increased use of fertilizers, (iv) plant protection chemicals, (v) strengthening of marketing infrastructure and (vi) introduction of subsidies[65]. The production of grains was, however, not uniform across the IGP regions because of the spatial variation in land-resource characteristics and socio-economy in the region. These management interventions for 'money economy' have resulted (i) widespread degradation, (ii) depletion of natural resources, (iii) declining water level, (iv) loss in soil fertility, (v) nutrient imbalance/deficiency, (vi) drainage congestion and (vii) loss in soil carbon[66–69].

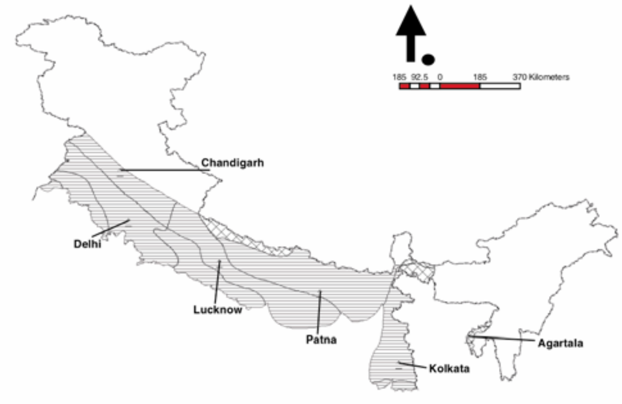
The sustainability ratings of some soil series of the IGP for the rice–wheat cropping system indicate many soil constraints, including low soil organic carbon (SOC)[9]. This demands focused attention to monitor the soil health of the IGP. Soil carbon dynamics as a robust parameter offers a unique opportunity in this endeavour. However, restoration of organic and inorganic balance and its follow-up require basic information of carbon stocks in soils of the IGP. This was realized by the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP; ICAR) at Nagpur, which provided carbon stocks that may help facilitate on deciding the appropriate soil and land management techniques[9].

The SOC and inorganic carbon (SIC) stocks of the IGP (0–150 cm depth) are 2.0 and 4.58 Pg respectively. The SOC stock of the IGP constitutes 6.45% of the total SOC stock of India, 0.30% of the tropical regions and 0.09% of the world in the first 30 cm depth of the soil. The corresponding values of SIC are 3.20% for India, 0.17% for the tropical regions and 0.06% for the world respectively. Thus the soils of the IGP are impoverished in OC compared to tropical regions and the world in general and to India in particular[9].

To delineate the sufficient and deficient zones in India in terms of SOC content, 1% OC was considered as the tentative boundary between sufficient and deficient zones[69], considering OC equilibrium value[70] at 1–2%. For soils of the IGP, Bhattacharyya and co-workers[9] indicated that five AESRs (warm to hot moist, hot moist humid to perhumid, warm to hot per-humid, warm to hot per-humid and warm to hot per-humid) covering 6% area of the IGP are in the sufficient zone of OC and the remaining nine AESRs covering 94% area are under deficient zone (Figure 8). However, some areas under humid climate do not have sufficient SOC because of intensive agricultural practices[66].

It is generally observed that among the agricultural systems such as rice–wheat, rice–rice, cotton–wheat and groundnut, the cereal-based systems contribute to higher accumulation and stabilization of organic matter, especially in rice–wheat systems[71], because decomposition of organic matter in the absence of oxygen is slow, incomplete and inefficient. It is also due to the formation of recalcitrant complexes with organic matter in these soils that render organic matter less prone to microbial attack[72]. Thus the SOC built up under submerged conditions is the reason for high status of organic matter and productivity in rice–rice and rice–wheat systems in the IGP. The NBSS&LUP reassessed the SOC stock of the IGP in 2005, and observed[73,74] that there has been 30% increase in SOC in 0–20 cm depth over the value assessed in 1980.

The SIC stocks in soils of the arid and semi-arid ecosystems of the IGP seem to be useful during the establishment of vegetation by appropriate ameliorative methods in these soils, as the plant roots can dissolve the immobile $CaCO_3$ and can ultimately trigger the process of Ca release in the soil and thus act as a natural ameliorant for sodic soils (Figure 9)[9]. After 30 months of reclamation of sodic soils of the NW part of the IGP with gypsum followed by rice cropping showed[55] that rice as the first crop creates an environment for the dissolution of native $CaCO_3$ as reflected in the increase of Ca^{2+} and Mg^{2+} ions in the exchange complex and simultaneously a decrease in the native $CaCO_3$. It has been established that application of gypsum in the sodic soils of the IGP has been effective in reclaiming the soils. Experiments at the Central Soil Salinity Research Institute (ICAR) Karnal, indicated that the application of gypsum followed by cropping, increased the urease and dehydrogenase activity (which is a measure of the biological activity of crops) by about threefold[75]. Growing of trees for 12 years



LEGEND

Symbol	OC content (%) 0-30cm	AESRs		
		Nos.	Area ('000 ha)	%
	Sufficient Zones > 1.0	13.2, 15.3, 16.1, 16.2, 17.2	2519	6
	Deficient Zones < 1.0	2.1, 2.3, 4.1, 4.3, 9.1, 9.2, 13.1, 15.1, 18.5	41172	94

Figure 8. Map showing sufficient and deficient zones of soil organic carbon in the IGP. (Source: Division of Soil Resource Studies, NBSS&LUP (ICAR), Nagpur.)

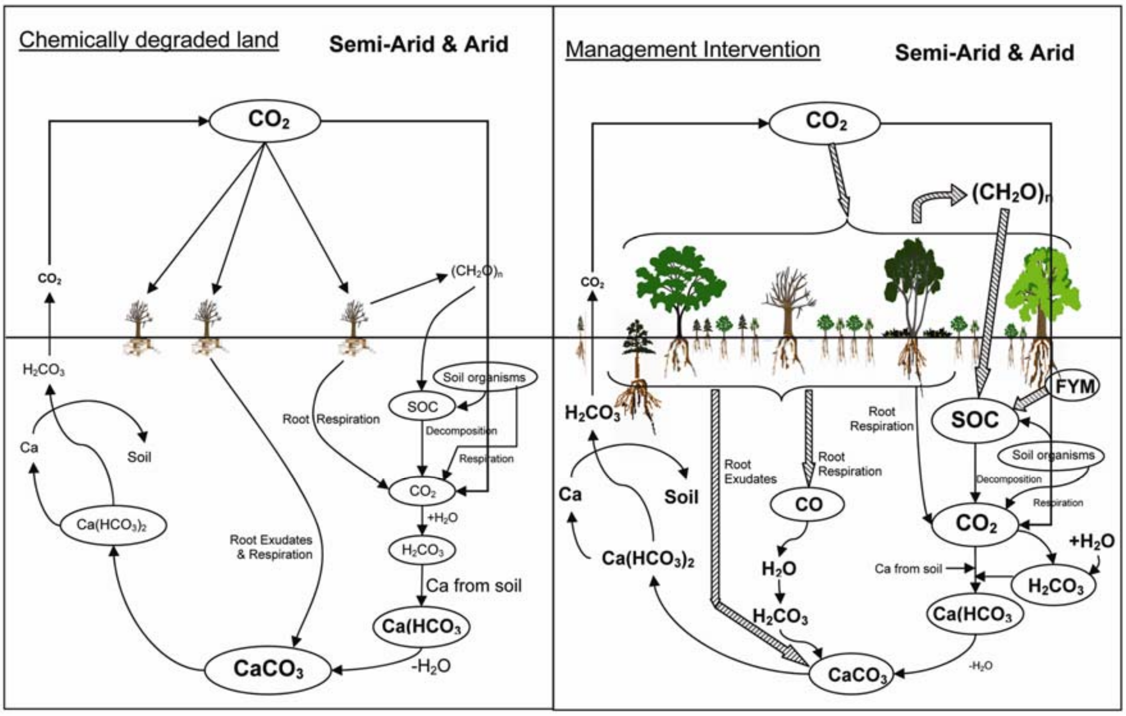


Figure 9. Schematic diagrams showing how $CaCO_3$ can be used as an ameliorant for reclaiming sodic soils through appropriate management interventions (the size of circles and letters indicates relative proportion of individual components). (Source: Division of Soil Resource Studies, NBSS&LUP (ICAR), Nagpur.)

reclaimed the soils and improved the biological activity[75]. It also resulted in a decrease in $CaCO_3$ content during the corresponding 12-yr period by 1, 1.5 and nearly 2% with cereal cropping, grasses and agroforestry respectively[76]. Although the presence of $CaCO_3$ has been considered of doubtful significance as displacement of exchangeable Na by Ca (from $CaCO_3$) in the soils with pH 8.0, it can be greatly affected by factors like management interventions[76] through which SOC content increased considerably[77]. Thus this fact assumes importance as this component is more than double the SOC stock in the first 150 cm depth. This huge SIC stock remains as a hidden treasure that would improve the drainage and help in the establishment of vegetation and also sequestering OC in the soils[9,55].

Information on soils of the IGP has recently been organized through the GEFSOC Project[78] and is available in several publications on Benchmark soil series[27], SOTER[28,79]; SOC stock[71] and evaluation of fertilizer trials to judge soil productivity[73]. The overall increase in SOC stock in the Benchmark spots under agriculture, practised for the last 25 years, suggests that agricultural management practices of the National Agricultural Research System (NARS) did not cause any decline in SOC[74] even amidst the increase in SIC level, indicating the initiation of chemical degradation[55].

Concluding remarks

This review indicates that research contributions of both earth scientists and soil scientists have led to state-of-the-art information on the historical development of the IGP and the soils therein, including the subtilities of pedogenesis and polygenesis due to recorded tectonic, climatic and geomorphic episodes and phenomena during the Holocene. The present scenario of change in climate in major geographical areas of the IGP will continue to remain as a potential threat. A situation of this nature will therefore, demand careful management intervention in terms of restoring and maintaining soil health for sustainable agricultural production in the IGP. It highlights also how soil carbon dynamics can help in determining the appropriateness of management interventions of the NARS to raise as well as to maintain agricultural productivity of soils of the IGP. However, in view of the vast area of the IGP, new research initiatives are necessary to create the historical soil–climate-crop databank that would not only help in the fine-tuning of the existing management interventions to control the increasing levels of SIC, but also help system modellers to make future projections on the sustainability issue of the rice–wheat cropping system and agro-forestry interventions in the IGP.

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