Edaphic Stresses: Concerns and Opportunities for Management

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Abstract

Sustainable intensification of soil resources is inevitable to maintain food and nutritional security with ever-increasing demographic pressures. However, the major gains in agricultural productivity in the recent past have led to severe land degradation and the resultant edaphic constraints. These include chemical stresses like emerging nutrient deficiencies (93, 91, 51, 43% soils rated low in N, P, K, Zn, respectively) with mining (8–10 million Mg of NPK annually) along with acidity (pH < 5.5 in 17.93 M ha), salinity (6.73 M ha), and pollutants, while severe soil erosivity (water 82.47 M ha and wind 12.40 M ha), shallow soils (26.4 M ha), soil hardening (21.4 M ha), and low water-holding capacity (13.75 M ha) constitute the major physical constraints. The Indian soils are inherently low in low organic carbon, and climate change is further impacting the farming systems. Even the conservative estimates are that the edaphic stresses cause about two-third loss of agricultural production. Several land and water management practices have been put forward to minimize the impact of these stresses including conservation agriculture, rainwater harvesting, integrated nutrient management, integrated farming systems, etc. However, to alleviate the effects of multiple stressors, a holistic approach to build up systems perspectives is a need of the hour. The new tools emerging especially in the areas of resource-conserving farming systems, conservation agriculture, precision irrigation technologies, biotechnology and omic sciences, etc. are opening up new opportunities for tackling these stresses. The database compiled here should allow for better focus of research to develop the best combination of agroecosystem-based technologies. Moreover, these should improve awareness among decision makers to evolve policy guidelines and take up measures toward "sustainable development goals."

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4.1 Introduction

The food and nutritional security warrants the availability of adequate and quality food to meet the dietary and nutritional requirements for a healthy and productive life. The Indian agriculture has registered a phenomenal growth during the past four decades. However, it is still facing the challenge of ensuring food security for the ever-increasing population amidst constraints such as deterioration of soil quality, reduction in per capita land availability, forecasted water scarcities, climate change, etc. Nevertheless, most observers still agree that food security must be achieved through more productive use of land resources and that this must occur without further degradation. With increased pressures on land from urban agglomerations, horizontal expansion in agriculturally suitable land seems no longer a feasible option and rather the cultivated area has since long been static around 141 million hectares (DAC 2015). Thus the only way possible is considerable improvements in soil productivity (Yadav 2007; Singh 2010). But the past endeavors in meeting the demands of ever-increasing population have accompanied with land degradation and the impact of episodic climate change, those that have consequently increased number of edaphic stresses and their varied levels for crop production (NRAA 2011). This has happened because the focus was more on exploitation of soil and water resources and less on improving, restoring, reclaiming, and enhancing their productivity and sustainability (NIASM 2015). As a result, the agricultural productivity has been witnessing stagnation even in irrigated areas. Emergence of widespread multiple nutrient deficiencies, depletion of organic carbon stocks, pollutants/contamination by toxic substances, soil sealing and subsoil hardening, development of secondary salinity and waterlogging in canal-irrigated areas, low-input use efficiencies (nutrient and water use), and decreasing total factor productivity of fertilizers, etc. are all the consequences of application of component-based technologies for short-term yield gains. Additionally, the fragile dryland ecosystems are characterized by limited and erratic rainfall, intense pressure on resource use, and sensitivity to climatic risks and populations that are highly vulnerable to food insecurity (WG-NRMRF 2011). Therefore, sustenance of agricultural growth would require processes that would help us to meet current and long-term societal needs for food, fiber, and other resources, while maximizing benefits through conservation of natural resources and maintenance of ecosystem functions.

4.2 Processes and Extent of Soil Edaphic Stresses

The edaphic constraints are either natural or anthropogenic in origin and afflict almost all global land resources to variable degrees. Some stresses like soil salinity/acidity and erosion, for example, may have both origins. The major stresses as described in Friedrich et al. (2008) are given in Table 4.1. Natural stresses may be either intrinsic (i.e., a consequence of characteristics specific to the soil and its internal processes) or extrinsic (i.e., a consequence of ambient conditions in the external environment of the soil). A further point regarding these edaphic stresses is that

Table 4.1 Edaphic constraints to food production

Category	Examples of stress factors
(a) Natural stresses	
(i) Stresses caused by internal soil processes	
Chemical conditions	Nutrient deficiencies; excess of soluble salts; salinity and alkalinity; low base saturation; low pH; aluminum and manganese toxicity; acid sulfate condition; high P and anion retention; calcareous or gypseous conditions, low redox (hydromorphic conditions)
Physical conditions	High susceptibility to erosion; steep slopes; shallow soils; surface crusting and sealing; low water-holding capacity; impeded drainage; low structural stability; root-restricting layer; high swell/ shrink potential
Biological conditions	Low or high organic matter content
Ecosystem conditions	Low soil resilience; natural soil degradation
(ii) Stresses caused by external conditions and processes	
Climate-controlled conditions	Extreme climatic regimes; extreme high or low temperature; insufficient length of growing season; waterlogging; excessive nutrient leaching; global warming
Biological conditions	Pests and diseases; high termite population
Catastrophic events	El Niño and extreme storm events/cyclones; floods; droughts; landslides; earth quake activity; volcanic eruption
Ecosystem conditions	Impaired ecosystem functions and services; loss of soil quality and soil health
(b) Anthropic stresses	
Chemical conditions	Acidification by acid rain and acidifying fertilizers; drainage of wetlands; exposure to mine wastes; contamination with toxins
Physical conditions	Accelerated soil erosion; soil compaction; subsidence of drained organic soils
Biological conditions	Diminished biodiversity; high incidence of pests and diseases; allelopathy; loss of predators

Source: Friedrich et al. (2008)

rather than singly, these commonly exist in combinations. A typical example is of salinity and aridity (water stress) which are known to occur together. Also the shallow basaltic soils with low moisture retention capacity are prone to water stress in addition to having constraints like nutrient deficiencies, surface crusting, etc. Often the severity of stress controls the degree of adverse impacts in terms of decline in ability of the soils to support plants and animals. This obviously occurs due to reduction in the capacity to retain and supply adequate moisture and nutrients required for optimal growth of crops. As an example, the typical characteristics of selected soil types of India leading to different edaphic constraints are listed in Table 4.2, and area under each soil order is as given in Velayutham et al. (1999).

So far the concepts of edaphic stresses have been generally applied, and the knowledge on their assessment and management is limited and diverse. Still there are many perceptions on how these vary over time and space. But the edaphic stresses often lead to situations where cost-effective production is not feasible under a given set of site conditions and cultivation practices. Therefore, based upon the

Table 4.2 Edaphic constraints of some major soil groups in India

Soil group	Area[a] (M ha)	Characteristics leading to edaphic constraints
Vertisols	25.9 (8.5%)	Very hard when dry and very plastic, sticky and untrafficable when wet; deep cracking; narrow workable soil moisture range; low infiltration and poor internal drainage; salinity and alkalinity; macro/micronutrient deficiencies
Inceptisols	122.79 (39.7)	Vulnerable to erosion and degradation; structural instability, low soil–water retention; rapid surface sealing after rain and crusting with subsequent drying and hardening; limited soil moisture range for optimal soil tilth; sodicity and *Kankar* pan to restrict tree root proliferation
Entisols/Aridisols	98.37 (32.3%)	Low water retention capacity and unsaturated movement; poor structure and high erodibility; low nutrient reserves and high leaching losses; shallow depth; secondary salinization; high wind erosion
Alfisols	41.87 (13.5%)	Surface crusting and sealing; low water retention; low fertility; acidity; high erosivity due to undulating/rolling topography

Source: [a]NBSS&LUP Staff (2002)

soil's edaphic limitations that lead to the marginality of agricultural production, the soils are often classified as degraded lands, marginal soils, underutilized lands, unproductive soils, wastelands, etc. Usually the edaphic constraints are used as synonymous to these terms and antonymous to the soil quality. Though authenticity and accuracy of various estimates are questionable, it is reported that about 2 billion ha (23% of the world's usable land) is affected by degradation resulting in edaphic stresses to a degree sufficient to reduce their productivity (FAO 2011). About 5.8 M ha of land gets degraded annually and overgrazing, deforestation, agricultural activities, overexploitation of vegetation, and industrial activities contribute 35, 39, 27, 7, and 1%, respectively. Similarly 56, 28, 12 and 4% of land area is prone to degardation with water erosion, wind erosion, chemical and physical processes, respectively.

Land degradation estimates by different organizations have also been at variance in India. This is attributed to different approaches, methodologies, and criteria followed for assessment. Nevertheless, a large land area is under degradation due to various factors. These datasets were harmonized in GIS environment in 2010 (ICAR and NAAS 2010). The estimates are that 36.5% (120.72 M ha) of the total geographical area are degraded. The soil erosion due to water and wind are the major cause of soil degradation (94.97 M ha) and this is followed by chemical degradation (24.68 M ha). The latter includes decline in soil fertility as indicated by nutrient deficiencies and loss of organic matter, acidity, salinity/alkalinity, pollutants, etc. The waterlogged and flood-prone area is about 12 M ha.

A matrix which was earlier used by Friedrich et al. (2008) to define 25 stress classes in world soils is given in Table 4.3. The most limiting has been considered to be continuous moisture stress, while high shrink/swell potential is the least limiting factors. Nine inherent land quality classes (the land quality prior to human

Table 4.3 Land area of major edaphic stress classes and land quality classes

Quality class	Class code	Kind of land resource stress	Criteria for assigning stress	World (M ha)[a]	India (M ha)[b]
IX	25	Continuous moisture stress	Aridic SMR, rocky land, dunes	3648.0	11.46
VIII	24	Continuous low temperatures	Gelisols	2177.6	5.43
	23	Steep lands	Slopes >32%	48.4	0.91
VII	22	Shallow soils	Lithic subgroups, root-restricting layers <0.3 m	735.8	26.40
	21	Salinity/alkalinity	"Salic, halic, natric" categories	306.8	6.73
VII	20	High organic matter content	Histosols	122.1	NA
VI	19	Low water-holding capacity/high permeability	Sandy, gravelly, and skeletal families	336.3	13.75
	18	Low moisture and nutrient status	Spodosols, ferritic, sesquic and oxidic families, aridic subgroups	346.2	14.06
	17	Acid sulfate conditions	"Sulf" great groups and subgroups	11.2	0.03
	16	High anion retention	Anionic subgroups, acric great groups, oxidic families	249.8	NA
	15	Low nutrient-holding capacity	Loamy families of ultisols, oxisols	778.8	36.72
V	14	Excessive nutrient leaching	Soils with udic, perudic SMR, but lacking mollic, umbric, argillic	447.1	13.75
	13	Calcareous, gypseous conditions	With calcic, petrocalcic, gypsic, petrogypsic horizons; carbonatic and gypsic families	247.1	NA
	12	High exchangeable aluminum	pH < 5.5 in 0.3 m and Al saturation > 60%	406.2	17.93
	11	Seasonal moisture stress	Ustic or xeric suborders but lacking mollic or umbric epipedon, argillic or kandic horizon	1034.2	14.30
IV	10	Impeded drainage/marshy	Aquic suborders, "gloss" great groups	282.9	1.16
	9	High anion exchange capacity	Andisols	91.3	NA
	8	Low structural stability/soil hardening	Loamy soils and entisols except fluvents	136.9	21.57

(continued)

Table 4.3 (continued)

Quality class	Class code	Kind of land resource stress	Criteria for assigning stress	World (M ha)[a]	India (M ha)[b]
III	7	Seasonal low temperatures	Cryic or frigid STR	300.9	15.20
	6	Minor root-restricting layer/subsurface hard pan	Soils with plinthite, fragipan, duripan, densipan, petroferric, placic <100	151.7	11.31
	5	Seasonal excess water/ temporary waterlogging	Recent terraces, aquic subgroup	136.2	6.24
II	4	High temperatures	Isohyper and/or isomegathermic STR excluding mollisol and alfisol	250.6	14.30
	3	Low organic matter content	With ochric epipedon	310.1	111.5
	2	High shrink/swell potential	Vertic subgroups	92.5	28.00
I	1	Few constraints	Other soil	408.8	NA

Sources: [a]Friedrich et al. (2008); [b]Compiled by Minhas and Obi-Reddy (2017)

interference) were established using the stress factors as a key. Class I has the most and Class IX the least favorable attributes. The criteria used in soil taxonomy to define these stress classes and land quality classes by Eswaran et al. (2003) have been included in this matrix. The areas falling in Classes VII (60–80% risk for sustainable agriculture), VIII, and IX (>80% risk) is over half the global land (54%), i.e., it shows severe or prohibitive constraints for agriculture. Another nearly a third of the land area (30%) falls under Classes V and VI (40–60% risk), i.e., having serious limitations. Only meager land (13%) is under Classes II, III, and IV (20–40% risk), i.e., with moderate limitations. Land with no or few constraints (< 20%; Class I) make up a minuscule 3%. About 52% of the land area falls under classes (25, 24, and 11) where stresses are mainly controlled by climate. The above classification was basically intended to focus on the inherent ability of the soil to produce grain crops on sustainable basis but the impact of some other management factor including irrigation and climate were not considered. A similar attempt was made by Minhas and Obi-Reddy (2017) to equate and estimate areas under different stress classes in India (Table 4.3). Though, the estimates need to be harmonized with respect to overlaps, e.g., most of the sandy terrains and dunes of Northwest India fall under aridic zone with continuous moisture stress and low water- and nutrient-holding capacities (Hipher arid Soil Moisture Regime, i.e., AER 2.1 and 2.2). Similarly salinity and aridity go together. Anyhow the overall situation seems to be a little better than the world averages. It is since about half the soils are grouped under classes V and VI (40–60% risk) and the rest is equally distributed under severe and moderate limitations. Even the conservative estimates are that all these stresses are limiting the agricultural production to one-third of the potential. Low organic carbon and thereby nutrient deficiencies are the most limiting factors followed by shallowness of soils in peninsular India. Among the processes of degradation, water erosivity is afflicting the most land area (about 25% of the geographic area) followed by aridity (13%).

The soil-forming factors like parent material, climate, relief, organisms, and time basically define the intrinsic stress conditions, e.g., intense leaching of nutrients in humid tropics may lower soil fertility in the long run. Further the landscape factors like steep terrain, boulders, undulations, and sand dunes may add to these constraints. Unfavorable climatic conditions like droughts, cyclones, hailstorms, heat/cold waves, etc. also play a role by exuberating edaphic stresses, e.g., landslides and episodes of soil erosion may be triggered by the intense rainfall during cyclonic events especially in coastal areas. These conditions are essentially beyond human control, but increasing population pressures, poor land management practices, and the emerging inequities in land and resource access have been the major driving forces for these stresses since the past about half a century (since the green revolution era). Further the mismatch between land use and its attributes, lack of restorative management, and deforestation to meet ever-increasing fuel and energy demands have aggravated the constraints. However, the emerging concerns about edaphic constraints are those being caused by inappropriate agricultural practices. Some of these are discussed below along with possible remediation measures.

4.3 Chemical Stress Conditions

The chemical constraints in Indian agriculture occur mainly due to mining of nutrients, loss of organic matter, and through buildup of salinity and pollutants.

4.3.1 Nutrient Deficiencies and Mining

Nutrient mining has increased with cropping intensity during the post green revolution period and multiple nutrient deficiencies are emerging due to low inherent fertility of most of Indian soils (Sanyal et al. 2014). Of the soil samples analyzed so far, about 93, 91, and 51% for N, P, and K fall under low to medium category (IISS 2015). Unfortunately, with continued low-input agriculture (current annual fertilizer consumption being only 154.6 kg ha^{-1}), the adequate replenishment of nutrients is not happening, and there is a net negative balance of about 8–10 million Mg of NPK. The most mined nutrient from soils is K with its removal and additions being about 7 and 1 million Mg (Sharma and Singh 2012). The continued mining of soil nutrients is impairing soil health and crop productivity. Once a nutrient becomes limiting, the overall fertilizer responses vis-à-vis crop productivity is lower since it does not allow for the full expression of other nutrients. Benbi et al. (2006) reported a drop in partial factor productivity of NPK for food grain production from 81 in 1966–1967 to 16 kg grain per kg of NPK in 2003–2004. The irrigated areas are afflicted more, e.g., the response was 13.4 kg grain per kg NPK in 1970 which has declined to 3.7 kg grain per kg NPK in 2005. In other words, to produce around 2 Mg ha^{-1} in 1970, the requirements for NPK fertilizers were only 54 kg NPK ha^{-1} was while about 218 kg NPK ha^{-1} are being now used for the same yield. Evidences have been generated that unfertilized exhausted soils can produce wheat, rice, and maize yields only in the ranges of 0.8–1.1, 1.5–1.6, and 0.3–0.7 Mg ha^{-1}, respectively (Swarup and Wanjari 2000). The yields can be increased and also sustained at higher levels of 4.0–5.0, 2.4–4.6, and 2.5–3.0 Mg ha^{-1} for rice, wheat, and maize, respectively, if deficient nutrients are brought to sufficiency levels through chemical fertilizers. Integrated use of various types of organic sources of nutrients like FYM, crop residues, and green manures along with fertilizers (INMS) not only maintain the yield but also reduce input cost, enhance profit, and improve soil health (Yadav et al. 2000). Yields of crops could be sustained with substitution of 50% nutrients by FYM, crop residues, or green manure.

Moreover, the deficiencies of micronutrient like zinc, boron, molybdenum, iron, manganese, and copper have been reported to exist in 49, 33, 13, 12, 5, and 3% of soils, respectively (Sharma and Singh 2012). Widespread deficiencies of zinc occur in alluvial soils of Indo-Gangetic plain, black soils of Deccan Plateau, and red and other associated soils. About 86 and 73% of soils in Maharashtra and Karnataka have been reported to be deficient in zinc, respectively. Similarly, the secondary nutrients like sulphur (41% samples) are becoming increasingly deficient. The boron deficiency is found in red and lateritic, acidic, coarse-textured alluvial and highly calcareous soils. Iron deficiency has been noticed in the paddy on coarse-textured alluvial soils while that of manganese are appearing on wheat when cultivated after paddy on coarse-textured alkaline soils These deficiencies are also being translated in terms of human and animal health.

4.3.2 Depleting Soil's Organic Carbon (SOC)

Soil organic carbon (SOC) governs soil productivity by influencing physicochemical-biological environment of the soils and is already low in more than one-third of Indian soils and has declined by 30–60% as a consequence of cultivation (Swarup and Wanjari 2000). This is being further negatively impacted with imbalanced use of fertilizers, removal and burning of crop residues, and reduced use of FYM and other organics. The reduced productivity of the rice–wheat system in IGP plain has been linked with declining soil organic matter contents. The earlier report on declining productivity in Haryana and Punjab (Sinha et al. 1998) had hinted at decrease in SOC from 0.5% in the 1960s to 0.2% in 1998 in major rice–wheat regions of Northwestern India. However, the recent evaluation of large soil test data for 25 years (1981–1982 to 2005–2006) has brought out that the SOC rather increased by 38%, i.e., 2.9 g kg^{-1} in 1981–1982 to 4 g kg^{-1} in 2005–2006 that has been ascribed to higher root biomass, stubble, and rhizo-depositions with increase in rice–wheat productivity from 5.9 to 8.1 Mg ha^{-1} by Benbi and Brar (2009). The fear of IGP losing SOC under intensive agriculture were also annulled by Milne et al. (2006) who predicted SOC to increase by about 4.5% from 1990 to 2000. Prediction also shows that SOC can be maintained at the base level of 0.45% in alfisols with conjunctive use of chemical fertilizers and FYM, while it would reduce to 0.30 and 0.36% under no fertilizer and chemical fertilizer treatments, respectively (IISS 2015). Adaptation of management practices like conservation agriculture/residue recycling, diversification/intensification of crops, integrated nutrient management, and agroforestry have been shown to enhance possibilities of carbon sequestration. The increase in crop yield ranges between 15–33 kg ha^{-1} with increase of 1 Mg C ha^{-1} SOC (Benbi and Chand, 2007), while in case of rainfed crops of rice, pearl millet, groundnut, lentil, finger millet, and soybean, the increase was 160, 170, 13, 18, 101, and 145 kg ha^{-1}, respectively (Srinivasarao et al. 2014).

4.3.3 Soil Contaminations

4.3.3.1 Geogenic Toxic Elements

The geogenic sources and the anthropogenic sources like sewage water, industrial effluents, urban solid wastes, fertilizers, etc. are polluting soils. The pollutants are becoming a potential hazard to the health of humans and animals since these enter into their food chain. The soils in about 34,000 km^2 of area in Malda, Murshidabad, Nadia, North and South 24 Parganas, and Bardman districts of West Bengal adjoining Bhagirathi river are contaminated with arsenic (Sanyal et al. 2012). With consumption of contaminated food, nearly 30 million people inhabiting these areas are exposed to arsenic poisoning. Similarly, high levels of fluoride occur in about 200 districts in India. The soils of seleniferous region of Northeastern Punjab suffer due to problem of selenium toxicity. Since the selenium content of crops grown on these soils is many times higher than the permissible limit of 5 mg Se kg^{-1}, chronic selenosis (selenium poisoning) in animals and human beings is caused with the intake of contaminated food. Nitrate pollution occurs in intensively irrigated and high productivity regions due to excessive use of chemical fertilizers in India, especially in states like Punjab, Haryana, and western Uttar Pradesh.

4.3.3.2 Urban Effluents Toxicities

The sewage generated is estimated to be 38,354 million liters per day (MLD) in major cities of India, while the wastewater generated by industries is about 13,468 MLD (CPCB 2015). Since the conventional treatment technologies for wastewaters are often cost prohibitive, only about one-fifth of this water is treated that too until secondary treatment level. However, with increased quantities of wastewater being generated with urbanization and industrial development, their disposal is becoming a major problem (Minhas and Samra 2004). Thus, land disposal in peri-urban areas seems the most logical sink due to restrictions in their disposal into surface streams. In addition to irrigation, the other benefits of sewage use include the additions of nutrients especially N and P and also the organic matter (Minhas et al. 2015). It is estimated that with a potential to annually irrigate about 2.5 M ha, sewage waters can add about 1 million Mg of nutrients and generate employment of 220 million man-days. However, their disposal is associated with accumulation of salts, toxic constituents, and heavy metals in addition to pathogenic contaminations. Therefore for minimizing sewage water-related bio-transfer of heavy metals and pathogenic contaminations, guidelines and regulatory measures have been advocated. Among treatment technologies, the low cost include the biological mechanisms like phytoremediation, etc. Disposal in tree plantations around urban areas to create green belts is another alternative, but their loading rates need standardization (Yadav et al. 2016). Though the astute management practices can minimize the risks of wastewaters, the national water development strategies so far have not come out with the policies for promotion of environmentally safe use of these waters. National policies have to be based on reasonably accurate estimates of the quality and quantity and the expected damage associated with their uncontrolled use/disposal. The other techno-economic issues relate to treatment standards, pricing/subsidies, and markets for non-conventional water use in addition to creating awareness of risk management through educational and political campaigns.

4.3.3.3 Sewage Sludge Toxicities

About 57 million Mg of urban solid wastes are generated per annum from over 450 class I and class II cities in India (Sharma and Singh 2012) and this would increase to 107 million Mg by 2025. Though a rich source of organic matter and nutrients, it has toxic substances of wastewater concentrated in the solid phase. Thus in the absence of any proper management system, these wastes could become a potential source of soil pollution. Such contaminations could be avoided by segregating the industrial waste containing heavy metals and toxic chemicals from the biodegradable waste. The biodegradable component of wastes is, generally, rich source of nutrients and organic carbon. Its conversion into compost is desired to serve the twin objectives of cleaning the environment and augmenting the supplies of organic manure. There should, therefore, be growing interest in development of cost-effective and eco-friendly composting technologies both in public and private sectors.

4.3.3.4 Brackish Water Use

Development of irrigation facilities has played a major role in enhancing agricultural productivity, and these areas now contribute about three-fifths of the country's total food production. Especially the groundwater withdrawals have increased manifold during the second half of the last century, and groundwater use soared from 10–20 km^3 in 1950 to 240–260 km^3 during 2000. However, groundwater in about 19.3 M ha area has been rated brackish in states like Rajasthan, Haryana, Punjab, and others. The indiscriminate use of these waters in the absence of proper soil–water–crop management strategies poses grave risks to soil health and environment (Minhas and Gupta 1992; Minhas 2012). It is since the emerging salinity, sodicity, and toxicity problems in soils and their impact on crop productivity and quality. For their effective use, not only the typical characteristics of the waters but factors like soil texture, rainfall, and crop tolerance have to be considered. However, if their use is not viable for agricultural crops, a shift to alternative uses like salt-tolerant forest/fruit trees and other high-value crops should be equally remunerative (Dagar and Minhas 2016).

4.3.4 Soil Salinity

About 6.73 M ha of land is afflicted with salinity (2.96 M ha) and alkalinity (3.77 M ha) mainly in Gujarat, Uttar Pradesh, Rajasthan, West Bengal, and Andhra Pradesh (ICAR and NAAS 2011). The expansion of the canal works has led to the occurrence of waterlogging and secondary salinity in their irrigation commands. The area under salinity has been increasing at the rate of 3000 to 4000 ha per annum. This is mainly because the emphasis has been on their water distribution and the associated drainage and efficient water use usually have been sidelined. The major achievement with respect to their reclamation has been on alkali soils where about 45,000 ha are being put under cultivation using the gypsum-based technology. A total of about 1.8 M ha of alkali land has been reclaimed so far, contributing 12–15 million Mg of paddy-wheat annually and changed the socioeconomic profile of more than 9 million people residing in rural India (CSSRI 2015). The reclamation of saline soils does not require any amendment. The leaching of salts is induced by providing subsurface drainage system, and the effluent is disposed (Minhas and Sharma 2002). Subsurface drainage technology has been demonstrated successfully on farmers' fields in Haryana, Gujarat, and Rajasthan, reclaiming nearly 60,000 ha of waterlogged saline lands (Kamra 2015). However, the problems associated with its operation, maintenance, and appropriate disposal of drainage water in addition to high investment for installation (Rs. 75 and 100,000 for alluvial and black soils, respectively) are the major bottlenecks for large-scale expansion of drainage networks. The alternatives are also being proposed in terms of agroforestry/bio-drainage, but combinations of agronomic, engineering, and agroforestry measures, as suited to the site conditions, are now considered to be more realistic (Minhas and Dagar 2016).

4.3.5 Soil Acidity

About 17.93 M ha of acidic soils (pH < 5.5) suffer from deficiencies as well as toxicities of certain nutrients and have very low productivity (< 1 Mg ha^{-1}). Depending upon the level of acidity, type of soil, crop grown, and climatic conditions, acid soils can reduce productivity by 10–50% (Sharma and Sarkar 2005). The reduction is attributed to low base saturation (20–25%); deficiency of calcium, magnesium, molybdenum, boron, and zinc; low cation exchange capacity of kaolinitic clay and poor nutrient retention; poor organic matter build up and nitrogen availability; high P fixation and its low availability; and excess/toxicity of iron, aluminum, and manganese. For reclamation via neutralizing acidity, these soils must receive lime and adequate supplies of fertilizers. The liming at 0.2–0.4 Mg ha^{-1} (one-tenth of lime requirement) in furrows along with recommended fertilizers was quite effective in realizing higher and economic yields. Cheaper liming materials include basic slag, lime sludge and low-grade lime stones, etc.

4.4 Physical Stress Conditions

4.4.1 High Erosivity

4.4.1.1 Water Erosion

The water erosion takes away productive topsoil to cause decline in crop productivity, erosion of biodiversity, flash floods, and siltation into rivers and other water bodies. About 5.3 billion Mg of soil gets eroded annually that carries along with it about 8 million Mg of plant nutrients (Sharda 2011). The erosion rates monitored among different land resource regions are 23.7–112.5, 80, 27–40, and 2.1 Mg ha^{-1} for the black soil, Shiwalik, northeastern region with shifting cultivation and the north Himalayan forest regions, respectively. While 61% soil gets moved and deposited at unwanted locations with the result of increased off-site costs, nearly 29% is transported to the sea. The remaining 10% was deposited in multipurpose reservoirs reducing their holding capacity by 1 to 2% per annum (Dhruvanarayana and Ram-Babu 1983). The annual loss in production of major crops due to soil erosion has been estimated to vary from 7.2 million Mg (UNEP 1993) to 13.5 million Mg (Bansil 1990). The loss in production for 11 major crops varied from 1.7 to 4.1% of total production (Brandon et al. 1995). Experimental studies in lower Himalayan region indicated that removal of 1 cm of topsoil caused 76 kg ha^{-1} reduction in maize grain yield and 236 kg ha^{-1} in straw yield (Khybri et al. 1988). The reduction was observed to be 103 kg ha^{-1} in Shiwalik region of Punjab (Sur et al. 1998). Soil loss from sorghum, pearl millet, and castor bean was computed to be 138, 84, and 51 kg ha-cm^{-1}, respectively (Vittal et al. 1990). Recent computation on the loss of productivity of food grains due to soil erosion was 1.34 billion Mg from alluvial, black, and red of which the contribution of cereals, oilseeds, and pulses was 68.3, 20.9, and 12.8%, respectively. Among oilseed crops, groundnut, and soybean occupying 26.5 and 36.5% of total area contribute 12.3% and 10.4% to total monetary loss (Sharda et al. 2010). Similarly, in pulse crops, gram (6.4%) and pigeon pea (2.9%) are the main contributors to total monetary loss as compared to other crops. The appropriate soil and water conservation measures have been recommended for reducing the losses due to soil erosion. For this integrated watershed management has been advocated as an excellent strategy to achieve optimal production. This involves water harvesting through construction of check dams along gullies, land leveling, bench terracing, contour bunding, and planting of grasses (Palanisami et al. 2002). Thereby, substantial investments on integrated soil and water conservation programs over the past about five decades have yielded local successes and the development of participatory watersheds models. Area under wasteland got decreased but that under irrigation to horticultural/fodder/fuel plantations increased. The grazing of animals changed to stall feeding and seasonal migration stopped. A meta-analysis of 311 case studies on watershed management programs showed a mean benefit–cost ratio, and the internal rate of return of programs was 2.14 and 22% while these performed best in rainfall zone of 700–1000 mm (Joshi et al. 2008).

4.4.1.2 Wind Erosion

Wind erosion causes decrease in land productivity at both the sites from where the finer particles are blown away and at sites where they are deposited. Wind erosion is prevalent in arid and semiarid regions of the country covering an area of about 28,600 km^2 in the states of Rajasthan, Haryana, Gujarat, and Punjab (ICAR and NAAS 2011). About 68% of the affected area is covered by sand dunes and sandy plains. It has been estimated that out of 2,08,751 km^2 mapped area of Western Rajasthan, 30% is slightly affected by land degradation, while 41% is moderately, 16% severely, and 5% very severely affected (Narain and Kar 2006). Decrease in rainfall gradient and increase in wind strength from east to west are responsible for the spatial variability in sand reactivation pattern. According to recent estimates, about 75% area of Western Rajasthan is affected by wind erosion hazard of different intensities (Narain et al. 2000) besides 13% area under water erosion and 4% under waterlogging and salinity/alkalinity. The spatial extent of the problem is increasing in the recent decades, especially due to increased cultivation and grazing pressures on the erstwhile stable sandy terrain leading to depletion of vegetation cover. However, under desert development program (DDP) and watershed development projects, affected areas are being rehabilitated along with stabilization of sand dunes through appropriate soil conservation measures. The harmonized area statistics on land degradation in the country shows that 12.4 M ha area on arable lands is affected by wind erosion of more than 10 Mg ha^{-1} $yr.^{-1}$ (Maji 2007).

4.4.2 Waterlogging

The area prone to waterlogged and floods has been estimated to be 12 M ha. In high rainfall areas of Central India, the *vertisols* are kept fallow during rainy season, and only one crop is possible during post-rainy season. However, their productivity can be enhanced by raised–sunken bed system that allows to cultivate soybean on raised beds while paddy in sunken beds (Tomar et al. 1995). The cropping is also possible in sunken bed during post-rainy season. Likewise, by growing *Rabi* legumes on raised beds under raised–sunken bed system, the productivity of rice fallows in Eastern India could be increased. The water stagnation occurs for more than 6 months in the alluvial plains of eastern India and the conditions allow for only one paddy crop that has a very low yield potential (<1.0 Mg ha^{-1}). The low productivity of the land resource is the prominent cause of poverty in the region. There is a need for switch over to integrated farming systems that could convert threat of water abundance into opportunities for enhancing income and employment. One such farming system model involving aquaculture enhanced water productivity by 136% and cost–benefit of the system was 1.52-fold over the farmer's practice of Rs. 3.3 m^{-3} of water (DAC 2014).

4.4.3 Other Soil Physical Constraints

About 89.5 M ha suffers from one or another form of physical constraint in the country (Painuli and Yadav 1998). These include shallow depth, soil hardening, slow and high permeability, subsurface compacted layer, surface crusting, and temporary waterlogging. Maximum area is affected by shallow depth (26.4 M ha) followed by soil hardening (21.6 M ha) and the least by temporary waterlogging (6.25 M ha). Soil compaction is a management problem resulting from movement of heavy machinery and repeated tillage operations accompanied with reduction in organic matter and destruction of soil aggregates. Compaction causes deterioration in soil structure and impedes root growth and biological activity besides generating high amount of runoff during intense storms. Soil scaling due to surface hardening and crust formation together affects 31.82 M ha area. The technologies for treating the soil affected by subsurface mechanical impedance and compaction include chiseling, chiseling plus amendment application, construction of ridges, and raised and sunken bed technology. The impact assessment of technologies developed for soils having subsurface mechanical impedance under field conditions show spectacular increase in production of major crops varying from 12 to 63%. The raised and sunken bed (RSB) technology for vertisols having high clay content has been found to be highly remunerative on sustainable basis (Painuli et al. 2002). The technology is equally effective in subsurface compacted soils as effective rooting depth is increased by 0.30 m in raised beds. The technologies for checking subsurface mechanical impedance and compaction also help in conserving soil and water besides increasing productivity. For example, the conservation agriculture (CA) has now emerged as a new paradigm to attain sustainability and overcome soil physical constraints induced by rice–wheat systems in the IG Plains (Hobbs et al. 2008). The CA technologies becoming popular in irrigated systems include zero-tillage/bed planting with residue recycling, direct drilling of wheat in to paddy residues, direct seeding of paddy, and laser-assisted precision land leveling. The other practices that alleviate these physical constraints include integrated nutrient management, cropping systems to include legumes, optimal tillage, mulching and amendment use, etc.

4.5 Extrinsic Stresses

4.5.1 Climate Variability Impacts

There is increasing evidence that climate change-related elements are contributing to accelerated resource degradation and the resultant edaphic stresses. The average increase in temperature in India during 1901 and 2005 has been 0.51 °C compared to 0.74 °C at global level. The increase was in the order of 0.03 °C per decade during 1901–1970 while it was around 0.22 °C per decade for the period from 1971 to 2004 indicating greater warming in the recent decades. Increase in the twenty-first century is projected to vary between 3 to 6 °C with southern regions registering 2–4 °C increase, while the increase (> 4 °C) would be more pronounced in the northern states and eastern peninsular region. The resultant heat stress would have serious impact on agriculture, water resources, forests, national ecosystems, fisheries, and energy sectors, e.g., a simulation study on the impact of high temperature on irrigated wheat in North India indicated that grain yield can decrease by 17% if the temperature increased by 2 °C (Aggarwal et al. 2001). Moreover, the increased temperature would result in reduced quantity and quality of soil's organic matter which is already low in Indian soils. The OSC loss per degree of warming may increase by 8–9% in areas with temperatures of 10–15 °C, while only 2% for areas with 35 °C. The N mineralization would increase but its availability may decline with gaseous losses via volatilization and denitrification.

The normal season rainfall from the period 1961–1990 has been projected to increase in India by 15 to 40% till the end of the twenty-first century. Monthly rainfall data for all the 36 subdivisions of the country indicate that it is exhibiting an increasing trend in June and August, while the July rainfall showed a decreasing trend (Guhathakurta and Rajeevan 2006). Analysis of long-term rainfall data for over 1100 stations across India shows pockets of deficit rainfall over Eastern Madhya Pradesh, Chhattisgarh, and Northeast region in Central and Eastern India (Subba-Rao et al. 2007), especially around Jharkhand and Chhattisgarh. In contrast trends indicate increase in rainfall (10–12%) along the west coast, northern Andhra Pradesh and parts of NW India (NAPCC 2008). In the southern peninsular region, a shift in peak monthly rainfall by 20–25 days from September to October is recorded. Further, the intensification of hydrologic cycle due to global warming may result in higher intensity rains, frequent floods and droughts, shift of rainy season toward winter, and receding glaciers causing higher flow during few decades followed by substantial reductions thereafter. Analysis of rainfall data with intensities of 10, 100, and above 100 mm revealed that in the recent period, the frequency of rain events of more than 100 mm intensity have increased, while the frequency of moderate events over Central India has significantly decreased during 1951 to 2000 (Goswami et al. 2006). Thus high-intensity storms would cause high erosion losses leading to severe land degradation problems.

The climate change would disturb the water balance in different parts and ground water quality due to intrusion of seawater in coastal areas. Thermal expansion of seawater due to global warming coupled with melting of glaciers and snowfields would result in the rise of sea level by 0.1–0.5 m by the middle of the twenty-first century (IPCC 2013). It is expected that by the end of the century, 68 to 77% of the forest areas are likely to experience shift in forest types with corresponding reduction in forest produce and livelihood prospects. Coastal wetlands would have serious impact due to change in the composition of plant species and expected sea level rise. The marine and aquatic life would be impacted due to rise of seawater temperature and sea level resulting in their migration to favorable regions, thus affecting livelihood of coastal people. The energy requirements in summers in plains would increase more than being compensated by saving in energy due to increased temperature in winter in northern mountainous regions. The demand for energy would also increase for irrigation needs due to high evaporative demands in cropped areas.

4.5.2 Catastrophic Events

Occurrence of floods, droughts, and other weather extremes are a common feature in many parts of the country. These natural disasters cause widespread land degradation apart from heavy monetary losses and a serious setback to economic development of the country. It has been estimated that eight major river valleys spread over 40 M ha area of the country covering 260 M population are affected by floods. Besides environmental degradation, poverty and marginalization are other major factors which force the poor to live in threatened and exposed conditions. About 60% of total flood-prone area in the country lies in Indo-Gangetic basin, which supports 40% of India's population with 60 M ha of cultivable land. The Brahmaputra basin is also critical as it experiences several floods within a year thus seriously affecting all developmental activities. The incidence of floods is not restricted to humid and subhumid regions but has also caused extensive damage in the desert districts of Rajasthan and Gujarat in the recent years. Average flood damage to houses, crops, and public utilities during 1953–2002 has been estimated as Rs. 13.76 billion affecting an area of 7.38 M ha and a population of 32.97 million (CESI 2014). Human and cattle loss has been put at 1560 and 91,555 affecting 3.48 M ha of cropped area. The maximum damage to area, human and livestock population, crops, and public utilities occurred during the years 1977, 1978, 1979, 1988, and 1998.

The impact of drought on the techno-economic and socioeconomic aspects of agricultural development and growth of the nation is severe, and droughts often result in huge production and monetary losses (Samra et al. 2006). About 68% of total sown area and 23% of land area covering a total of 183 districts and 12% of population are accounted as drought prone. In a state like Rajasthan (arid), about 56% of the total area and 33% of the total population are chronic drought-prone-affected areas followed by Andhra Pradesh, Gujarat, and Karnataka with corresponding figures as 30 and 22%, 29 and 18%, and 25 and 22%, respectively. Except Kerala, Punjab, and northeastern region, every state has one or more drought-prone areas. Apart from floods and droughts, cyclones frequently occur in the entire 5700 km long coastline of Southern and Peninsular India besides the Islands of Lakshadweep and Andaman and Nicobar Islands affecting 10 M population. Nearly 56% of the total area of the country is susceptible to seismic disturbances affecting 400 M people.

India has experienced 40 major droughts during the 200 years between 1801–2002 with 10 years under severe drought category (> 39.5% area affected) and 5 years under phenomenal drought (> 47.7% area affected) (Subbareddy et al. 2008). Since Independence, India has experienced 15 droughts out of which 3 were of severe, 7 of moderate and 5 of slight intensity affecting 13.3–49.2% of total geographical area of the country (DAC 2009). Drought-prone areas are more vulnerable to land degradation. In a good or normal rainfall year, they substantially contribute to agriculture production particularly for groundnut, millets, and sorghum crops where they account for one-third to one-fourth of the total national production.

Similarly, one-sixth to one-tenth of other important crops like ragi, maize, and cotton and 12% of rice production is realized from these areas besides sizeable contribution to the production of pulses and oilseeds.

4.6 Anthropic Stresses

4.6.1 Biological Processes

Deforestation, overgrazing, mismanagement of agricultural land, overexploitation, and bio-industrial activities are the main anthropogenic causes of loss of organic matter and soil's biodiversity. Farm level practices which sustain carbon on soils such as integrated nutrient management, reuse of crop residues via conservation tillage, diversified cropping, etc. are not being followed adequately and thus imbalanced use of fertilizers, removal of crop residues or in situ burning, intensive cropping, etc. are causing depletion of organic matter and in turn result in loss of a soil's biological population.

A decline of carbon stock especially of soils is resulting in various soil constraints in soil. It is since disruption of carbon cycle between pedosphere and atmosphere as a result of deforestation, desertification, and soil erosion. India is the lowest contributor of the GHG compared to North America and many other industrial and developed countries (0.29 Mg per capita consumption compared to 5.37 and 4.63 by the USA and Australia at 1996 level). However, with growing industrialization and economic development, India may become the second fastest growing GHG contributor in the world (increase in per capita consumption to 1.02 Mg by 2004) next to China (NAPCC 2008). While the CO2 emissions at 1997 level had been 237 million Mg, it is projected to increase to 775 million Mg by the end of the century if coal consumption continues at the present rate (Ravi Sharma 2007).

4.6.2 Vegetation Degradation

Widespread vegetation degradation is occurring in pasture lands and open forests affecting the biodiversity. The permanent pastures and grazing lands exist in major portion, e.g., 32, 10, 6, 5.1, 5, 4.5, and 4% of land in states like Himachal Pradesh, Sikkim, Madhya Pradesh (including Chhattisgarh), Karnataka, Rajasthan, Gujarat, and Maharashtra, respectively. In India, with about 500 million livestock population, more than 50% of fodder demand is met from grasslands. The grazing intensity in India is about 42 animals per ha of land, while the threshold is 5 animals per ha. About 100 million cow units graze in forest lands while sustainable level is 31 million per annum and thereby 78% of India's forests are being affected. Per capita forest area in India is only 0.07 ha which is far below the world average of 0.8 ha. Dense forests are losing their crown density and productivity continuously, the current productivity being one-third (0.7 Mg ha^{-1}) of the actual potential. The combined availability of green fodder from pasture lands and grazing lands, agricultural lands, and forest (899.3 million Mg) is far short of the actual demand of 1820 million Mg (DAC 2009). It causes indiscriminate grazing on forest lands leading to large-scale degradation thereby seriously affecting natural regeneration of forests. The present forest cover of 20.6% (Indiastat 2011–2012) is far below the 33% cover recommended by National Forest Policy of 1988, the proportion being 60% in the hill regions and 20% in the plains. The net annual loss of forest areas is put at 74000 ha which is mainly attributed to overgrazing and over-extraction of firewood from 78% of the forest areas and fire hazards in 71% of forest lands.

4.7 Epilogue

As stated above, the Indian soils are being degraded leading to multiple edaphic constraints that are threatening the sustainability of agricultural production. Except few, the processes leading to these constraints are generally insidious and show up only gradually as the problem becomes more severe to cause yield declines. Farmers may ultimately be forced to either shift to less remunerative crops or, in extreme cases, soils can turn unfit for agriculture. The situation is further going to worsen with global warming when edaphic stressors are expected to show greater impacts. Even by conservative estimates, mitigation of about half the edaphic stresses can raise the food production level to about two-fold. Thus development and promoting strategies to minimize the edaphic constraints and improving the quality and health of soils are fundamental to sustained agriculture and food security of the country. The coping strategies for minimizing the impacts of edaphic constraints include (i) mitigation through improved methods of soil and land management, (ii) adaptation though selection of crops those are tolerant to the specific constraints or develop tolerant cultivars as a result of bioengineering, and (iii) shifting to alternative uses for the land. In fact the options to be adopted are defined by the typical edaphic factors and available opportunities. Moreover, the research and policy strategies should aim at both to negate the impacts of edaphic stresses and also to prevent their further spread. Some of these are listed below:

- Several research and developmental organizations are in fact working on edaphic stressors, but their efforts are too inadequate considering the magnitude of the problem. Looking at the past scenario, it comes out that these organizations have been working in isolation and within their disciplinary boundaries. But to alleviate the effects of multiple stressors, a holistic multidisciplinary approach to build up systems perspectives is a need of the hour to get best combination of technologies for a particular agroecosystem that are often featured by multiple stressors and that needs to be defined with greater precision. For this, national networks should be built up on priority.
- Geo-referenced information system needs to be created for edaphic stresses using remote sensing, geographic information system (GIS), and scientifically designed indicators. The prognosis of hot spots for various edaphic stresses

would help in prioritization of action plans for developing integrated frameworks to alleviate the stressors.

- New tools have emerged from decades of research in the areas of conservation agriculture, precision irrigation technologies, biotechnology, remote sensing, geospatial technologies, information technology, nanotechnology and polymer sciences, etc., which have opened up new opportunities for tackling edaphic stresses. Therefore, it is of national importance to not only initiate high-quality research programs, which are of global standard in this important area, but also to capture, synthesize, adopt, and apply the technological advances taking place within and outside the country.
- Crop diversification and other measures in land use for improving soil quality such as conservation agriculture, integrated nutrient management, and efficient water management through modern irrigation and drainage methods are needed. The approaches like agroforestry and integrated crop–livestock systems can further improve soil health, biodiversity, and ecosystem services. All these need up-scaling with the ultimate goal to develop "Sustainable Agricultural Systems" those that are less vulnerable to shocks and stresses.

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