

Soil degradation challenges for sustainable agriculture in tropical India

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Soil degradation is a pervasive, systemic phenomenon and an urgent priority in order to ensure human well-being, protect biodiversity and ecosystem services. Agriculture sector is frequently affected by soil loss resulting into unproductive soil and lowered crop yields. This article focuses on critical sustainable challenges of Indian agriculture, soil degradation status and mitigation strategies as well as policies and management response options in respect of development of degraded lands. It also provides policymakers with the necessary information to develop appropriate mitigation technologies at the local, regional and national scale.

Keywords: Soil degradation, sustainable agriculture, mitigation strategies, policies.

FROM the very beginning, agriculture sector is playing a prime role in the Indian economy. According to the International Monetary Fund's (IMF's) *World Economic Outlook*, the country's gross domestic product (GDP) projected as US\$ 2972 billion as per 2019 prices. In exchange rate basis, India subsidizes 3.36% of the world's total GDP. Foreign trade is completely linked with agriculture sector as it accounts for about 14.7% of the total earnings from the export of goods. In India, the agriculture sector occupies roughly 46% of land area and 43% of total geographical area (TGA) according to the land-use statistics report. The 2011 census indicates that, 69% of the Indian population is still living in rural areas. By 2027, the Indian population is estimated to be 1.47 billion which will be higher than that of China and by 2059, it is projected to reach 1.65 billion which is way too large compared to our present resources. To meet the requirements of this burgeoning population, we need to produce more food. During 2017–18, the production of coarse cereals, pulses, oil seeds, milk, eggs, meat and fish was about 46.99, 25.23, 31.31, 176.30, 95.25, 7.71 and 12.61 million tonnes (mt) respectively. Due to population pressure, by 2050 the total foodgrain production should be increased to 377 mt; it was 284 mt during 2017–18

according to the *Indian Council of Agricultural Research (ICAR) Data Book*, 2019. There is a 30% loss of the total food produced annually in India, mainly during the production, transport and storage stages of the supply chain. Escalating population in the country poses several problems related to soil degradation. Also, soil degradation under intensive agriculture is being widely documented in India as lowered crop yields and productivity compared to other countries, high external input usage and declining profits, soil-use intensity and changing cropping patterns^{1,2}.

Sustainability challenges of Indian agriculture

Sustainable development that preserves soil, water, plant and animal genetic resources, is environmentally safe, economically feasible and socially acceptable, and also ensures the achievement and satisfaction of human needs for the existing and coming generations. So to attain long-term development in agriculture, the optimal usage of human resources, as well as natural, economic and technological resources is necessary³. The lithospheric part of the earth, which is comprised of solid rock material is known as land. On the other hand, soil is the surface covering of land (almost top 30 cm) and acts as a medium for plant growth. Land degradation is one of the prominent problems of mankind which not only reduces the production capacity of an area, but also affects the overall ecosystem⁴. Various types of physical, chemical and biological land degradation result in degradation of soil quality (Figure 1).

In addition, chemical fertilizers coupled with inappropriate irrigation management also result in worsening of groundwater quality in the country. The impact of chemicals on groundwater quality is much higher in shallow and unconfined aquifers. Majority of the Indian rural population uses water for domestic purpose from shallow private boreholes which are contaminated by nitrate (NO₃⁻) pollution⁵. Rapid human-induced secondary salinity in the last few decades has rendered vast tracts of land in dryland and irrigated regions of the world uncultivable⁶. Annually, 0.25–0.5 m ha agricultural lands is lost due to secondary salinization⁷.

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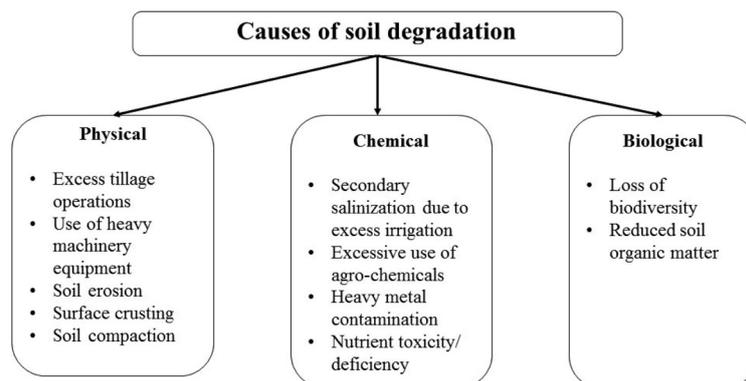


Figure 1. Different types of soil degradation.

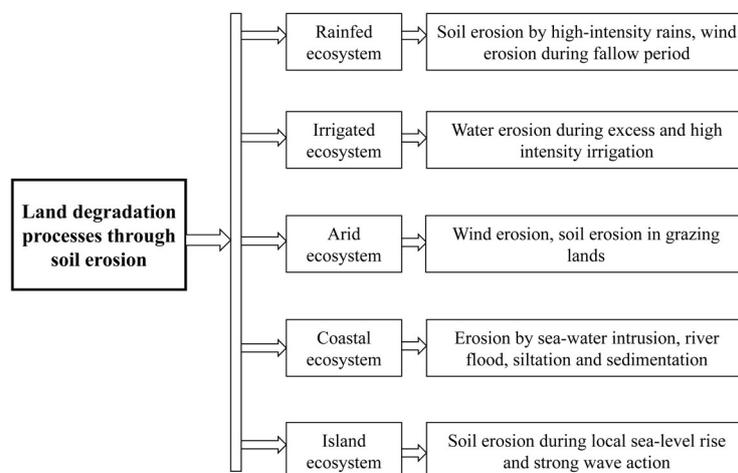


Figure 2. Soil erosion-led land degradation processes in different ecosystems of India.

Expected land scarcity and a drastic reduction in crop yields and productivity of food crops under the scenario of climate change are foreseen by 2050. Changing temperature and rainfall patterns and intensity due to increased extreme events of climate change, soil degradation as well as pest and disease infestation impose serious threats on traditional agricultural systems⁸. The main causes of low productivity are excessive pressure of population on land, social environment, land degradation, uneconomic land holdings, uncertain monsoons and inadequate irrigation facilities, incidence of pests and diseases, etc.⁹.

Status of soil degradation

Soil is the most affected natural resource through land degradation; thus it receives more attention than other natural resources. Soil erosion (water and wind erosion processes) and removal of vegetative cover (human activities) are the key reasons for the degradation of soil (Figure 2). Approximately more than 5000 tonnes of top-soil is being eroded every year, and nearly 30% of soil

(about 1600 tonnes) is lost to the sea in the form of river flow¹⁰. On an average, every year India loses approximately 0.8, 1.8, and 26.3 mt of N, P and K respectively¹¹. The 2010 published data of Indian Council of Agricultural Research (ICAR) and National Academy of Agricultural Sciences (NAAS) about soil degradation provided by different institutions show that 120.72 m ha of the land is degraded every year out of 328.73 m ha. Figure 3 shows the percentage of degraded land to total ground area in different states of India². According to the desertification and land degradation atlas of India 2016 by the Indian Space Research Organisation, most of the land degradation is contributed by the following states in ascending order: Telangana, Madhya Pradesh, Odisha, Jharkhand, Karnataka, Jammu & Kashmir, Gujarat, Maharashtra and Rajasthan. The remaining states individually contribute <1%. The most significant process of land degradation in dry, sub-humid and semi-arid regions is water erosion and removal of vegetation, whereas in arid regions wind erosion dominates.

Water and wind erosion are the major land degradation causes which contributes more than 70% and salinity contribute 15% of the total degraded area¹². According

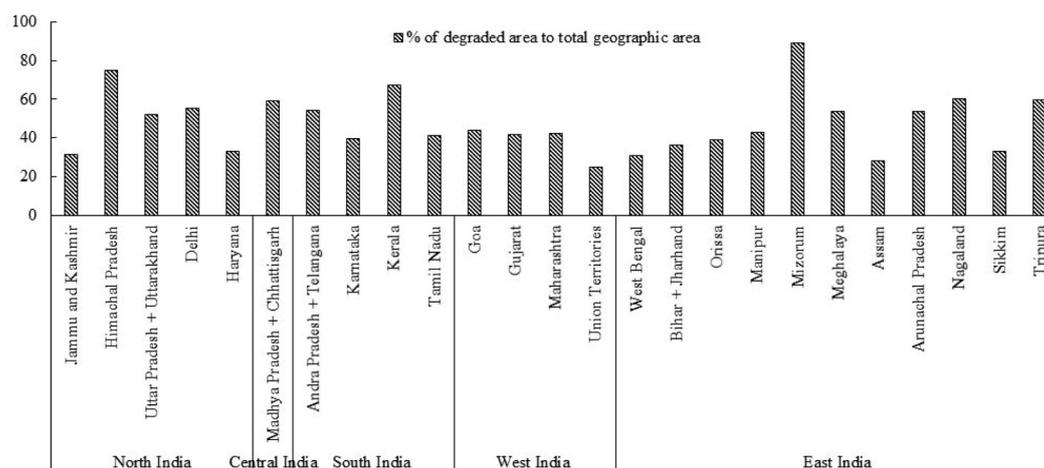


Figure 3. Status of degraded land areas in different states of India².

to region-wise statistics, central, northeastern and southern regions are badly affected. Nearly 50% of the total area of these regions is affected by land degradation; however, the statistics differs based on the method of estimation and source. The National Remote Sensing Agency (NRSA) estimations based on remotely sensed satellite data are expected to be more authentic than other estimations.

The population of our country has increased from 36.1 crores in 1951 to 125.03 crores in 2011. Thus the area under agriculture also increased from 119 m ha in 1950–51 to 140 m ha in 2014–15. On the other hand, area under uncultivable barren land, cultivable wasteland and fallow land has shown significant decrease from 1950 onwards due to urbanization and developmental activities. We are constantly stressing the land resources as we cannot increase the land area for higher productivity.

Technologies and mitigation strategies

There are several panaceas for the issues and processes of soil degradation. Table 1 provides an overview of the response level of different technologies with respect to financial, technological, political and other capacities for appropriate selection of land restoration techniques.

Contour bunding, terracing and other engineering structures

Contour bunding is an earthen embankment across land slopes that divides the area into strips and restricts water flow by reducing the amount and velocity of the run-off. Such bunds protect soils from a variety of erosions to the extent of 25–162 tonnes/ha/year and are suitable for slope of about 6%. Graded bunds are suitable in areas where rainfall is >80 cm/year, irrespective of soil texture. It consists of a wide–low embankment constructed on the

lower edge of a channel. These bunds are used at about 2–10% land slope. Bench terracing is one of the most popular soil conservation practices adopted on sloping and undulating lands having slope between 16% and 33%. Original slope is converted into level fields; all the manure and fertilizers applied are retained in the field, thus helping in proper water management. Contour trenches are suitable for high-rainfall hilly areas having a slope of steeper than 33% with badly eroded soil. Length is 3–3.65 m and the inter-space between trenches is 2.4 and 3 m. Due to construction of contour bunds in maize crop cultivation, around 21% of the crop land was saved, with 10% increase in yield¹³.

Intercropping, crop rotation and contour farming

Intercropping system involves the cultivation of two or more crops simultaneously in the same piece of land with distinct row arrangement for efficient utilization of available natural resources that enhance the overall crop productivity. It is suitable for landholding farmers who have limited land resources and low productive soils. In an intercropping system, maize–cowpea/ladies finger, maize is sown at a wider row spacing (60–90 cm) that provides enough space for soil erosion, and cultivating cowpea¹⁴ and ladies finger¹⁵ in between the maize crop protects the soil from erosion. Introduction of legumes in maize¹⁶ aids in the provision of atmospheric nitrogen (N₂), mitigation of the drought effects by acting as a live mulch and reduction of soil erosion and evaporation¹⁷. Especially, in sandy loam textured soils, soil erosion may be reduced by a good canopy cover during early stages. In the maize–wheat cropping system, inclusion of cowpea (Table 2) resulted in highest gross return (11%), net return (17%) and B:C ratio (7%) in maize + cowpea (1:1)–wheat treatment than pure maize (90 × 20 cm)–wheat plots¹⁸.

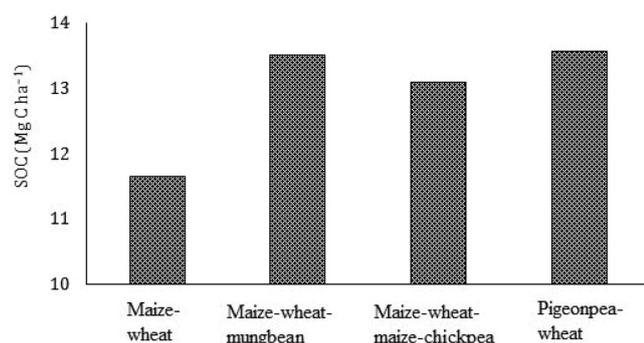
Table 1. Response level of different technologies for soil degradation

Technology	Response level					
	Environmental desirability	Technical feasibility	Political acceptability	Cultural acceptability	Social acceptability	Economic feasibility
Contour bunding, terracing and other engineering structures	H	M–H	M	M–H	M–H	M
Intercropping	M–H	L–M	L	M	M	H
Crop rotation	H	M–H	L	M	M	H
Contour farming	H	M–H	M	M–H	M–H	M
Integrated nutrient management	H	M–H	M	M–H	M–H	H
Sub-soiling	M–H	M	L	M–H	M	M
Conservation agriculture	H	M–H	L	H	H	H
Integrated farming systems	H	M–H	M	H	M–H	M
Agroforestry	H	M–H	M	H	M–H	M
Reclamation of acid and salt-affected soils	H	M–H	M	H	H	M

Note: H, High; M–H, Moderate to high; M, Moderate; V, Variable; L–M, Low to moderate; L, Low.

Table 2. Economics (mean of five years) of maize–wheat cropping system with different treatments¹⁸

Treatment	Gross return (US\$ ha ⁻¹)**	Net return (US\$ ha ⁻¹)	B : C ratio
Pure maize (90 × 20 cm) – wheat	1134	557	1.96
Pure maize (150 × 20 cm) – wheat	984	484	1.97
Maize + cowpea (1 : 2) – wheat	1190	540	1.83
Maize + okra (1 : 2) – wheat	1037	510	1.97
Maize + cowpea (1 : 1) – wheat	1279	674	2.11
Maize + okra (1 : 1) – wheat	1138	560	1.97

**Figure 4.** Soil organic carbon (SOC) as influenced by long-term crop rotation²⁰.

Pulse crops like pigeon pea, mung bean, cowpea, chickpea, soybean, etc. have higher root biomass, biological nitrogen–fixation capacity, and can enrich the soil with organic carbon, enhance soil fertility by redistributing the soil profile nutrients¹⁹. After long-term continuous cropping, the pulse inclusive crop rotations (Figure 4) brought significant changes in soil organic carbon (SOC) compared to the cereal–cereal cropping system²⁰.

Contour farming is an effective practice of tillage, planting and other farming operations carried on the contour of the field slope in order to control soil erosion and increase crop productivity; it is suitable for moderate slopes. Contour ridging results in rainwater ponding, reduces velocity of run-off and soil erosion, and increases infiltration²¹. Soil nutrients in the run-off are retained better in contour ridge tillages. Cultivation and planting

along contour lines reduced soil and water loss to the tune of 49.5% and 32% respectively.

Integrated nutrient management and organic amendments

Practice of integrated nutrient management (INM) by combining organic amendments with appropriate management options is considered as a viable strategy to combat climate change and improve carbon stocks^{22,23}. Combined application of 50% NPK and farmyard manure (FYM) @ 10 tonne ha⁻¹ in groundnut crop increased yield and exerted a significant effect on the mineralization of SOC²⁴. Cereal crop residues retained on the field also aid in the provision of plant nutrient sources²⁵.

Application of azolla compost along with recommended doses of NPK helped effectively build-up soil carbon (27.43%) followed by NPK + cowdung (22.76%) over NPK alone²⁶. Azolla application also improved the soil carbon storage (2.88 mg ha⁻¹) capacity with grain yield of 6.55 mg ha⁻¹ compared to other treatments (Table 3). Generally, in the slope areas (0.5–2.0%) run-off and soil loss are higher. In such areas, INM practice efficiently protect the soil from losses. Application of recommended rate of fertilizer along with FYM (Figure 5a and b), minimizes soil run-off and losses²⁷.

Adoption of INM in the drylands under groundnut-based cropping system registered higher C accumulation rates (0.45–tonne ha⁻¹ year⁻¹) compared to the other

Table 3. Comparison of grain yield and C fixed under integrated nutrient management (INM) in monsoon rice ecosystem²⁶

Treatment	Total C fixed in grain (mg ha ⁻¹)	Grain yield (mg ha ⁻¹)	% increase in yield over control
NPK	2.02 ± 0.06	5.14 ± 0.17	–
NPK + cow dung	2.66 ± 0.05	6.31 ± 0.11	22.76
NPK + green manure	2.41 ± 0.08	5.69 ± 0.18	10.70
NPK + Azolla compost	2.88 ± 0.07	6.55 ± 0.11	27.43
NPK + rice husk dust	2.42 ± 0.08	6.01 ± 0.16	16.93
<i>P</i> value (Treatment)	0.000	0.000	
Year × Treatment	0.901	0.987	
LSD (Treatment)	0.109	0.229	

Table 4. Carbon accumulation rate in soil (0–20 cm) under different INM practices²⁸

Crop production system	Soil order	Suggested INM practice	C accumulation (tonne ha ⁻¹ year ⁻¹)	
			Farmer's practice	Suggested practice
Sorghum-based	Vertisols	25 kg N ha ⁻¹ (through FYM), 25 kg N ha ⁻¹ (through urea)	0.101	0.288
Groundnut-based	Alfisols	50% RDF + 4 tonne groundnut shell ha ⁻¹	0.08	0.45
Pearl millet-based	Aridisols	50% N (inorganic fertilizer) + 50% N (FYM)	-0.252	-0.110
Finger millet monocropping	Alfisols	FYM 10 tonne + 100% RDF (NPK)	0.046	0.378
Rice-based	Inceptisols	100% organic (FYM)	-0.014	0.128
Soybean-based	Vertisols	6 tonne FYM ha ⁻¹ + 20 kg N + 13 kg P	-0.219	0.338

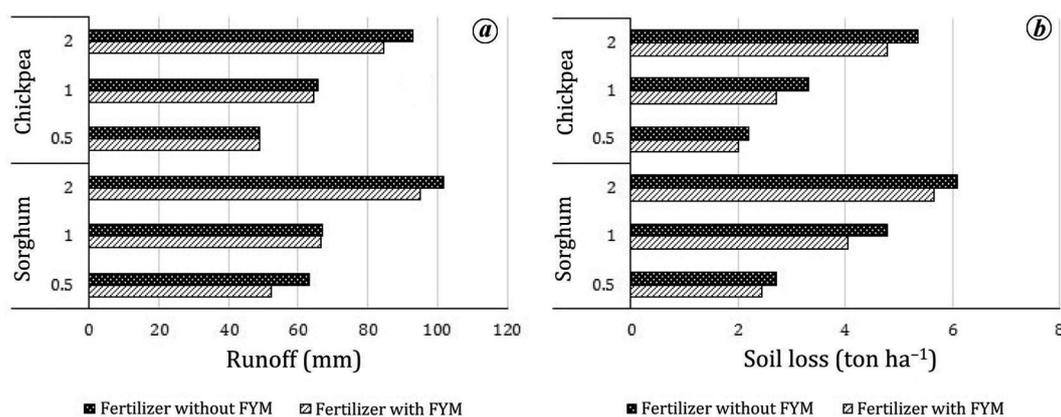


Figure 5. Runoff (a) and soil loss (b) under sorghum and chickpea at varying slopes²⁷.

systems over farmer's practice (Table 4)²⁸. Each tonne of SOC increment has a yield benefit of about 0.02–0.16 t ha⁻¹ among several rainfed crops^{29,30}. The INM practice, specifically in rainfed regions of India, takes complete advantage of locally available organic resources and external fertilizers towards achieving sustainability of rainfed systems³¹.

Subsoiling

Soils may become deeply compacted due to heavy machinery operation during cultivation. Such compacted soils restrict the movement of water, air and roots that hampers plant growth. Soil compaction is one of the severe forms of soil degradation that affects around 11% of the land area³². Especially, in black soils (Vertisols) such issues further increase the problems of crop cultivation. Subsoiling is an effective technique in both cropping

and pastoral agriculture to alleviate soil compaction and to improve its physical condition. Subsoiling in sugarcane significantly influenced the yield and quality; it also reduced the soil bulk density and increased infiltration rate³³.

Conservation agriculture

Conservation agriculture (CA) is a type of farming system that prevents degradation of arable lands through its interlinked principles, namely maintaining permanent soil cover, minimal soil disturbance and diversified cropping system³⁴. CA minimizes soil and water loss (45% and 50% respectively) over traditional system³⁵. Maximum yields of maize and wheat (2000 and 1700 kg ha⁻¹ respectively) were noticed under CA over conventional plots (1570 and 950 kg ha⁻¹ respectively). Almost 58.5 mm of moisture was conserved in wheat under CA

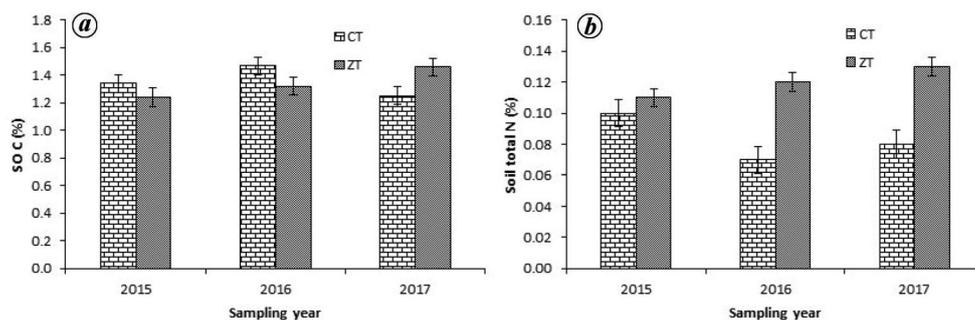


Figure 6. Effect of tillage practice (conventional tillage (CT) and zero-tillage (ZT)) on (a) SOC ($n = 3$) and (b) total soil N ($n = 3$) at 0–15 cm depth for a three-year period³⁹.

Table 5. Crop productivity and conservation efficiency as affected by conservation agriculture under 2% slope in maize–wheat cropping³⁵

Particulars	Conventional agriculture	Conservation agriculture
Maize grain yield	1570	2000
Wheat grain yield after maize	950	1700
Equivalent yield of wheat (kg ha^{-1})	2320	3470
Oil yield	–	4.0
Dry grass yield ($\text{kg ha}^{-1} \text{ year}^{-1}$)	–	610
Weed biomass for mulching	–	2100
Water loss (% of rainfall)	39.8	21.9
Soil loss ($\text{tonne ha}^{-1} \text{ year}^{-1}$)	7.2	3.5
Moisture conservation for wheat compared to fallow (Mm)	28.1	58.5

compared to fallow systems under conventional agriculture (Table 5).

Zero tillage (ZT) is highly effective for the Himalayan regions of India due to its minimum cost of cultivation, moisture retention and SOC protection³⁶. Combining ZT system or CA with various organic amendments like vermicompost, FYM, poultry manure and weed mulching potentially benefits the economic and environmental status³⁷. Soil physical properties like bulk density, field capacity and porosity are improved by adopting conservation tillage³⁸. Over a period of time, zero-tillage system enhanced the SOC and soil nitrogen status over the conventional tillage after three years (Figure 6)³⁹.

Integrated farming system and agroforestry

Adoption of an integrated farming system (IFS) is highly advantageous to the farmers due to optimal resource utilization, employment creation and waste recycling⁴⁰. It also helps solve the energy crises⁴¹. Table 6 presents various components that are suitable for the IFS models^{42–46}.

Introduction of forestry in the agriculture system along with dairy, apiculture, goat-rearing, etc. is an effective risk management strategy to combat drought seasons and heavy flooding⁴⁷. The three important environmental benefits of adaptation of agroforestry are enhancement of

water quality, carbon sequestration and soil improvement⁴⁸. Important soil properties like organic carbon, cation exchange capacity (CEC), available phosphorus (P), exchangeable potassium (K) and magnesium (Mg) are improved in agroforestry system, where coffee, black pepper and pipli were grown compared to natural fallow (Table 7)⁴⁹.

Compared to agricultural crops, few trees are less vulnerable to salinity. Thus cultivation of such trees helps regenerate the saline soils. Planting of *Prosopis juliflora* in alkaline wastelands could overcome the problem of poor root proliferation because of the vertically penetrating roots into a hard pan⁵⁰. Different tree species are tolerant to saline conditions at different electrical conductivity (ECe) levels. Species such as *Prosopis juliflora*, *Salvadora oleoides*, *Tamarix troupii*, etc. are tolerant at high salinity ($\text{ECe} > 35 \text{ dS m}^{-1}$); species such as *Tamarix articulata*, *Acacia farnesiana*, *Parkinsonia acculeat*, etc. are tolerant at moderate salinity ($\text{ECe} 25\text{--}35 \text{ dS m}^{-1}$); species such as *Casuarina glauca*, *obesa*, *equisetifolia*, *Acacia tortilis*, *Pongamia pinnata*, *Eucalyptus camaldulensis*, etc. are tolerant at the ECe value of $15\text{--}25 \text{ dS m}^{-1}$ and the species such as *Eucalyptus tereticornis*, *Casuarina cunninghamiana*, *Acacia catechu*, *Dalbergia sissoo*, etc. are tolerant at $\text{ECe} 10\text{--}15 \text{ dS m}^{-1}$ to reclaim the saline soils.

Reclamation of acid and salt-affected soils

Soil acidity, salinity and alkalinity are considered as the major land degradation processes in agricultural lands that are adversely affecting crop yields. Acidic soils are ameliorated by lime application. Lime raises the soil pH to the desired level, increases the plant nutrient availability, and minimizes Fe and Al toxicity⁵¹. Leaching is the only effective reclamation technique for saline soils which have a deeper water table. Application of $12\text{--}15 \text{ tonne gypsum ha}^{-1}$ at 0–15 cm soil depth is sufficient to reclaim highly deteriorated soil ($\text{pH} > 10.0$) under rice–wheat crops rotation⁵². Gypsum application method is successfully promoted by the All India Coordinated Research

Table 6. Suggested components for integrated farming system (IFS) models

Components of IFS	Source
Agriculture–dairy, fish farming, duck-rearing, horticulture, forestry.	
Mushroom cultivation – azolla farming, kitchen gardening, fodder production, nursery, sericulture.	42
Seed production – goat-rearing, poultry, pigeon-rearing, vermiculture, apiary.	
Sheep-rearing – piggery, rabbitry, value addition	
Crop + dairy	
Crop + horticulture + goats + dairy	
Crop + horticulture + goats	
Crop + vegetables + dairy	43
Dairy + horticulture + vegetables	
Dairy + vegetables	
Dairy + companion animals + crops	
Agricultural crops like rice + pea, ragi, maize, pigeon pea and groundnut, horticultural crops like banana, tapioca, yam, and vegetables + poultry and vermicomposting.	44
Inter cropping with groundnut + pigeonpea (7 : 1) and maize + black gram (2 : 2); double cropping of fodder millet – green chilli system.	
Tamarind + pearl millet or sunflower and simarouba + chickpea-based agri-horti systems; <i>Leucaena leucocephala</i> (K-63) + gobi – sarson in rabi and fodder maize in kharif.	45
Relay cropping of castor in green gram, pear millet + cluster-bean strip cropping system (4 : 4) and pearl millet + green gram (8 : 4).	
Integrated fish-cum-duck farming; integrated paddy-cum fish farming in low-lying areas (Dhubri, Assam); water reed cum-fish farming (Manipur) and duck-cum-fish integrated farming (Ri-Bhoi, Meghalaya).	46

Table 7. Important soil properties as affected by different land-use systems⁴⁹

Land-use	Component	pH (1 : 2.5)	Organic C (%)	Available P (ppm)	CEC (c mol (p+) kg ⁻¹)	Exchangeable cations (cmol (p ⁺) kg ⁻¹)		
						K	Ca	Mg
Agroforestry	Coffee, pipli and black pepper	4.80	1.60	2.90	9.10	0.30	0.90	0.80
Natural fallow	Grasses	5.70	1.47	1.40	5.20	0.20	0.90	0.60

Project (AICRP) at the Centres in Indore, Kanpur, Gan-gavathi, Tiruchirappalli and Bapatla, to reclaim alkali soils in the respective states. Incorporation of dhaincha lowered the exchangeable sodium percentage (ESP) (23.54 in 2016–17 and 22.62 in 2017–18) followed by sunhemp (26.70 in 2016–17 and 25.90 in 2017–18). Green manuring also helps in the reduction of ESP, enhances crop yields and improves the soil fertility status⁵³. Some crop varieties are resistant to salinity, e.g. rice: CSR-10, 13, 23, 27, 36, 43, 46, 56 and 60; wheat: KRL-1-4, 19, WH 157, Raj. 3077, KRL-210, 213, 283; mustard: Pusa Bold, Varuna, Kranti, CS-52, 54, 56, 58 and 60; barley: CSB 1, 2, 3, DL 200 and 348, Ratna, BH 97, AZAD, and chickpea: Karnal Chana-1 are highly tolerant to saline conditions⁵².

Programmes and policies

In 1977–78, the Desert Development Programme (DDP) was initiated in the country to deal with the adverse effects of desertification. In 1985, the National Waste-lands Development Board (NWDB) was set-up under the Ministry of Environment and Forests (MoEF), Government of India to reverse the land degradation. To combat drought situations, in 1973–74, the Drought Prone Areas

Programme (DPAP) was launched. The Integrated Was-telands Development Programme (IWDP) was estab-lished in 1989–90. The Scheme of Soil Conservation in the Catchments of River Valley Project and Flood Prone Rivers (RVP and FPR; 1961–62) was launched to incen-tivize states to draw up comprehensive agriculture devel-opment plans. Reclamation and Development of Alkali and Acid Soils (RADAS) was launched in 1985–86. The National Mission for Sustainable Agriculture (NMSA) was started in 2010 to address issues regarding ‘sustaina-ble agriculture’ through climate change adaptation and mitigation strategies. The Green India Mission (GIM) was launched in 2015 to enhance the country’s diminish-ing forest cover. Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) was rolled out in 2015 to achieve con-vergence of investments in irrigation at the field level. The Soil Health Card (SHC) scheme was launched in February 2015 to estimate the actual fertilizer dosage. The Mahatma Gandhi National Rural Employment Guar-antee Act (MGNREGA) was enacted during 2005 with a major focus on improving soil fertility and soil health, soil erosion control, reclamation of degraded soils and carbon sequestration. Neem Coated Urea (NCU) scheme was introduced to improve soil health. The National Project on Organic Farming (NPOF) scheme was launched in 2004 in order to promote organic farming

practices. Climate-smart agriculture under the National Innovations on Climate Resilient Agriculture (NICRA) was developed for strengthening the resilience of farmers to the adversaries of climate change. The National Agroforestry Policy was initiated in 2014 for carbon sequestration and to control soil erosion.

Conclusion

Understanding the key reasons for soil degradation is imperative to find appropriate solutions and mitigate the problems. Judicious management of existing resources through sustainable agricultural technologies would aid in checking soil erosion and in the effective management of degradation losses. Combining and simultaneous application of location-specific and low-cost technologies, viz. CA, diversified cropping system, crop rotation, intercropping, residue management, use of soil amendments, INM approach, agroforestry, etc. would provide advantage in optimizing resource-use efficiency and maximize the overall crop productivity, especially in the tropical regions of India. Formulation and development of location-specific strategies and mechanisms for scaling-up the technologies through proper policies and programmes at local, regional and national scale would help in finding a comprehensive solution.

Way forward

Though there has been substantial improvements in checking soil degradation, the visible impacts of these on the ground is inadequate. A short-term analysis would suggest the following:

- Development of authentic estimation protocols to better understand and quantify the biodiversity loss and degradation is required.
- Sustainable agricultural practices are to be highly focused to deal with the soil degradation.
- Estimation of short-, medium- and long-range costs and benefits associated with mitigation of soil degradation is critical.
- Provision of scientific knowledge, tools and skills related to the monitoring of soil condition for land managers and planners is necessary.
- Support of public policies and programmes for the sustainable management of existing resources, knowledge transmission, infrastructure creation and employment generation is highly essential.
- Enforcement of frequent soil-quality monitoring at village level plays a significant role.
- Future research must concentrate on linking solutions to specific terrains and land forms, environmental situations, societies and economic demands.

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