Strategy Paper

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Progress Through Science

Managing Soils of India for Addressing Challenges of the 21st Century

Prof. Rattan Lal

Director, CFAES Rattan Lal Center for Carbon Management and Sequestration,
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Progress Through Science

Trust for Advancement of Agricultural Sciences (TAAS)

GOAL

Harnessing the potential of agricultural sciences for the welfare of people of India.

MISSION

Promoting growth and advancement of agriculture through science based policy advocacy, public awareness and effective research and development partnerships.

OBJECTIVES

- To act as a Think Tank to deliberate on key issues relating to agricultural research and innovation for development (ARI4D) and to influence policy decisions
- To organize workshops, conferences, brainstorming sessions, seminars, policy dialogues and special lectures on emerging issues and new developments in agricultural sciences
- To disseminate knowledge among stakeholders through publication of proceedings, strategy papers, policy briefs and success stories
- To confer awards on the scientists and farmers of Indian and foreign origin for their outstanding contributions
- To facilitate scientific interaction and partnerships of non-resident Indian agricultural scientists with Indian scientists

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Foreword

India's agricultural transformation over the past seven decades is among the most remarkable development achievements of modern times. From a food-deficit nation dependent on imports and food aid in the 1950s, India has become a global agricultural powerhouse capable of ensuring food security for more than 1.4 billion people. This progress has been driven by visionary policies, scientific innovation, improved crop varieties, investments in research and extension, and the resilience of millions of farmers.

The challenges facing Indian agriculture today differ fundamentally from those of the past. The goal is no longer simply to produce more food, but to produce nutritious food sustainably while conserving the natural resources on which agriculture depends. Persistent malnutrition, declining soil fertility, groundwater depletion, biodiversity loss, environmental degradation, and climate change demand a transformative shift in agricultural development.

At the heart of this transformation is soil—the foundation of agricultural productivity, ecosystem health, and human well-being. Healthy soils sustain crop yields, improve nutritional quality and water-use efficiency, conserve biodiversity, sequester carbon, and strengthen resilience to climate stress. By placing soil health at the centre of agricultural and environmental policy, India can advance food and nutritional security, climate resilience, ecological sustainability, and farmers' livelihood.

This Strategy Paper advocates a shift from input-intensive, production-centric agriculture to a soil-centric framework that integrates productivity with environmental stewardship and climate action. It emphasizes regenerative agriculture, climate-smart farming, carbon sequestration, restoration of soil organic matter, balanced nutrient management, efficient water use, and stronger linkages among soil, plant, animal, human, and ecosystem health within the broader *One Health* framework.

I commend Prof. Rattan Lal World Food Laureate for his global leadership in soil health and thank him for attempting this highly relevant strategy paper entitled, "*Managing Soils of India for Addressing Challenges of the 21st Century*". His contributions to soil science and sustainable agriculture have inspired researchers and policymakers worldwide. This publication offers a practical roadmap for restoring soil health and securing a more sustainable, resilient, and prosperous future for Indian agriculture.

In fact, healthy soils are the cornerstone of a healthy nation, and investing in them today is an investment in India's food, nutrition, environmental, and economic security for generations to come. I am confident that this strategy paper will serve as a valuable resource for policymakers, researchers, teachers, extension professionals, students, and farmers.

Raj Paroda
(Padma Bhushan Awardee)
Chairman, TAAS
Former Secretary, DARE & Director General, ICAR

Acronyms and Abbreviations

ACC	Anthropogenic Climate Change
As	Arsenic
BMP	Best Management Practice
B Mg	Billion Metric Tons
BIFAD	Board for International Food and Agricultural Development
BNF	Biological Nitrogen Fixation
C4SH	Coalition for Action on Soil Health
CA	Conservation Agriculture
CFAES	College of Food, Agricultural, and Environmental Sciences
CT	Conventional Tillage
GCHERA	Global Confederation of Higher Education Associations for Agricultural and Life Sciences.
GWP	Global Warming Potential
ICAR	Indian Council of Agricultural Research
IFFCO	Indian Farmers Fertiliser Cooperative
IGP	Indo-Gangetic Plains
IITA	International Institute of Tropical Agriculture
INM	Integrated Nutrient Management
ISTRO	International Soil Tillage Research Organization
IUSS	International Union of Soil Sciences

LUCC	Land Use and Cover Change
M Mg	Million Metric Tons
MRT	Mean Residence Time
PAU	Punjab Agricultural University
Pg	Petagram (10^{15} grams or 1 billion metric ton)
RW	Rice-Wheat
SAB	Scientific Advisory Board
SDGs	Sustainable Development Goals
SERDP	Strategic Environmental Research and Development Program
SIC	Soil Inorganic Carbon
SOC	Soil Organic Carbon
TAAS	Trust for Advancement of Agricultural Sciences
UIMP	Universidad Internacional Menéndez Pelayo
WASWAC	World Association of Soil and Water Conservation

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ABSTRACT

India's global success story - an impressive increase in food grain production from 1950 to 2025 - must be repeated in other developing regions of the world. However, even greater challenges lie ahead for India. Despite increase in agronomic production, under-nutrition and malnutrition persist, and must be addressed. Further, often excessive and unbalanced use of inputs, coupled with inappropriate plowing and excessive flood/furrow-based irrigation and in-field burning of crop residues, have degraded soils, depleted terrestrial carbon stocks and plant nutrient reserves, polluted water and lowered ground water levels, denuded steep-lands, and dwindled biodiversity. Therefore, there is an urgent need for a paradigm shift in Indian agriculture. The aim is to achieve sustainable agronomic yield but with a high nutrient density especially that of micronutrients and protein content. The miracle crop varieties and genetically improved livestock and other animal species dependent on them can realize their full production potential only when supported by soils having favorable physical, chemical, biological and ecological health. Therefore, the aim is to adopt resource-based (soil-centric) innovations which lead to production of adequate, nutritious and safe food for all while protecting, restoring and sustaining soil health and doing its share of limiting global warming to <2°C. This strategy is also pertinent to achieving Sustainable Development Goals of the United Nations. Promoting "carbon farming" by which farmers can be rewarded for growing soil carbon (organic and inorganic), tree carbon (above and below ground), and blue carbon in wetlands (swamps and marshes) is a win-win-win option because it mitigates climate change, reduces rural poverty, and produces nutritious food. India is already producing enough food for its growing, rapidly urbanizing, and increasingly affluent population. Now, the focus

should be shifted towards obtaining optimal agronomic yield while restoring the environment. The concerted effort being made jointly by the Indian Council of Agricultural Research (ICAR), Trust for Advancement of Agricultural Sciences (TAAS) and Isha Foundation in developing "*Bharat Soil Health Policy*" is an encouraging and a positive step. The objective is to transform agro-ecosystems so that agriculture becomes an integral part of the solution rather than a contributor to environmental degradation. In other words, the need for food production must be reconciled with that of the urgency for improving the environment and restoring/sustaining the natural resource base (i.e., soil, water, air, biodiversity). There is also a need for change in educational curricula at primary, middle and high school, and college level to promote the One Health Concept. The strong link between soil health with that of plants, animals, people, and ecoregions; must be taught in medical colleges and public health institutions as a natural solution to improving human health by reducing under–and malnutrition, enhancing the quality of water and air, strengthening biodiversity, and restoring the environments so that humans live in harmony with nature.

Introduction

India's geographical area spans from 8°4' to 37°6'N latitude and 68°7' to 87°25' E longitude. The total land area of 329 M ha comprises a large number of diverse ecoregions and soil types (i.e., alluvial, vertisolic, lateritic, forest, mountainous, acidic, aridic, peats, marshy and salt-affected soils (Mishra, 2020). Population of India has grown from ~350 million in 1947 to ~ 1.46 billion in 2026 and is projected to be 1.7 billion by early 2060s but is likely to be followed by a declining trend thereafter to stabilize approximately at 1.5 billion by 2100. With limited land (2.45% of the world) and fresh water (4% of the world), India has the humongous task of creating an environment that enhances and sustains the wellbeing of 18 per cent of the global population of 8.3 billion in 2026. India is also home to 15 per cent of the world's livestock population. Thus, an already high pressure on limited land and water resources is likely to be aggravated unless critical actions are taken in near future. Specific resource stresses include non-availability of prime land for agricultural uses with low land-to-person ratio (0.2 ha in India compared with 2.89 ha globally) whose effect is being aggravated by severe soil degradation which adversely affects quality and quantity of food, water renewability and purification, and loss of biodiversity. Soil is a source of numerous and essential ecosystem services (ESs) (Figure 1) which are being jeopardized by degradation of soil functions.

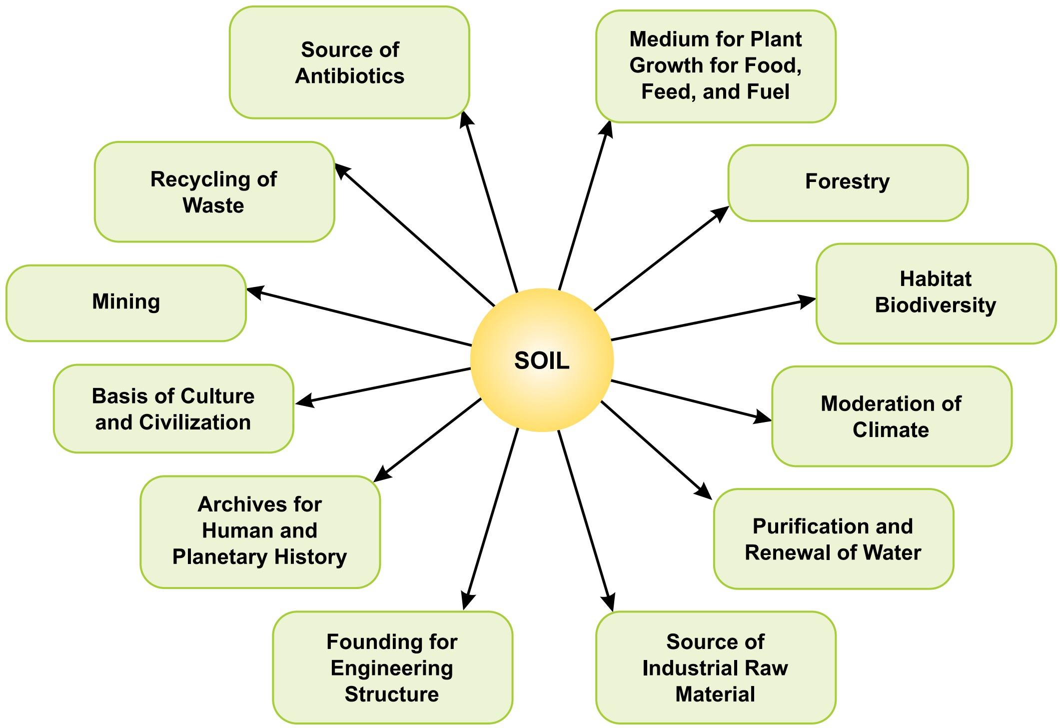

Figure 1. *Essential ecosystem services from soils as foundation of human wellbeing and nature conservation*

Degradation of soils of agro-ecosystems, by a range of processes, is also a serious problem (Figure 4). Among serious problems of anthropogenic soil degradation include removal of 1.0 m of top soil for brick making due to rapid urbanization and non-agricultural uses. Depletion of soil organic matter (SOM) content in the plow layer is another problem which is often ignored and yet some soils of the northwestern region of India has SOM content of < 0.25 per cent in comparison with concentration of 1.5 to 2.5 per cent under optimal conditions. Adverse effects of soil degradation are being aggravated by climate change, while ground water resources of which 70 per cent are being used for irrigation and other agricultural purposes are declining rapidly. A holistic approach to soil management for protection, restoration and management of soils is outlined in Figure 2.

However, this article is focused on the most basic determinant of soil health, the soil organic carbon (SOC) and its management. Management of low soil fertility, erosion control, soil acidity, salinity, sodicity and soil pollution and contamination are beyond the scope of this article. Nonetheless, basic principles of soil management are schematically depicted in the following sections.

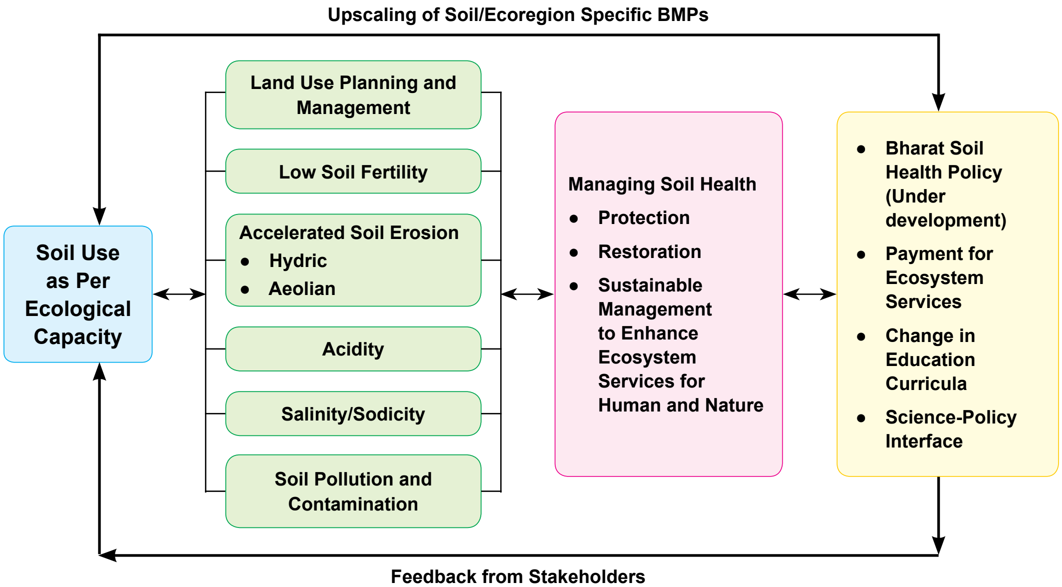

Figure 2. *A holistic approach to sustainable management of soil resources by upscaling of best management practices (BMPs)*

The objective is to deliberate, identify and suggest strategies for implementation of innovative approaches to address the issues of the 21st century. Rather than focusing just on agronomic productivity, the specific objective is to present a positive approach of reconciling the need for producing nutritious and safe food with the absolute necessity of restoring the environment. Thus, it is essential to transform agriculture through sustainable management of soil health for advancing food and nutrition security and improving the environment (soil, water, air, biodiversity) by protecting, restoring and sustainably managing the limited and fragile soil and water resources under the conditions of changing and uncertain climate.

Era of Food Self-Sufficiency

Since 1960s, India has witnessed an impressive agronomic growth including increase in food grain production. An impressive food grain production in India, especially from mid 1960s to 2025, is attributed to use of input-responsive varieties grown on irrigated land with heavy input of fertilizers (especially N) and pesticides. There was a 6.5-fold increase in food grain production between 1950 and 2024 (Table 1), along with corresponding increase in per capita grain production from 142 kg to 231 kg, an increase of 62.7 per cent.

The fact that the rate of increase of food grain production exceeded that of population growth, proving neo-Malthusians wrong, is a testimonial to dedication

Table 1. Temporal changes in food grain production in India (1950-2021)

Year	Food Grain Production (Mt)	Population (M)	Per Capita (kg)
1950-51	50.82	357.0	142
1960-61	52.02	436.0	119
1970-71	108.42	545.8	199
1980-81	129.59	687.4	189
1990-91	176.39	865.0	204
2000-01	196.81	1057.9	186
2010-11	244.49	1243.5	197
2020-21	310.74	1402.6	222
2021-22	314.51	1410.0	223
2023-24	332.30	1438.0	231

Akrom Series #4; Anonymous 2022; 2026

and commitment of farmers and agricultural researchers. Indeed, India has succeeded in feeding 18 per cent of the world population on only 2.4 per cent of the world land area and merely 4 per cent of the world's fresh water resources. This is a commendable accomplishment. However, total food grain production can still be increased up to about 550 M Mg by adoption of proven agronomic practices and by modern soil management practices. For example, use of a system-based conservation agriculture (CA) was practiced on merely 1.5 M ha of cropland during 2025 (Kassam *et al*., 2015) out of the global uptake on about 150 M ha to 200 M ha during the same period. Although the food grain production was impressive, yet it was accompanied by severe degradation and contamination of soil, depletion of water, pollution of air, loss of biodiversity and severe decline in overall environments.

While the average food grain supply increased impressively (Table 1), the economic growth has not been translated into action to minimize risks of soil degradation and enhance the wellbeing of general population. Because of degraded soils and polluted environment, there has been an overall decline in human health as indicated by a trend of decrease in food and nutritional security and prevalence of malnutrition (Figure 3).

While India's Global Hunger Index improved from 29.3 in 2016 to 27.3 in 2024 (Upadhyay and Palanivel, 2011), undernutrition remains to be a grave issue with

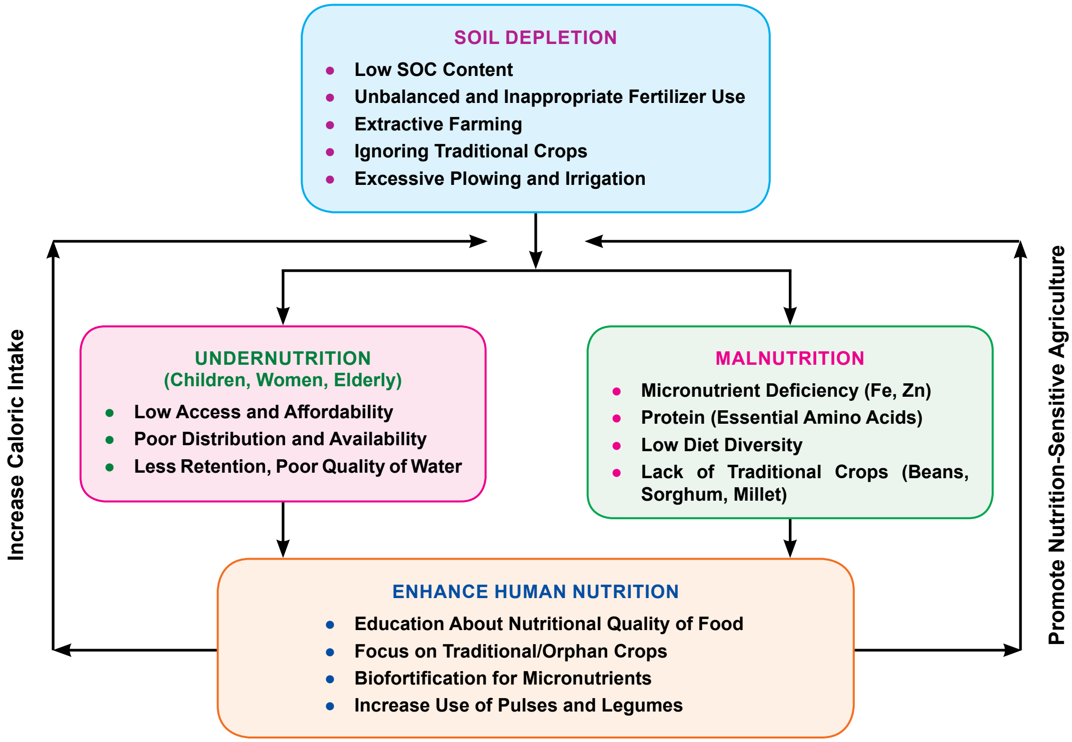

Figure 3*. Prevalence of undernutrition and malnutrition in India*

estimates of 13.7 per cent in children under 5 years of age. There is also a growing incidence of anemia affecting 67 per cent of children under 5 years and 52 per cent of pregnant women (15-49 years) (KPMG, 2026). Approximately 200 million people are undernourished and over 32 per cent of children under 5 years are underweight. Despite tremendous increase in total food grain production, India accounts for the largest share of the world's food-insecure population. Among socioeconomic and political factors, undernutrition is also attributed to lack of improvement in agricultural productivity (Upadhyay and Palanivel, 2011). These problems are aggravated by soil degradation, anthropogenic climate change, and rapid/ad hoc urbanization. Therefore, the focus should be on translation of proven agronomic science into action that protects soil health, conserves and purifies natural waters, improves air quality and produces nutrient-dense and safe food for all. In this context, managing soil health is the most critical component to be addressed.

Soil Health in Ancient Indian Philosophy

Mother Earth (*Prithvi, Bhumi, Dherra, Vasundherra*) is the basis of Indian civilization and culture since the *Vedic* era. The *Atharvaveda* vividly states that "*mātā* *bhūmiḥ putro'haṃ pṛthivyāḥ*” (The Earth is my mother and I am her son). In this context, humans are children and caretaker of Mother Earth rather than masters of nature. The concept of spiritual world sacred ecology, dharmic ecology, *Bhumi Devi*, and sustainable use of natural resources are integral components of Indian civilization (*Prithvi Sukta of Veda*). Basic concepts of *Vedic* cultures include the following: (i) interconnectedness of all planetary systems, (ii) ecological reverence in the context of “limited consumption lifestyle”, (iii) respect for nature as a sacred entity, and (iv) sustainable living based on preservation and restoration. Prominent philosophers who emphasized ecological harmony include *Maharishi* Veda Vyasa who promoted the idea of “*panch bhuta*” (5 elements), Rabinder Nath Tagore who promoted environment based education and learning, Mahatma Gandhi who championed the cause of respect for the environment and sustainability, and Sri Aurobindo who focused on integral education including physical and vital aspects of nature. These and other ancient philosophers have strongly emphasized that Mother Earth is more than just a resource to be exploited but a living entity (*Prakriti*) which must be protected and respected.

Similar concepts are depicted in the western culture. Important among these are the Gaia (Earth) hypotheses as the self-generating primordial deity promoted by Hesiod (800 BCE). Similar to the Hinduism concept of “*panch tatva*”, western philosophers also emphasized the interconnectedness of all living things through the Earth.

In the modern soil science, soil is considered the connector of all natural spheres with pedosphere in the center and other spheres (atmosphere, biosphere, hydrosphere and lithosphere) connected with it through interactive processes. It is the interconnectedness of these planetary spheres which is the foundation of all terrestrial life. Thus, it is critically important to reconnect humanity with the *Prikriti*, Mother Earth, Soil or the Pedosphere.

Soil Degradation in India

Alas, humanity has lost the concept of inter-connectivity and reverence for Mother Earth, Hence, the modern era (since 1960s) witnessed a degradative trend in soil, water, air and other natural resources. Among the serious problem of soil degradation of 147 M ha of land, soil erosion by water is the most dominant process (Figure 4). In terms of the area affected, degradation processes are in the order of water erosion>acidification>flooding>wind erosion>salinity. Combination of all factors affect 44.7 per cent of land area (147 M ha out of 329 M ha). However, some important factors e.g., depletion of SOC stock, elemental imbalance, top soil removal for brick making, decline of soil structure and susceptibility to drought,

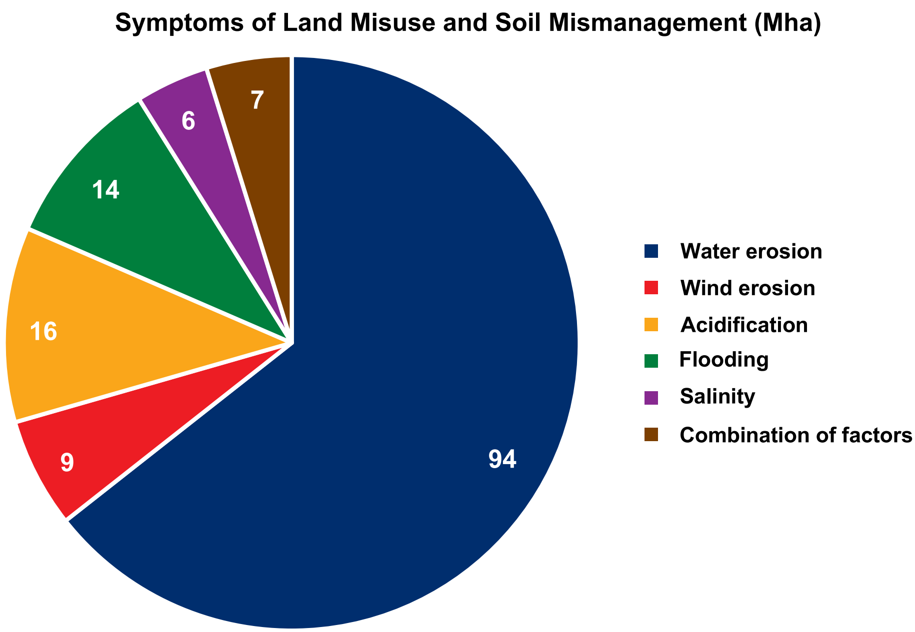

Figure 4. *Soil degradation in India affecting 147 M ha of land (adapted from Bhattacharya et al. (2025)*

plastic pollution, etc. are not included in the estimates shown in Figure 5. Thus, there is a need for more research on this topic and for identification of emerging issues of soil degradation and land desertification. These effects must be measured in terms of the loss of ESs of relevance for nature conservancy and human welfare.

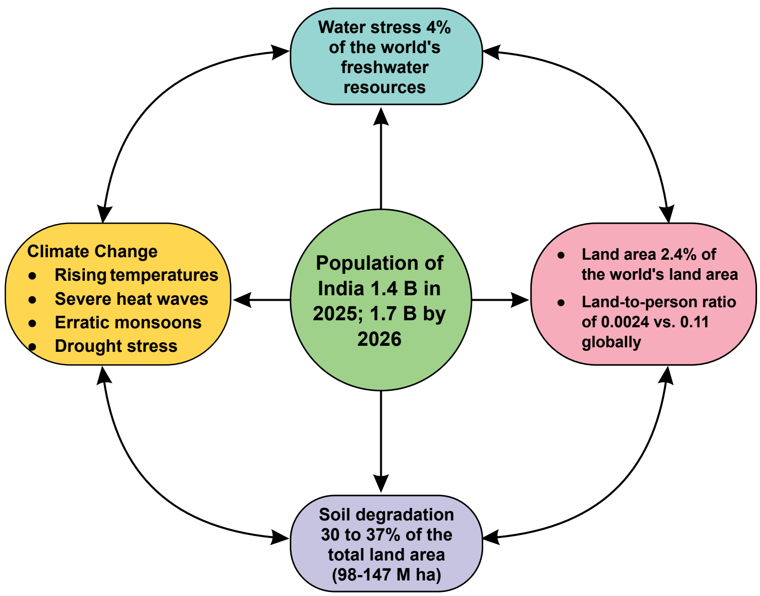

Figure 5. *Population growth coupled with limited resources of land and water: primary drivers of soil degradation*

The serious problem of degradation of soils of agroecosystems in India is driven by rapid population growth coupled with limited land and water resources (Figure 5) which force small land holders and resource-poor farmers to use extractive farming practices.

The resource poor farmers are compelled to maximise production from land without observing the Law of Return. The latter states that whatever resources (i.e., plant nutrients, SOM, water reserves) are taken from land must be returned to the same place by one way or another. Consequently, as much as 45 per cent of India's total area has soils prone to degradation affecting food security of a large number of the population. There are also numerous emerging causes of accelerated soil erosion and desertification (Figure 6).

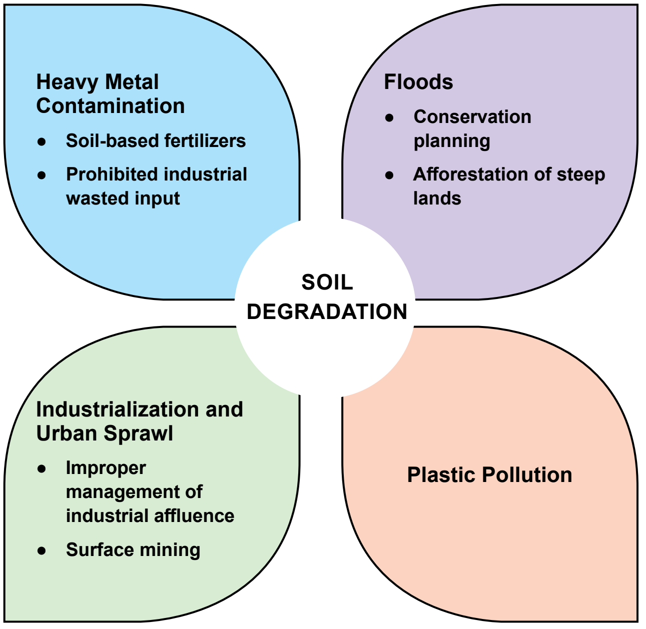

Figure 6. *Emerging causes of soil contamination/pollution and environmental degradation in India*

In addition to erosion, salinization and acidification, loss of SOM content, elemental imbalance, decline in activity and species diversity of soil biota (macro, meso and micro) and soil pollution are prominent factors affecting rate, severity and extent of degradation. The problem of SOM and nutrient depletion, aggravated by accelerated soil erosion, is a severe issue in all ecoregions. It is estimated that about 1 mm of topsoil is lost annually in India due to soil erosion of ~16.4 Mg/ha/yr (Katsir *et al*., 2024). India is losing 5.3 B Mg of soil by erosion annually which is having adverse impact on SOC and nutrient reserves, and on plant available water capacity. Rapid industrialization and land application of industrial wastes are among the major causes of soil pollution and contamination. Plastic pollution has become a serious issue throughout Asia because of the wide spread adoption of plasticulture. Consequently, microplastic has contaminated food systems and potable water resources. Soil degradation and contamination are also the primary causes of low productivity and low nutrient density, and these factors are important determinants of the agrarian crisis in India. Key drivers of soil degradation, inappropriate land use and soil mis-management along with deforestation, are being aggravated by changing and uncertain climate. Indeed, the mutually enhancing effects of soil degradation and anthropogenic climate change are vividly identified in diverse agro-ecoregions of India.

Effects of Soil and Environmental Degradation on Ecosystem Services in India

There are severe adverse effects of soil degradation/pollution on quality of natural resources and on provisioning of ESs (Figure 7). Indeed, agriculture is facing the dual crisis of soil degradation and climate change which are mutually reinforcing processes. Thus, protection, restoration, and sustainable management of soil is a high priority for India. In this context, understanding properties and processes as affected by land use and soil/crop management, is a pertinent and urgent strategy. Indeed, agriculture must be transformed into a part of the solution for climate change to restore and sustain the environment quality (water, air, and biodiversity). Degraded soils reduce productivity and nutritional quality, aggravate volatility, pollute environments, jeopardize asset values, and increase risks of civil strife and political instability.

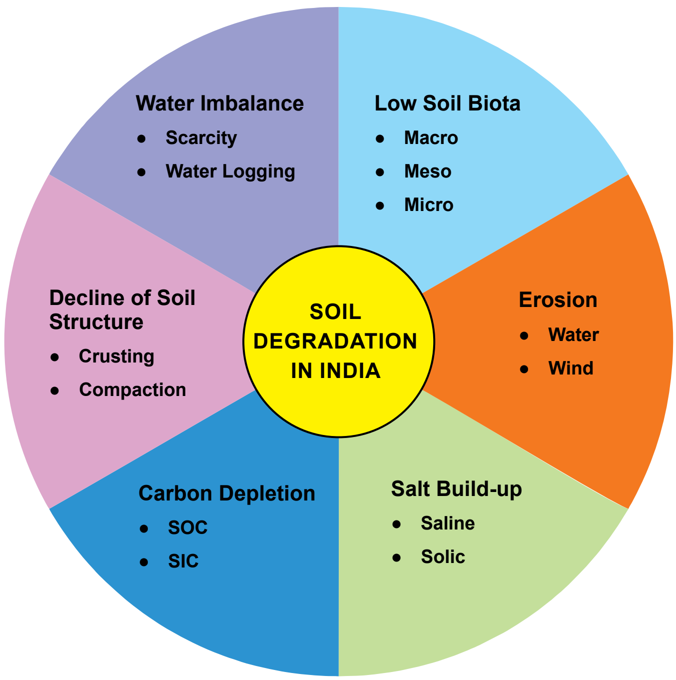

Figure 7. *Adverse effects of soil degradation on the quality of natural resources*

Soils and ecoregions of India are threatened by the growing and increasingly affluent population. Soil degradation, desertification and contamination are severe and widespread problems in India. A large part of India's geographical area is prone to soil erosion (Raj *et al*., 2023), and a large proportion of sloping terrains to landslides (Kadpal, 2023; Agrawal and Dixie, 2024). In addition to traditional soil degradation processes (erosion by hydric and aeolian processes, landslides, salinization, nutrient imbalances) (Bhattacharya *et al*., 2023), soils are increasingly threatened by emerging challenges which are briefly discussed below and outlined in Figure 8. There are several types of soil contaminants/pollutants with adverse effects on ecosphere. These contaminants may originate from natural and anthropogenic sources, and may be either organic or inorganic. Plastic sheet, widely used as mulch in soil and in green house agriculture, has become a serious problem in developing countries, like India. Examples of inorganic pollutants in soil are heavy metals with density of 4 g/cm^3. Important among heavy metals in soil with adverse impacts on human health are Co, Cr, Cs, Cu, Mg, Ni, Sr, Ti, V, and Zn. Examples of organic pollutants in soil are: polycyclic aromatic hydrocarbons (PAHs), oil, hydrocarbons, chlorinated compounds. These are briefly discussed below.

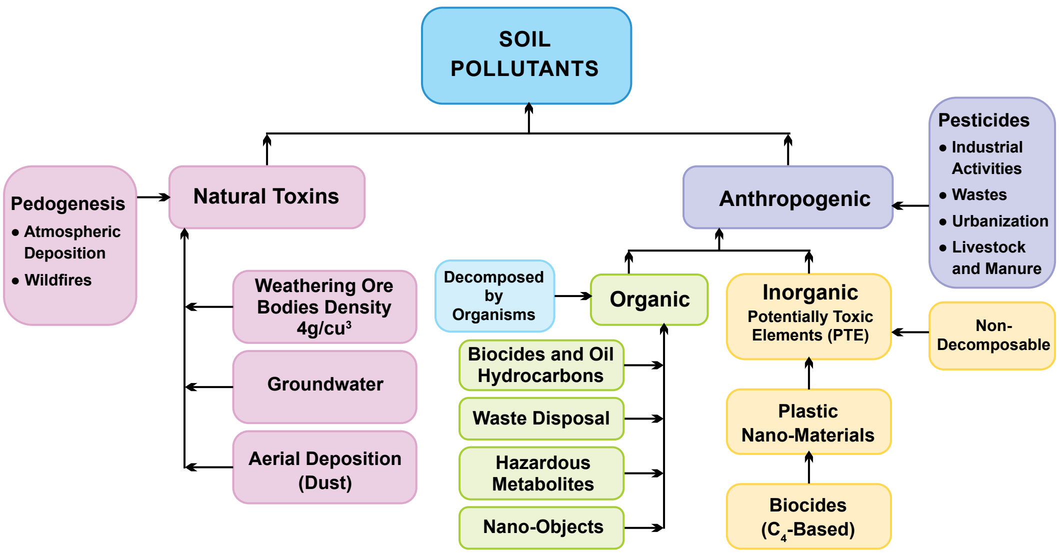

Figure 8*. Soil pollutants and contaminants in agro-ecosystems of India*

(a) Soil Contamination

Contamination of soil by heavy metals is aggravated by land disposal of industrial and urban waste. Commonly observed soil contaminants include heavy metals (Cr, Fe, Cu, Mn, Co, Ni, Pb, Zn, Cd) as well as excessive concentrations of some macronutrients (Ca, Mg). A study on coconut fields by Sreejamol *et al*. (2026) exhibited increase in contents of Cd, Pb, Zn, and Cr from contaminated fertilizers and agro-chemicals, and suggested soil-specific fertilization. Flooding/inundation can also cause contamination of soil and water, especially by urban pluvial floods (Singh *et al*., 2023). Surface mining, along with disposed coal mine spoil (Singh and Kumar, 2022) due to inversion of soil profiles, are among major causes of soil contamination.

(b) Plastic Pollution

Plastic pollution has become a major issue globally and especially in India (Vithanage and Prasad, 2023; Karwadiya *et al*., 2025; Do Costa *et al*., 2026; Uddin and Zaman, 2026). On the farmland, plastic is used for mulch, irrigation tubing, seedling trays, and bags for storage. The growing practices of "plasticulture" is a major cause of contamination of farmland soils including micro and nano-plastics (Figure 9).

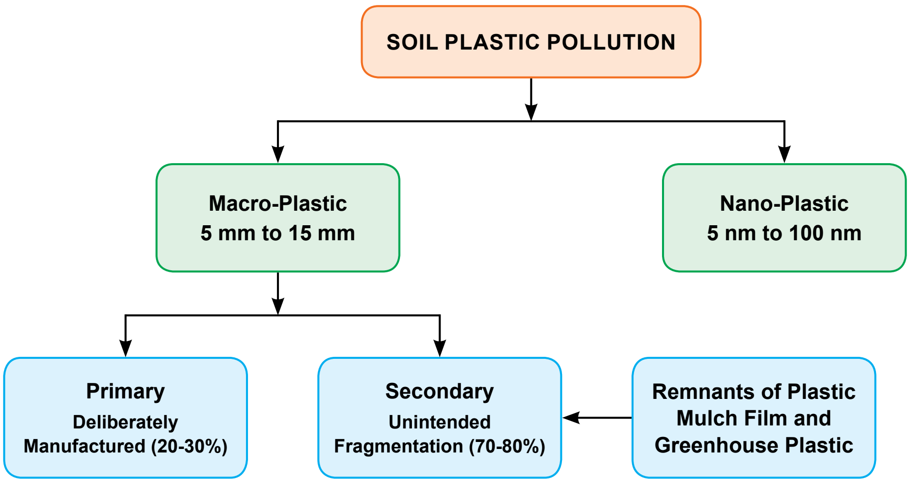

Figure 9. *Soil plastic pollution by macro and nano-plastics*

Nano-plastics (<100 nm) can be absorbed by plant roots, enter into the food chain, and cause severe adverse effects on soil and human health (De Souza Machado *et al*., 2018; Gigault *et al*., 2018). Thus, plastic use in agro-ecosystems should be kept on a tight leash (Holmberg and Presson, 2023). Despite its short-term benefits on water conservation and moderation of soil temperatures, its long-term effects on environmental pollution is a serious global issue of the present era. The microplastic, because of in-field decomposition over time, enters the water system and food chain with adverse effects on human health and wellbeing. There is a strong need for regulation of plastic use on soil as mulch and for other on-farm purposes. Asia uses about half of the 12.5M Mg of plastic used globally of which the amount of plastic use in India is a significant part. India generates about 5.6M Mg of plastic wastage annually across all sectors including agriculture. The use of plastic has with adverse effects on soil health including absorption of heavy metals (Pb, Cu, Cr, Cd, Co, As, and Zn).

(c) Soil Organic Carbon Depletion

The SOC content in the root zone has a significant effect on soil functions and its ESs (Paramesh *et al*., 2022). An optimal range of SOC content for typical soils of the humid tropics may be 1.0 to 1.5 per cent in the surface layer. Soils of most agro-ecoregions of India are depleted of their SOC stock especially in the root zone (0-30 cm layer) where SOC content can be <0.5 per cent by weight. In this regard, soil texture is an important determinant of SOC stock (Binsiya *et al*., 2024). Soil is like a bank account, and in this case, soil C stock is the currency. For the bank balance to increase, the influx (the amount deposited) of the currency (biomass-C) must exceed that of the efflux (the amount withdrawn). In soil, the amount withdrawn is *via* decomposition, erosion and leaching. Therefore, increasing the soil C currency necessitates that the addition of biomass C exceeds that of the losses by decomposition, erosion and leaching. In this context, long-term studies on SOC balance under on-farm conditions are of critical importance.

Ecosystem Services Strengthened by Restoration of Soil Organic Matter Content

The SOM content, the elixir (recipe) of life and heart of soil health, is critical to maintaining soil function, which strengthens key ESs for human and nature (Figure 10). Indeed, restoration of SOM content in degraded and depleted soils of India can be achieved by a holistic and integrated approach which creates a positive soil/ ecosystem C budget. The strategy is to produce more from less via enhancement of eco-efficiency and increasing influx of biomass C into the soil, and by reducing losses (efflux) of soil carbon stock into the environment by accelerated erosion,

Figure 10. *Management of soil organic matter: the elixir of life and heart of soil health*

decomposition by supra-optimal soil temperatures and leaching with excessive irrigation or high precipitation. Some examples of the positive effects of restoring SOC content on provisioning of ESs are outlined in Table 2.

Table 2. Some examples of strengthening ecosystem services by upscaling of proven practices which restore soil organic carbon content in major agro-ecoregions of India

Site/Region	Cropping/ Farming System	Response		Plant Nutrients	Reference
		SOC	Aggregation		
Southern India	N does and cropping systems irrigation	+	+	NA	Kumari *et al.* (2025)
South Asia	Cropping systems + C stabilization	+	+	NA	Roy *et al.* (2024)
Semi-Arid Savanna Grasslands (SGs)	Age of grass planting	+	NA	NA	Bhan *et al.* (2025)
Central India (MP)	Residue burning	+	NA	+ (k)	Lenka *et al.* (2014)
Central India (Vertisols)	Conservation agriculture (CA)	+	NA	+ (N)	Raghuwanshi *et al.* (2025)
Indo-Ganjectic Plains (Haryana)	Conservation agriculture (CA)	+	+	–	Dash *et al.* (2022)

Increases in SOC stock are associated with use of N fertilizer, supplemental irrigation and duration of grass planting. Residue burning, an environmentally-negative practice, can lead to increase in availability of potassium (K) and other plant nutrients along with availability of water in the root zone (Lenka *et al.*, 2014). The response to conservation agriculture with residue retention on diverse soils and crops of India is given in Table 3.

The overall improvement in soil health by restoration of SOC content can also have a positive effect on human health especially in low-income countries such as India. Kishore (2023) observed that high level of SOC content can significantly reduce the negative impact of rainfall shock on children's weight-for-height z-scores but not on height-for-age z-scores (Kishore, 2023). Children's weight-for-height z-scores measure how many standard deviations a child's weight is above or below the average weight of children of the exact same height and sex. Climate-resilient practices (a scientifically pertinent term rather than the popular term of climate-

Table 3. Response to conservation agriculture with residue retention on diverse soils and crops of India

Site/Region	Cropping System	Crop Yield CA vs. CT	SOC Content CA vs. CT	Reference
Hilly Ecosystems, NE	Maize-Mustard	+	+	Saha and Gosh (2013)
Hill Region	Groundnut-based	+	+	
Semi-Arid	Diverse crops	+ -	+	Srinivasarao *et al.* (2012)
Sub-Continent	Rice-Wheat cropping system	+	+	Padhbushan *et al.* (2024)
Indo-Genjetic Plains	Rice-Wheat cropping system	+	+	Leharwan *et al.* (2023)
West India	Rice-Wheat cropping system	+	+	Kumar *et al.* (2022)
Western Uttar Pradesh (Sub-Tropical)	Rice-Maize-Rice			Naresh *et al.* (2016)
Orissa, East India	Rice-Fallow-Rice			Mandal *et al.* (2014)
Semi-Arid Region/ Cambial	Maize-Wheat-Cowpea (balanced application of NPK)			Kanchikerimath and Singh (2001)

smart management) have to be carefully selected for specific soil, topography, land use, and climatic factors during the growing season. Commonly used climate-resilient practices, also outlined in Table 2, are system-based conservation agriculture (CA), integrated soil fertility management, and complex farming systems based on integration of crops with trees and livestock. Recycling of biowaste, farm by-products such as residues of crops and animals, is pertinent to promoting climate-resilient agricultural practices. Some examples of strengthening of ESs by increasing SOC content in diverse soils of agro-ecoregions shown in Table 3 indicate improvement in productivity under site-specific conditions.

Ecosystem Services Strengthened by Increase in Soil Inorganic Carbon

Soil C stock has two related but different components (SOC content discussed in the above paragraph) and soil inorganic carbon (SIC) content. Whereas the SOC content is more in soils of cool and humid regions, the SIC stock is more in soils of warm and arid/semi-arid climates. The SIC stock, not as widely studied as that of SOC stock, is an important component of the global C cycle. It is a major part of the total C stock in arid and semi-arid ecoregions. In top 2 m depth, SIC stock in global soils may be 2305 ± 636 Pg C (Pg or petagram=10^{15} g = billion metric ton) over 2 m depth. Despite its important role in the global C cycle and flux from soil into the environment, the impact of SIC dynamics on climate change, quality of water resource, and impacts on soil processes and properties is being overlooked and not receiving the attention that it deserves. One of the reasons of relatively low scientific attention to SIC is the perception that it is rather inert. However, recent research has shown that SIC is affected by land use and soil management especially by fertilizer use, plowing and irrigation. In contrast to the positive effects of increase in SOC stock on soil health and agronomic productivity, formation of pedogenic carbonates leading to an increase in SIC stock can be a bane and degrade some soil functions chemically (Bhattacharya, 2024).

The SIC stock is negatively affected by acidification with input of nitrogenous fertilizers which may reduce the global SIC stock by 23 Pg C between 2024 and 2054 (30-year period), and soils of India and China will be greatly affected by the decline of SIC stock (Huang *et al*., 2024). Furthermore, as much as 1.13 ± 0.33 Pg of SIC stock is lost annually from soils to inland waters. In Bikaner (Rajsthan), Moharana *et al*. (2021) assessed the SIC stock of 187 soil profiles. The SIC content ranged from 0.27 to 27.85 g/kg in 0-5 cm depth, 0.31 to 27.84 g/kg in 5-15 cm depth. Further, SIC content varied strongly because of differences in annual precipitation and precipitation seasonality in soil below 30 cm depth. A study in Tamil Nadu showed that SIC content ranged from 0.3 to 20.1 g/kg and, in some cases, increased with increase in soil depth. Increase in SIC content can also improve SOC content because of the potential stabilization of SOC by Ca from SIC in soils under silvo-pastoral systems (Lalitha *et al*., 2022). A study conducted in semi-arid forests of northwest India showed that the highest SOC stock in 0-10 cm and 10-20 cm depth was observed during winter (22.81 Mg C/ha) and the lowest during the monsoon season (2.34 Mg C/ha). The rate of SOC sequestration ranged between 0.046 and 0.741 Mg C/ha/yr compared with that of SIC between 0.013 and 0.023 Mg C/ha/yr to 20 cm depth (Tomar and Baishya, 2020). Similar to SOC content, SIC content can also be increased by adoption of CA (Dey *et al*., 2020).

There is a strong relationship between SOC and SIC and these two are mutually-reinforcing components of total soil C stock. For example, increase in secondary carbonates can enhance formation of soil aggregates which encapsulates and protects SOC and increases its mean residence time (MRT). Improvement in soil structure by carbonates also has positive effects on total porosity and pore size distribution with strong effects on water infiltration rate, soil water storage in the root zone and in creating a drought resistant soil. Some examples of the effects of land use change and management practices on SIC content and soil functions are outlined in Table 4.

Table 4. Effect of land use and management practices on soil inorganic carbon in India

Site/Region	Management	Response		References
		SIC	Soil Functions	
Tropical Dry Evergreen Forest (Tamil Nadu)	Agroforestry	+	NA	Rieder *et al*. (2025)
Tropical India	Climate-smart soils	NA	-	Battacharya (2024)
Karnataka	Clay content	+	NA	Mitran *et al*. (2021)
Vertisols of Central India	Conservation agriculture	No effect	+	

However, it is important to note that research on SIC dynamics in relation to land use and management has not been given the attention that it rightfully deserves. Dynamics of both SOC and SIC stocks must be studied on the same long-term land use and soil management experiments in diverse agro-ecoregions of India.

Potential of Conservation Agriculture

Anthropogenic climate change (ACC) is becoming an increasing important determinant of soil functions/health, use efficiency of inputs, and agronomic productivity. It is widely reported that overall crop productivity may decrease in India by 17 per cent in cotton and 30 per cent in sugarcane (Rajath *et al*., 2023) along with that of wheat and other crops. It is precisely in this context the adoption of CA is timely and appropriate.

A system-based CA, involving integration of site-specific attributes (soil type, terrain, climate, etc.) with climatic and ecological parameters, can reduce adverse effects of ACC by maximizing efficiency and sustaining productivity (Kumbhar *et al*., 2024; Khokar *et al*., 2022). Whereas there has been a drastic increase in the input of chemical fertilizers, use of organic nutrient sources (compost, manure, use of biological N fixation, mycorrhizae and other biofertizers) can also lead to economic sustainability and yield optimization (Tania *et al*., 2024). Adoption of CA can also enhance activity and species diversity of soil biota, especially that of earthworms (Cremonesi *et al*., 2021; Tiwari and Joshi, 2023), ants (Chate, 2022) and termites (Bera *et al*., 2020). Soil biota are considered as ecosystem engineers because of their major role in bio-transformation and modifications of soil functions. Strengthening soil biota, with long-term adoption of a system-based CA and complex crop rotations, which enhance soil biodiversity, can have a significant and positive effect on the edaphic factors of the agro-ecosystems by improving soil structure and nutrient availability. Adoption of CA can also enhance water retention and nutrient availability by restoring SOC content (Yadav *et al*., 2021) including those of Vertisols in central India (Yadav *et al*., 2021). Activity and species diversity of soil biota (i.e., microbial activity) is enhanced by long-term use of organic manure (Majhi *et al*., 2021). Field experiments by Bhattacharyya *et al*. (2025) showed that adoption of CA produced 5.17 Mg/ha of rice.

Management of Soil Health as a Source of Wealth for Small Landholder Farmers

The term soil health refers to its capacity to generate critical ESs for human and nature. In addition to soil biological properties, soil health is also determined by some key physical, chemical, and ecological properties. The soil health status affects sustainability of soil use and agro-ecosystems dependent on it. Sustainable management of soil health is the foundation for economic development, environment quality, and wellbeing of communities. Thus, protection, restoration, and sustainable management of soil health by innovations and emerging concepts is a need of the hour. India's Soil Health Card (SHC) scheme was launched in 2015 through use of site-specific fertilizer use (Timilsina *et al*., 2025) to advance food security for future generations (Khambalkar *et al*., 2025) and reduce reliance on chemical fertilizers. However, soil health is a dynamic property and varies among seasons because of changes in Glomalin-related soil protein and other properties e.g., Abruscular Mycorrhizal fungi and Ergasterol and other bio-indicators (Bhattacharyya *et al*., 2025). Some basic principles and techniques of managing problem soils of India are outlined in Table 5.

Readers are also referred to extensive literature available at ICAR institutions on management of different types of degradation. The ICAR has done a commendable and an exemplary task of establishing and sustaining high class research /education/extension centers for assessment and management of each of these soil degradation problem.

Table 5. Basic concepts and techniques to restore and manage degraded soils of agro-ecosystems of India

Soil Degradation	Basic Concept	Techniques
1. Soil Fertility	• Integrated nutrient management (INM) • Observe law of return	• Compost manure • Micronutrient inputs • Biofortification • Inorganic fertilizers • Precision farming
2. Erosion Control	• Maintain soil cover • Reduce runoff • Enhance soil structure • Manage slope	• No-till farming • Cover cropping • Mulch cover • No burning of residue • Land forming and terraces • Farm ponds • Wind breaks
3. Acidity	• Enhance soil buffering capacity • Restore SOC content	• Judicious use of N fertilizer • Liming • Organic amendments
4. Drought	• Conserve soil water • Manage soil temperature • Improve soil structure • Enhance water infiltrability	• Drought-tolerant crops • Conservation agriculture • Drip sub-irrigation
5. Salinity/Sodity	• Create negative salt budget • Good quality irrigation water • Drainage • Manage groundwater level	• Salt-tolerant crops • Leaching • Use of organic amendments
6. Soil Pollution/ Contamination	• Avoid use of city sludge and urban waste • Judicious use of fertilizers • Soi test-based fertilizer rate	• Bio-remediation • Ban plastic mulch • Ban application of plastic • Replace fertilizer subsidies with payments for ESs

Adoption of INM is also a pertinent option to manage soil health under rice cultivation in the Indo-Gangetic Plains (IGP) (Chhetri *et al.*, 2025). In accordance with the “One Health” concept, sustainable management of soil health is also important to enhancing human health. In this context, availability of soil micronutrients is critical to human health and wellbeing. A study by Morton *et al*. (2023) linked health data from 0.3 million children and one million adult women across India with over 27 million soil tests from a nationwide health program. The study showed that soil Zn is positively correlated with children's height, and soil Fe availability with hemoglobin levels. Morton and colleagues observed that robust-9 one standard deviation increase in satisfactory soil Zn tests is associated with approximately 11 fewer children stunted per 1000. These authors concluded that agronomic fortification may be a beneficial intervention.

A study conducted in two agro-climatic zones of Haryana, India showed that farmers are aware of the benefits of INM, integrated farming systems, and organic farming. However, major constraints include high fertilizer costs, and handling of the large bulk mass of manure.

Managing Soil Carbon Stock

As stated above, soil C stock has two related components: SOC and SIC. The SOC is more in cold and humid regions and SIC in arid and warm regions. The SOC stock in soils of India's agro-ecosystems is depleted because of long-term use (millennia) of extractive and plow-based farming systems. Among numerous innovations, adoption of CA is gaining momentum. Padbushan *et al.* (2024) observed that SOC content increased with CA than conventional tillage.

SOC Stock

Increasing SOC stock leads to observable beneficial effects on agronomic productivity and use efficiency of inputs. Legume-based cropping systems, including forages and cover crops, are known to enhance soil health by improving SOC content. Furthermore, legumes (pulses) also produce protein-rich grains and have capacity of biological nitrogen fixation (BNF) and lead to soil ecology improvement (Sharma *et al*., 2025)

Some examples of ecoregion and soil-specific practices with mostly positive (+) effects on crop yield and SOC content are listed in Table 4. In general, adoption of a system-based CA in conjunction with complex crop rotations and INM have a positive effect on SOC content and agronomic yield. It is also important to note that in addition to CA, long-term use of INM (NPK along with manuring) is also important to restoring SOC content and improving crop yield (Ram *et al*., 2016; Sharma *et al*., 2025). While CA is beneficial in diverse soils and ecoregions, continuous tillage and cropping can be useful for physical and chemical restoration of sodic soils (Singh *et al*., 2016). Thus, there is no "one size fits all" situation.

With soil/site-specific adaptation, CA can be used on a wide range of soil environments and crops in India. In addition to alluvial soils of the Indo-Gangetic Plains and other river basins, CA is also proven to produce acceptable agronomic yields on Vertisols of central India. The key is availability of suitable machinery to cut through the residues of previous crops. An experiment conducted by Kumawat *et al.* (2022) showed that after four years of CA adoption, the SOC and labile C fractions were increased by 13.6 to 61.7 per cent and 6.0 to 22.0 per cent, respectively, in 0-10 cm depth. Furthermore, CA with residue retention also increased $KMNO_4$-N, Olsen-P, NHOAC-K, and total fungal and actinomycetes density in surface soil.

Nonetheless, it is important to note that adoption of CA may also reduce crop yield during the initial years. A meta-analysis by Padbhushan *et al*. (2024) showed that in a long-term study, yield reduction was observed from 2009-2016 but an increase from 2017 to 2020. Furthermore, sandy loam and clayey soils exhibited higher crop yield under CA than that under conventional tillage (CT), while SOC content and C sequestration under CA increased by 8.9 and 7.3 per cent, respectively. Padhbushan and colleagues concluded that promotion of CA in India may have to be location-specific taking into consideration the crops and climate conditions. In some soils under rice-wheat systems, Leharwan *et al*. (2023) observed that residue retention by using mulcher with a Happy Seeder can ensure crop productivity and production sustainability of rice-wheat (RW) system in Haryana, India. Similar results were reported by Kumar *et al*. (2022) who observed that compared with the farmer's practice, the total global warming potential (GWP) of the RW system was reduced by 43 per cent with CA-based management and that direct seeding of rice and CA in wheat with full residue retention improved SOC content and nutrient availability in soil. Residue retention with CA is critical to enhancing SOC stock.

The Way Forward

India has observed remarkable economic growth during the decade from 2014 to 2025 during which period its GDP has more than doubled from $2 trillion to $4.8 trillion. The 105 per cent growth in GDP is the fastest in the world. India has moved from the 10th place to 4th place in global ranking and is projected to be in the 3rd place in 2026-2027 fiscal year. In comparison with the overall annual growth of 6 to 7 per cent, growth in agricultural sector of approximately from 4.4 to 4.6 per cent per year can and must be increased to reduce rural poverty and enhance the wellbeing of rural population. However, the growth of the agricultural sector is strongly determined by numerous factors including increase in crop yield and bridging the yield gap, crop diversification, value addition, improving market and above all restoring and sustaining soil health in conjunction with that of the water and nutrient reserves in the root zone which are dependent on the soil C dynamics and its sustainable management. This is the time to adopt innovations in agriculture aimed to transforming it into a solution to improving the environment while meeting the food demands of the growing and increasingly affluent population (Figure 11).

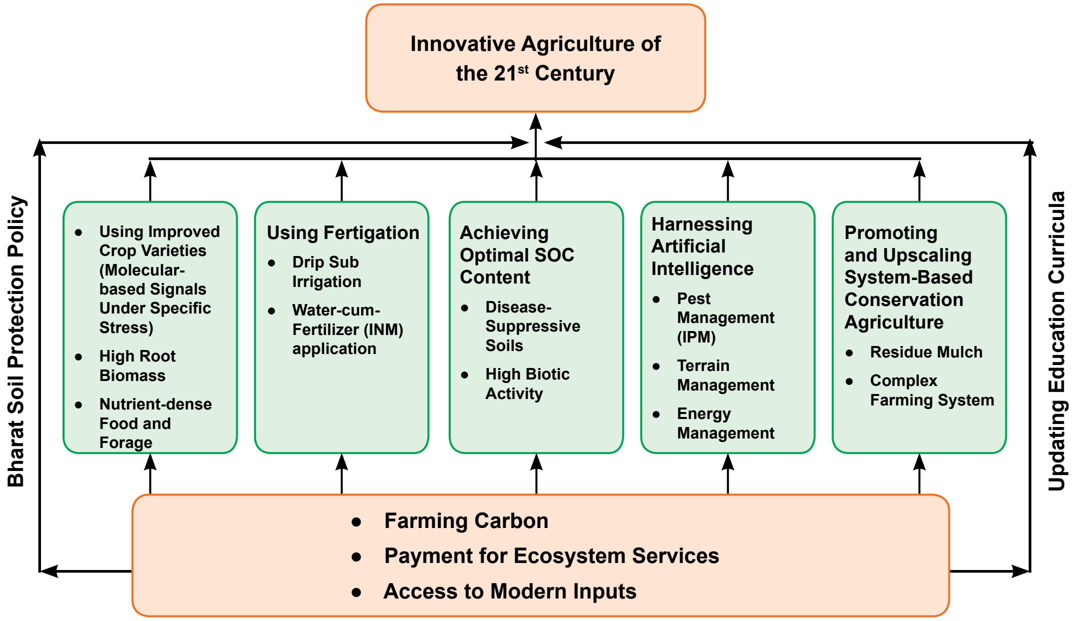

Figure 11. *Transforming Indian agriculture through innovation, sustainable soil management and effective technology transfer*

Degraded soils must be improved, depleted SOC content restored and soil health enhanced. A high priority must be given to restoration and sustainable management of soil health as determined by its SOC content and its effects on soil physical, chemical, biological and ecological processes.

There is a strong need to address processes, causes, factors and policies of all forms of soil degradation, Predominant processes include low soil fertility, accelerated soil erosion, acidification, drought, salinity /sodicity and soil pollution/ contamination. Plastic pollution has emerged as a major soil and environmental issue in India as elsewhere. Most of these problems are caused by land misuse and soil mismanagement. Therefore, judicious land use, based on land capability assessment and planning are critical strategies to reduce risks of soil degradation. Soil contamination and pollution, an emerging and serious problem, is caused by land application of urban/industrial waste which contains high concentration of heavy metals (e.g. Pb, Hg, As, Cr). Some fertilizers also contain heavy metals. Poor management of groundwater in the Indo-Gangetic alluvium has aggravated the problem of As buildup in soil, water, crop plants and food grains (e.g. rice).

India has made commendable progress in enhancing food grain production. However, for a complete and wholistic development, similar advances must be made in sustainable management of soil resources. It is also important to realize that the yield potential of improved varieties can be achieved only through restoration and sustainable management of soil health. Thus, some new and innovative strategies suggested include:

- ***Carbon Farming*:** Growing carbon rich crops can strengthen food security while improving the environment quality and generate additional income stream for farmers. Farmers must be rewarded for payment of ESs they provide through restoration and enhancement of soil C stock, especially the SOC content.
- ***Upscaling Conservation Agriculture*:** Plow tillage must be replaced with system-based approaches (no-till, residue mulching, forages and cover crops, diversified crop rotations, and integrated soil fertility management) by following a 10-year soil restoration and soil health plan. Since restoring SOC content is a slow process operating at decadal or generational time scale, adoption of CA should be accorded a high priority.
- ***Promoting Drip Fertigation*:** Drip fertigation, combination of fertilizer and irrigation with drip system, must be promoted to enhance use efficiency of water and fertilizer and reduce the water use for irrigation while expanding the area equipped for irrigation. India's total agricultural area equipped for irrigation is among the largest in the world. Current statistics indicate a net irrigated area of approximately 79.3 M ha and a gross irrigated area of over 122 M ha. Thus, nearly 55.7 per cent of India's gross cropped area is irrigated. However, water use efficiency must be improved.
- ***Producing More from Less*:** The Green Revolution of the 1960s was based on intensive use of inputs including chemicals and irrigation. Because of the severe problem of soil degradation, the use efficiency of the inputs (e.g. nitrogen, irrigation water) is low. Thus, producing more from less inputs, an important and innovative option, should be promoted by increasing the use efficiency and reducing losses of inputs into the environment.
- ***Adopting Nutrition-Sensitive Agriculture*:** Adopting nutrition-sensitive agriculture is the need of the present era for India and elsewhere in the developing world because of the severe and widespread problem of malnutrition

and hidden hunger. The issue of malnourishment is even more serious than that of undernourishment. Improvement and sustainable management of soil health is pertinent to address this issue by promoting the "One Health" concept or the interconnectedness based on protection, restoration and sustainable management of soil health for improving the nutrient density of food and forages.

- ***Promoting Forgotten/Orphan Crops*:** The Green Revolution of the 1960s, being cereal-centric, was focused on improving the yield of three crops (e.g. rice, wheat, corn). Not only did the increase in yield caused the dilution effect by reducing the concentration of 17 micronutrients essential for human health (along with protein, vitamins, etc.) but it also caused an adverse impact on soil and environment. The problem of malnutrition has been aggravated by ignoring the traditional grain crops (millet, sorghum, chickpea, mungbean, pigeonpea, urd, and others). Omitting leguminous crops in the rotation cycle depleted the soil fertility, degraded soil structure and reduced activity and species diversity of soil biota. Thus, these native crops must be given the attention that they deserve for the sake of restoring soil health and addressing the problem of human malnutrition.
- ***Adopting Bharat Soil Health Policy*:** The Indian Council of Agricultural Research (ICAR), Trust for Advancement of Agricultural Sciences (TAAS) and Isha Foundation has taken a historic initiative towards developing Bharat Soil Health Policy. Once approved and implemented by the Government of India at all levels (district, state, national), this policy has the potential to position India to demonstrate the leadership role at regional and global levels in transforming agriculture and addressing issues of national and regional importance.
- ***Rewarding Farmers* via *Payments for Ecosystem Services*:** One of the important policies to divert subsidies (irrigation, N fertilizers, procurements, etc.) is the concept of payments for ESs. Farmers who adopt BMPs and restore soil health by increasing the terrestrial C stock (soil and trees) must be rewarded. Farmers must be rewarded on the basis of the "Social Value of Soil Carbon", which is to be established by researchers (soil scientists, agronomists, economists and social scientists) for diverse soils and ecosystems.
- ***Revising the Education Curricula*:** Study of soil properties and processes must be included in curricula at school, college and advanced education levels. Primary school books, with focus on soil/environment and food systems, must be written in major languages of India so that children understand the importance of soil resources from the very young age. This is also an important

strategy of attracting the best and the brightest students to the soil and agronomy profession. The One Health concept, linking health of soil to that of plants/animals and people, must be taught in colleges of medicine and public health.

- ***Banning In-Field Burning of Crop Residues*:** In-field burning of crop residues must be banned with immediate effect. A judicious use of crop residue is indispensable to recycling plant nutrients, conserving soil and water, enhancing activity and species diversity of soil biota and sustaining soil health. No one should be allowed to burn the precious resource.
- ***Banning Flooded Paddy Rice Cultivation*:** Flooded paddy rice is a wasteful use of water. The modern system cultivation is aerobic rice grown in a manner similar to that of wheat and other upland cereals. While there may be a small reduction in agronomic yield during the initial 2 to 3 years, farmers should be compensated for saving water through payments for water credits.
- ***Enhancing Respect for the Farming/Agriculture Profession*:** The importance of soil and environment is directly related to the respect given by a society to the farming and agricultural profession at all levels: farmers, extension agents, researchers. This is a societal problem because the modern civilization has lost contact with nature in general and soil in particular.

Indian agriculture has a bright future ahead. Growth of the agronomic sector must also be improved to be equal to those of other sectors. The technical potential of producing 550 M Mg of food grains per year can be realized within the next 25 years (2050) by restoring soil health and giving the respect to the farming profession that it rightfully deserves.

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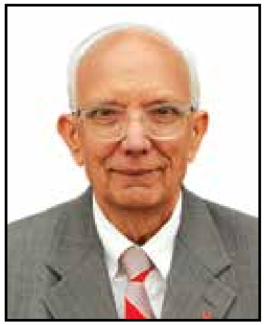
Brief Resume



Prof. Rattan Lal, Ph.D. is a Distinguished University Professor of Soil Science and Director, CFAES Rattan Lal Center for Carbon Management and Sequestration at The Ohio State University. He received a B.S. from PAU, Ludhiana (1963); M.S. from IARI, New Delhi, (1965); and Ph.D. from the Ohio State University (1968). He was Senior Research Fellow at the University of Sydney (1968-69) and Soil Physicist at IITA, Ibadan, Nigeria (1970-87). He has authored/co-authored over 1145 refereed journal articles, more than 590 book chapters, and has written and edited/co-edited more than 100 books. He was ranked #1 globally and in the U.S. among Agricultural Scientists (Plant Scientists and Agronomists) of the world by Research.com (2023, 2024). He has received an *Honoris Causa* degree from nine universities in Europe, USA and Asia; the Medal of Honor from UIMP, Santander, Spain (2018); the Distinguished Service Medal of IUSS (2018); and is the Fellow of the five professional societies. Dr. Lal has mentored over 430 professionals from 60 countries. He was President of the WASWAC (1987-1990), ISTRO (1988-1991), Soil Science Society of America (2006-2008), and the IUSS (2017-2018). He is Co-Chair of the Coalition for Action on Soil Health (C4SH). He was a member of the BIFAD in the Department of Agriculture (2022-2025) and Chair of the SAB/SERDP in the Department of Defense (2023-2025). Dr. Lal is laureate of the GCHERA World Agriculture Prize (2018), Glinka World Soil Prize (2018), Japan Prize (2019), U.S. Awasthi IFFCO Prize (2019), Arrell Global Food Innovation Award (2020), World Food Prize (2020), India's Padma Shri Award (2021), Mahatma Ghandi Award for Environmental Protection (2022), and the Gulbenkian Prize for Humanity (2024). He donated funds to establish an Endowed Professorship at The Ohio State University and launched an international Scholar Exchange Program among his three alma maters.

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