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Soil Restoration: A Generational Imperative for a Green Future

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Abstract: -

Soil is the foundation of food production, climate regulation, water security and biodiversity, yet it is being degraded faster than it can form. Roughly one-third of the world's soils are already degraded, and India alone reports nearly 98 million hectares under land degradation. This article reviews the global and Indian status of soil degradation, outlines its consequences for food, climate and water systems, discusses evidence-based restoration strategies, and examines future prospects, including policy frameworks, carbon markets and precision technologies, that can make soil restoration the defining agricultural mission of this generation.

Keywords: *soil degradation, soil organic carbon, restoration, conservation agriculture, legume-based systems, sustainable development etc.*

1. Introduction:

Soil is a living, finite and slowly renewable resource. Formation of 1 cm of topsoil may take from a hundred to several hundred years, depending on climate, parent material and vegetation, whereas a single intense monsoon season on a bare, sloping field can remove it in a fraction of that time. More than 95% of our food is produced directly or indirectly on soil, and the Food and Agriculture Organization (FAO) has described soil as the basis of nearly all terrestrial life (FAO and ITPS, 2015).

The twenty-first century has placed a double burden on this resource. By 2050 the global population is projected to approach 9.7 billion, raising food demand by an estimated 50-60% over 2012 levels, while the land available to meet it is shrinking in quality and, in many regions, in quantity. Earlier generations were tasked with expanding

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production. The present generation must increase production while repairing the resource base that supports it. This is the central argument of this article: soil restoration is no longer an optional conservation activity but a prerequisite for food security and a green future.

2. Status of Soil Degradation

2.1 Global scenario

The *Status of the World's Soil Resources* report estimated that about 33% of global soils are moderately to highly degraded through erosion, nutrient depletion, acidification, salinization, compaction and chemical pollution (FAO and ITPS, 2015). The UNCCD *Global Land Outlook* (2022) reports that up to 40% of the planet's land is degraded, directly affecting about half of humanity. Estimates of erosion losses reach approximately 24 billion tonnes of fertile soil each year, and the associated economic loss runs to hundreds of billions of US dollars annually through reduced productivity and ecosystem services.

2.2 Indian scenario

India supports about 17% of the world's population and 15% of its livestock on only 2.4% of global land area, which places exceptional pressure on its soils. The Desertification and Land Degradation Atlas of India (ISRO-SAC, 2021) reported that 97.85 million hectares, about 29.7% of the total geographical area, was under land degradation during 2018-19. Water erosion is the largest single process, followed by vegetation degradation and wind erosion. Soil loss through water erosion has been estimated at over 5 billion tonnes annually.

Fertility indicators are equally concerning. Large areas of the Indo-Gangetic Plain have soil organic carbon (SOC) below 0.5%, which is considered the threshold for a productive soil in tropical conditions. Widespread deficiencies of nitrogen,

Table 1. Selected indicators of soil degradation

Indicator	Estimate	Source
Global soils moderately to highly degraded	~33%	FAO and ITPS (2015)
Global land degraded	up to 40%	UNCCD (2022)
Fertile soil lost to erosion globally	~24 billion t per year	UNCCD
India: area under land degradation (2018-19)	97.85 Mha (29.7% of TGA)	ISRO-SAC (2021)
India: water-erosion soil loss	> 5 billion t per year	Sharda and Ojasvi (2016)
Nitrogen use efficiency, Indian cereals	often < 40%	Multiple field studies

Note: *Figures are rounded and should be checked against the latest editions of the cited sources before use in a formal manuscript*

phosphorus and zinc, with increasing sulphur, boron and iron deficiencies, have been documented. Nitrogen use efficiency in Indian cereal systems is frequently reported to be below 40%, meaning that more than half of the applied nitrogen is lost to leaching, volatilization and denitrification. This is both an economic loss to the farmer and an environmental burden.

3. Why Soil Restoration Matters

3.1 Food and nutritional security

Degraded soils directly depress yield. Meta-analyses and regional assessments indicate that crop yield losses from soil degradation may range from a few percent to more than 20% in severely affected areas, and that increasing SOC in the root zone by 1 t/ha can improve yields of cereals and legumes by measurable margins in degraded tropical soils **(Lal, 2006).** Soil health is also linked to the nutritional quality of food, as micronutrient availability determines the zinc and iron content of grain and, ultimately, human dietary status.

3.2 Climate change mitigation and adaptation

Global soils hold roughly 1,500-2,400 Gt of organic carbon in the top 1-2 metres, which is more than the atmosphere (about 850 Gt) and terrestrial vegetation (about 560 Gt) combined. Historical land use has already released an estimated 133 Gt of carbon from soils. Lal (2004) estimated that restoring degraded and desertified soils could sequester 0.4-1.2 Gt of carbon per year globally. The *4 per 1000* initiative, launched at COP21, proposed that an annual 0.4% increase in soil carbon stocks could offset a substantial share of anthropogenic greenhouse gas emissions, although later analyses suggest that its realistic contribution is smaller and varies by region (Minasny et al., 2017). Even so, SOC gain is a rare win-win: it mitigates emissions and simultaneously improves resilience to heat, drought and erratic rainfall.

3.3 Water security

Soil with good structure and organic matter acts as a sponge. Each 1% increase in SOC can raise plant-available water-holding capacity appreciably, which is a decisive buffer in rainfed regions where nearly 50% of the net sown area of India depends on monsoon rainfall. Improved infiltration reduces runoff, flash floods and siltation of reservoirs, and promotes groundwater recharge.

3.4 Biodiversity and ecosystem services

Soil is one of the most biodiverse habitats on Earth. A single gram of fertile soil may harbour billions of bacteria, thousands of fungal and protozoan species, and a complex community of nematodes, earthworms and arthropods that drive decomposition, nutrient cycling and disease suppression. Practices that

damage this community, such as excessive tillage, monoculture and indiscriminate agrochemical use, reduce the biological capital on which the crop depends.

4. Strategies for Soil Restoration

4.1 Organic matter management

The application of farmyard manure, compost, vermicompost, biochar and crop residues remains the foundation of soil restoration. Long-term fertilizer experiments in India have repeatedly shown that integrated use of organic and inorganic sources sustains yield and SOC, whereas continuous use of nitrogen, phosphorus and potassium alone, or of nitrogen alone, leads to yield decline and deterioration of soil physical condition. Green manuring with *Sesbania*, sunhemp or cowpea can add substantial biomass and, depending on species and management, contribute in the range of 40-100 kg N/ha.

4.2 Legume-based and diversified cropping systems

Including pulses in cereal-based rotations is among the most economical restoration tools available to smallholders. Short-duration legumes such as greengram (*Vigna radiata*) fix atmospheric nitrogen through symbiosis with *Rhizobium*, with reported residual benefits in the order of 20-40 kg N/ha for the succeeding crop, and the leaf fall and root biomass add organic matter. The inclusion of summer greengram in the rice-wheat system uses the otherwise fallow period between wheat harvest and rice transplanting, improving farm income while restoring soil fertility. Diversification also breaks pest, disease and weed cycles, thereby reducing herbicide dependence.

4.3 Conservation agriculture

Conservation agriculture, based on minimum soil disturbance, permanent soil cover and crop rotation, is now practised on more than 200 million hectares worldwide (Kassam et al., 2019). Zero tillage with residue retention reduces erosion, conserves moisture, lowers fuel and labour costs, and, importantly for north-western India, offers an alternative to residue burning. Results vary with soil, climate and system, and benefits in yield may appear only after several seasons, which means that farmer support during the transition years is essential.

4.4 Integrated nutrient and weed management

Site-specific nutrient management, balanced fertilization based on soil testing, the use of biofertilizers, and the integration of cultural, mechanical and need-based chemical weed control improve input efficiency while limiting contamination of soil and water. Integrated weed management in particular reduces repeated use of a single herbicide mode of action, which is the primary driver of herbicide resistance.

4.5 Agroforestry, cover crops and land reclamation

Trees on farms, shelterbelts and cover crops protect the surface from raindrop impact, add litter and deep-root carbon, and moderate microclimate. For salt-affected soils, gypsum application, subsurface drainage and salt-tolerant crop varieties have reclaimed substantial areas in the Indo-Gangetic Plain, while acid soils respond to liming and organic amendments. Watershed-based approaches, including contour bunding, check dams and vegetative barriers, remain central to controlling erosion in hilly and rainfed regions such as the Himalayan foothills.

Table 2. Restoration practices and their principal benefits

Practice	Primary soil benefit	Additional benefit
Compost, FYM, biochar	Raises SOC and water holding	Nutrient supply
Green manure, pulses	Biological N fixation	Lower fertilizer need
Zero tillage and residue retention	Reduces erosion, protects structure	Lower cost, no residue burning
Integrated nutrient and weed management	Improves input efficiency	Reduced resistance and pollution
Agroforestry, cover crops	Surface protection, deep carbon	Income diversification
Gypsum, lime, drainage	Reclaims saline, sodic and acid soils	Return of land to production

5. Policy and Institutional Framework

Several global and national initiatives now provide an enabling environment. The United Nations Decade on Ecosystem Restoration (2021-2030) and the UNCCD target of land degradation neutrality under Sustainable Development Goal 15.3 set a global direction. India has committed to restoring 26 million hectares of degraded land by 2030, a pledge announced at the UNCCD COP14 in 2019. At the national level, the Soil Health Card scheme (2015), Paramparagat Krishi Vikas Yojana, the National Mission for Sustainable Agriculture, the Pradhan Mantri Krishi Sinchayee Yojana and the more recent PM-PRANAM programme for reducing chemical fertilizer use all contribute to soil-centred management.

The weakness lies less in the design of schemes than in their last-mile delivery. Soil Health Card recommendations are not always translated into field practice, and farmers receive limited support during the economically risky transition to restorative systems. Extension services, farmer producer organisations and agricultural universities have an important role in closing this gap through local-language, demonstration-based communication.

6. Future Prospects

6.1 Carbon markets and payment for ecosystem services

Voluntary and compliance carbon markets are beginning to recognise soil carbon credits. If measurement, reporting and verification can be made affordable for smallholders, with aggregation through cooperatives, soil restoration may become a source of additional income rather than a cost. India's Green Credit Programme and emerging domestic carbon market frameworks create an opportunity to include agricultural soils, provided protocols are scientifically robust and equitable.

6.2 Digital and precision technologies

Remote sensing, soil spectroscopy, low-cost sensors, drones and machine learning are making high-resolution, near real-time soil assessment feasible. Digital soil mapping can reduce the cost and time of conventional grid sampling, and decision-support tools can deliver crop- and field-specific recommendations by mobile phone, which strengthens the Soil Health Card system. Controlled-environment and protected cultivation, where nutrient and water supply are tightly managed, will also complement open-field restoration by reducing pressure on marginal land.

6.3 Biological innovations

Microbial consortia, plant growth-promoting rhizobacteria, mycorrhizal inoculants, nano-fertilizers and biochar-based formulations are active research areas. These tools hold promise for improving nutrient use efficiency and stress tolerance, but they require standardised quality control, multi-location validation and long-term assessment of ecological effects before large-scale adoption.

6.4 Research priorities

Future work should focus on long-term, multi-location experiments that quantify SOC dynamics under diversified systems; on region-specific thresholds for soil health indicators; on the interaction of restoration practices with climate extremes; and on socio-economic studies of adoption. A shared, open and standardised national soil database would greatly improve research quality and policy planning.

6.5 Human capital

The success of restoration depends on people. Young scientists, agripreneurs and farmers need training in soil science, data tools and sustainable systems. Integrating soil literacy into school and college curricula, and recognising and rewarding stewardship in farmer incentive systems, can build the social foundation that technology alone cannot provide.

7. Conclusion

The evidence is consistent: roughly a third of the world's soils are degraded, India carries nearly 98 million hectares of degraded land, and continued decline threatens food security, climate stability and water resources. The evidence is equally clear that the tools of restoration, from organic matter management and legume-based diversification to conservation agriculture and integrated nutrient and weed management, are available, affordable and effective. What is required now is scale, coordination and sustained investment, supported by credible science, enabling policy and empowered farmers.

A green future will not be built on degraded land. Restoring soil is one of the few interventions that feed people, cool the climate, secure water and revive biodiversity simultaneously. For this generation of scientists, farmers and policymakers, it is not only an opportunity but a responsibility.

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