Supplementary Materials

1. Causes and Extent of Soil Degradation by Region

General causes and extent of soil degradation in India are discussed in the manuscript. Here, region-wise major causes and extents of soil degradation are discussed in detail. The regions are: Hilly and mountainous areas, Trans- and upper Indo-Gangetic Plains (IGP), middle & lower Indo-Gangetic Plains and coastal areas, dryland and desert areas, southern peninsular India and central India.

1.1. Hilly and Mountainous Areas

The Indian Himalayas occupy an area of 53.7 Mha, constituting 16.4% of the TGA of the country. It consists of two distinct sub regions *viz*; eastern Himalayas region or northeastern hills (NEH) and western Himalayas region or northwestern hills (NWH). Annual rainfall in the NEH region is high (2800–12,000 mm) compared with the NWH region (350–3000 mm). Other than soil erosion by water, mass erosion, land slide/land slips, *etc.* cause soil loss. Human-induced intensification of land sliding has been caused by vegetation clearing, construction of roads and buildings, mining, and building of hydro-power projects.

1.1.1. Erosion by Water

The major cause of degradation in hilly areas is soil erosion by water. The Himalayas have steep slopes, fragile geology, and intense storms, all of which trigger soil erosion. Erosion rates are high for the Shiwalik hills (~80 ton ha^{-1} $year^{-1}$) and shifting cultivation areas (~40 ton ha^{-1} $year^{-1}$). Nearly 39% of the area has a potential erosion rate of >40 ton ha^{-1} $year^{-1}$. The extent of water erosion is more severe in the NEH region (22.3% of TGA) than in the NWH region (12.6% of TGA) (Table S1).

Table S1. Extent of land degradation area (%) in various states of the Indian Himalayas (Source: CSWCR&TI Vision [1]).

Region/All India	Degradation Classes										
	1	2	3	4	5	6	7	8	9	10	11
NWH	9.13	2.72	0.22	0.76	0.54	0.95	0.11	11.55	13.68	41.74	18.69
Total for NEH	8.77	5.44	4.32	8.51	25.04	5.54	0.94	1.02	4.33	0.64	35.71
Total for Himalayas	8.96	3.97	2.11	4.34	11.84	3.06	0.49	6.69	9.37	22.79	26.54
All India total	22.3	2.8	1.6	1.74	2.2	2.5	0.3	1.8	1.6	3.9	59.4

Degradation classes	Description	Degradation classes	Description
1.	Exclusively water erosion (>10 ton ha^{-1})	7.	Waterlogged and marshy (permanent)
2.	Water erosion under open forest (<40% canopy)	8.	Barren/Stony waste
3.	Exclusively acid soils (pH < 5.5)	9.	Snow covered & glacial area
4.	Acid soils under water erosion	10.	Area not surveyed
5.	Acid soils under open forest	11.	Others
6.	Exclusively open forest		

NWH = Northwest hills; NEH = Northeastern hills.

Rivers and torrents (seasonal streams with flash flow during monsoon) in the Himalayan region also cause degradation. A recent example is that of the flood-induced deluge occurring in the Kedranath valley of Uttarakhand state during mid-June 2013, which took a toll of thousands of lives and destroyed property including agricultural lands.

1.1.2. Shifting Cultivation

Shifting cultivation, also known as *Jhum* cultivation, is the most traditional and dominant land use system in the NEH. On average, 3.9 Mha of land is under shifting cultivation every year [1]. The system involves cultivation of crops on steep slopes. Land is cleared by cutting the forest or bush to stump level, leaving cut materials to dry and eventually burn to prepare the land ready for sowing before the onset of rains. Excessive deforestation coupled with shifting cultivation practices have resulted in tremendous soil loss (>200 ton $ha^{-1}year^{-1}$) in some areas with poor soil physical condition. Shifting cultivation had the highest soil loss (30–170 ton $ha^{-1}year^{-1}$) followed by conventional-tillage agriculture (5–68 ton $ha^{-1}year^{-1}$) [2].

1.1.3. Deforestation

The area under open forests with canopy <40% is greater in the Himalayan region (~3.1% of TGA) than the national average (2.5% of TGA). Also, the area affected by barren and stony wastelands is greater in the Himalaya region (~6.7% of TGA) than the national average (~1.8% of TGA). Burning of vegetation by forest fire and decline in biodiversity are important in the NEH region. Climate change has an impact on Himalayan forests by changing the forest community structure.

1.1.4. Soil Fertility Decline and Soil Acidity Development

Whilst decline in fertility is indeed a major consequence of erosion in the Indian Himalayan states, processes other than erosion include: (i) declining soil organic matter (SOM) associated with declining soil biological activity; (ii) degradation of soil physical properties (structure, aeration, water holding capacity), as brought about by declining SOM; and (iii) reduction in availability of major nutrients and onset of micronutrient deficiencies (Table S2). The extent of soil and nutrient transfer by water erosion causing environmental degradation in the NEH region was estimated at ~601 Mt of soil, and 685.8, 99.8, 511.1, 22.6, 14.0, 57.1, and 43.0 thousand tonnes of N, P, K, Mn, Zn, Ca, and Mg, respectively [1]. Soils are deficient in available N since it is lost through leaching (in levelled terraces) and runoff. Due to intensive cultivation of cereal based cropping systems [e.g., rice-maize (*Zea mays* L.)–wheat] without proper application of a balanced fertiliser dose, Zn deficiency occasionally appears. Soils are typically deficient in S, B and Mo in areas of the NWH region. Toxicities of Al and Mn are also prevalent in the NEH region.

Table S2. Nutrient addition and removal in the north-western Hills (Source: Ghosh *et al.* [3].

States	Fertilizer Use ($kg\ ha^{-1}\ year^{-1}$)	Nutrient Removal ($kg\ ha^{-1}\ year^{-1}$)	Gap ($kg\ ha^{-1}\ year^{-1}$)
Uttaranchal	8	70	62
Himachal Pradesh	35	130	95
Jammu & Kashmir	40	147	107

1.1.5. Potential Effects of Global Climatic Change

Significant global warming phenomena have already been observed and are projected to continue [4]. It is possible that this may lead to modifications to the general atmospheric circulation with consequent changes in rainfall. Warming is expected to lead to changes in climate variables such as precipitation, temperature, wind speed, and solar radiation. For instance, the numbers of rainy days are likely to decrease along with a marginal increase of 7%–10% in annual rainfall over the sub-continent by the year 2080, leading to high intensity storms. While monsoon rainfall over the country may increase by 10%–15%, the winter rainfall is expected to decrease by 5%–25%, and seasonal variability would be further compounded [1].

These climate changes have the potential to affect soil erosion in a variety of ways. Direct impacts on soil erosion include changes in the erosive power of rainfall due to changes in rainfall amounts and intensities [5]. Shiono *et al.* [6] compared the rainfall erosivity, R-factor of farmland areas in a near-term period (2031–2050) and a future period (2081–2100) with a recent period (1981–2000) in Japan. They observed that: (i) climate changes (A2: occurring in the future up to 2100) would increase soil erosion of farmlands in Japan by 20% based on adjustment of the R-factor and (ii) relative changes in average seasonal EI30 (where E is the total storm kinetic energy and I30 is the maximum 30 min rainfall intensity) during the two future periods compared to the recent period would vary seasonally. We found no such study relating climate change impacts on soil erosion/erosivity in India (searched at Scopus webpage on 13/10/2014 with "climate change and high intensity rain and India and soil erosion and soil loss" keywords). However, it was observed that at Dehradun, the number of occasions when daily rainfall exceeded 60 mm were 2, 4, 4, 4, 4, 3, 5, 1, 8, 6 and 6 in 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011 and 2012, respectively. In 2010, daily rainfall was >200 mm on three occasions and in 2013 there was a 242 mm rainfall-day. Those high intensity storms had great impacts on runoff and soil loss of arable soils (~2% slope) of the foothills of the Indian Himalayas with maize-wheat cropping system. Those extreme rain events also resulted in >60% contribution of total annual soil loss. During 2007–2012, a combination of conservation measures (grassed buffer strip + minimum tillage + organic manure and weed mulching) resulted in ~66% reduction in soil loss during the extreme rain events [7].

1.2. Trans- and Upper Indo-Gangetic Plains (IGP)

The Trans-Gangetic Plains consists of Punjab, Haryana, Delhi and union territory Chandigarh and parts of Uttar Pradesh (UP). The upper IGP consists of parts of UP and Delhi. In this region, the major causes of land degradation are water erosion, residue burning, SOM and nutrient depletion, soil physical, chemical and biological degradation caused by inappropriate crop rotation, inappropriate irrigation and water management (over-pumping of groundwater, unsuitable management of canal irrigation), overuse of pesticides, and reduced use of organic matter and poor crop cycle planning. Erosion by water is the major process of soil degradation in this region too. The soils of UP are highly susceptible to degradation by water erosion, covering 54% of TGA (Table 4 of the manuscript). Large areas of Delhi, Punjab and Haryana are affected by water erosion.

1.2.1. Residue Burning and Soil Organic C and Nutrient Depletion

The rice-wheat cropping system is the backbone of India's food security. These two crops, grown on an estimated area of ~40 Mha for rice and ~25 Mha for wheat, together contribute more than 70% of total cereal production in India [8]. The major sustainability concerns in rice-wheat cropping system are fatigued natural resources and declining factor productivity, declining SOM levels, high tillage costs, generally increasing input costs, and high emission of GHGs due to burning of residues. About 90–140 Mt per year of crop residues are burnt in the field to clear land of straw and stubble after harvest [9]. The problem is more severe in irrigated agriculture, particularly in the mechanized rice-wheat system of northwest India. The problem of on-farm burning of crop residues has intensified in recent years due to use of mechanized harvesters and high cost of labours in removing crop residues. Emission of GHGs, loss of plant nutrients such as N, P, K and S, adverse impacts on soil properties and wastage of valuable crop residues are some of the ill effects of residue burning [10]. While most of the wheat residue is removed from the field and used as animal fodder, 82% of rice residue is burnt in the field [11].

1.2.2. Soil Physical and Chemical Degradation

Other problems of the rice-wheat system are: low soil fertility, pesticide–health hazard, sodicity and salinity, depletion of ground water levels, lowering of water quality and groundwater pollution. Apart from burning, nutrient extraction by crop plants is not always matched by nutrient inputs via fertilizers, manures, and crop residues, often leading to nutrient imbalance. Unbalanced fertilizer use and use of only mineral fertilizers depletes SOM and plant nutrients, mainly N. Excessive tillage, formation of new beds (for vegetable cultivation) every season and use of heavy machinery cause soil physical degradation. Repeated cultivation for wheat and/or soil physical problems caused by puddling of soil for rice further adds to soil degradation. Important among physical processes are a decline in soil structure leading to crusting and compaction. In intensively cultivated soils, repeated use of heavy farm machinery for tillage and other operations often results in compaction throughout the plough layer. This is more rampant in the rice –wheat systems, where puddling is done for rice followed by several tiller and disc harrow passes for wheat cultivation. Several studies have revealed that puddling increased soil bulk density (BD; >1.60 Mg m^{-3}) in the sub-surface layer (15–30 cm) in rice based systems [12–14]. An increase in BD invariably increases penetration resistance (PR) and obstructs root development. Critical values that severely restrict root growth have been estimated to vary from 1 to 4 MPa depending on the soil, water content and crop.

Physical degradation also occurs when soil is uncovered and exposed to direct impact of rain and wind causing soil erosion. When high intensity raindrops strike bare soil surfaces, soil aggregates break down and clog soil pores, causing more runoff and topsoil loss. All these practices with little or no manure addition aggravate the problem of soil physical degradation due to progressive reduction in SOM. This in turn degrades habitat for soil organisms, decreases microbial biomass C and decreases enzymatic activities.

Soil chemical degradation in the region is mainly in the form of salinity development and decreased SOM, total and available N and other nutrients. Other chemical processes include, acidification, leaching, decrease in cation retention capacity, and fertility depletion. A greater influence of sodic soils on crop growth may be from soil physical degradation (either by crusting or hardpan formation) rather than from soil chemical degradation.

Declining water tables force farmers to pump water from great depths, and many irrigated areas are prone to salinity and sodicity problems, which interfere with nutrient management in wheat. Salinity and alkalinity problems are much more aggravated in low-precipitation areas with multiple sources of irrigation, improper cropping pattern, and poor drainage that lead to accumulation of salt in the root zone. The expansion of canal irrigation has been associated with widespread waterlogging and salinity problems in several areas. Lowering of the water table is a self-explanatory form of land degradation, brought about by tube-well pumping of groundwater for irrigation. Pumping for urban and industrial use is a further cause of water table decline.

Use efficiency of N fertilizers for crops is very low due to loss by volatilization in saline and alkaline soils [15] and by leaching and runoff in waterlogged areas. Rates of both mineralization and immobilization of N in soils decreased considerably at higher levels of soil sodicity [16]. Zn availability was also inhibited in saline soils used for rice production due to reduction of sulfate (SO_4^{-2}) to sulfides and subsequent precipitation of Zn as Zn-S. Zn deficiency is also widespread in alkaline soils where it and other micronutrients like Fe, Mn, and Cu are precipitated as hydroxides and carbonates. Soils with high amount of $CaCO_3$ can also induce Zn and Fe deficiency [17].

1.3. Middle & Lower Indo-Gangetic Plains and Coastal Areas

The middle and lower IGP consists of parts of UP and West Bengal and whole of Bihar. The area is characterized by sub-tropical monsoon climate with smaller and more diversified farm holdings. The coastal zones of east and west India occupy an area of about 10.8 Mha [18].

1.3.1. Erosion by Water

The major cause of soil degradation in the middle & lower IGP is erosion by water. About 11 and 14% area of Bihar and West Bengal, respectively, are affected by water erosion. More than 50% of the area has soil loss of 10–15 Mg ha^{-1} $year^{-1}$ (moderate); whereas ~25% of the area has soil loss of 15–20 Mg ha^{-1} $year^{-1}$ and ~25% of the area has soil loss of 20–40 Mg ha^{-1} $year^{-1}$ (severe) [19].

1.3.2. Soil Acidity and Salt-Affected Soils

Acidic soil covers ~0.04 and 0.42 Mha of Bihar and West Bengal, respectively [19]. Productivity of acid soils is very low (<1.0 ton ha^{-1}) due to deficiencies of P, Ca, Mg, Mo and B and toxicities of Al and Fe [20]. Sodic soils occur on 106,000 ha; whereas saline soils occur on 0.05 Mha in Bihar [21]. Because of lower osmotic potential in saline soils, plants commonly suffer from drought stress. Other effects of salinity are decreased availability of P, K, or essential ions due to high concentrations of Ca; decreased uptake of K and Ca because of high Na concentrations (in sodic soils); and decreased uptake of NO_3-N due to excess levels of sulfate and chloride in soil [22].

The coastal saline soils spread over an area of ~3.1 Mha [23]. Salinity build-up in coastal soils takes place due to (1) excessive withdrawal of ground water from aquifers; (2) seawater intrusion; (3) relatively less recharge; and (4) poor land and water management. In coastal saline soils (where EC varies from 0.5 dS m^{-1} during monsoon to 50 dS m^{-1} during summer), the dominant soluble salt is NaCl followed closely by Na_2SO_4 [24]. About 0.3 Mha in Kerala and the Andaman and Nicobar group of islands are characterised by acid sulfate soils. In acid sulfate soils, production of acid from oxidation of pyrites exceeds the neutralizing capacity of soil and pH is <4. There are location specific problems such as sea-water intrusion in unbounded low-lying areas, Fe toxicity in Orissa, impeded drainage in coastal Andhra Pradesh and Tamil Nadu, and severe erosion problem in some parts of Maharashtra, Goa, Karnataka and Kerala.

1.3.3. Waterlogging

In the eastern IGP, drainage and flood water management is the major problem. Some major rice growing soils of this region suffer from waterlogging. The waterlogged alluviums in eastern India have water stagnation above ground for about six months each year. The adverse physical conditions allow only one anaerobic paddy crop with a very low yield potential of <1 ton ha^{-1}.

1.3.4. Excessive Tillage and Residue Removal

Some agricultural practices such as continuous cropping with limited supply of organic amendments, removal of crop residues and excessive tillage cause loss of soil functioning. Mandal *et al.* [25] recorded significant loss of SOC (7%–33%) from this region under long-term rice based cropping systems without addition of any fertilizer inputs. Saha *et al.* [26] also reported similar decline in SOM under rice-wheat-jute (*Corchorus capsularis*) (Chor) cropping. This loss was, however, less than reported by other researchers (30%–60%) [27,28]. Lower SOM depletion may be due to slower decomposition when soils are flooded for 3–4 months to produce rice during the wet season.

Nutrient depletion is a concern in the middle and lower IGP. Growing two rice crops in a rice-jute-rice system exhausts more nutrients than a single crop of wheat in the traditional jute-wheat system [29]. Negative P balance has been reported from the Lower IGP [29]. In the case of rice-wheat and rice-rice-rapeseed (*Brasica napus*) systems, available P declined, despite a slightly positive P balance. Soil P availability may decline due to alternate aerobic-anaerobic periods and its influence on dynamics of Fe- and Ca-phosphates in soil [30,31]. The negative annual K balance in many rice-based cropping systems in West Bengal ranges from 39 to 179 kg ha^{-1} $year^{-1}$ and there is a declining trend in available soil K [29]. High K fixation in alluvial soils, where illite is the dominant clay mineral [32], may cause depletion of available K. Furthermore, Swarup and Wanjari [33] estimated that rice-wheat-jute system removes 210 kg K ha^{-1} $year^{-1}$ under long-term manuring practices in West Bengal.

Approximately 55% and 35% of soil samples from Bihar and West Bengal, respectively, were deficient in available Zn [34]. Boron deficiency occurs in acidic alluvial, red-lateritic soils of West Bengal and alluvial and red-yellow soils of Bihar [35]. About 35% and 70% of soils of Bihar and West

Bengal, respectively, are deficient in available B [36]. However, available B content in coastal soils is high enough to be toxic to almost all plants [37]. Under salt-stressed conditions, N uptake by crops is negatively affected [38]. An increase in Cl^- uptake is accompanied by a decrease in shoot nitrate concentration.

1.3.5. Soil Contaminations with Arsenic (As)

Approximately 3.4 Mha in West Bengal adjoining Bhagirathi river are contaminated with As. Contamination of groundwater with As concentrations exceeding the permissible limit of 50 μg L^{-1} [39] has also been detected in Bihar [40]. The primary cause of the problem is excessive withdrawal of ground water for summer paddy rice. This causes oxygenated decomposition of pyritic sediments which contain high amounts of As and are deposited in the Bengal deltaic plains. The sediments upon oxidation release sulfuric acid that solubilizes the As. The solution moves down to aquifers, polluting the groundwater. Irrigation with As-rich water has resulted in considerable accumulation of As in soils [41]. Summer (*boro*) rice irrigated primarily with ground water contained more As than *kharif* rice. Edible parts of leafy and underground vegetables (e.g., spinach (*Spinacia oleracia*), fenugreek (*Trigonella foenum-graecum*), beet (*Beta vulgaris*) and radish (*Raphanus sativus*)) had much greater As concentrations than vegetables with edible fruit parts (e.g., brinjal (*Solanum melongena*), beans (*Phaseolus vulgaris*), okra (*Abelmoschus esculentus*), and tomato (*Solanum lycopersicum*)).

1.3.6. Coastal Erosion and Tsunami

Presently, ~23% of the coastline along India's mainland is affected by erosion [42]. A tsunami can generate fast moving, large onshore currents that move objects far inland, forcing collapse of structures, eroding beaches of sand, and stripping coastal vegetation. It is also capable of inundating coastal lands [43]. In December 2004, India was the third most affected country by tsunamis with ~4000 ha of land devastated [44].

1.4. Dryland and Desert Areas

Almost 25% of India's TGA is a desert, and as much as 69% of the country's area is classified as "dryland" [45]. The dryland and desert areas consist of parts of Gujrat, Andhra Pradesh and the whole of Rajasthan. In the desert region, land degradation is caused by high wind speed, increased frequency of high-wind events (due to climate change), less rainfall, high rainfall variability with many drought spells each year, soils with low resistance to wind erosion (sandy soil with very low SOM), little or no natural vegetation, overgrazing, little or no residue recycling, crop residue burning, imbalanced plant nutrition, termite infestation, and deep tillage [46]. Wind erosion and erosion of topsoil through occasional high intensity rains are most prominent.

1.4.1. Residue Burning and Organic Matter Depletion

Little crop residue recycling, excessive tillage and long non-crop periods are important reasons why SOM and total N are being depleted. Many dryland crop residues are burned regularly, particularly cotton (*Gossypium hirsutum* L.), pigeon pea (*Cajanas cajan*), castor (*Ricinus communis*), chili

(*Capsicum annuum*), and maize For example, in the Nalgonda district of Andhra Pradesh, a 100-household village (e.g., Nandyalagudem) burns about 1000 tonnes of cotton stalks and 400 tonnes of pigeon pea residue each year [47]. Farmers realize the importance of crop residue recycling, but decomposition of these hardy residues is considered a barrier for subsequent crop production and therefore the residues are burned [46].

1.4.2. Wind Erosion and Desertification

Wind erosion is a serious problem leading to loss of fertile topsoil, especially for. Camborthids and Solorthids, which are major soils with sandy, loamy sand or sandy loam textures. Many also have high calcium carbonate so crusting is a problem. These coarse-textured soils hold little moisture and nutrients. Soil salinity is another common problem associated with extreme aridity and poor quality groundwater [48]. Causes of desertification include: change in frequency and amount of rainfall, reduction in vegetal cover, poor agricultural management practices, cultivation on marginal lands, over-exploitation of natural resources, and excessive grazing [49].

1.5. Southern Peninsular India

1.5.1. Erosion by Water and Wind

Water erosion is the major problem in this region [50]. This is mainly due to high intensity rainfall, deforestation, overgrazing and poor land use practices. Soil loss is severe to extremely severe in most of the hilly areas of Madhya Pradesh, Chhattisgarh and Western Ghats (Table 7). The states of Andhra Pradesh, Goa, Karnataka, Kerala and Tamil Nadu have 21%, 18%, 38%, 13% and 16% of TGA, respectively, of moderate or moderate to severe soil loss (Table S3).

Table S3. State-wise area under different soil loss classes due to water erosion in the Peninsular India (Data source: NBSS&LUP [51]).

State	**Proportion of Total Geographical Area under Each Category (Soil Loss, ton ha^{-1} year^{-1})**					**Total Geographical Area (TGA); Mha**
	Moderate (10–15)	**Moderate Severe (15–20)**	**Severe (20–40)**	**Very Severe (40–80)**	**Extremely Severe (>80)**	
Andhra Pradesh	13	8	13	7	-	27.5
Goa	9	9	27	22	4	0.4
Karnataka	27	11	9	2	-	19.2
Kerala	10	3	2	0	-	3.9
Tamil Nadu	11	5	4	0	-	13.0

1.5.2. Waterlogging

Waterlogging affects ~14.3 Mha [51] of land in the country and this is increasing every year, particularly in the canal irrigated areas. Waterlogging is a major problem in Kerala, as well as in Andhra Pradesh, Karnataka and Tamil Nadu. The main factors causing waterlogging are: lack of natural drainage, upheaval in the river bed or drainage channel, indiscriminate cultivation in the drainage channel bed, interception of natural drainage due to construction of roads and embankments, and discharge of surplus canal water into channels with inadequate capacity [52].

1.5.3. Soil Acidity, Salinity/Alkalinity

Excessive leaching due to high rainfall leads to depletion of bases. Other factors influencing soil acidity are: acidic parent material, type of vegetation and human induced processes including erosion of topsoil, exposure of poor fertility subsoil, and excessive application of N fertilizers. Loss of fertile topsoil not only leads to progressive degradation, but also causes considerable damage in downstream through sedimentation, waterlogging, and salinisation. Development of salinity, alkalinity or sodicity in ~85% of the lowlands is the major cause for land degradation [53]. Hence, even the stand of a single crop of paddy rice is in a very poor state in many areas of the command areas. Due to progressive salt accumulation in the soils, crop choice has changed from rotation of paddy rice and sugarcane to paddy rice only, and ultimately to a barren-like desert with no cropping.

1.5.4. Nutrient Imbalances and Soil Organic Carbon Depletion

Even in drylands, overall nutrient balances are negative as removals exceed additions by 7 to 1 [54] (Table S4). Soil nutrient indices calculated from different years showed that N fertility index decreased in Kerala (from 2.11 to 1.66) and Karnataka (2.33 to 2.05) and increased in Tamil Nadu (1.1 in 1967 to 1.34 in 1997) (Table S5).

Table S4. Nutrient addition (thousands of tonnes) through fertilisers, nutrient removal by crops, and apparent balance in the major states of India (Data Source: Tandon [54]).

State	N			P_2O_5			K_2O			$N + P_2O_5 + K_2O$		
	Add	Rem	Bal	Add	Rem	Bal	Add	Rem	Bal	Add	Rem	Bal
A.P.	1256	477	779	576	497	79	191	817	−625	2024	1791	233
Karnataka	681	473	209	374	239	135	216	604	−388	1272	1315	−43
Kerala	87	149	−62	44	53	−9	87	176	−89	219	377	−158
Tamil Nadu	484	405	79	145	111	34	162	398	−236	791	914	−123

Add = Additions, Rem = Crop uptake, Bal = Balances.

Table S5. State-wide nutrient indices for agricultural soils in India (Data source: Tandon [54]).

State	N			P			K		
	1967	1977	1997	1967	1977	1997	1967	1977	1997
Andhra Pradesh	1.55	1.38	1.55	1.5	1.19	1.57	2.3	2.54	2.52
Karnataka	2.33	1.53	2.05	1.06	1.23	1.9	2	2.21	2.54
Kerala	2.11	1.7	1.66	1.11	1.7	2.35	1	2	1.98
Tamil Nadu	1.1	1.08	1.34	1.6	1.4	2.11	2	2.54	2.4

Rajan *et al.* [55,56] found that soil organic C (SOC) was the most discriminative measurement among 24 land quality indicators used for monitoring land degradation. Soil organic C in forest soils under teak (*Tectona grandis*) and sal (*Shorea robusta*) with low management was twice that for corresponding cropped soils. Soils in the peninsular plateau are also characterized by low SOC concentration (0.4%) due to high tropical temperature. As a result, this region contributes only 17% of the total SOC stock of the country despite occupying about one-third of the land area [57]. The labile pools of SOC are also very low, comprising 3.2% to 5.6% of total SOC in Vertisols.

1.5.5. Sand Mining

At Bangalore Rural district Rajendra, Hegde *et al.* [58] reported that 25% of sand supplied for construction work in Bangalore is extracted from coarse surface soils by washing. This activity causes severe ecological consequences by way of loss of surface soil and nutrients, crop yield declines, siltation of tanks, excessive ground water exploitation, and exposure of fine-textured subsoil to erosion. An estimate of 0.02 Mha of soil surface amounting to 43.8 million cubic meter of soil is used for sand extraction per year near Bangalore. The process also uses 48,180 million litres of water.

1.6. Central India

The central zone consists of three states namely, Madhya Pradesh, Chhattisgarh and Maharastra and covers 23% of the TGA of the country. Major soil types of central India are black soil or Vertisols. Vertisols and associated soils in India occupy 73 Mha, of which 38% are Vertisols, 37% Vertic-Inceptisols and 21% Entisols. Vertisols developed on gneisses and schists are moderately shallow (50–75 cm) to moderately deep (75–100 cm), whereas those developed on basalt are deep (100–150 cm) to very deep (>150 cm). These soils have high clay content varying from 30%–80%. The clay is dominantly smectitic in nature, which has high coefficient of expansion and contraction, leading to the development of gilgai micro-relief, deep and wide cracks and closely intersecting slickensides. Soils developed on calcareous clay parent material have high $CaCO_3$ content that increases irregularly with depth. These soils have pH values ranging from 7.8 to 8.7 and may reach up to 9.4 in sodic soils. Although the black soils have relatively high moisture holding capacity (150–250 mm/m), water is not all available to plants because the water is held tenaciously by the smectitic clay. These soils are extremely sticky when wet and extremely hard when dry. These soils have low permeability as well. The main constraints to crop production are: poor workability, poor drainage, water erosion, and soil fertility loss with residue burning.

1.6.1. Poor Workability

The high clay content and predominance of montmorillonitic clays impart certain characteristics to Vertisols which make them difficult to work. When too dry they crack; ploughing if possible, results in very large clods. When wet they are sticky; tillage is difficult, if not impossible due to poor trafficability. Thus, farmers get a narrow window of time for crop sowing, so some Vertisols remain fallow even during the rainy season.

1.6.2. Poor Drainage and Water Erosion

Poor drainage, both surface and internal is one of the main causes of low production from Vertisols. With the initial showers of rain, particularly when the soil is dry, the rate of infiltration is high because of cracks and granular structure. But as soon as the profile becomes filled, swelling of the soil decreases infiltration rates and affects internal drainage. The flat relief and decreased infiltration subsequently create surface drainage problems, particularly when the soils are fully saturated. Thus, Vertisols without proper land treatment and crop cover during the rainy season are prone to huge soil and water loss.

1.6.3. Soil Fertility Loss and Residue Burning

Vertisols generally have low SOM, N, P, S and Zn concentrations. Low and unbalanced use of fertilizers are causing micro-nutrient deficiencies in this region. Nutrient recycling through residues is low as most of the residues are either removed from the field or burnt. Deep soils when irrigated are very much prone to salinity and sodicity particularly in the subsoil. The calcareous nature of these soils affects nutrient availability.

2. Strategies to Mitigate Land Degradation

General soil degradation mitigation strategies are discussed in the manuscript. Here, region-wise major mitigation technologies are discussed in detail. The regions are: Hilly and mountainous areas, Indo-Gangetic Plains (IGP), Dryland and desert areas, Southern peninsular India, central India and coastal areas.

2.1. Hilly and Mountain Areas

2.1.1. Landslide and Minespoil Rehabilitation and River Bank Erosion Control

High soil erosion rates were checked and brought within permissible limits (Table S6) by using bioengineering treatments on landslide affected (Nalotanala watershed; area ~60 ha) and minespoil affected (Sahastradhara watershed; area ~64 ha) areas. Restoration of limestone minespoil areas resulted in improved water quality through a reduction in Ca content (Table S7). For river bank erosion control, bio-engineering technologies such as spurs, retaining walls and earthen embankments may be used in conjunction with suitable vegetation such as giant cane (*Arundo donax)*, five-leaf chaste trees (*Vitex negundo)*, morning glory (*Ipomoea sp.)*, Bamboo (*Bambusa vulgaris*), napiergrass (*Pennisetum purpureum*) or munja (*Saccharum munja)* [1].

Table S6. Effect of bioengineering measures on landslide (1964–1994) and minespoil rehabilitation (1984–1996) project (Data source: CSWCR&TI Vision [1]).

Particulars	Landslide Project		Minespoil Project	
	Before Treatment	After Treatment	Before Treatment	After Treatment
Sediment load (ton ha^{-1} $year^{-1}$)	320	6	550	8
Vegetative cover (%)	<5	>95	10	80

Table S7. Water quality parameters (mg L^{-1}) for treated and untreated minespoils (Data source: CSWCR&TI Vision [1]).

	Ca	**Mg**	**SO_4**
Treated mine	74	34	138
Untreated mine	188	39	240

2.1.2. Agroforestry

Erosion can also be controlled by using agroforestry systems such as the **Agri-horti-silvi -pastoral land use model**, in which horticultural crops are grown in the upper two-thirds of the area and forests are developed in the lower portions. The middle portion is managed with contours and trees planted in "half-moon" terraces. Vegetables, root crops, or other crops are then cultivated in the interspaces of the contours. This land use model performed better compared to shifting cultivation. It increased organic C by ~45%, mean weight diameter of soil aggreagates by 29%, and *in-situ* soil moisture content by 21%, and decreased clay dispersion by 53%, soil loss by ~99%, and soil erosion ratio by 45.9% under moderate to steep slopes (Table S8). Multipurpose trees (MPTs) like *Michelia oblonga* were identified as a better bio-ameliorant for these soils because continuous leaf litter and root exudates improved soil physical behaviour and SOC [2].

Mixed horticultural land use-Generally, two-thirds of the upper hillside is converted to cropland with 3 to 4 contours developed using fruit trees. Contour bunds are generally planted to pineapple with 3 to 4 terraces used for vegetables. **Horticultural land use-**Fruit plants such as orange (*Citrus sinensis*) or banana (*Musa paradisiaca*) are planted either in half moon terraces or in contour bunds. If the slope is <30°, intercropping may be practised (like four rows of pineapple with 10 rows of fruit trees across the slope). Legume vegetable may be used as an intercrop. The **Horti-silvi-pastoral system** maintains an acceptable level of production of fruits, vegetables, fuel wood, timber, or fodder, while at the same time conserving basic resources (mainly soil) on which the production depends. This system was an economically viable alternative to *jhuming (*shifting cultivation). Shifting cultivation is a system in which plots are cultivated temporarily, then abandoned and allowed to revert to their natural vegetation while the cultivator moves on to another plot. Typical **Multi-tier horticultural systems** include: (1) Horti-horti three-tier system: arecanut (*Areca catechu*) + black pepper (*Piper nigrum*) +ginger/turmeric/pineapple (*Ananas comosus*)/lemon (*Citrus limon*); (2) Silvi-horti-three tier system: multi-purpose trees (MPT) + black pepper (*Piper nigrum* L.) + ginger/turmeric/pineapple; (3) Silvi-horti-two tier system: Parkia (*Parkia biglobosa*) + pineapple or subabool (*Leucaena leucocephala*) + pineapple, alder with vegetables like potato (*Solanum tuberosum* L.)) and cole crops or with cereals like maize and rice, *etc.* in Nagaland, or alder (*Alnus spp.*) + large cardamom (*Elettaria cardamomum*) in Sikkim and MPT + lemon. **Multi-tier system for plantation crop-**Tea (*Camellia sinensis* L.) and coffee (*Coffea arabica* L.) plantations require sparse shade and *Albegia*, *Dalbergia*, *Accasia* have been used as the major tree species for this purpose. Some other measures are multi-tier cropping where crops of different heights at the same time on the same piece of land and thus using land, water, and space most efficiently and economically. An example is: *Albegia sp.* + black pepper + tea/coffee.

Table S8. Effect of various MPTs on soil properties (adapted from Saha *et al.* [2]).

MPTs	Organic C (g kg^{-1})	Aggregate Stability	Available Water (m^3 m^{-3})	Infiltration Rate (mm h^{-1})	Erosion Ratio
Pinus kesiya	35.4	75.6	0.220	8.04	0.20
Alnus nepalensis	32.2	72.1	0.201	7.28	0.23
Parkia roxburghii	23.1	63.4	0.192	4.85	0.30
Michelia oblonga	33.6	73.2	0.210	6.10	0.22
Gmelina arboria	28.6	67.9	0.183	5.36	0.24
Control (No tree)	15.6	56.8	0.151	3.84	0.39

2.1.3. Conservation Agriculture (CA)

Currently studies using these CA components under rainfed conditions in India are limited. However, minimum tillage (MT, 50% tillage reduction) with *in-situ* crop residue, mulching with sunhemp (*Crotalaria juncea* L.), *Sesbania*, or cowpea as well *ex-situ* mulching with *Leucaena leucocephala*, kudzu (*Pueraria lobata*) and lantana (*Lantana camara*) have been shown to increase productivity and conserve natural resources [59]. Conservation technology with aromatic grass as vegetation strip along with MT and organic amendments (vermicompost, poultry manure and farm-yard manure) decreased runoff by ~30% and soil loss by ~34% (Table S9). This technology not only delivered greater maize and wheat yields (~16%), but also consumed ~56% less energy [60].

Table S9. Conservation tillage, vegetative barriers, organic amendments and weed mulch impact on resource conservation and productivity, Dehradun, UK. (Data Source: Ghosh *et al.* [60]).

Particulars	***Panicum*** **as VB + NPK + CT**	***Palmarosa*** **as VB + OA + WM + MT**	**% Increase/ Decrease**
Runoff loss (% of total rainfall)	32.8	22.8	−30.4
Soil loss (ton ha^{-1} $year^{-1}$)	5.24	3.47	−33.8
Wheat equivalent yield (kg ha^{-1})	2860	3330	16.5
Water use efficiency for wheat (kg/ha-mm)	4.72	6.61	40.0
Nutrient (NPK) use efficiency for crops (maize+ wheat) cycle (kg $ha^{-1}year^{-1}$)	54.3	81.0	49.0
Carbon management Index (CMI)	42.0	55.0	31.0
Energy intensiveness (MJ Indian $Rupees^{-1}$)	0.50	0.22	−56.0

VB—Vegetative barrier, CT—Conventional tillage, MM—Weed mulch, MT—minimum tillage, OA—Organic amendments (FYM/vermicompost/poultry manure). Carbon management index is derived from the total SOC pool and C lability and is useful to evaluate the capacity of management systems to promote soil quality.

Soil degradation can also be reversed with a combination of technologies (application of organic amendments with MT and use of buffer strips). For example, in a valley of NWH that had 4% slope, MT + crop residue decreased runoff by 40% and 11% and soil loss by 69% and 28% compared to cultivated fallow and conventional tillage (CT), respectively. MT + crop residue produced 11% greater greater maize (2.8 ton ha^{-1}) and toria (*Brassica rapa*) (0.9 ton ha^{-1}) yields compared to CT [61]. In the mid-hills, novel conservation tillage practices include: seasonal tillage alteration under rainfed cropping system [62] as continuous ZT under rainfed soybean based cropping systems did not work due to perennial weed infestation [63] despite improvements in total SOC and soil hydraulic properties [64].

2.1.4. Vegetative Barriers and Using Natural Geotextiles, Mulching and Diversified Cropping

Mulching at 4 ton ha^{-1} in maize-rows decreased soil loss from 36.5 ton ha^{-1} to 6.2 ton ha^{-1} and decreased runoff from 49% to 22% compared to normal ploughing on 8% slope [1]. Another study showed that mulching decreased water use by potato (*Solanum tuberosum*) from 146 mm to 123 mm and increased tuber yield by 26% compared to a no mulch treatment under rainfed condition [1].

Other novel practices that may be adopted in the mid-Hills region include relay cropping of vegetables [65], location specific organic farming [66,67], balanced fertilization [68], water harvesting with a low-density polyethylene tank, fodder (hybrid napier; *Pennisetum purpureum*) production beneath pine trees, production of dual purpose crops (wheat, barley and oat) for grain and green fodder, planting of fuel-cum-fodder trees, vermi-composting, use of biofertilizers in conjunction with mineral fertilizers [69], and several agro-forestry options like growing of turmeric (*Curcuma longa*) and ginger (*Zingiber officinale*) under fodder trees in silvi-horti system [70].

Besides these, other major options are: Water harvesting, terracing and other engineering structures, *reforestation*, *grassland and horticulture development* and fertilization, and these are discussed in the manuscript.

2.2. Indo-Gangetic Plains (IGP)

Mitigation strategies for the entire IGP are discussed together. Key strategies for soil restoration are to maximize retention and recycling of organic matter (OM) and to use resource conservation practices that minimize leaching, runoff and erosion. Those goals could be achieved by adopting management practices such as afforestation, agroforestry, CA, appropriate grazing densities, judicious water management (including micro-irrigation), integrated family farming for small land holders, construction of windbreaks and buffer strips to address wind and water erosion, and extension of irrigation facilities by the government to targeted areas. In the western IGP, specific CA practice is appropriate under a particular cropping system. For instance, direct seeded rice-ZT wheat with relay cropping of greengram (*Vigna radiata* L.) [7] under rice-wheat cropping system; permanent broad beds with residue retention under irrigated cotton (*Gossypium hirsutum* L.)-wheat [71], and maize-wheat cropping systems [72], and permanent narrow beds with residue retention under irrigated soybean-wheat cropping system [73]. Zero tillage with all crop residue retention under limited irrigation in finger millet-chickpea (*Cicer arietinum* L.); clusterbean-mustard (*Brassica nigra* L.) and greengram-barley (*Hordeum vulgare* L.) cropping systems yielded higher system productivity than ZT plots alone [74]. Other technologies are: relay intercropping, drip irrigation, N management (using neem coated urea and leaf color chart, high basal application of N under CA), use of short duration and high yielding cultivars, and wheat sowing date alteration to combat terminal heat (sudden temperature increase at physiological maturity of crops). Neem (*Azadirachta indica*) is a tree widely available in India.

2.2.1. Conservation Agriculture (CA)

In the IGP, more than 13,500 on-farm trials were conducted to evaluate different resource conservation technologies in rice and wheat in India, Nepal, and Bangladesh during 2007–2008. Proven technologies developed for wheat over the past 10 years are: decreased-till and ZT-seeded wheat, ZT-seeded wheat with residue mulch, and broadcast wheat in high-moisture soil without tillage. Bed-planted drill-seeded wheat performed better than farmers' current practices [75]. Decreased and ZT for planting wheat is gaining acceptance with farmers in this region and in South Asia, because of decreased land preparation costs [76,77]. Sowing of a crop in the presence of huge quantities of residues of preceding crop can be a problem. But new variants of ZT seed-cum-fertilizer drill/planters such as Happy Seeder, Turbo Seeder, rotary-disc drill and easy seeder have since been developed to facilitate direct drilling of seeds in the presence of residues (both loose and anchored residues up to 10 ton ha^{-1}). ZT-drilling in crop residues keeps canopy temperatures lower by 1–1.5 °C during grain filling stage and sustains soil moisture availability [78].

Experiences from several locations in IGP show that with partial CA technologies like ZT, farmers may save ~Rs 2500 per ha on land preparation and decrease diesel consumption by 50–60 L per ha [79]. The major reasons for improved crop productivity could be higher soil aggregation, higher C stocks and decreased sub-surface compaction along with higher root water uptake and radiation use efficiency in the PBB+R plots [71]. Soil aggregate stability and their dynamics are integral to ecosystem functioning, in governing many processes such as nutrient cycling [80], water transport [80,81], microbial diversity [82], and SOC protection [83,84].

Table S10. The effect of rice straw as mulch, fertilizer N rate, and method of fertilizer application on grain yield (ton ha^{-1}) and agronomic efficiency (kg grain kg^{-1}of N applied) in wheat at Ludhiana, India (Data source: Brar *et al.* [85]).

Straw Treatment	N Level (kg ha^{-1})	Grain Yield (ton ha^{-1})		Agronomic Efficiency (kg Grain kg^{-1} N Applied)	
		Fertilizer N Band Placed	Fertilizer N Broadcast	Fertilizer N Band Placed	Fertilizer N Broadcast
Rice straw burnt	0	1.62	1.86	-	-
	60	2.63	2.77	16.8	15.2
	120	3.86	3.70	18.7	15.4
	180	5.04	4.80	19.0	16.3
Rice Straw mulch	0	1.57	1.77	-	-
	60	2.38	2.44	13.6	11.1
	120	3.62	4.26	17.1	20.7
	180	4.58	4.63	16.8	15.9
$P = 0.001$		0.11		1.6	

In another study, Brar *et al.* [86] in Punjab, India observed that when fertilizer N was broadcast, retention of rice straw during the growth of wheat in the rice–wheat rotation did not decrease wheat yields compared to where straw is burnt (Table S10). Band placement of N fertilizers did not result in higher yields than when broadcast under rice straw retained as mulch, suggesting that farmers using the Happy Seeder™ could retain rice straw and could grow wheat without compromising yield [86].

In a soybean–wheat rotation in subtropical semi-arid soils, Aulakh *et al.* [87] observed equal or better soybean yield under CA than under CT with either application of 25 kg N and 33 kg P ha^{-1} or 10 ton FYM ha^{-1} in conjunction with 20 kg N and 26 kg P ha^{-1}. In addition, CA conserved more water in the soil profile than CT by reducing evaporation losses from soil through a mulching effect of crop residues retained on the soil surface, and created a cooler environment at the soil surface during the initial three weeks of soybean development.

2.2.2. Intensive Cropping and Integrated Farming Systems (IFS)

Productivity of rice in rainfed upland soils of eastern India is very low (<1 ton ha^{-1}) and unstable because of erratic monsoon rains, moisture deficit during dry spells, coarse-textured soil with low fertility, and several biological constraints. Considering the agro-climatic (rainfall variability, probability and onset of effective monsoon) and edaphic (soil water retention properties) constraints and prospects outlined by Kar *et al.* [88], there is an urgent need for augmenting the productivity of vast rainfed upland rice ecosystems of eastern India (4.3 Mha) through crop diversification. In deficit rainfall years (2000 and 2002), rice yield was adversely affected in coarse-textured upland soils, while greater rice equivalent yield and rain water use efficiency were obtained from groundnut (*Arachis hypogeae* L.) + pigeonpea intercropping followed by sole groundnut and sole pigeonpea. Double cropping in rainfed upland rice soils was also explored through maize–horsegram (*Macrotyloma uniflorum* L.)/sesame (*Sesamum indicum* L.) rotation with increased productivity and rainwater use efficiency. Crop diversification technology was found to be very effective for drought mitigation [88]. Green manure cover crops and crop residues as surface mulch not only protect the soil against erosion, but also lead to significant N supply of up to 200 kg ha^{-1} depending on growth conditions. This can lead to 50%–75% reduction in N fertilizer need [89].

2.2.3. Fertilization

In eastern India, where crop residues have competing uses such as animal feed, roof thatching and domestic fuel, at least some parts of the stubble should be left in the fields to contribute to SOC [90]. Depth distribution of SOC can be achieved by planting deep-rooted species with high below-ground biomass production. Biswas *et al.* [29] observed an increase in SOC in rice-jute-potato system compared to rice-rice or rice-wheat system in West Bengal. This might be due to greater rhizodeposition and leaf shedding of jute during its growth period and due to the incorporation of potato haulm at harvest, both contributing to an increase in SOC. Yadav *et al.* [91] reported that available N, P and K content accumulated with long-term application of recommended NPK or integrated supply of nutrients in rice-wheat cropping of lower IGP. Ghosh *et al.* [3] also reported a beneficial effect of INM and organic manure in increasing availability of N, P and K under the same system.

Micronutrients Zn and B can be applied either to soil or as foliar sprays. Application of 5 to 10 kg Zn ha^{-1} and 0.5 to 2.0 kg B ha^{-1} to soil is typically sufficient to correct deficiency. Significant response of Zn application to crops was reported from a large number (1391) of trials conducted on farmers' fields in Bihar [91,92] and 84% of those trials showed a yield response of above 200 kg ha^{-1} to Zn over control (no Zn). Singh *et al.* [93] observed significant yield response of cereals, pulses, and oilseed with application of 0.5–1.0 kg B ha^{-1} in calcareous soils of Bihar. Sarkar [94] recorded 33%, 21%, 16%, 5% and 17% greater grain/tuber yield of mustard, wheat, potato, lentil, and coriander, respectively, with B application over no B control in B deficient soils of West Bengal. Sarkar *et al.* [95] suggested that split applications of B either through soil or foliar sprays were more effective than a single B application for mustard and potato.

Other major technologies are: Reclamation of Acid and Salt Affected Soils, Afforestation and Agroforestry, Soil Erosion Control and Remediation of As contamination and Water Management and Pollution Control. These are mentioned in the manuscript.

2.3. Dryland and Desert Areas

In desert soils, some key mitigation practices include: vegetative barriers, including both contour hedgerows and grass strips, windbreaks and shelterbelts, tree and grass plantation, improved pastures and perennial legumes, improved fruit and crop cultivars, improved agri-horticulture, agri-silviculture, horti-pasture and silvi-pasture system for the arid region, improved cistern and pond development for rainwater harvesting, drip irrigation for vegetables and fruit crops, rodent control and organic production of high value crops.

2.3.1. Diversified Cropping with INM

Balanced fertilization along with application of farm-yard manure, compost, green manure and biofertilizers should be practised for sustained soil health and enhanced productivity of vegetables. On farm generation of OM during the off season and its incorporation before the crop season and tank silt addition showed substantial improvement in SOM in drylands. Integrated nutrient management under diversified production systems in rainfed regions sequestered significantly greater SOC compared to farmers' practice and contributed to soil health improvement of the system.

2.3.2. Conservation Agriculture

As mentioned in the manuscript, availability of residues is the major constrain of adopting CA in this region. Conservation tillage without residue retention is not advisable in these areas and CT is better than MT. Even after the eighth year of a long-term study, CT remained superior to MT, which could be attributed to more weed growth and less infiltration of water due to compaction of the surface soil under MT (Table S11). In this case, the surface residue applied at 2.0 ton ha^{-1} was inadequate to create the desirable soil ameliorative effect.

Table S11. Long-term (8 years) effects of tillage and residue application on crop yield (Data source: Sharma *et al.* [96]).

Residue Treatment	Sorghum Yield (ton ha^{-1})		Castor Yield (ton ha^{-1})	
	CT	MT	CT	MT
Sorghum at 2 ton ha^{-1}	1.13 ^{a}	0.81 ^{b}	0.82 ^{m}	0.48 ^{n}
Gliricidia loppings at 2 ton ha^{-1}	1.20 ^{a}	0.90 ^{b}	0.93 ^{m}	0.51 ^{n}
No residue	1.10 ^{a}	0.84 ^{b}	0.84 ^{m}	0.45 ^{n}

Means followed by different lowercase letters within a row of a same crop yield are significant at $P < 0.05$. CT = Conventional tillage, MT = Minimum tillage. In addition, appropriate land management practices are very effective mitigation technologies in this region.

2.4. Southern Peninsular India

In view of global climatic changes and the poor SOC stock in this region, it becomes necessary to consider new initiatives in restoring the SOM and productivity of black cotton soils [97].

2.4.1. Detailed Land Resource Inventory

It is well known that the first thing needed is a detailed site- specific database (like soils, climate, minerals and rocks, ground water, vegetation, crops, land use pattern, socio-economic conditions, infrastructure, marketing facilities, *etc.*) on land resources and soil quality for all the villages. From the data collected at farm level, viable and sustainable land use options suitable for each and every land holding can be more easily prescribed [98].

2.4.2. Water Harvesting and Mechanical Measures

A specific set of case studies that were conducted in the region [99] are: **Recharging of bore wells**-in the Nalgonda district of Telangana about 35 open wells and 9 bore wells were recharged in surrounding areas using rainwater harvested and reducing evaporation losses, benefiting 99 farmers. **Construction of check dams-** These were constructed to collect and store excess runoff in streams. The water table increased by 2–3 m in Anantpur, Andhra Pradesh. Mechanical measures were necessary when the slope of agricultural land was >3% and simple agronomical practices alone were not effective. **Contour bunding**-practiced in Tamil Nadu on red and brown soils when slopes of 2%–6% with scanty or erratic rainfall (<800 mm annually).

Other practices include: **Graded bunding or channel terraces-**recommended in areas receiving annual rainfall >800 mm and coarse-textured soils. **Bench terracing-**recommended for slopes of 16%–33%. **Conservation bench terracing** (CBT)-terrace ridges to impound runoff on a level bench (recipient area) of a donor watershed. Crops such as maize, which require drainage are cultivated on sloping areas, while water intensive crops like paddy rice are cultivated on the level bench [100].

2.4.3. Diversification of Cropping Systems and Agroforestry

Farmers have diversified cropping systems from cereals to included vegetables/flowers in Tumkur district, Karnataka, where *Chrysanthemum* yield has been 2.2 ton ha^{-1}. Alternate land use systems not only help in generating much needed off-season employment in mono-cropped rainfed areas, but also utilize off-season rains that may otherwise be lost as runoff [101]. Lenka *et al.* [102] identified two N_2 fixing trees species of *Gliricidia sepium* and *Indigofera tysmani*a long with a grass, *Saccharum spp.*, for controlling runoff and erosion. A particular multipurpose cropping model (including 13 crops: pepper (*Piper nigrum*), coffee (*Coffea arabica*), pepper (*Catimor sp.*), coconut (*Cocos nucifera*), arecanut (*Areca catechu*), banana (*Musa paradisiaca*), lime, nutmeg (*Myristica* sp.), clove (*Syzygium aromaticum*), jak (*Artocarpus heterophyllus*), bread fruit/avacado (*Annona* sp.) and mango (*Mangifera indica*) was established to assess soil loss, which was almost 31 times lower compared with farmers' practice. The model had greater cost/benefit ratio, net present value and internal rate of return [103]. In addition, acid tolerant crops like alder (*Ainus glutinosa)*, rattlepods (*Crotalaria anagyroids)*, *Junglisaru/*jhau *(Casuarina equisetifolia)*, *Coffee-sena (Cassia obtusifolia)*, copper-beech *(Fagus sylvatica)*, pine *(Pinus sp.) and poplar (Populus sp*.) have been used [104]. The salt tolerant fodder grasses like: buffalo grass (*Cenchrus ciliaris)*, pongame oil tree *(Derris indica)*, white siris *(Albizia procera)* can be recommended for salinity control.

2.4.4. Nutrient Management

Zeolite nano-particles (Ca-zeolites and gypsum) in naturally degraded Vertisols of the Peninsular India and in sodic soils can be used for enhancing use efficiency of water and nutrients [105,106]. Better nutrient use can be achieved with multi-nutrient formulations, other novel controlled release fertilizers to minimize nutrient losses, scheduling nutrient application to match requirements of crops/cropping systems, and germplasm screening for efficient nutrient use.

Intercropping and contour farming and participatory resource conservation and management are other major options for land degradation mitigation and are discussed in the manuscript.

2.5. Central India

2.5.1. Rainwater Harvesting and its Efficient Recycling

Rainwater must be harvested properly either *in-situ* or *ex-situ* and the harvested water must be used most efficiently using site specific technology. The aim of any efficient water management system is to maximize productivity per unit of irrigation water (transported or pumped) or rainwater (harvested or retained *in situ*) in a sustainable way. The graded broad bed and furrow (BBF) system retained more soil water in the profile than FOG during the later stage of crop growth in the deficit rainfall year. The BBF system had 13%–18% greater soybean yield than FOG. Yield of soybean was lower in soybean/maize intercropping system due to competition between the crops for light and nutrients; but in soybean/pigeonpea intercropping yield of soybean was not affected. Similarly, maize grain yield in the sole maize treatment under BBF was 12%–16% greater than the same treatment under FOG. Pigeonpea grain yield under soybean/pigeonpea and maize/pigeonpea intercropping was greater in BBF than in FOG. Chickpea yield was similar in the three cropping systems where it was grown, thus the residual effect of previous crops on chickpea yield was not significant. Thus, systems involving maize crop, either as sole or intercrop (as in maize-chickpea, soybean/maize intercropping-chickpea and maize/pigeonpea intercropping systems) showed better promise in producing yield improvements than soybean based systems under both BBF and FOG.

Irrespective of irrigation to chickpea and cropping systems, system productivity as soybean equivalent yield was greater in BBF than FOG; and system productivity was greater with pre-sowing plus 1 post sowing irrigation than with pre-sowing irrigation only. Diversifying cropping systems to maize-chickpea, soybean/maize intercropping-chickpea, or maize/pigeonpea intercropping than sole soybean hold promise for increasing productivity [107].

2.5.2. Conservation Tillage

Research results on CA in this region are scant. However, there are some valuable information on conservation tillage and hence those are mentioned. Conservation tillage practices *viz.*, ZT and decreased tillage (RT) for soybean-wheat system have yielded similarly to CT. The SOC content and soil physical properties of aggregation and saturated hydraulic conductivity under ZT and RT systems improved compared to CT due to retention of residues and minimum disturbances [107]. The ZT system accumulated greater SOC near the surface (Figure S1). Continuous ZT to soybean and wheat with balanced dose of fertilizer can be a viable alternative to CT for sustainable production with concomitant improvement in physical properties and C sequestration in Vertisols.

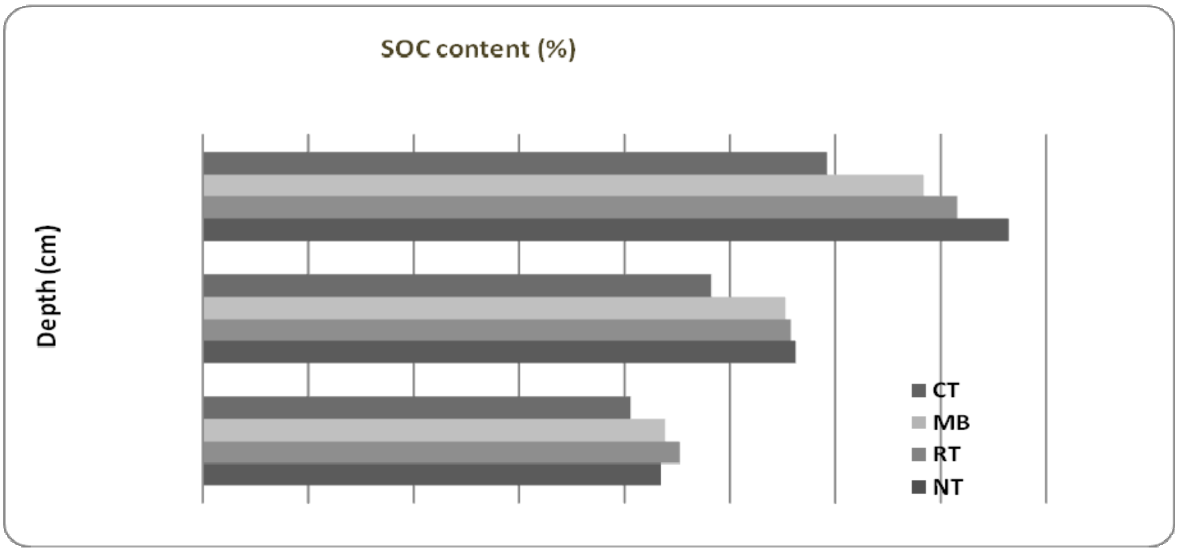

Figure S1. Effect of conservation tillage on organic carbon content of Vertisols (Source: Hati *et al.* [107]).

2.5.3. Balanced and Integrated Nutrient Management

Integrated supply of nutrients through FYM and inorganic fertilizers under a soybean-mustard system on Vertisols increased SOC content and consequently improved soil physical health as substantiated by better aggregation, greater saturated hydraulic conductivity and infiltration characteristics, and decreased mechanical resistance and bulk density. The long-term (28 years) application of balanced fertilizer alone or in conjunction with FYM induced clear accumulation of SOC under a soybean–wheat–maize (fodder) system (Table S12). The greater SOC under INM treatments was favourably associated with improvement in soil aggregate size and stability, water retention, microporosity and available water capacity compared to suboptimal or imbalanced fertilizer application treatments. (Table S13) Thus, application of balanced rate of mineral fertilizers with organic manure could sequester C, and helps in conserving soil from erosion through improved aggregation and increased water conductivity [108].

Table S12. Bulk density and aggregate stability of soil as influenced by long-term cropping, fertilizer and organic manure use in Vertisols of Jabalpur (Source: Hati *et al.* [108]).

Treatment	Bulk Density ($Mg\ m^{-3}$)	Mean Weight Diameter (mm)	Water Stable Macroaggregates (%)
Control	1.34 ^{a}	0.51 ^{c}	46.8 ^{c}
100% N	1.34 ^{a}	0.52 ^{c}	49.2 ^{bc}
50% NPK	1.32 ^{ab}	0.56 ^{bc}	55.3 ^{b}
100% NPK	1.32 ^{ab}	0.60 ^{b}	58.2 ^{b}
100% NPK+FYM	1.28 ^{b}	0.69 ^{a}	71.0 ^{a}

The difference between values in a column followed by different superscripts is significant at ($P < 0.05$).

Table S13. Effect of fertilizer and organic manure application on porosity and available water capacity (AWC) after 28 cycles of soybean-wheat- maize (fodder) crop rotation.

Treatment	Micro-Porosity (%)	Total Porosity (%)	AWC up to 15 cm Depth (cm)
Control	38.7 ^{c}	49.5 ^{b}	1.45 ^{c}
100% N	39.8 ^{c}	49.5 ^{b}	1.49 ^{c}
50% NPK	40.3 ^{c}	50.1 ^{b}	1.50 ^{c}
100% NPK	42.5 ^{b}	50.3 ^{ab}	1.65 ^{b}
100% NPK+FYM	45.8 ^{a}	51.6 ^{a}	2.08 ^{a}

The difference between values in a column followed by same superscripts is not significant at ($P < 0.05$) (Hati *et al.* [108]).

Other major technologies are judicious use of distillery effluent, subsoiling and irrigation management for improving input use efficiency and are discussed in the manuscript.

2.6. Coastal Areas

2.6.1. Drainage (Desalinization)

Different agro-hydro-salinity models like "SALTMOD", "DRAINMOD-S" or "SAHYSMOD" [109,110] have been tested in the field to predict water distribution and salt balance in the soil profile. SALTMOD was tested in coastal clay soils of Andhra Pradesh where subsurface drainage system was laid out at several drain spacing [111]. Relative performance of artificial neural networks (ANNs) and SALTMOD was studied in simulating subsurface drainage effluent and root zone soil salinity in coastal rice fields [112]. Three ANN models such as back propagation neural network (BPNN), general regression neural network (GRNN) and radial basis function neural network (RBFNN) were developed for this purpose. The BPNN with feed forward learning algorithm was a better model than SALTMOD in predicting salinity of drainage effluent.

2.6.2. Nutrient Management

Several workers suggested that INM should be very useful to achieve greater sustainable crop yields [16,113,114]. In coastal soils of Tamil Nadu, application of agro-industrial wastes significantly improved SOC, pH, EC and population of soil bacteria, fungus and actinomycetes and thus enhanced the soil fertility status (macro and micro nutrients) and improved the crop productivity of finger millet. Application of pressmud at 12.5 ton ha^{-1} resulted in better growth and yield of finger millet followed by composted coirpith at 12.5 ton ha^{-1} [115].

2.6.3. Integrated Water Management (IWM)

Yadav *et al.* [116] highlighted that in actual practice, application efficiencies of surface systems range between 30% and 60% with the latter figure being found in modern, well designed and managed systems; sprinkler systems generally achieve efficiencies in the range of 60%–85%, and drip systems commonly operate at 85%–95% efficiency [117,118]. The prospects of using poor quality water for plant growth have been discussed by Minhas and Rao [119] and Gupta [120]. They emphasized the use of fresh water layer floating on the dense saline underground water through skimming and the use of freshwater alone stored at the surface as well as consumptive use through judicial combination of saline and freshwater available at the surface and at sub-surface layers. Various skimming well configurations such as single, multi-strainer, radial collector and scavenger wells are possible to selectively obstruct fresh water from thin layers overlying saline ground water [117]. Large diameter open skimming wells with sump based technology are operated on a large scale in coastal sandy soils of Andhra Pradesh. Using skimming water, farmers are raising paddy rice, tobacco, chili nurseries, vegetables, flowers plants and groundnut using jerries, which can decrease water drop effect on tender plants. Besides this, the system also could supply water for dairy and drinking in rural areas [117].

2.6.4. Watershed Approach

Coastal watersheds are different from inland watersheds. Salinity gradients occur at the mouth of rivers and are important hydrologically and ecologically. Salt wedges occur with incoming tides at estuaries where rivers meet up with ocean water resulting in various combinations of fresh and salt waters. Coastal watersheds not only include tidal influence but also sea-spray influence. Salt water spray even affects the salinity of freshwater watersheds. A land conservation plan should be separately formulated. Other specific target areas are maintenance of hydrology of rivers and streams and improvement of surface water storage, estimation of the water balance of the entire watershed through an integrated approach of drainage and surface water recharge, conservation of floodwater discharge from uplands or inland ecosystems for recharging surface water resources, mitigation of problems arising out of sedimentation, seawater intrusion, pollution, hypoxia and eutrophication, sustenance of the ecology as diverse habitat for wildlife, flora and fauna, and creation of recreational opportunities.

Another major technology is use of amendments for salt affected soils and that is well described in the manuscript.

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