Decadal changes in land degradation status of India

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Robust data on the spatial distribution of land degradation is important for resource conservation planning. Spatial land degradation status of India was mapped using multi-temporal Linear Imaging Self Scanning Sensor (LISS-III) data acquired from Resourcesat-1/2 during 2005–2006 and 2015–2016 under the Natural Resources Census programme of the Indian Space Research Organisation. Heads-up on-screen visual interpretation of multi-season satellite data was carried out, supported by digital elevation model and other historical maps available. Visual interpretation cues were developed and employed across various partner institutions to achieve consistency in mapping. The outputs were subjected to two-stage quality check. Results indicate that the total land degradation of India was 91.2 M ha (27.77% of the geographical extent of the country) during 2015–2016 against 91.3 M ha during 2005–2006. During the ten-year period, there was an overall decrease of around 0.1 M ha in degraded land. However, noticeable intra- and inter-class changes were observed in land degradation during the ten-year period. Major reclamation was noticed in sand dunes which were converted into crop lands by levelling them. Substantial decrease in severity and extent of salt-affected soils was noticed in Uttar Pradesh.

Keywords: Change detection, land degradation, visual interpretation, sand dunes, soil erosion, spatial distribution.

LAND degradation (LD) is a temporary or permanent impairment of productivity of land through deterioration of physical, chemical or biological aspects. India is bestowed with vast natural resources. However, it suffers from a variety of LD problems affecting the quality and quantity of available land. India homes more than 18% of world's population over an area that is just 2.42% of global spread[1]. At present per capita arable land is around 0.15 ha in India and it is expected to decrease to a meagre 0.09 ha by 2075 (ref. 2). Ensuring sustainable land management is important, with India having an estimated 28% of its geographical area under LD[3]. Development or reclamation of these degraded lands is an important option available to increase food production in the country, to meet the requirements of the growing population as well as restoring fragile ecosystems. The lack of proper land-use planning and adequate information on soil resources has resulted in many of the present-day LD problems in India. These are mainly severe erosion in catchments leading to siltation of reservoirs, salinity/alkalinity and waterlogging in command areas, etc.[4].

LD neutrality is gaining importance to compensate for the natural resources requirement of the ever increasing population. During the recent Conference of Parties (COP-14), India has committed to United Nations Convention to Combat Desertification (UNCCD) to achieve LD neutrality by 2030 (https://www.unccd.int). The country is the torchbearer for development of watersheds, in which information on LD status becomes an important component for prioritization. All these efforts need to be supported with thorough technical inputs, effective policies, adequate financial resources, participation of stakeholders, and a strong institutional mechanism to execute and monitor the efforts.

Remote sensing data are being regularly employed in the survey of degraded soils, because of the development of operational methodologies[5]. Several attempts have been made by various organizations to map/derive the spatial distribution of LD status in India. Table 1 summarizes some of these efforts.

To assess and monitor the status of LD in India, a nationwide LD mapping at 1 : 50,000 scale using multi-temporal Resourcesat-1/2 LISS-III data was taken up by the Indian Space Research Organisation (ISRO). This mapping had been carried out using satellite data of 2005–2006 as well as 2015–2016 with due support from partner institutions like State Remote Sensing Centres, Central Arid Zone Research Institute (CAZRI), Jodhpur, Rajasthan, academia and other ISRO Centres with the objectives to monitor LD status at 1 : 50,000 scale using Resourcesat LISS-III satellite data for three seasons (*kharif*, *rabi* and *zaid*). The exercise will help in finding changes in LD status between 2005–2006 and 2015–2016. The present study highlights the results obtained on decadal changes as well as the current status of LD in India.

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Table 1. National estimates of land degradation (LD) in India

Organization	Year	Area mapped as land degradation (M ha)	Broad methodology
National Remote Sensing Centre (NRSC)/(ISRO) (present study)[14]	2015–16	91.20	Visual interpretation of multi-season LISS-III data
Space Applications Centre (SAC)/ISRO	2011–13	96.40	Visual interpretation of multi-season AWiFS data
NRSC/ISRO[3]	2005–06	91.29	Visual interpretation of multi-season LISS-III data
SAC/ISRO	2003–05	94.53	Visual interpretation of multi-season AWiFS data
Department of Land Resources	2005	55.27	Visual interpretation of satellite data at 1 : 50,000 scale
National Bureau of Soil Survey (NBSS) & Land Use Planning (LUP) (revised)[15]	2005	146.82	Based on 1 : 1 million scale soil map
Department of Land Resources	2000	63.8	Visual interpretation of satellite data at 1 : 50,000 scale
NBSS and LUP[16]	1994	187.7	Mapping on 1 : 4 million scale based on the Global Assessment of Soil Degradation (GLASOD) guidelines
Ministry of Agriculture (MoA), Government of India (GoI)[17]	1994	107.4	Elimination of duplication of area. The area reclaimed also counted
National Remote Sensing Agency[18]	2000	53.3	Mapping on 1 : 1 million scale based on remote sensing techniques
National Wasteland Development Board[19]	1985	123	–
Society for Promotion of Wastelands Development[20]	1984	129.58	Based on secondary estimates
Department of Environment[7]	1980	95.0	–
MoA-Soil and Water Conservation Division[21]	1978	175	Based on the National Commission on Agriculture's estimates. No systematic survey was undertaken
National Commission on Agriculture[22]	1976	148.0	Based on the secondary data

Materials and methods

Study area and database

LD status was mapped for the whole land mass of India. For this, the Resouresat-1/2 LISS-III data acquired during August to October (*kharif*), November to March (*rabi*) and April to May (summer) of 2005–2006 and 2015–2016 were used. About 900 LISS-III images per season and per year were used in the study. Besides, the salt-affected soil maps prepared during 1985–1990, land-use/land-cover maps prepared at 1 : 50,000 scale as well as wasteland maps generated by the National Remote Sensing Centre (NRSC; http://bhuvan.nrsc.gov.in) were used as reference. Digital elevation model (DEM) employing Cartosat-1 data was used to derive slope information.

Methodology

The overall approach is based on visual interpretation of ortho-rectified multi-temporal LISS-III satellite data. Initially, a national workshop was conducted in 2005 to achieve consensus on the classification system to be adopted for LD mapping, with the active participation of various State Remote Sensing Centres, Indian Council of Agricultural Research (ICAR) organizations, Agriculture Universities and others. These discussions culminated in the identification of eight major LD processes for mapping, namely water erosion, wind erosion, waterlogging, acidification, salinization/alkalization, anthropogenic, glacial and others with 36 LD classes. Table 2 presents the detailed classification scheme along with class definitions.

Initially, the multi-temporal satellite data of three seasons were ortho-rectified and provided to the partner organizations. To achieve consistency of mapping across various partner institutions, interpretation cues for mapping LD using multi-temporal LISS-III data were developed during the first cycle of LD mapping (2005–2006). The process includes ortho-rectification and radiometric normalization of multi-temporal satellite data, which were used subsequently for preliminary visual interpretation of multi-temporal LISS-III data. Based on the consistency/variation of LD across terrains with respect to slope, elevation, historical information of salt-affected soils as well as wastelands, field sampling sites were selected. Soil samples were collected from 0 to 15 and 15 to 30 cm depths wherever salinity/alkalinity or acidification processes were active. About 2913 soil samples collected from across India exclusively under this project were analysed and results used in the categorization of classes under salinization/alkalization as well as acidification processes. Soil chemical analysis was carried out for pH and electrical conductivity (EC; 1 : 2 soil water suspensions) for identification of nature and degree of the LD problem.

Quality checks at various stages were made as an integral part of the study. These were conducted at data

Table 2. Definition of LD classes

Class	Description
Water erosion: sheet erosion – slight	A decrease in depth of the topsoil layer (A horizon) due to more or less uniform removal of soil material by run-off water resulting in soil loss of 10–20 tonnes/ha/yr
Water erosion: sheet erosion – moderate	A decrease in depth of the topsoil layer (A horizon) due to more or less uniform removal of soil material by run-off water resulting in soil loss of 20–40 tonnes/ha/yr
Water erosion: sheet erosion – severe	A decrease in depth of the topsoil layer (A horizon) due to more or less uniform removal of soil material by run-off water resulting in soil loss of more than 40 tonnes/ha/yr
Water erosion: rills	An irregular displacement of soil material causing clearly visible scars in the terrain – moderate
Water erosion: gullies	Gullies – network of rills – severe
Water erosion: ravines – shallow	Ravines – shallow – very severe
Water erosion: ravines – moderately deep to deep	Ravines – moderately deep to deep – extreme
Wind erosion: sheet – slight	Sheet erosion – slight uniform displacement of topsoil wind action
Wind erosion: sheet – moderate	Sheet erosion – moderate uniform displacement of topsoil wind action
Wind erosion: sheet – severe	Sheet erosion – severe uniform displacement of topsoil wind action
Wind erosion: stabilized dunes	Stabilized dunes – slight stabilized sand dunes with good cover of sod-forming plants (>60% cover)
Wind erosion: partially stabilized dunes	Partially stabilize dunes – moderate. Partly stabilized sand dunes with moderate cover of sod forming plants (30–60%) subjected to moderate deformation Deformation with moderate cover of sod-forming plants (30–60%).
Wind erosion: unstabilized dunes	Unstabilized dunes – severe. Sand dunes subjected to severe deformation. They are generally devoid of any vegetation cover
Waterlogging: surface ponding – seasonal	Surface ponding – slight. Waterlogging with 4–6 months of ponding affecting one crop (excluding paddy)
Waterlogging: surface ponding – permanent	Surface ponding – moderate. Permanent waterlogging with more than 6 months ponding affecting one crop (excluding paddy areas)
Waterlogging: subsurface	Subsurface water logging. Area with water table close to the surface affecting crop growth and performance. Areas with water table <2 m are considered.
Salt-affected: saline – slight	pH < 8.5 and electrical conductivity (EC) of 2–4 dS/m for black soil and 4–8 dS/m for other soils (1 : 2 soil water suspension)
Salt-affected: saline – moderate	pH < 8.5 and EC of 4–8 dS/m for black soil and 8–16 dS/m for other soils (1 : 2 soil water suspension)
Salt-affected: saline – severe	pH < 8.5 and EC of >8 dS/m for black soil and >16 dS/m for other soils (1 : 2 soil water suspension)
Salt-affected: sodic – slight	pH > 8.5 (1 : 2 soil : water suspension), and exchangeable sodium percentage (ESP) of 5–10% for black soil and 15–40% for other soils
Salt-affected: sodic – moderate	pH > 8.5 (1 : 2 soil : water suspension), and ESP of 10–20% for black soil and 40–60% for other soils
Salt-affected: sodic – severe	pH > 8.5 (1 : 2 soil : water suspension), and ESP of >20% for black soil and >60% for other soils
Salt-affected: saline sodic – slight	pH < 8.5, EC 2–4 dS/m and ESP of 5–10% for black soil, and EC of 4–8 dS/m and ESP of 15–40% for other soils
Salt-affected: saline sodic – moderate	pH < 8.5, EC 4–8 dS/m and ESP of 10–20% for black soil, and EC of 8–16 dS/m and ESP of 40–60% for other soils
Salt-affected: saline sodic – severe	pH < 8.5, EC > 8 dS/m and ESP of >20% for black soil, and EC of >16 dS/m and ESP of >60% for other soils
Rann	Large contiguous area of salt marshes
Acidity – moderate	Acidity – moderate: pH 4.5–5.5 (1 : 1 soil-KCl) Forest and paddy areas excluded
Acidity – severe	Acidity – severe: pH < 4.5 (1 : 1 soil-KCl) Forest and paddy areas excluded
Frost heaving	Frost heaving. Areas with ice in the subsurface horizons leading to expansion of soil, forming undulations on the surface. This restricts the growth of plants.
Frost shattering	Frost shattering. Areas with shuttered material because of freezing and thawing in periglacial environments.
Industrial effluent-affected areas	Industrial effluent-affected areas. The areas affected with effluents discharged from industries (areas under industry per se excluded)
Mining and dump areas	Mining. Surface/open-cast mines, including mine dumps
Brick kiln areas	Brick kiln areas
Mass movement/mass wastage	Mass movement/mass wastage: areas with landslides.
Barren rocky/stony waste	Barren rocky/stony waste. Rock outcrops/sheet rock exposures devoid of vegetation
Miscellaneous – riverine sands/sea ingress areas	Miscellaneous – riverine sands/sea ingress, etc. Includes mainly sands other than desert areas
Normal	No apparent land degradation

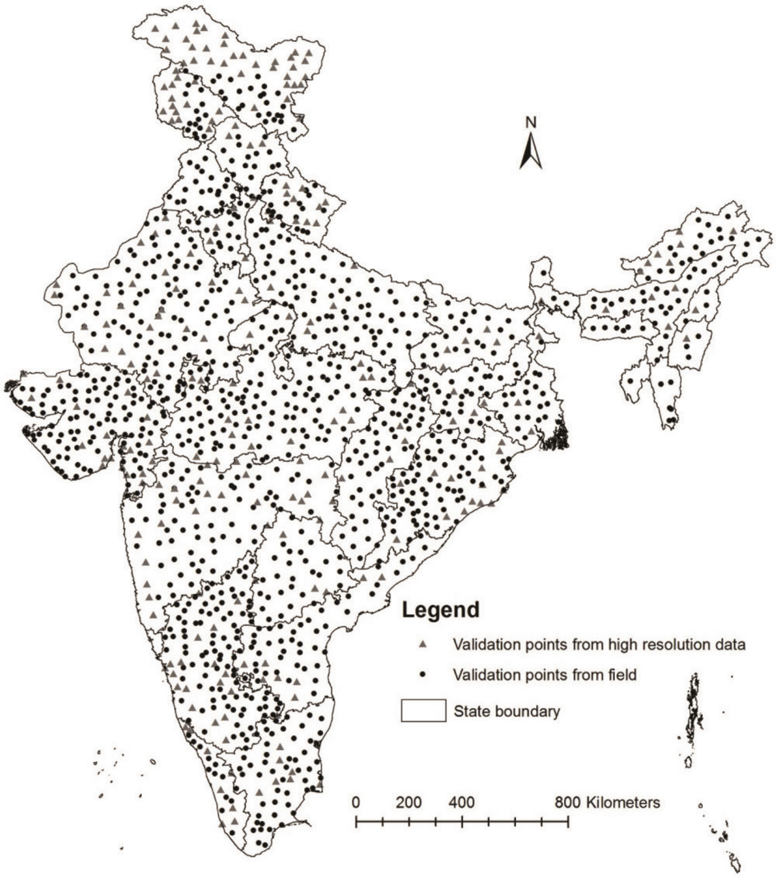

Figure 1. Location of observations used for accuracy assessment.

ingest level, preliminary visual interpretation and final thematic output by the duly constituted inter-centre teams. The quality checks for soil sample analysis were also conducted based on their location vis-à-vis historical maps, temporal variations in reflectance from satellite data, logical range in values and historical soil sample results available with us.

For 2015–2016, changes in area were identified based on visual representation of features in 2005–2006 and 2015–2016 in multi-season LISS-III data and the 2005–2006 polygons were updated appropriately. A polygon of 3 mm × 3 mm size (equivalent to 2.25 ha area) and a minimum mapping unit on 1 : 50,000 scale were retained, except for the significant classes like brick kilns and mass movements, where even smaller than 2.25 ha area was retained. Overlay analysis for LD status of 2005–2006 and 2015–2016 was performed to understand the geospatial variation in LD changes.

Accuracy assessment

The accuracy of the LD map was estimated using validation data consisting of 1931 points collected across the country (Figure 1). The contingency matrix was generated using field data as reference points and kappa coefficient of the map estimated for 2015–2016. The error matrix represents cross tabulation of various LD class categories assigned on the map vis-à-vis ground-truth data. The various LD processes classified in the map and reference classes were represented in rows and columns respectively, in the confusion matrix. The kappa coefficient represents the extent of agreement between frequencies of two sets of data collected on two different occasions[6]. The following equation was used to compute the confidence interval of kappa statistic[7]

$$\mu = z * [p * (1 - p)/n]^{1/2},$$

where μ is the confidence interval, z the function of the level of confidence of the test, p the first-level accuracy of the system/assumed accuracy and n is the number of samples.

Results and discussion

LD is evidently distributed across various parts of India. The total LD status of the country was estimated at 91.30 M ha during 2005–2006, while it was 91.21 M ha

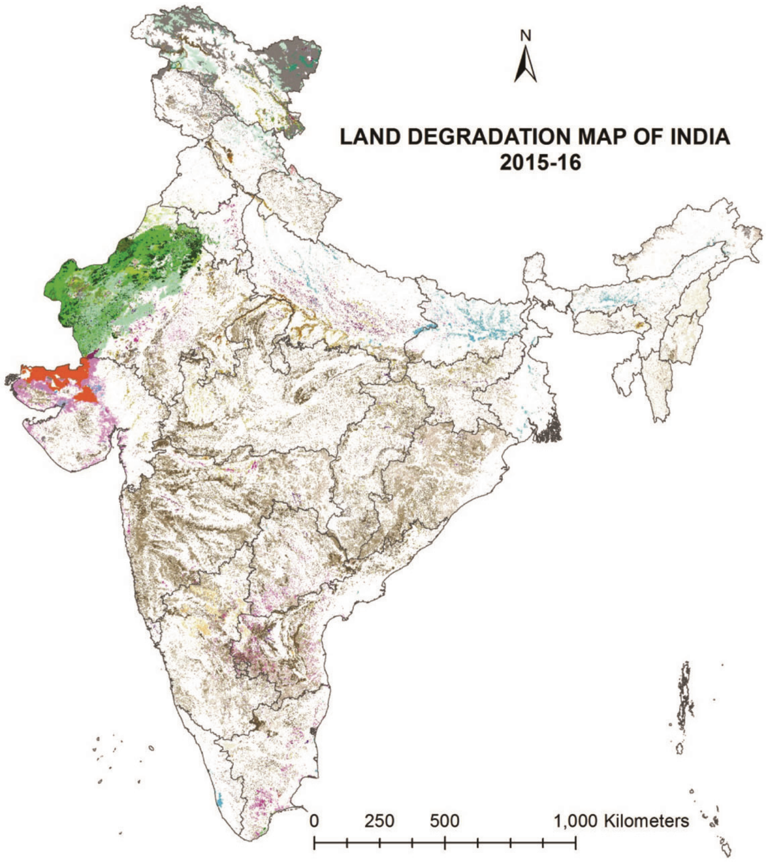

Figure 2. Land degradation map of India 2015–16.

Process	Code	Land degradation class	Symbol
Water erosion	A1	Sheet erosion – slight	
	A2	Sheet erosion – moderate	
	A3	Sheet erosion – severe	
	A4	Rills	
	A5	Gullies	
	A6	Ravines – shallow	
	A7	Ravines – deep	
Wind erosion	B1	Sheet erosion – slight	
	B2	Sheet erosion – moderate	
	B3	Sheet erosion – severe	
	B4	Stabilized dunes	
	B5	Partially stabilized dunes	
	B6	Unstabilized dunes	
Waterlogging	C1/C2	Surface ponding – seasonal/permanent	
	C3	Subsurface waterlogged	
Salinization/alkalization	D1-D3	Saline – slight/moderate/severe	
	D4-D6	Sodic – slight/moderate/severe	
	D7-D9	Saline sodic – slight/moderate/severe	
	D10	Rann	
Acidification	E1/E2	Acidic – moderate/severe	
Glacial	F1	Frost heaving	
	F2	Frost shattering	
Anthropogenic	G1	Industrial effluent-affected areas	
	G2	Mining and dump areas	
	G3	Brick kiln	
Others	H1	Mass movement/mass wastage	
	H2	Barren rocky/stony waste	
	H3	Riverine sands/sea Ingress, etc.	

Table 3. Category-wise distribution of LD (2015–2016) in different states of India (area in ha)

State	Water erosion	Wind erosion	Waterlogging	Salinization/ alkalization	Acidification	Glacial	Anthro-pogenic	Others	Total
Andhra Pradesh	4,773,702	15,556	4,399	365,639			59,452	292,008	5,510,756
Arunachal Pradesh	442,920		35,033		3,36,881	585		167,442	982,861
Assam	359,168		268,671		73,885		11,703	27,990	741,417
Bihar	345,027		711,112	113,918			4787	16,834	1,191,678
Chhattisgarh	3,236,127				94		37,451	356,281	3,629,953
Goa	24,732		769	1,347	37		8823	7,373	43,081
Gujarat	1,618,709	1,328	85,339	3,793,377			35,645	454,500	5,988,898
Haryana	107,110	131,052	35,260	95,852			9,078	10,869	389,221
Himachal Pradesh	315,119		41			737,847	1,797	225,037	1,279,841
Jammu and Kashmir	247,647		1,187			100,909	1,135	1,039,725	1,390,603
Jharkhand	1,196,920		354				45,979	76,523	1,319,776
Karnataka	4,876,020		2,004	116,510	33,797		62,217	179,657	5,270,205
Kerala	74,695		69,037		54,092		5,691	94,021	297,536
Ladakh	500,070	236,594		45,602		1,786,476		6,313,507	8,882,248
Madhya Pradesh	5,630,509		92	25,601			42,598	210,642	5,909,442
Maharashtra	10,613,283			183,433	1351		46,212	148,627	10,992,906
Manipur	221,931		1,343		631,463			261	854,998
Meghalaya	86,767		304		458,765		7,387	83,264	636,487
Mizoram	266,577				469,594				736,171
Nagaland	35,843				743,388		888		780,119
Odisha	5,832,981	335	16,091	3,057	18,835		34,370	61,448	5,967,117
Punjab	62,568	44,311	11,447	4,252			12,614	23,463	158,655
Rajasthan	2,752,487	13,805,182	8,769	536,207			91,655	839,766	18,034,066
Sikkim	5362					11,271		59,657	76,290
Tamil Nadu	1,766,278	45,382	10,540	346,468	124,141		28,495	119,237	2,440,541
Telangana	2,879,100		2,499	230,639	249		48,855	72,079	3,233,421
Tripura	6076		298		94,906		1,050	392	102,722
Uttar Pradesh	1,695,505		444,966	600,630			24,300	92,509	2,857,910
Uttarakhand	621,798		188			246,776	2,040	74,731	945,533
West Bengal	341,584		111,657	753			30,219	9,327	493,540
Andaman and Nicobar Islands	47,388						191	5,349	52,928
Chandigarh	57								57
Dadra Nagar Haveli	5802		28						5,830
Daman and Diu	329		364				133	41	867
Delhi	6098						21	1179	7,298
Lakshadweep								42	42
Puducherry	16		3	1326				303	1,649
Grand total	50,996,301	14,279,746	1,821,795	6,464,608	3,041,478	2,883,858	654,791	11,064,073	91,206,650
% Total geographic area	15.53	4.35	0.55	1.97	0.93	0.88	0.20	3.37	27.77
% LD	55.91	15.66	2.00	7.09	3.33	3.16	0.72	12.13	100.00

(which is 27.77% of the geographical extent of India) during 2015–2016. Figure 2 shows the LD map of India for 2015–2016.

Table 3 shows the process-wise overall status of LD in India during 2015–2016.

In 2005–2006, about 91,298,198 ha of land was under various processes of LD in India, while it had reduced to 91,206,650 ha during 2015–2016, showing a marginal decrease in LD status just over a decade. The process-wise extent of LD during 2015–2016, along with necessary explanation is presented in the following sections. Table 4 presents the crossmatrix of decadal changes in LD. Table 5 lists the positive and negative changes in LD extent during the ten-year period.

Spatial distribution of land degradation during 2015–2016

Water erosion was the major process causing LD in India, accounting for 55.91% of total LD or 15.53% of total geographical area (TGA) of the country. This was followed by wind erosion spread over nearly 14,279,746 ha and accounting for 15.66% of total LD or 4.35% of TGA. The salinization/alkalization (comprising various categories like saline, sodic and saline–sodic and Rann) was spread over 6.5 M ha, accounting for 7.09% of total LD. Acidification covered over 3.04 M ha (3.33% of total LD); this spatial extent excluded paddy lands, dense forests and plantations. The barren rocky, mass movement

Table 4. Processwise changes in LD status of India (area in ha)

	LD process	A (2015–16)	B (2015–16)	C (2015–16)	D (2015–16)	E (2015–16)	F (2015–16)	G (2015–16)	H (2015–16)	N (2015–16)	Total	Total (2005–06)
2005–06	A	50,721,583		66	39			54,710	340	241,205	51,017,942	
	B		14,279,651		6			799		119,370	14,399,826	
	C			1,736,640	9,551			873	523	102,815	1,850,402	91,298,198
	D			2117	6,442,877			4,293		70,000	6,519,287	
	E	286				3,041,478		95	221	3,445	3,045,525	
	F						2,883,858			0	2,883,858	
	G	249						479,983		8,461	488,692	
	H	257		841	11,397			24,758	11,048,828	6,583	11,092,665	
	N	273,926	95	82,131	738			89,281	14,160		460,331	
	Total	50,996,301	14,279,746	1,821,795	6,464,608	3,041,478	2,883,858	654,791	11,064,073			
	Total (2015–16)				91,206,650							

A, Water erosion; B, Wind erosion; C, Waterlogging; D, Salinization/alkalization; E, Acidification; F, Glacial; G, Anthropogenic; H, Others; N, Normal.

Table 5. Major positive and negative decadal changes in LD status of India

Negative changes	Area (ha)
Water erosion moderate → water erosion severe	314,158
Normal → water erosion	273,926
Water erosion slight → water erosion moderate/severe	194,833
Normal → waterlogging	82,131
Water erosion → industrial effluent-affected areas/mining/brick kiln	54,710
Normal → industrial effluent-affected areas/mining/brick kiln	63,318
Normal → mass movement/riverine sand	14,160
Riverine sand → salinity	11,397
Saline slight → saline moderate/severe	10,481
Waterlogging → salinity	9,551
Seasonal waterlogging → surface permanent/subsurface waterlogging	5,643
Saline moderate → saline severe	3,945
Normal → salinity	738
Riverine sand → waterlogging	841
Sodic slight → sodic moderate/severe	824
Wind erosion → industrial effluent-affected areas/mining/brick kiln	799
Saline sodic slight → saline sodic moderate/severe	645
Water erosion → mass movement/riverine sand	340
Acidity moderate → acidification severe	1,351
Waterlogging → mining/brick kiln	857
Positive changes	**Area (ha)**
Partially stabilized/unstabilized dunes → stabilized dunes	439,210
Water erosion severe → water erosion moderate	418,631
Water erosion moderate/severe/rills → water erosion slight	350,644
Water erosion → normal	219,165
Wind erosion → normal	119,448
Waterlogging → normal	103,643
Salinity → normal	69,942
Barren rocky → mining	24,447
Saline moderate → saline slight	19,525
Saline severe → saline moderate/slight	16,914
Stabilized/unstabilized dunes → wind sheet erosion	15,676
Industrial effluent-affected areas/mining/brick kiln → normal	8,493
Mass movement/barren rocky/riverine sand → normal	8,310
Surface permanent/subsurface waterlogging → seasonal waterlogging	6,328
Salinity → industrial effluent-affected areas/mining/brick kiln	4,293
Saline sodic severe → saline sodic moderate	4,089
Acidification → normal	3,448
Saline sodic moderate → saline sodic slight	2,767
Sodic moderate → sodic slight	2,226
Salinity → waterlogging	2,117
Unstabilized dunes → partially stabilized dunes	953
Waterlogging → riverine sand	523
Sodic severe → sodic slight/moderate	460

Note: Though transformations in salinity and waterlogging are mentioned as positive and negative changes, they are associative problems in majority of areas.

and riverine sands ('others' category) accounted for 12.13% of total LD (3.37% of TGA).

Among the states, Rajasthan had maximum LD extending over 18.03M ha and accounting for 19.77% of total LD of the country. The main process of LD was wind erosion in this state, followed by water erosion. Rajasthan was closely followed by Maharashtra with 10.99 M ha land under LD, accounting for 12.05% of total LD (Table 3). In Maharashtra, the major LD process was water erosion, followed by salinization/alkalization.

Water erosion was found to be the dominant process in majority of the states, especially in the central plateau region of India. It was highest in Maharashtra, followed by Odisha and Madhya Pradesh. High rainfall variability and intensity, undulating terrain conditions and moderate to high erodibility of soils were the major factors for extensive water erosion in these areas. Soils of Maharashtra are mainly black with high clay content. Here, farmers allow the water to flow out during rainy season to avoid water logging associated with low infiltration capacity in these soils, the main reason for soil erosion by water in such areas. In the red soil region of the southern plateau, the undulating terrain conditions and cultivation practices along the slopes are the main factors for sheet erosion by water[8]. The decadal changes in soil erosion status indicate a marginal decrease in the spatial extent. However, substantial decrease in severity of water erosion classes was noticed, associated with better land-cover conservation measures mainly through surface canopy cover.

Wind erosion occurred over 14.28 M ha land, contributing to 15.66% of total LD in India or 4.35% of TGA. Wind erosion was predominant in the arid regions, mostly in Rajasthan (hot desert) as a dominant process, followed by Ladakh (cold desert) and Haryana. It occurred to a lesser extent in Tamil Nadu, Punjab, Andhra Pradesh, Gujarat and Odisha, in decreasing order. Sand dunes formed due to localized sand deposition were the main form of wind erosion, followed by removal of fine soil in the form of sheet erosion. Lack of natural vegetation cover due to the prevailing arid conditions and poor binding capacity of soils were the main reasons for wind erosion in these areas. The accelerated wind erosion problems in western Rajasthan due to anthropogenic interventions have been highlighted by many researchers[9].

Acidification was spread over 3.04 M ha (3.33% of total LD), excluding paddy lands and dense forest areas as well as plantations. It was pronounced in Nagaland, Manipur, Mizoram, Meghalaya, Arunachal Pradesh, Tamil Nadu, Tripura, Assam, Kerala, Karnataka, Odisha and Maharashtra, in a decreasing order. This was mostly confined to the high-rainfall regions and mainly formed due to leaching of alkaline salts to lower depths[10]. In these areas, the acid soils under plantation crops and paddy fields were excluded from mapping. The areas under dense forests/plantations were excluded since acidification does not affect the yield significantly. In paddy-growing areas, pH of soils increases under submerged conditions[11], thereby neutralizing the ill-effects of low pH on crop performance.

Waterlogging was found to be highest in Bihar, followed by Uttar Pradesh and Assam. It was spread over an area of 1.82 M ha, accounting for 2.00% of total LD in India. It was observed to a lesser extent in Himachal Pradesh, Madhya Pradesh, Uttarakhand, Tripura, Meghalaya, Jharkhand, Goa, Manipur, Jammu and Kashmir, Karnataka and Telangana, in increasing order of area. However, this LD process was not found in Chhattisgarh, Maharashtra, Mizoram, Nagaland and Sikkim. It was mainly confined to the coastal areas and lower slope elements. The reasons for waterlogging vary from area to area due to localized factors. For example, in Uttar Pradesh, waterlogging is mainly observed in the central and eastern parts where vertical movement of water is restricted due to the presence of subsurface kankar layer. While in undulating granitic terrain of NorthEast, Central and South India, water logging is confined to the lower elements of slope due to accumulation of sub-surface seepage from the adjacent upland irrigated paddy fields. The duration of water logging in these areas is seasonal.

The salinization/alkalization was spread over 6.46 M ha, accounting for 7.09% of total LD in India. It was found extensively in Gujarat (4.2% of total LD), followed by Uttar Pradesh (0.66%) and Rajasthan (0.59%). This process was significant in Andhra Pradesh, Tamil Nadu, Telangana, Maharashtra, Bihar, Karnataka, Haryana, Ladakh, Madhya Pradesh, Punjab and Odisha, in decreasing order of area. In Gujarat, it was mainly due to saline water intrusion into coastal areas from the sea. In the northern alluvial belt, the salt-affected areas were mainly saline–sodic and sodic in nature with geogenic origin from alluvium. Alkalization in the southern plateau was mainly located in the valley-fill areas, formed due to chemical weathering of plagioclase feldspar. The salinization source was mainly coastal saline water intrusion in this region. Distribution of sodic soils showed common occurrence in the arid and semi-arid regions[12]. Besides, states such as Rajasthan and Haryana are affected with poor-quality groundwater. Continuous use of pumped water for irrigation has contributed to the problem of salinity and sodicity[13].

Glacial processes consisting of frost shattering and frost heaving covered an area of 2.88 M ha, i.e. 3.16% of total LD or 0.88% TGA. Glacial processes, as the name suggests, occur in the cold desert areas in Jammu and Kashmir, Ladakh, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh. The dominant degradation type is frost shattering, followed by frost heaving. The frost heaving occurs in the valley regions where the subsurface is frozen, making it difficult for useful plants to grow. Most of these lands remain as pastures and cannot support any crops.

The anthropogenic processes which include industrial affluent areas, mining and dumps and brick kilns extended to an area of 6548 km^2, accounting for 0.72% of total degraded land in the country. The extent of LD due to anthropogenic activities was found maximum in Karnataka, Rajasthan and Andhra Pradesh followed by Telangana. The main source of LD due to anthropogenic activities was mining, followed by brick kilns.

Other LD processes like barren rocky outcrops, mass movement and riverine sand were observed to a maximum extent in Ladakh, Jammu and Kashmir and Rajasthan, followed by Gujarat, accounting for 12.13% of total LD or 3.37% of TGA. Barren rocky areas are considered as degraded land with no further possibility of severity change. Mass movement was mainly distributed in the foothill zones of the Himalayan region.

Decadal changes in land degradation status

Area under LD in India during 2005–2006 (first cycle) was 91.30 M ha, which reduced marginally to 91.21 M ha during 2015–2016 (second cycle). The change analysis between the first and second cycles of LD revealed an

Table 6. Accuracy assessment

Class description	LD class code	Producer's accuracy	User's accuracy	Producer's confidence interval	User's confidence interval
Normal areas (with no apparent land degradation)	Normal	0.926	0.959	0.016	0.013
Water erosion: sheet erosion – slight	A1	0.711	0.794	0.086	0.081
Water erosion: sheet erosion – moderate	A2	0.781	0.826	0.060	0.057
Water erosion: sheet erosion – severe	A3	0.692	0.806	0.086	0.079
Water erosion: rills	A4	0.867	0.867	0.102	0.102
Water erosion: gullies	A5	0.806	0.833	0.117	0.112
Water erosion: ravines–shallow	A6	0.909	0.811	0.082	0.106
Water erosion: ravines – moderately deep to deep	A7	0.917	0.825	0.076	0.099
Wind erosion: sheet – slight	B1	0.750	0.632	0.126	0.129
Wind erosion: sheet – moderate	B2	0.886	0.838	0.088	0.100
Wind erosion: sheet – severe	B3	0.852	0.719	0.112	0.131
Wind erosion: stabilized dunes	B4	0.806	0.833	0.117	0.112
Wind erosion: Partially stabilized dunes	B5	0.875	0.800	0.096	0.111
Wind erosion: unstabilized dunes	B6	0.935	0.967	0.073	0.054
Waterlogging: surface ponding – seasonal	C1	0.781	0.893	0.120	0.096
Waterlogging: surface ponding – permanent	C2	0.871	0.794	0.099	0.114
Waterlogging – subsurface	C3	0.947	0.857	0.084	0.126
Salt-affected: saline – slight	D1	0.680	0.810	0.153	0.141
Salt-affected: saline – moderate	D2	0.871	0.844	0.099	0.106
Salt-affected: saline – severe	D3	0.870	0.833	0.116	0.125
Salt-affected: sodic – slight	D4	0.875	0.840	0.111	0.121
Salt-affected: sodic – moderate	D5	0.897	0.765	0.093	0.120
Salt-affected: sodic – severe	D6	0.950	0.760	0.080	0.141
Salt-affected: saline sodic – slight	D7	0.778	0.875	0.132	0.111
Salt-affected: saline sodic – moderate	D8	0.964	0.900	0.058	0.090
Salt-affected: saline sodic – severe	D9	0.926	0.893	0.083	0.096
Rann	D10	0.919	0.895	0.074	0.082
Acidity – moderate	E1	0.783	0.857	0.141	0.126
Acidity – severe	E2	0.913	0.724	0.097	0.137
Frost heaving	F1	0.966	0.875	0.056	0.096
Frost shattering	F2	0.964	0.794	0.058	0.114
Industrial effluent-affected areas	G1	0.923	0.828	0.086	0.115
Mining and dump areas	G2	0.960	0.828	0.064	0.115
Brick kiln areas	G3	0.938	0.909	0.070	0.082
Mass movement/mass wastage	H1	0.923	0.828	0.086	0.115
Barren rocky/stony waste	H2	0.730	0.871	0.120	0.099
Miscellaneous – riverine sands/sea ingress areas	H3	0.821	0.821	0.119	0.119

overall decrease to a tune of 915 km^2 (0.03% of TGA of the country) during a ten-year time span.

Various efforts of land reclamation and soil conservation measures have resulted in the conversion of 0.55 M ha of LD area to normal category (no apparent LD) during these 10 years (Table 5). The conversion of LD areas to normal category was observed in water erosion (0.24 M ha) followed by wind erosion (0.12 M ha), waterlogging (0.10 M ha) and salinity (0.07 M ha) areas. Majority of such changes were found in Rajasthan, Odisha, Haryana, Gujarat, Maharashtra and Madhya Pradesh.

A sizable increase in LD was observed in Mizoram, Assam, Arunachal Pradesh, Bihar, Manipur, Nagaland and Meghalaya, mainly due to landslides and shifting cultivation. The changes were not only from normal class to other LD classes or vice versa, but also within the classes of the same LD process/between different LD processes. Table 5 presents the decadal changes in LD processes. It is obvious that the anthropogenic-related degradation was the main cause for increase in LD during the study period. It can also be noted that a sizable area was brought to normal use mainly through soil conservation programmes as well as salt-affected soil reclamation programmes adopted under specific missions, and under the watershed development programmes of the Union and State Governments.

During the ten-year period of analysis, an area of 0.46 M ha of normal land was observed to have degraded. Among the main processes, water erosion contributed maximum (0.27 M ha), followed by anthropogenic activities (0.09 M ha) and waterlogging (0.08 M ha). Such changes were found in Mizoram, Odisha, Assam, Bihar and Arunachal Pradesh.

Table 5 also provides category-wise decadal changes in LD. These include both positive and negative changes and are arranged in decreasing order of areal extent. The main improvement in LD status was stabilization of sand dunes. During this period, nearly 0.22 M ha of land was restored to normal from water erosion. The changes from waterlogged areas to normal (nearly 0.1 M ha) could be achieved through improved drainage conditions and also due to less rainfall during 2015–2016.

In Rajasthan, Jharkhand, Punjab and Odisha, the normal category (no apparent LD) was converted to degraded land by anthropogenic activities. Areas under waterlogging during 2005–2006 in Haryana, Kerala, Gujarat, Assam and Punjab have been changed to normal category, while in Bihar, Assam, Haryana and West Bengal normal lands became waterlogged in 2015–2016.

It was observed that majority of area under water erosion was being converted to mining and brick kilns. These changes to brick kilns were noticed in alluvial plains, while mining was noticed in the Deccan Plateau region. Waterlogged areas were converted to saline patches in parts of Haryana, Uttar Pradesh, Gujarat and Punjab. The areas covered by sand dunes were changed to normal category in parts of Rajasthan and Haryana with the introduction of irrigation facilities.

Positive changes observed were from partially stabilized and unstabilized dunes to stabilized dunes (0.44 M ha), followed by water erosion–sheet erosion–severe/rills to water erosion–moderate (0.41 M ha) and water erosion to normal (0.22 M ha). Discernible negative changes occurred in the category of severe water erosion (0.78 M ha). This has resulted mainly due to improper agriculture practices followed in the tribal areas.

Accuracy assessment

Accuracy assessment was carried out to quantify the reliability of the LD map. Table 6 presents the accuracy estimation. Result shows an overall accuracy of 87.2%, with a kappa coefficient of 0.851. The producer's accuracy varied between 0.632 and 0.967, while the user's accuracy varied between 0.680 and 0.966.

Among all the classes, the 'slight' category of water as well as wind erosion showed relatively poor accuracy owing to the uncertainty associated with demarcation from normal lands due spectral similarity. Use of slope information from the DEM has improved its delineation to a great extent. Use of high spatial resolution datasets helped in improving the delineation associated with land conservation information, such as field bunds. The ravines have relatively clear signature, making it possible to delineate them with better accuracy (more than 0.9). Accuracy of gullied land (A4) delineation was mainly influenced by interference from scrub land. Due to usage of short wave infrared (SWIR) band, delineation of waterlogged areas could be improved substantially. Owing to the spectral contrast from normal background and knowledge obtained from historical salt-affected soil maps, salt-affected lands have been delineated with much better accuracy. The usage of location-terrain association and lithology of the area has helped in sub-categorizing these into saline, sodic and saline–sodic soils. Better accuracy of brick-kiln delineation was possible using high-resolution data and local knowledge available with partner institutions.

Among all these classes, the land with no apparent degradation (normal category) had the lowest confidence interval (CI) for both producer's and user's accuracy of 0.013. The highest CI was for the salt-affected–sodic–severe (D6) class with respect to producer's accuracy, while it was for the salt-affected–saline–slight (D1) class with respect to user's accuracy.

Conclusion

Resourcesat-based LISS-III sensors data were used for the assessment of LD characterization at district level. The existing geospatial database on LD should be useful for understanding vulnerability of soil resources for degradation, decadal changes in LD in the country, and prioritizing areas for land reclamation programmes. It should also serve as an important input to address the various components of LD neutrality to which India is committed in the recent COP-14 of UNCCD. For field-scale implementation planning of land reclamation programmes, use of very high spatial resolution data from sensors like Cartosat-2E is envisaged. Efforts are also being made to develop object classification based methodology for mapping large-scale LD status.

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