Annals of Arid Zone 63(4): 17-31, 2024

Land Degradation Neutrality: Concepts and Implementation Mechanism

Ajai*, Rimjhim Bhatnagar and A.S. Arya

Space Applications Centre, ISRO, Ahmedabad 380 015, India

Received: June 17, 2024 Accepted: September 26, 2024

Abstract: All forms of life on Earth depend on 'land' through varied means, such as finding habitats, getting the right environment for human beings to survive, using land as substrate for agriculture etc. In the recent times, land-based ecosystem goods and services have gone to unprecedented levels of land exploitation causing a sharp increase in the process of land degradation. About one-third of the global land surface has been affected by desertification and land degradation (DLD). More than 100 countries, comprising of about 2.6 billion people are under the effect of DLD- directly or in directly. In Asia alone, 38 out of 48 countries are affected while in India, about 32% of its geographical area is undergoing the process of DLD. The present paper discusses the fundamental concepts of land degradation, its causes and drivers and methods to mitigate it. National, regional and global efforts on mapping, monitoring and assessment of land degradation have been reviewed. United Nation's Land Degradation Neutrality (LDN) program, its conceptual framework and its implementation mechanisms in India has been discussed in detail.

Key words: Land degradation. desertification, land degradation neutrality, sustainable land management, remote sensing

OPEN ACCESS

****Correspondence***
Ajai
drajai_in@yahoo.com

Citation
Ajai, Bhatnagar, R. and Arya, A.S. 2024. Land degradation neutrality: Concepts and implementation mechanism. Annals of Arid Zone 63(4): 17-31

doi.org/10.56093/aaz.v63i4.152832

https://epubs.icar.org.in/index.php/AAZ/article/view/152832

Desertification and land degradation (DLD) is a slow but consistent geo-environmental hazard that manifests in the form of negative changes in the condition of soil and vegetation, quantity and quality of available water, ecosystem functions and services, changing climate etc. It is a consequence of complex interactions between physical, biological, meteorological, and many times socio-economic and cultural factors. DLD is found to occur in all the climatic zones of the world and has been a cause of concern with respect to the living conditions of tens of thousands of persons globally. More than 100 countries, comprising of about 2.6 billion people are affected by DLD- directly or indirectly (Ajai and Bhatnagar 2022). Globally, about one third of land has been severely affected with over 12 mha of land is lost every year to DLD. Looking at India's situation, about 32% of the total geographical area is facing land degradation and that too in the scenario when the country supports 16.7% of the world population and 18% of the cattle population while possessing only 2.4% of world's land and 0.5% of the grazing land respectively (Ajai *et al.*, 2009).

Land is one of the vital geo-resources for the man-kind which forms the basis of the life support system; land resources facilitate provisioning of several ecosystem goods and services such as food, and hence human well-being. Sustainable livelihood is dependent upon the health and productivity of these resources. While growing population and the associated demands are posing severe pressure on the land resources, climate change is also adding stress to the health of terrestrial ecosystems. Thus, there is an urgent need to take required steps towards arresting the process of land degradation, preventing the good and productive land from getting degraded as well as to restore the degraded land. In other words, we can say that we need to adopt the practice of land degradation neutrality or LDN (a term coined by UNCCD). At this point of time achieving land degradation neutrality is more of a need than choice. Achieving land degradation neutrality requires restoration of the degraded land, and prevention of the productive and healthy land from degradation by arresting the processes of degradation. Before diving deep into the details about the concept of LDN, the actions required and the implementation mechanism to achieve it, we need to understand the processes, causes and drivers and the strategies to combat land degradation and desertification.

Land Degradation and Desertification

In most simple terms, land degradation is a process that negatively impacts agricultural crops, livestock, and the land's ability to support forests and other vegetation.. In fact, a large number of definitions are available in the literature for both, land degradation and desertification (e.g. Thomas and Middleton, 1994; Eswaran *et al.,* 2001; Reynolds *et al.,* 2007; Puigdefabregas *et al.,* 2009; Ajai *et al.,* 2009; Brabant, 2010; Reynolds *et al.,* 2011; Christian *et al.,* 2018 a, Singh and Ajai 2019, Ajai and Bhatnagar 2022). However, the definition of land degradation given by UNCCD in 1994 (Anonymous 1994) is the most comprehensive one and well accepted; it states, "land degradation refers to the persistent reduction or loss of the biological or economic productivity of land resulting from land uses or from a process or a combination of processes, including processes arising from human activities and habitation patterns", such as (i) soil erosion due to wind or water, (ii) decline in physical characteristics through compaction, waterlogging etc.; chemical characteristics such as through acidification, and salinization; and biological or economic properties of soil, and (iii) vegetal degradation or loss. Millennium Ecosystem Assessment (Anonymous, 2005) has included the term ecosystem services and defines land degradation (LD) as 'the reduction in the capacity of land to provide ecosystem goods and services'.

Desertification is a special case or a subset of land degradation. It refers to the land degradation occurring in drylands. UNCCD (Anonymous 1994) provides a more comprehensive definition of desertification "desertification refers to land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities". Drylands, being the extremely fragile ecosystems, are most vulnerable towards degradation. Degradation of these ecosystems is mostly due to their over exploitation, far beyond their land's natural capacity, thereby leading to lowering of the soil quality, depleting sweet water resources and changing the vegetation quality. Thus, it has profound impact on the human wellbeing and the social system, the environment as well as the ecosystem goods and services.

The terrestrial part of the biosphere comprising of the natural resources, such as soil, vegetation, water, near-surface air, the topography, ecology, including the human settlements, is termed as land. Now the question arises, what is a dryland? The explanation comes from the understanding of the aridity index. All those pieces of land where the aridity index falls within the range 0.05 and 0.65, are considered as drylands. They constitute about 41% of the world's land area and about 69% of the Indian landmass. Out of the total geographical are of India, about 50.8 mha (15.8%) is arid, 123.4 mha (37.6%) is semi-arid while about 54.1 mha (16.5%) falls within the dry sub-humid region (Anonymous, 2001).

Causes and drivers

Drivers of desertification and land degradation can be both anthropogenic as well as natural. DLD is a complex process and involves both the biophysical as well as social domains of causative factors such as, social, economic, cultural, political, and natural factors. Often, it is difficult to ascribe a single factor that is responsible for land degradation. Mostly, a combination of two or more driving forces (which can also be a combination of anthropogenic and natural factors) is responsible for DLD to take place.

While natural factors are, in general, causative, human activities are the major triggering factors which also accelerate the desertification processes. Some of the anthropogenic activities that are responsible for land degradation and desertification are: i) change in land use and land cover, and improper land use practices, ii) cultivation of marginal/fragile/eroded land, iii) shortening the fallow period of land, iv) overgrazing, especially, in pasture land, grazing land, grassland and scrub land, v) deforestation for agriculture etc. and overexploitation of forests for forest goods such as fuel wood and fodder, vi) uncontrolled utilization of fire for regenerating pasture/forest, and shifting cultivation, vii) unsustainable agricultural management practices that may destroy the soil structure, e.g., use of heavy agricultural machinery, viii) over irrigation of soils prone to salinization, alkalinisation or water logging, and ix) developmental activities such as urban development, mining, industrialization etc. All of the above activities derive from the following two types of basic causes: i) underdevelopment, poverty, illiteracy, inappropriate government policies, and ii) development without the perspective of sustainability. Such measures of development do not consider the impact of technologies upon land or climate sustainability (Ajai and Bhatnagar 2022).

Land degradation and desertification are strongly affected by the socio-economic conditions (poverty and illiteracy) of the people. This is because the increasing population of both humans and the cattle exert undue pressure on natural resources which initiates the process of land degradation. Globally, arable land per capita is declining, which poses a threat to the food security, especially in poor and rural areas. This often causes humanitarian and economic crises, which further puts pressure on land and speeds up the process of land degradation. Globally, arable land per person has declined from 0.36 ha in 1961 to 0.18 ha in 2021 (data.worldbank.org/indicator/AG.LDN.ARBL.HA.PC).

In addition to the above-mentioned anthropogenic causes and drivers, natural hazards such as droughts, extreme weather, climate change, etc and the natural denudational processes such as erosion/geological hazards etc. are the natural causes of land degradation and desertification. The natural causes of land degradation include the following: i) decline in frequency and amount of rainfall (increase in frequency of droughts), ii) large variability in temperature, iii) reduction in vegetation cover, iv) climate change, frost shattering and frost heaving in cold arid regions, v) geological hazards, and vi) mass wasting in mountainous areas.

Land degradation processes

There are a large number of processes of DLD which are frequently observed in different parts of the world, such as physical (soil erosion caused by water and wind, water logging, soil compaction and crusting, frost shattering and heaving, mass wasting), chemical degradation (acidification, alkalinization, salinization), and biological degradation (change in vegetal cover/species composition/loss of biodiversity) (Lal, 1994; Eswaran *et al.*, 2001; Christian *et al.*, 2018, a b). A brief on these processes is given below. Degradation processes are discussed in details by Brabant (2010), Ajai *et al.*, (2007a & b; 2009), Ajai and Bhatnagar (2022).

Vegetal degradation

Vegetal degradation includes reduction in the biomass, canopy cover and density, loss of biodiversity, and a change in species composition. It is observed mainly as forest-blanks/deforestation, agriculture (including shifting cultivation), and degradation in grazing/pasture-land/scrubland. When the vegetal cover declines or gets fragmented, it leads to the loss of biodiversity because of reduction in the available habitats of forest dependent faunal species. Plantations in place of natural forests also come under forest or vegetal degradation because plantations are usually associated with reduced biodiversity. Intrusion of invasive plant species in grasslands, rangelands and scrublands also come under vegetal degradation as they are threat to native biodiversity and might also change the water balance and nutrient dynamics.

Soil erosion

Soil erosion refers to 'the process of detachment of the soil particles from the topsoil by the action of water, wind, ice (glacial)' (Ajai and Bhatnagar 2022). It is a natural process and also the dominant land degradation process present throughout the globe. Soil erosion is a slow process which might have begun along with the formation of soil through the process of weathering. In its natural state, soil erosion is also called geological soil erosion where rate of erosion is equivalent to the rate at which soil in a particular environment would erode under native vegetation. In the scenario where rate of soil erosion is higher than the rate of soil formation, it is termed as accelerated soil erosion, which is a point of concern. Anthropogenic activities such as changes in land use/land cover, inappropriate land use practices, overgrazing, deforestation, cultivation on marginal land etc. are the major cause of accelerated soil erosion, and hence it is also known as human induced soil erosion.

Soil erosion caused by water is called water erosion. Here, the soil material is displaced by the surface runoff water which can result in either loss of topsoil or terrain deformation or both. Processes like splash erosion, sheet erosion, rill and gully erosion come under this category (Ajai and Bhatnagar 2022). When the soil erosion is an outcome of the action of wind, it is called wind erosion. In this case, soil particles are spread by the lift and drift effects of the wind. This process is more pronounced in arid and semi-arid regions but is also prevalent in sub-humid regions. Based upon the depth and the spread of sand sheet/dunes and branches, various categories of wind erosion and their severity are defined.

Soil compaction

The process of soil compaction refers to the reduction in the porosity of the soil. In this case, soil particles are pressed together, causing a decrease in the pore space and increase in the soil bulk density. Under such conditions, the rate at which water is infiltrated decreases and hence soil gets saturated faster. This often leads to water logging. Under such conditions, the functions of the sub-soil get disturbed which may hamper the penetration of the roots, water and gas exchange, thereby affecting the plant growth.

Salinization/alkalization

Salinization/alkalization pertains to the chemical processes of land degradation. In the event of high concentration of salt in the root zone (> 4 dS m^{-1}) (Richards 1954), soils are considered as saline or salt affected. Usually, it occurs in the cultivated lands, especially in the irrigated regions. Apart from the inherent salinity/alkalinity in the soil, the over irrigation may lead to this kind of degradation (Ajai and Bhatnagar 2022).

Acidification

When the soil becomes acidic, nutrient uptake by the plants is affected, which affects the productivity adversely. Acidification mainly occurs in lateritic regions, coastal regions, and due to oxidation of pyrite containing soils.

Water logging

Water logging refers to the state of soil where there is free water in pore spaces. The water table rises to such an extent that the soil pores in the root zone become saturated. This restricts the normal air circulation, decreases oxygen levels while increasing carbon dioxide levels. Even the shallow water tables come under this category. Parts of land with poor drainage accumulate standing water for more time. Broadly, waterlogged land can be classified in two categories: i) seasonal-where waterlogging takes place in one cropping season only, and ii) perennial-water logging occurs for the entire year.

Mass wasting/movement

Mass wasting is pre-dominantly found in hilly terrains and is defined as the process of land degradation where rock, regolith and debris move down the slope through the action of gravity, e.g. debris flow and landslides. It takes place when the gravitational force is more than the resistive forces of the mountain.

Frost shattering and heaving

The freeze and thaw action of water, especially occurring in the periglacial environment is called frost shattering. Water entering through the crevices and pores in rock freezes, it expands by almost 10 times, putting tremendous pressure on the rocks resulting in their breakdown. In the case of frost heaving, intense frost and freezing of water below the surface horizon leads to micro relief variations in the surface causing peculiar forms of rock, regolith and soil. This process has a negative impact upon the germination and root growth of several crops, and thus the productivity of the land is affected.

Man made

DLD processes caused directly or indirectly by anthropogenic interventions and whose origin is not natural, are called as manmade land degradation processes. It includes urbanization, industrialization, mining and quarrying, brick kiln etc.

Land Degradation Neutrality

In order to achieve the Sustainable Development Goal-15 (SDG-15), UNCCD came up with the concept of Land Degradation Neutrality (Minelli *et al.,* 2017). The aim of SDG 15 is towards sustaining of life on land. It includes a target related to combating desertification, and makes clear reference to Land Degradation Neutral World (target 15.3) by 2030 (Anonymous 2015, Orr *et al.,* 2017, Cowie 2018).

Land Degradation Neutrality (LDN) means no gain and no loss in area under land degradation, i.e. the proportion of degraded land remains constant. UNCCD defines LDN as "a state whereby the amount and quality of land resources necessary to support ecosystem functions and services and to enhance food security remains stable or increase within specified temporal and spatial scales and ecosystems" (Anonymous 2015, Minelli *et al.,* 2017, Orr *et al.,* 2017, Cowie 2018). This means losses due to land degradation should be compensated with the restoration of already degraded land (gain). In other words, we can say that LDN aims at stopping the ongoing loss of productive land as a consequence of unsustainable land management practices and unsuitable land conversions.

The main elements of the scientific conceptual frame work for LDN and their inter-relationships are shown in Fig. 1 (Orr *et al.,* 2017). The portion at the top of the fugure depicts the vision of LDN, which basically emphasizes the linkage between human prosperity and the land-based natural capitals (stocks of natural resources which provides the flow of ecosystem services)

In order to achieve the target, set under LDN, the following tasks are required to be carried out (Minelli 2017 *et al.,*, Orr *et al.,* 2017):

- Prevent degradation of healthy/productive land,
- Arrest the ongoing land degradation process, and
- Offset any extra land degradation (newly degraded land) by restoring/rejuvenating equivalent amount of already degraded land of similar type, at another location.

Thus, LDN can also be called as 'zero net land degradation' (Chasek *et al.,* 2015, Lal *et al.,* 2012). UNCCD has identified 2015 as the base or reference year and 2030 as the target year for achieving the zero net land degradation. It means, in the year 2030, the area of degraded land, in any country, should at least remain the same as it was in 2015. Every member country has been asked by the UNCCD to set a target in terms of the area of degraded land that will be restored in that country by 2030. Under LDN, India has committed to restore 26 Mha of its degraded land (Singh *et al.,* 2023).

In order to carry out the-above mentioned tasks for achieving LDN, we need to prepare appropriate action plans to address land degradation for both types of land: i) the land which is currently undergoing the process of degradation, and ii) land which are already degraded. In additions to the above, appropriate sustainable land management practices, such as soil and moisture conservation measures, needs to be adopted so as to prevent the healthy and productive land from degradation. For the preparation of suitable strategies or action plans to combat land degradation and desertification, the following information are required: i) location and spatial extent of the degraded land as well as the land undergoing the process of degradation, ii) the type of the land degradation processes, and iii) severity of the land degradation. Alternatively, it can be said that we require a map or the spatial data providing the above three information on land degradation and desertification.

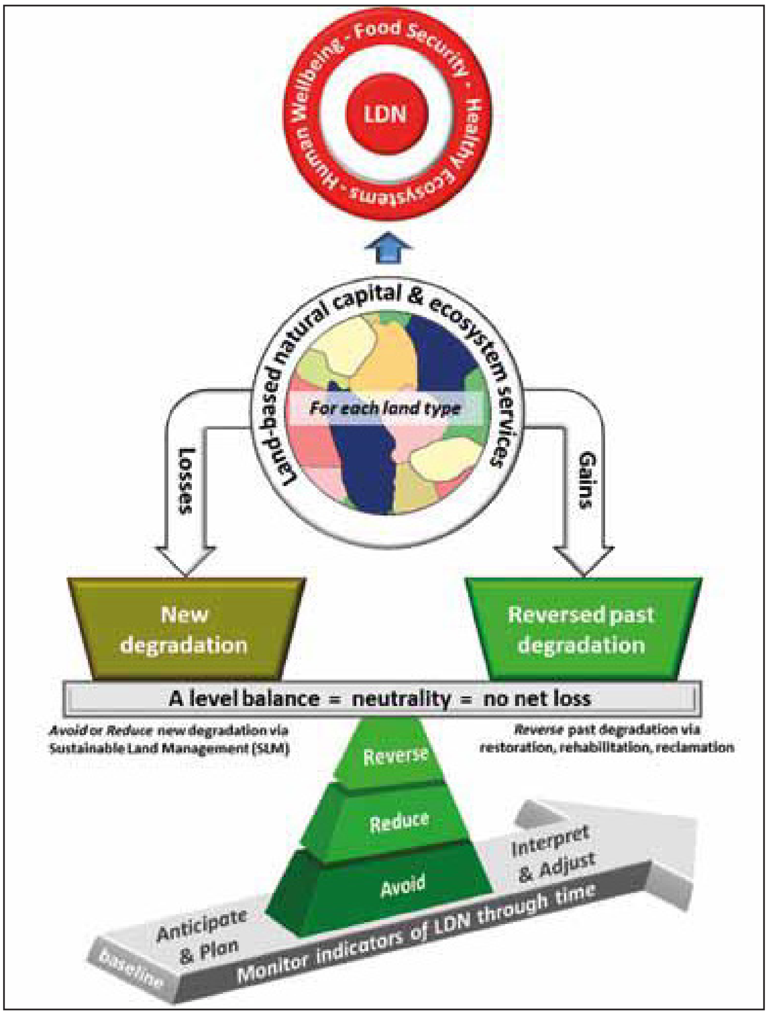

Fig. 1. Conceptual framework for LDN (source: Orr et al., 2017).

Desertification and land degradation mapping and assessment

The methodologies for mapping of desertification and land degradation can be broadly classified in to the following two categories (Christian *et al.*, 2018a, Ajai and Bhatnagar 2022): i) indicator-based methods, and ii) mapping of DLD processes

Indicator based methods for mapping DLD are indirect methods; because of their simplicity, these methods may not require a very high level of expertise for implementation (Ajai and Bhatnagar 2022). The major limitation of this methodology is - types or processes of land degradation cannot be mapped using this method. While in the second method, land degradation processes can also be mapped (Brabant 2010, Christian *et al.*, 2018a). Several indicators have been used to map and assess DLD (Ajai and Bhatnagar 2022, Wang *et al.*, 2023). Wang *et al.*, 2023 have provided the details on the indicators that can be used to map soil degradation using satellite remote sensing. UNCCD has identified the following three indicators to map DLD and also to compute the SDG indicator 15.3.1, namely: i) Land Cover Change, ii) Land Productivity Dynamics, and iii) Carbon Stock above and below ground.

Both of the above methods for mapping DLD can be implemented by using either of the following methods: i) field survey/ground observation, and ii) remote sensing techniques

Methods based on field survey includes approaches such as ground observation and measurements, farm level studies, expert's/ land users' opinion etc. Field/ground-based approaches are more accurate but time consuming and costly. Such methods are used for mapping and monitoring of smaller areas, such as village or district. They cannot be used for land degradation mapping and monitoring at national, regional or global scale. The physical and conventional method of data collection (through field survey and measurements) is extremely difficult, time consuming and costly. Data from earth observation satellites, on the other hand, provide a viable and cost-effective alternative for creating spatial inventory of desertification and land degradation. Data from Earth Observation Satellites have been available on various spatial resolutions during the past few decades; and thus, it is possible to prepare thematic maps, including desertification and land degradation maps at all scales: local to global (George and Jeganathan 2018, Ajai and Bhatnagar 2022). On satellite images, various processes of DLD can be very well identified and mapped along with information on the severity of the degradation processes (Ajai *et al.,* 2007, 2009, Christian *et al.,* 2018a & b, Brabant 2010, 2019, Dwivedi *et al.,* 2016, Kar *et al.,* 2009, 2016, Sreenivas *et al.,* 2010, Kumar and Singh 2018, Sreenivas *et al.,* 2021).

Efforts have been made to map desertification status at global, regional and national levels. Detailed review on the mapping of desertification and land degradation at the global scale are given by Grainger (2009) and Zucca *et al.,* (2012). A large number of methodologies to map desertification and land degradation are reported in literature (Dregne, 1983, Anonymous, 1984, Oldeman *et al.,* 1991, Dregne *et al.,* 1991, Ajai *et al.,* 2009a,b, Kar *et al.,* 2009, Dwivedi *et al.,* 2016). For example, Jafari and Bak (2013) used fuzzy logic and GIS for mapping environmentally sensitive areas to desertification in central Iran, based on Mediterranean Desertification and land use approach.

In the Dominican Republic, land sensitive to desertification has been mapped by Izzo *et al.,* (2013) using ESA (Environmentally Sensitive Area) approach.

Global scale mapping

The first attempt to prepare a global map of human induced land degradation was made by GLASOD (Global Assessment of Soil Degradation) and a map was brought out in 1991 (Oldeman *et al.,* 1991). It was a UNEP funded project implemented by the International Soil Reference and Information Centre (ISRIC). GLASOD was mainly qualitative in nature, based on the expert judgement for identification of the main processes that led to soil degradation, such as wind and water erosion, salinization, loss of soil structure, soil organic carbon and nutrients etc. More than 250 experts, specialized in soil and environmental sciences, from all across the world were involved in this mapping work. The scale of mapping was 1:10 million and covered the aspects of area affected, type and severity of human induced soil degradation. This map considered only human induced land degradation and not the natural degradation processes (Oldeman *et al.,* 1991). The GLASOD global data base was used to prepare World Atlas of Desertification.

Later, LADA (Land Degradation Assessment in Drylands) followed up the GLASOD approach upgraded in a new worldwide effort sponsored by the United Nations Environment Program (UNEP), the Global Environmental Facility (GEF), and the Food and Agricultural Organization (FAO). Whilst retaining the original GLASOD soil degradation categories, LADA took a step forward by aiming at quantitative deliverables (Nachtergaele and Manzur 2008, Biancalani *et al.,* 2013). LADA has improved the definition of land degradation by including the term Ecosystem Services; and defined it as 'the reduction in the capacity of land to provide ecosystem goods and services over a period of time'. LADA assessment provided details about the geographic locations of the areas undergoing land degradation, its types and the degradation processes, as well as their spatial extent. In addition, LADA also assessed and mapped land improvement (Biancalani *et al.,* 2013). The LADA method was adopted and implemented at national level in six countries, namely, Argentina, China, Cuba, Senegal, South Africa, and Tunisia.

Between 2001 and 2005, the third global effort on land degradation assessment, the Millennium Ecosystem Assessment (MA) came into being (Anonymous 2005a & b). It emphasized the interlinkage between the ecosystems and well- being of the humans. The major objectives of MA were: i) to assess the impact of ecosystem change on the well-being of the humans, and ii) to establish the scientific basis for steps required to increase the conservation and ecosystem sustainability including human well-being (Anonymous 2005a & b).

World Atlas of Desertification (WAD), a joint venture of UNEP and European Commission's Joint Research Centre (JRC), another important global initiative that brought out the world map of land degradation. The first and second editions of WAD were brought out in 1992 and 1997 respectively (Anonymous, 1997 a). The third edition of world atlas, WAD 3 was brought out by UNEP, UNCCD and European Commission in 2018. WAD 3, the new World Atlas of Desertification initiative is a digital atlas (Cherlet *et al.,* 2018).

Regional level mapping

ASSOD: Assessment of Human-Induced Soil Degradation in South and South-East Asia (ASSOD) was a joint venture of United Nations Environment Program (UNEP), Food and Agriculture Organization (FAO), and International Soil Reference and Information Centre (ISRIC). The mapping and assessment involved physiographic base map and the modified GLASOD methodology. The map was compiled at a scale of 1:5 million (van Lynden 1997).

East Africa: Kirui *et al.,* (2021) have carried out mapping of land degradation in Eastern Africa, which includes Ethiopia, Kenya, Malawi and Tanzania, using the following two indicators: i) decline in the productivity of biomass, and ii) land use land cover change (LUCC). Biomass productivity decline was computed from the long-term trend in NDVI (1982-2006), derived from NOAA-AVHRR (Advanced Very High-Resolution Radiometer) data. These datasets were developed by the NASA Global Inventory Monitoring and Modelling Systems (GIMMS), at a spatial resolution of 8 × 8 km with 15-days revisit cycle during the time frame of 1982-2015. Land use land cover change was assessed using MODIS products.

Asian TPN-1: Asian TPN-1 on desertification monitoring and assessment has developed a set of indicators and methodology for mapping desertification in Asia using satellite data. It included four-level classification system including climatic zones, land use and land cover, land degradation processes and severity of degradation.

Mapping and Assessment of Land Degradation in India

The first ever desertification and land degradation map for India was prepared by Space Applications Centre, ISRO in collaboration with a large number of organizations of the country (Ajai *et al.,* 2007b, 2009). It was prepared at 1:0.5 million scale using IRS satellite data (AWiFS sensor data at 56 m spatial resolution). One of the most important tasks involved in preparation of the map was to evolve and standardized a national level classification system. The second important task was to standardize a legend for interpretation of the satellite images, as per the classification system, so as to prepare the DLD map. The methodology for the preparation of Desertification and Land Degradation Status Map of India using satellite data was developed by Space Applications Centre and is given in Fig. 2, (Ajai *et al.,* 2007a,b and 2009).

Three season satellite images of the study area corresponding to winter (November - April), summer (may-June) and monsoon (July- October) were analyzed to prepare desertification and land degradation (DLD) map. Three -level hierarchical classification system has been used in mapping of desertification and land degradation status of India (Ajai *et al.,* 2009). Level one in the classification system comprises of "land use", level two considers the "processes of land degradation" and level three provides the "severity of degradation". The first step in satellite data analysis is the geometric correction and geo-referencing of the multi season images. In order to delineate land use/land cover classes (level-1) of the study area, the geo-referenced satellite images were analyzed in conjunction with the ancillary and ground truth data. With the three-season data, better discrimination of the classes is possible, which are otherwise difficult to distinguish, e.g. wasteland and fallow fields. Based on their signatures, interpretation key and ground truth information, land degradation/desertification processes are identified on the satellite images. For the severity of degradations (level-3), assessments are carried out using the signatures on image as well as on ground truth. This includes soil sample analysis, if required. For example, in the case of low- moderate salinity/ alkanity, the signatures are not very clear in the

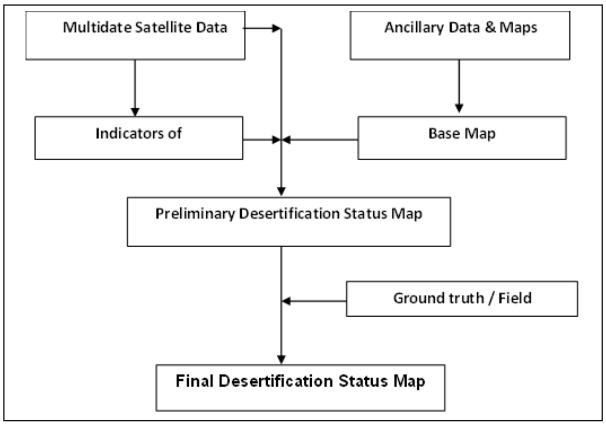

Fig. 2. Methodology for desertification mapping using satellite data (Source: Ajai et al., 2009).

satellite images, and hence soil sample analysis is needed.

Desertification and land degradation map prepared using the above-mentioned methodology (Fig. 2) and IRS AWiFS data of 2003- 05 time frames, is given in Figure 3 (Ajai *et al.*, 2007b, 2009). As per this map, 105.48 mha area (32.07% of the total geographical area) of India is undergoing the process of land degradation; 81.45 mha (about one fourth of the geographic area) is undergoing desertification. Out of the total 105.48 mha of land degradation area, water erosion, vegetal degradation, wind erosion, frost shattering and salinity accounts for 33.56%, 31.66%, 17.56%, 10.21% and 5.26% respectively. Soil erosion (water + wind) is found to occur in 51.12 mha area; vegetal degradation has been found in 31.66 mha area.

Subsequently, Space Applications Centre (SAC), ISRO Ahmedabad has carried out the second and third cycles of Desertification and Land Degradation Status mapping, using the same classification system, legend and the methodology as it was used in the first mapping cycle (Anonymous 2016, Anonymous 2021). Mapping at 1:0.5 million scale has been carried out using AWiFS data of 2011 -2013 and 2018-2019 time periods for the second and third cycle respectively. As per the mapping, based on satellite data of 2011 -2013 time period (second cycle), area undergoing land

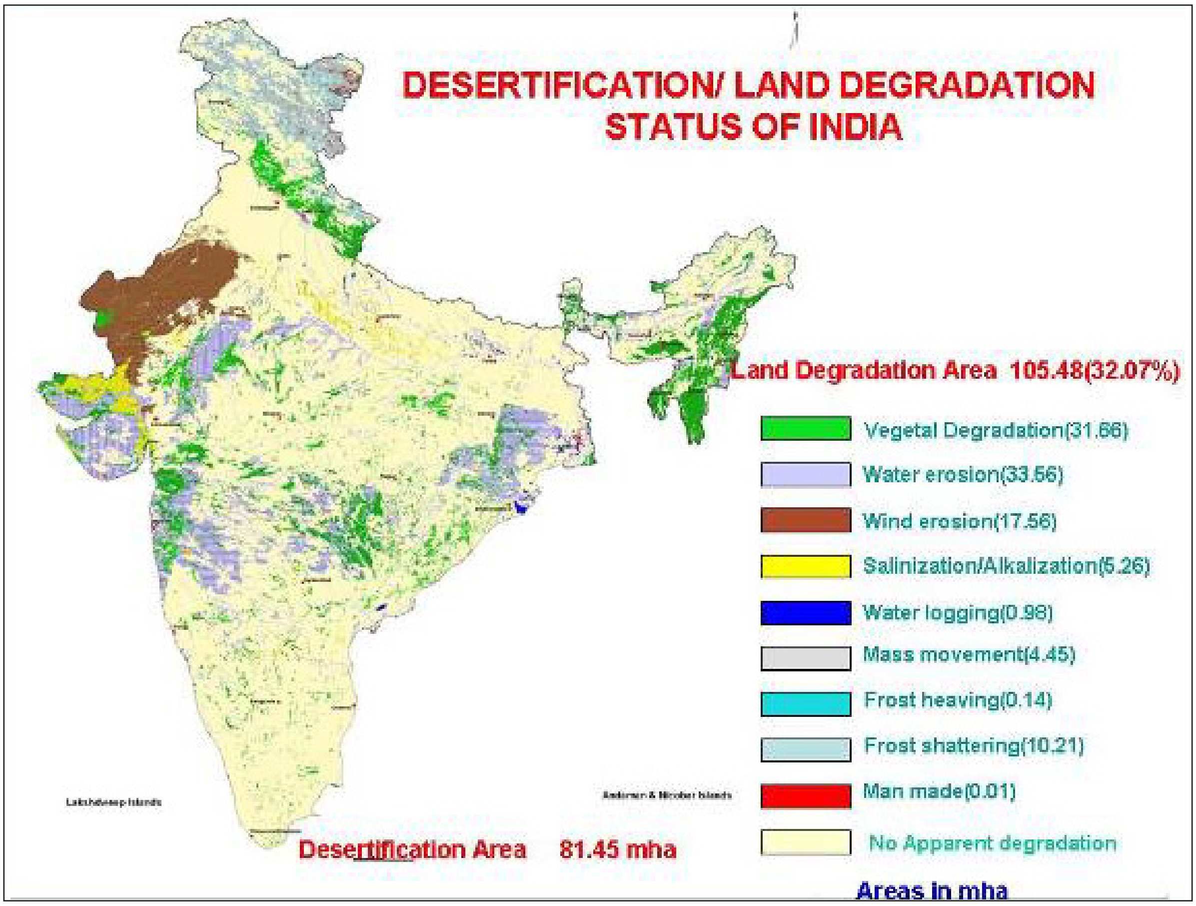

Fig. 3. Desertification/Land Degradation Status Map of India (Source: Ajai et al., 2007b and 2009).

degradation is 96.40 mha (29.32% of the total geographical area of the country). Soil erosion (water + wind) has been found to occur in 54.32 mha area; while vegetal degradation and salinity are in 29.30 mha and 3.67 mha respectively (Anonymous 2016). As per the third cycle mapping, using AWiFs data of 2018-2019, area undergoing the process of land degradation is 97.85 mha (29.77% geographic area) (Anonymous 2021).

Land degradation mapping of the country has also been carried out at a larger scale (1:50,000) by National Remote Sensing Centre (NRSC), ISRO using IRS LISS-III data having 23.5 m spatial resolution (Sreenivas *et al.*, 2021). Mapping was done for two-time frames, 2005 -2006 and 2015-2016. In both the cases IRS LISS-III data were used. On screen visual analysis of the multi-season LISS-III data was carried out, supported by digital elevation model (DEM) and historical data. As per this mapping, the total area under land degradation was 91.2 mha (27.77% of Geographic area) in 2015 -16; while it was 91.3 mha in 2005-06. Area under land degradation has decreased by 0.1 mha during the decade (2005-06 and 2015-16). In this mapping, the classification system used was slightly different from the one used by Space Applications Centre for mapping at 1:500,000 scale. Here the land degradation types mapped were: acidification, frost heaving, frost shattering, mass movement, man-made/other, water erosion, water logging, wind erosion, salinization/alkalization. In this mapping, vegetal degradation process was not considered. Whereas, in the maps prepared by SAC on 1:500,000 scale, vegetal degradation was also mapped. This is the major difference in the classification systems used by SAC and NRSC in mapping land degradation for the India.

Soil degradation map of India at 1:4 million scale was prepared by National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), ICAR (Sehgal and Abrol 1994, Dwivedi *et al.*, 2016). As per this map, 147.3 mha area was under soil degradation in the country. This mapping was based on the compilation and integration of available maps and data pertaining to the period 1985-1995. Following types of soil degradation were mapped: chemical deterioration, water erosion, wind erosion, physical deterioration, stable terrain and areas not fit for agriculture. Four severity levels of the above soil degradation processes, namely, slight, moderate, strong, and extreme, were shown on the soil degradation map.

Wasteland map of the country was produced at 1:50,000 scale by the National Remote Sensing Centre (NRSC) using IRS satellite data (Anonymous 2000). As per this map 63.85 mha area of the country was under wastelands. Subsequently, NRSC prepared wasteland maps of the country for the period 2008-2009 and 2015-2016, using IRS LISS III data. Total area under wasteland has been reported to be 55.776 Mha (16.96% of geographic area) during 2015-2016 and 56.61 (17.72%) in 2008-2009 (Anonymous 2019).

Mapping of salt affected soils was carried out for the entire country at 1:250,000 scale by NRSC using Landsat- TM data of 1986-1987 (Anonymous 1997b, Dwivedi *et al.*, 2016). Visual analysis technique was employed to prepare the map from the Landsat- TM False Colour Composite (FCC) images, acquired during the period January-March 1986 -1987. Soil samples were also collected, analyzed and used in preparation of soil salinity map. As per this mapping, the total area of salt affected soil in the country was 6.727 mha. Three severity levels (slight, moderate and strong) of salinity were also shown on the map. Kumar *et al.*, (2020) has provided a review on the remote sensing-based methods for mapping salt affected soil

Actions for achieving LDN

Combating land degradation is the essential step towards achieving the land degradation neutrality. Combating strategies must involve the actions that can prevent/arrest and reverse land degradation. In other words, the actions towards the following are required-i) restoration of the degraded land, ii) prevention of the healthy and productive land from getting degraded, and iii) arresting degradation in those land which are already undergoing the process of degradation. Sustainable Land Management (SLM) is one of the important approaches to prevent, arrest and restore land degradation (Kust *et al.*, 2017). There are several SLM practices that can help in combating land degradation. It includes, conservation practices for soil and moisture, enhancing green vegetation cover, agroforestry and agro-horticulture, silvipasture, restoration of rangeland/pastureland, restoration/creation of new water bodies, artificial recharge of ground water, rainwater harvesting etc. The above SLM practices helps in combating many of the land degradation processes. In addition, certain specific actions are required for combating a particular type of DLD process. These are as discussed below:

Water erosion

Soil and moisture conservation can be categorized as one of the most common methods for preventing the soil erosion. The soil and water conservation methods used for combating water erosion are contour bunding and contour trenching, drainage line treatment, check dam, contour farming, terrace farming, strip cropping, buffer striping, farm bunding, conservation tillage and mulching (Dhruva Narayana 1993, Narain and Kar 2007, Kar *et al.*, 2009, Ajai and Bhatnagar 2022)

One or more of the above methods may be required to be adopted depending upon the situations existing on the ground. Selection of the above-mentioned soil and moisture conservation methods depend upon the existing land use/land cover, surface topography, the terrain characteristics, soil type and the intensity and amount of rainfall in that area.

Wind erosion

Wind erosion in arid and semi-arid regions takes place, especially, when soil has no or scanty vegetation cover and wind is often very strong. The actions, most commonly used for combating soil erosion due to wind includes: agroforestry, silvipasture, shelterbelts, wind breaker

In the arid and semi-arid areas where severe wind erosion takes place, sand dune stabilization is one of the important actions to be taken. The following methods are commonly used in sand dune stabilization (Kar *et al.*, 2009, Ajai and Bhatnagar 2022): i) vegetative methods: planting trees, micro wind breakers, straw checkboards etc, ii) mechanical methods and iii) chemical methods

Salinization/alkalization

Primarily, there are two types of methods available for combating the problem of soil salinization and alkalization: soil leaching, and addressing the drainage.

In leaching, large quantity of water having extremely low quantity of salt is added to the soil surface to dissolve the salt present in the soil and move it to below the root zone. In this method, before leaching, soil is treated with chemicals (gypsum or calcium chloride) to reduce the exchangeable sodium content. After this treatment of applying gypsum/calcium chloride, sodium can be leached along with the other soluble salts (Kar *et al.*, 2009).

Salt accumulation in soil can also be prevented by appropriately creating vertical and horizontal drainages. There are a number of afforestation and agro-forestry techniques available that helps in rehabilitating the salt affected land.

Waterlogging

Waterlogging happens because of the following: i) over irrigation, and ii) flooding due to poor drainage in the event of excessive rain. This problem can be handled if the drainage is properly managed (Kar *et al.*, 2009). Bio drainage is also useful in combating the waterlogging problem in certain cases.

The actions required towards combating land degradation vary from one type of LD process to the other. It will also depend upon the local ground situations, such as, the present land use/land cover, soil type, topography/terrain conditions, drainage network and surface water bodies, availability of ground water, climate as well as the socio-economic conditions of the people living there. Thus, preparation of suitable action plans towards combating LD requires integration of spatial information on the above thematic layers in a GIS environment (Ajai and Bhatnagar 2022, Ajai and Dhinwa 2018).

Implementation Mechanism in India

As mentioned earlier, achieving LDN requires planning, preparation and implementation of suitable actions towards restoring the degraded land, arresting the process of land degradation as well as preventing the productive and healthy land from degradation. In order to carry out the above task, we need: i) land degradation map, showing the type and severity of the degradation processes, at an appropriate scale and ii) locale-specific action plans for combating land degradation, that are based on scientific inputs. The next step is to execute the land degradation combating plans at the ground. It is important to involve all the stake holders including the local people (farmers and land users) in both, preparation of action plans as well as in the implementation process. In India, the following two important programs were taken up in 1980s for controlling/ combating desertification and land degradation through implementation of desertification and land degradation action plans.: i) Desert Development Program (DDP), and ii) Drought Prone Area Development Program (DPAP). The important actions implemented under these two programs includes, soil and water conservation, afforestation, sand dune stabilization, rain water harvesting, artificial ground water recharge etc. Subsequently. all the activities related to combating land degradation and desertification, became the part of Integrated Watershed Management Program (IWMP). The major objectives of IWMP are to conserve and preserve the ecology, restore and develop degraded natural capitals through adopting appropriate SLM practices (Ajai and Bhatnagar 2022). Involvement of the local people has been one of the key elements in each of the above-mentioned program. The overall guidelines for IWMP are provided by the Government of India; whereas, execution of the program at ground level is the responsibility of state governments. Normally, the programs such as IWMP, which are supported by the government has the following stakeholders: state government, scientific organizations/technical experts, NGOs and local people (land users). Roles are well defined for each of the above stakeholders. The other important ongoing national and state government programs which also provides opportunity for implementation of actions towards land restoration, arresting land degradation, and combating DLD include Mahatma Gandhi National Rural Employment Guarantee and Joint Forest Management (JFM) among others.

India is a signatory to the UN Convention to Combat Desertification (UNCCD), and has formulated its National Action Program towards combating desertification and land degradation. Under its obligation towards achieving Land Degradation Neutrality (LDN), India has committed to restore 26 mha of degraded land by 2030 (Singh *et al.,* 2023). As mentioned earlier, India has 105.48 mha of land undergoing the process of degradation. Before, planning a strategy to restore 26 mha degraded land, the first and foremost tasks is to prioritize 26 mha land from the above said 105.48 land that can be taken up first for the purpose of restoration. While selecting or prioritizing the land for restoration, one of the criteria could be to first take up those land which requires less cost and efforts in its restoration and where implementation is also easy. The available land degradation map, showing land-use, process of land degradation and severity, can be used for the above purpose. The land where the process of land degradation is not severe can be taken up first, as the cost of restoration will be less as compared to the restoration cost involved for land with severe degradation. As far as the implementation of combating plan is concerned, it is easy to implement it in the government/community land as compared to the land owned by the people. So, to start with, the degraded land in forest area as well as the grassland/pasture land can be taken up first for implementation of the land restoration process. Actions towards combating land degradation and restoration of degraded land, as part of the India's commitment to UNCCD, are being implemented in the country by the respective state governments as part of several ongoing programs, including IWMP.

Ministry of Environment, Forests and Climate Change (MOEF&CC) is the national focal point for implementation of Convention to Combat Desertification in the country and is therefore, responsible for the coordination and implementation of LDN program in the country. MOEF&CC has identified CoE-SLM (Centre of Excellence for Sustainable Land Management) of Indian Council of Forestry Research and Education (ICFRE) as the focal point of the ministry for generating the desired statistics and reports for national reporting to UNCCD. CoE-SLM has identified and mapped the "hotspot" areas at national level where the severity of land degradation is high, and thus can be taken up for land restoration to achieve the LDN targets (Singh *et al.,* 2023).

The progress of the implementation of the actions taken towards combating land degradation and restoration of degraded land as well as its impact on the ecology and environment is being monitored in India using earth observation satellite data (Ajai and Bhatnagar 2022). Basically, the positive impact of the actions taken towards combating DLD. through SLM, are manifested in terms of increase in area under green vegetation cover as well as increase in the number and area of water bodies. which can be very easily monitored using satellite images.

References

Ajai and Bhatnagar, R. 2022. *Desertification and Land Degradation-Concept to Combating*, CRC Press, Boca Raton.

Ajai, Pathan, S.K., Dhinwa, P.S., Arya, A.S., *et al.*, 2007a. *Desertification Monitoring and Assessment Using Remote Sensing and GIS: A Pilot Project under TPN-1 UNCCD* SAC/RESIPA/MESG/DMA/2007/01

Ajai , Pathan, S.K., Arya, A.S. , Dhinwa, P.S. *et al.*, 2007b. *Desertification and Land Degradation Atlas of India*, Space Applications Centre, ISRO, Ahmedabad ISBN no. 978-81-909978-2-9.

Ajai, Arya, A.S., Dhinwa, P.S., Pathan, S.K. and Ganesh Raj, K. 2009. Desertification/land degradation status mapping of India. *Current Science*, 97 (25), 1478-1483.

Ajai and Dhinwa, P.S. 2018. Desertification and Land Degradation in Indian Subcontinent: Issues, Present Status and Future and Challenges, In Gaur, M.K. and Squires, V.R. (Edts) *Climate Variablity Impacts on Land Use and Livelihoods in Drylands*, pp 181-201. Springer.

Anonymous. 1984. *Provisional methodology for assessment and mapping of desertification*. FAO Rome.

Anonymous 1994. United Nations Convention to Combat Desertification in those countries experiencing serious drought and/or desertification, particularly in Africa UNEP final *text of the convention.*

Anonymous 1997. *Salt Affected Soils of India*, Technical Report, National Remote Sensing Centre, Hyderabad.

Anonymous. 1997. *World Atlas of Desertification* second ed., Arnold, New York. Arnold, London, p. 182. www.nnrms.gov.in.

Anonymous 2000.*Wasteland Atlas of India*, National Remote Sensing Centre, Hyderabad.

Anonymous 2001. *Agro-ecological sub-regions of India for planning and development*. Nagpur, Maharashtra: NBSS&LUP Publication, ICAR.

Anonymous 2005a. *Ecosystems and Human Well-Being: Synthesis*. Millennium Ecosystem Assessment, Island Press, Washington, DC.

Anonymous 2005b. *Ecosystems and Human Well-Being: Desertification Synthesis*. Millennium Ecosystem Assessment, World Resources Institute, Washington, DC.

Anonymous 2015 *parties on its 12th session Report of the conference* of held at Ankara during October 12-23, 2015, Part2: Action taken by Conference of parties at its twelfth session ICCD/CoP (12)/20/Add. Bonn, United Nations Convention to Combat Desertification

Anonymous 2015. *Transforming Our World: the 2030 Agenda for Sustainable Development*, Resolution adopted by the General Assembly on September 25, 2015. http:/www.un.org/ga/Search/View_doc.asp?Symbol=A/RES/70/1&Lang=E.

Anonymous 2016. *Desertification and Land Degradation Atlas of India* (Based on AWiFS data of 2011-13 and 2003-05), Space Applications Centre, ISRO, Ahmedabad.

Anonymous 2019. *Wasteland Atlas of India*, Department of Land resources, Ministry of Rural Development, Government of India and National Remote Sensing centre, Hyderabad.

Anonymous 2021. *Desertification and Land Degradation Atlas of India* (Assessment and analysis of changes over 15 years based on remote sensing), Space Applications Centre, ISRO, Ahmedabad.

Biancalani, R., Nachtergaele, F.O., Petri, M., and Bunning, S. 2013. *Land Degradation Assessment in Drylands - Methodology and Results*. Food and Agriculture Organizations, United Nations, Rome.

Brabant, M. 2010. A Land Degradation Assessment and Mapping Methodology Standard Guideline Proposal, Comite' Scientifique Francais de la *Desertification Les dossiers thematiques CSFD*. Issue 8, AGROPOLIS International

Brabant, P. 2019. *A land degradation assessment and mapping methodology, standard guideline proposal,* Comite' Scientifique Francais De la desertification les dossiers thematiques. Agropolis International, 8, 50 CSFD.

Chasek, P., Safriel, U., Shikongo, S, Fuhrman, V.F. 2015. Operationalizing zero net land degradation: The next stage in international efforts to combat desertification, *Journal of Arid Environments*, 112: 5-13.

Cherlet, M., Hutchinson, C., Reynollds, J., Sommer, S., and von Maltiz, G. 2018, *World Atlas of Desertification-3rd Edition*, Publication Office of European Union, Luxemburg

Christian, B.A., Dhinwa, P.S. and Ajai. 2018a. Long term monitoring and assessment of desertification processes using medium and high-resolution satellite data. *Applied Geography*, 97, 10-24.

Christian, B.A., Dhinwa, P.S. and Ajai. 2018b. Inventory and Monitoring of Land Degradation using Space Data, *Annals of Arid Zone*, 57 (3-4), 121-128.

Cowie, A.L., Orr, B.J., Sanchez, V.M.C., Chasek, P., Crossman, N.D., Erlewein, A., Louwagie, G., Maron, M., Metternicht, G.I., Minelli, S., Tengberg, A.E., Walter, S. and Welton, S. 2018. Land in balance: The scientific conceptual framework for land degradation neutrality. *Environmental Science & Policy*, 79: 25-35.

Dhruva Narayana, V.V. 1993. *Soil and Water Conservation Research in India*, Indian Council of Agriculture Research (ICAR), New Delhi 454 p.

Dregne, H. 1983. *Desertification of arid lands*. Harwood academic publisher, London.

Dregne, H, Kassas, M. and Rozanov, B. 1991. A new assessment of the World status of desertification. *Desertification control bulletin* UNEP 20: 6-18.

Dwivedi, R. S., Ramana, K. V. and Sreenivas, K. 2016, Land degradation, In Dwivedi, R S and Roy, P S, *Geospatial Technology for Integrated Natural Resources Management*, PP 249-294, Yes Dee Pub. Chennai, India

Eswaran, H., Lal, R. and Reich, P. F. 2001. Land degradation: An overview. In: bridges, E.M., Hannam, I.D., Oldeman, L.R., Pening De Vries, F.W.T., Scherr, S.J., Sompatpanit, S. (Eds.), *Response to land degradation*. Science Publishers Inc, Enfield, NH, pp. 20-35.

Grainger, A. 2009. Development of a baseline survey for monitoring biophysical and socio-economic trends in desertification, land degradation and drought report: UN Convention to Combat Desertification, Bonn. http://www.unccd.int/science/docs/developing%20a%20baseline%20survey%20-%20for%20the% 20web 2010.pdf.

Izzo, M., Araujo, N., Aucelli, P.P.C., Maratea, A., Sánchez, A. 2013. Land sensitivity to desertification in The Dominican Republic: An adaptation of the ESA methodology. *Land Degradation & Development* DOI: 10.1002/ldr.2241.

Jafari, R. and Bakhshandehmehr, L. 2013. Quantitative mapping and assessment of environmentally sensitive areas to desertification in central Iran. *Land Degradation & Development* DOI: 10.1002/ldr.2227.

Kar, A., Moharana, P.C., Raina, P., Kumar, M., Soni, M.L., Santra, P., Ajai, Arya, A.S. and Dhinwa P.S. 2009. In *Trends in Arid Zone Research in India*, Kar, A,Garg, B K, Singh, M P, Kathju, S (eds), CAZRI, Jodhpur, pp 1-47.

Kar, A., Ajai, and Dwivedi, R.S. 2016, Land degradation, In Dwivedi, R.S. and Roy, P.S., *Geospatial Technology for Integrated Natural Resources Management*, pp 295-320, Yes Dee Pub. Chennai, India

Kirui, O.K., Mirzaboev and A., von Braun. 2021. Assessment of land Degradation "on the ground" from "above", *Applied Science*, 3.318/ https://doi.org/10.1007/542452-021-04314-2.

Kumar, N. and Singh, S.K. 2018. Land Degradation assessment using MODIS NDVI time series data, In Singh, S.K., Chaterji, S., Chattaraj, S., Butte, P. S. and Sharma, R.P. *ICAR- NBSS&LUP Technologies*, NBSS&LUP Publ No 176, ICAR--NBSS&LUP, Nagpur, pp 102 110.

Kumar, N., Singh, S.K., Obi Reddy, G.P., Mishra, V.N. and Bajpai, R.K. 2020. Remote sensing applications in mapping salt affected soils *Agricultural Reviews*, 1-10. DOI: 10.18805/ag.R-2008.

Kust, G.S., Andreeva, O., and Cowie, A. 2017. Land degradation neutrality: Concept development, practical applications and assessment. *Journal of Environmental Management*, 195(1): 16-24. DOI: 10.1016/j.jenvman.2016.10.043.

Lal, R. 1994. Tillage Effects on Soil Degradation, Soil Resilience, Soil Quality, and Sustainability. *Soil and Tillage Research*, 27: 1-8.

Lal, R., Safriel, U., Boer, B. 2012. *Zero net land degradation: a new sustainable development goal for Rio.* A report prepared for the Secretariat of the United Nations Convention to Combat Desertification. http://www.unccd.int/Lists/SiteDocumentLibrary/secratariat//2012/Zero Net Land Degradation Report.

Minelli, S., Erlewein, A., Castillo, V. 2017. Land Degradation Neutrality and the UNCCD: From Political Vision to Measurable Targets. *International Yearbook of Soil Law and Policy*, Springer. https://doi.org/10.1007/978=3-319-42508-5.

Nachtergaele, F.O. and Licona Manzur, C. 2008. The LADA project: Reflections on indicators for land degradation assessment. In *The Future of Drylands*, Lee, C. and Schaaf, T. (eds). Springer, Dordrecht.

Narain, P. and Kar, A. 2007, Desertification and its Control in India, In *Human and Nature-Working Together for Sustainable Development of Drylands* (Eds. El-Beltagy, A, Saxena, M.C., Wang, T.) pp 84-94. Int. Centre for Agricultural Research in the Dryland (ICARDA), Aleppa, Syra.

Oldeman, L.R., Hakkeling, R.T.A. and Sombroek, W.G. 1991. *World Map of the Status of Human Induced Soil Degradation: An Explanatory Note*. GLASOD, International Soil Reference and Information Centre, Wageningen/UNEP, Nairobi.

Orr B.J., Cowie, A.L., Castillo, V.M., Sanchez, Chasek, P., Crossmand, N.D., Erlewein, A., Louwagie, G., Maron, M., Metternicht, G.I., Minelli, S., Tengberg, A.E., Walter, S. and Welton, S. 2017. *Scientific conceptual frame work for land degradation neutrality: a report of Science-Policy Interface*, United Nations Convention to Combat Desertification, Bonn, Germany.

Puigdefabregas, Juan, Gabriel del Barrio and Joachim Hill 2009. Advances in studies on desertification, Contributions to the International Conference in memory of Prof. Johm B. Thornes. -Murcia: Universidad de Murcia, editum. pp 77-87 *Ecosystemic Approaches To Land Degradation.*

Reynolds, J.F., Grainger, A., Stafford Smith, Bastin, D.M., Garcia-Barrios, G.L., Fernández, R.J., Janssen, M.A., Jürgens, N., Scholes, R.J., Veldkamp, A., Ver-straete, M.M., Von Maltitz, G., Zdruli, P. 2011. Scientific concepts for an integrated analysis of desertification. *Land Degradation & Development* 22: 166-183

Reynolds, J.F., Stafford, D.M., Smith, E.F., Lambin, B.L., Turner I.I., Mortimore, M., Batterbury, S.P.J., Downing, T.E., Dowlatabadi, H., Fernandez, R.J., Herrick, J.E,. Huber-Sannwald, E., Jiang, H., Leemans, R., Lynam, T., Maestre, F.T., Ayarza, M., Walker, B. 2007. Global desertification: Building a science for dryland development. *Science* 316: 847-851

Richards, L. A. 1954 Diagnosis and Improvement of Saline and Alkali Soils, *U S Department of Agriculture Handbook* No 60, U S Government Printing Office, Washington DC.

Sehgal, J.L. and Abrol, I.P. 1994. *Soil Degradation in India: Status and Impact,* Oxford: IBH Publication.

Singh, R.B. and Ajai. 2019. A composite method to identify desertification 'hotspots' and 'brightspots'. *Land Degradation and Development*, 1-15, https://doi.org/10.1002/ldr.3290.

Singh, S., Giri, K., Mishra, G., Kumar, M., Singh, R. K., Pandey, S., Mullick, M., Sharma, R. 2023. *Pathways to achieve land degradation neutrality in India*, Indian Council of Forestry Research and Education, Dehradun, India.

Sreenivas, K., Dwivedi, R.S., Singh, A.N., and Raviprakash, S. 2010. Detection of sub-surface water logging using Terra -1 MODIS Data. *Journal of the Indian Society of Remote Sensing* 38: 119-132.

Sreenivas, K., Sujatha, G., Mitran, T., Janaki Rama Suresh, K.G., Ravisankar, T. and Rao, P.V.N. 2021. Decadal Change in Land degradation Status of India, *Current Science*, 121(4): 539-550.

Thomas, D.S.G., Middleton, N.J. 1994. *Desertification: Exploding the myth*. John Wiley & Sons, Chichester

van Lynden, G.W.J. and Oldeman, L.R. 1997. *The Assessment of the Status of Human-Induced Soil Degradation in South and South-East Asia*. United Nations Environment Programme (UNEP), Food and Agriculture Organization (FAO), and International Soil Reference and Information Centre (ISRIC), Wageningen

Wang, J., Zhen, J., Hu, W, Chen, S., Lizaga, I., Zeraatpisheh, M., and Yang, X. 2023. *Remote Sensing of Soil Degradation; Progress and Perspectives*, Int Soil and Water Conservation Research, Doi: https://doi.org/10.1016/j.iswcr.2023.03.002

Zucca, C., Peruta, R.D., Salvia, R., Sommer, S., Cherlet, M. 2012. Towards a World Desertification Atlas: Relating and selecting indicators and data set to represent complex issues. *Ecological Indicators* 15: 157-170.

Printed in December 2024