Assessment of Desertification and Land Degradation Vulnerability in Humid Tropics and Sub-tropical Regions of India Using Remote Sensing and GIS Techniques

S. Kaliraj, Manish Parmar, I. M. Bahuguna, and A. S. Rajawat

Abstract The GIS-based Desertification Vulnerability Index (DVI) model has been used for mapping and assessment of potential vulnerability to desertification and land degradation in the two sites prevailing under different climatic conditions, namely Kasargod district in Kerala (humid tropics) and Virudhunagar district in Tamil Nadu (sub-tropics). The DVI model has executed multivariate statistical indices, namely Climate Index (CI), Soil Index (SI), Vegetation Index (VI), Land Use Index (LUI), and Socio-Economic Index (SEI). These multivariate indices are estimated using multiple geo-environmental and demographical parameters like land use/land cover (LULC), rainfall, soil properties, topography (slope), geomorphic landforms, geological settings, and climatic factors. The Desertification Vulnerability Index (DVI) is calculated using the equation expressed as DVI = $(CI * VI * SI * LUI * SEI)^{1/5}$. The result shows that the Kasargod district in Kerala is not identified with a higher category of desertification vulnerability, and 8.3% of the total area has no significant exposure. The area extend of 91.4% has been found under lower vulnerability conditions, and 0.23% of the area under moderate susceptibility to land degradation in the site-specific areas include Kodakkad, Timiri, Kilalode, Pullur, Panayal, Pallikere, and Bare due to human-induced activities like deforestation and LULC changes. The sub-tropical area of Virudhunagar district in Tamil Nadu shows that 1.4% of the total area has not fallen under land degradation; however, 65.4% of the area falls under low vulnerability and 33.2% under the moderately vulnerable zone. The spatially estimated area of 1428 km^2 (33.2%) is found with moderate vulnerability to desertification. Land degradation in various parts of the district includes Vembakottai, Panaikudi, Narikudi, Sivakasi, Virudhunagar urban proximity, and Aruppukottai, due to severe soil erosion and soil salinization. The 65.42% of the area is noticed as low vulnerability to land degradation; however, the land resources of the various sites are gradually undergoing degradation status due to both natural and anthropogenic activities that become causing adverse impacts on environmental ecosystems. Integrated

S. Kaliraj (✉)
National Centre for Earth Science Studies (NCESS), Ministry of Earth Sciences (MoES), Government of India, Thiruvananthapuram 695011, Kerala, India
e-mail: s.kaliraj@ncess.gov.in

M. Parmar · I. M. Bahuguna · A. S. Rajawat
Space Applications Centre (SAC—ISRO), Ahmedabad 380015, India

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remote sensing and GIS techniques provide an effective platform for sustainable land resources management on a long-term scale.

Keywords Desertification vulnerability index · Land degradation · GIS and remote sensing · Kasaragod and Virudhunagar · South India

1 Introduction

Desertification is one of the significant global issues affecting food productivity; it is caused by the continuous land degradation process in arid, semi-arid, and dry sub-humid landscapes due to climate change and human activities (UNEP 1992; Reynolds et al. 2011; SAC 2021). Desertification that occurs in any region is mainly due to altering the natural settings of biophysical factors that induce land degradation while exceeding the level of their restoration capacity and produce severe impacts on environmental ecosystems and food productivity (Giordano et al. 2003; Wang et al. 2006; Santini et al. 2010; UNCCD 2014; Karamesouti et al. 2015). UNCCD (2014) has reported that about 3.6 billion hectares of the global land surface have already fallen under land degradation, triggering critical impacts like loss of fertile soil and plant nutrients. 25% of the lands worldwide fall under desertification vulnerability due to human-induced factors (UNEP 1992; Ajai et al. 2009; Dasgupta et al. 2013; Kaliraj et al. 2017; Dharumarajan et al. 2018). The semi-arid areas mainly increase land degradation processes compared to other landscapes (Sehgal and Abrol 1994; Singh 2009; Sastry 2011; Kaliraj et al. 2019). Factors influencing land degradation are generally listed as soil erosion, deforestation, encroachment, overexploitation, water-logging, salinization, etc. (Salvati et al. 2009; Giordano et al. 2003; Kaliraj et al. 2014; Jafari and Bakhshandehmehr 2013; Dutta and Chaudhuri 2015; Kaliraj et al. 2015a, b, c; SAC 2016). The process of land degradation is a combined action of biophysical and socio-economic factors that induce irretrievable impacts on their natural settings (Kaliraj et al. 2019; SAC 2021). The increasingly adverse effects on various geo-environmental factors like soil, slope, vegetation cover, and climate directly affect environmental ecosystems and socio-economic conditions (Sastry 2011; Dutta and Chaudhuri 2015).

Nowadays, desertification is one of the severe problems that are directly affecting food production; significantly threatening ecosystems, agriculture, vegetative cover, basic infrastructure, and habitats (Sehgal and Abrol 1994; Kharin et al. 2000; Wang et al. 2006; Frattaruolo et al. 2009; Kaliraj 2016). India is a signatory to the UNCCD and is committed to achieving land degradation at neutral status by 2030. The various government bodies have joined together for combating desertification and land degradation processes in different parts of the country through scientific approaches (Sehgal and Abrol 1994; Ajai et al. 2009; Dasgupta et al. 2013; Dutta and Chaudhuri 2015; Kaliraj et al. 2015a, b, c; SAC 2016; Dharumarajan et al. 2018). In India, the various landscapes have experienced land degradation issues due to human-induced activities that increase adverse impacts on land and water resources.

In India, a total geographical area of about 228 Mha (69%) is noticed under land degradation conditions, especially in the landscapes of arid, semi-arid, and sub-humid regions. It is mainly due to changing natural and anthropogenic factors causing soil infertility, erosion, salinity, and sodicity. Recently, SAC (2021) has published a report on the desertification status of India in collaboration with NCESS and other 12 institutes. The report reveals that 29.77% of the total geographic area is undergoing land degradation during 2018–2019, whereas the major factors inducing desertification/land degradation are water erosion (11.01%), followed by vegetation degradation (9.15%) and wind erosion (5.46%) and the cumulative rate is increased up to 1.87 Mha compared the period of 2003–2005 to 2011–2013. Nowadays, assessment and monitoring of land degradation activities through scientific approaches is vital for sustainable development; hence, the integrated remote sensing and GIS techniques provide an effective platform for mapping the desertification vulnerability by analyzing the multiple geo-environmental parameters (Albaladejo et al. 1998; Wang et al. 2006; Ali and El Baroudy 2008; Dasgupta et al. 2013; Kaliraj et al. 2015a, b, c; Lalitha et al. 2021). GIS-based desertification vulnerability is very much valuable for policymakers in preparing strategic plans for combating these issues. Many studies are executed worldwide for assessing desertification vulnerability using GIS techniques (Frattaruolo et al. 2009; Vu et al. 2014). For mapping, the potentially vulnerable zone to desertification and land degradation, statistical indices are used for analyzing the biophysical and anthropogenic factors at a spatio-temporal scale with the aid of remote sensing images, geospatial tools, and field-based studies. GIS-based desertification vulnerability index (DVI) model is designed to execute multiple geo-environmental variables, i.e., physical (soil quality), environmental (vegetation quality), climatic (climate quality), and social indicators (management quality) for spatio-temporal monitoring and assessment of land degradation status. This study provides a primary data source for the preparation of comprehensive action plans for combating desertification processes. GIS-based DVI model is executed to map potential vulnerability to desertification and land degradation with a minimum cost and better accuracy at a regional and local scale.

2 Description of the Study Area

GIS-based DVI model is used to map desertification vulnerability in two different areas, namely Kasaragod district in Kerala and Virudhunagar district in Tamil Nadu. Figure 1 shows the geographical location of the study area of these two districts. The Kasaragod district covers beautiful landscapes of the coastal stretch of the Arabian Sea and the hill range of the Western Ghats at the northern tip of Kerala. The geographical extent of the area found at the 74°53′21.944"E–75°25′4.1"E longitude and 12°1′42.145″N–12°48′38.53″N latitude and the total area is about 1992 km^2. The landscapes cover the different landforms, including coastal settlements, low-lying wetlands, midland of lateritic plateaus with settlements and plantations, upland hill-range of forest cover, rocky exposure, and rivers with many tributaries.

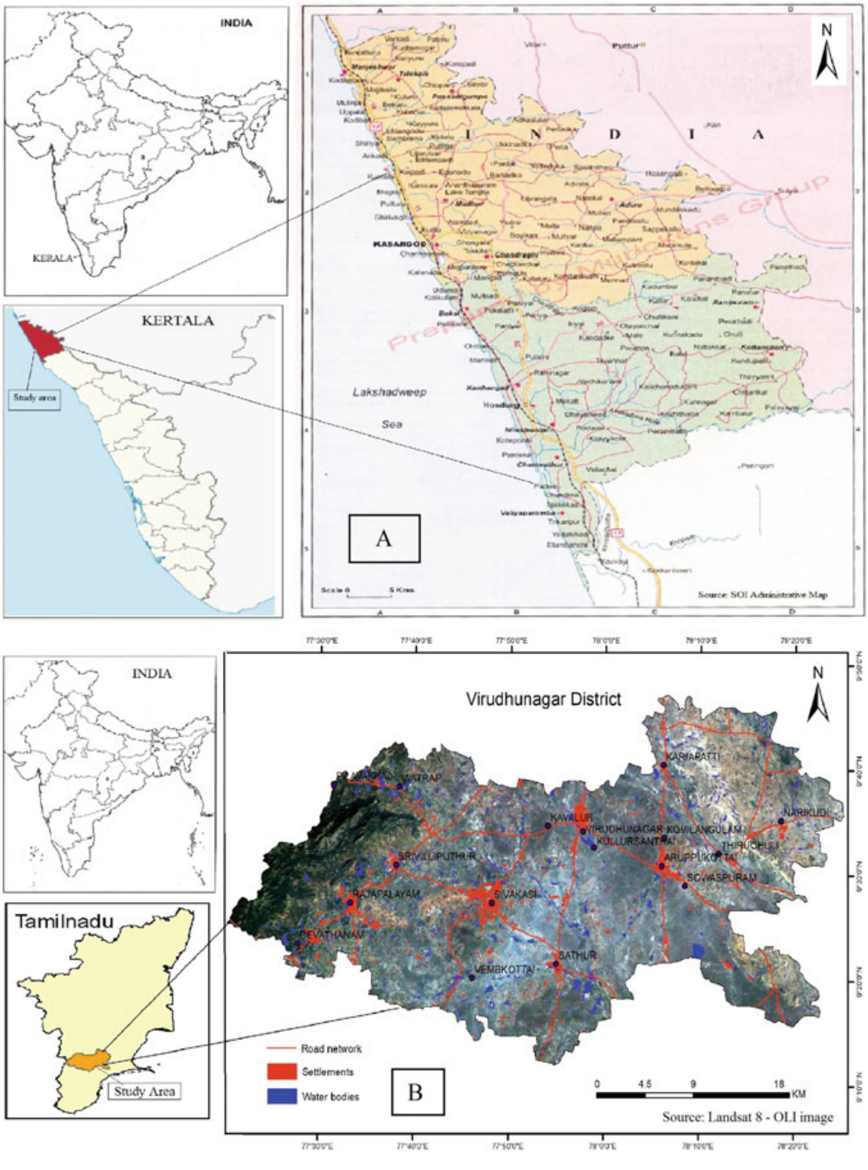

Fig. 1 Methodological workflow of GIS-based DVI modeling for mapping of desertification vulnerability

The tropical climatic conditions are found across the area with an annual average rainfall of 33.50 cm and a temperature range of 17–37 °C. Spatio-temporal distribution of LULC features depends on their landscapes and existing tropical climatic conditions, and it is frequently changing through impacts of natural and human-induced activities. The Virudhunagar district in Tamil Nadu prevails in the sub-tropical climatic condition, which covers the geographical extent of 77°20′26.671″E–78°25′9.097″E longitude and 9°11′5.748″N–9°47′19.758″N latitude. This region covers a total area of about 4232 km^2, whereas the Western Ghats has bounded on the western side, and the rest of the areas comprise the black cotton soils in all directions. This district covers major populated urban areas, namely Aruppukkottai, Kariapatti, Rajapalayam, Sattur, Sivakasi, Srivilliputur, Tiruchuli, and Virudhunagar. Major landforms encompass flood plains, bajada, peneplain, buried pediment, and structural hills in the western parts. In various parts of the district, alluvial plains consist of urban/rural settlements and agricultural lands. In this area, the drainage system encompasses rivers, streams, and water bodies found in non-perennial conditions except during the north-east monsoon, mainly used for dryland agriculture activities.

3 Materials and Methods

Mapping of desertification vulnerability is executed by analyzing multiple geo-environmental parameters using a GIS-based DVI model. Figure 2 shows the methodological workflow of GIS-based DVI modeling used in this study. The DVI model is executed using multivariate statistical indices, namely Climate Index (CI), Soil Index (SI), Vegetation Index (VI), Land Use Index (LUI), and Socio-Economic Index (SEI). Multiple geo-environmental parameters include land use/land cover (LULC), rainfall, soil properties, topography (slope), geomorphic landforms, geological settings, and climatic factors for mapping the vulnerable zone to desertification and land degradation. In this analysis, the CI is calculated using the Global Aridity Index (Global-Aridity_ET0) and Global Reference Evapo-Transpiration (Global-ET0) datasets. In this analysis, the VI is estimated using NDVI products of Landsat ETM + (R/NIR) images in addition to soils, drought resistance, fire risk, and vegetative cover, and it is expressed as VI = (Erosion protection * drought resistance * fire risk * plant cover percentage)$^{1/4}$. SI (also known as Soil Quality Index) is calculated using the equation, and it is expressed as SI = (Soil texture * parent material * slope)$^{1/3}$. The layer of parental material is derived from GSI published lithology map. The slope index is estimated using SRTM DEM (30 m) dataset. LUI is calculated using a Landsat (30 m) ETM + and OLI images-based LULC map; it is derived from a supervised classification technique using the Mahalanobis Distance algorithm. Socio-Economic Index (SEI) is calculated using demographic inputs that include population, unemployment, illiteracy, and poverty rate; and it is noted as SEI = (Population pressure * Unemployment * Illiteracy * Poverty)$^{1/4}$. The Desertification Vulnerability Index (DVI) is calculated using the cumulative value of multivariate indices, and it is expressed as DVI =

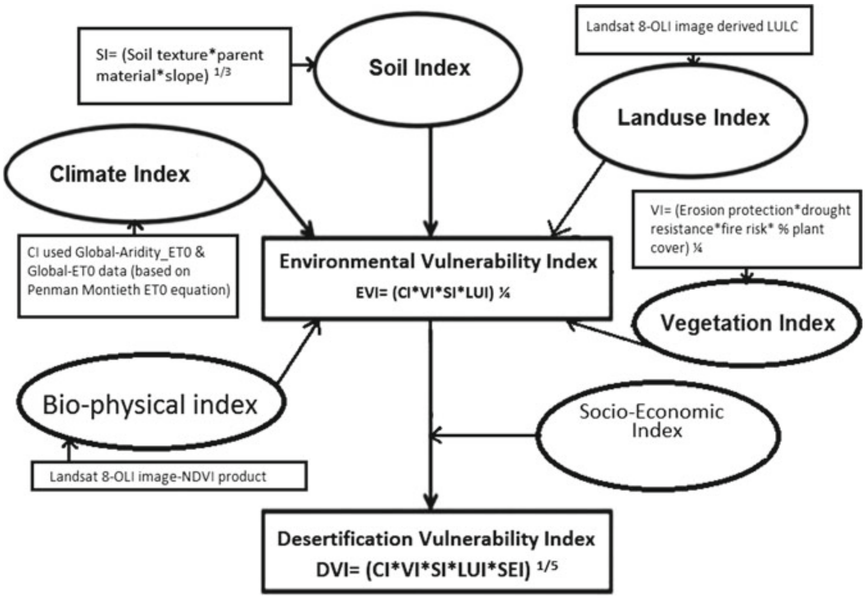

Fig. 2 Methodological workflow of GIS-based DVI modeling for mapping of desertification vulnerability

$(CI * VI * SI * LUI * SEI)^{1/5}$. These multivariate indices include Climate Index (CI), Soil Index (SI), Vegetation Index (VI), Land Use Index (LUI), and Socio-Economic Index (SEI) estimated using multiple geo-environmental and demographical inputs. Integrated remote sensing and GIS techniques are used to prepare these parameters from various data sources at a uniform coordinate system and scale. The GIS tools and functions have been applied to analyze multiple input parameters according to the different statistical indices from mapping the desertification status in the study area.

4 Results and Discussion

Mapping desertification vulnerability is a complex set of processes that incorporate the different statistical indices of multiple parameters affecting land productivity (Ajai et al. 2009; Frattaruolo et al. 2009; Kaliraj et al. (2016); Dharumarajan et al. 2018). In this study, the desertification vulnerability is carried out for two different locations in southern India, namely Kasargod district in Kerala and Virudhunagar district in Tamil Nadu. The GIS-based DVI model is executed to identify potential vulnerability to desertification and land degradation by analyzing multiple geo-environmental parameters. Figure 3 shows the desertification vulnerability map of the two districts of South India: Kasargod (A) and Virudhunagar (B) using the

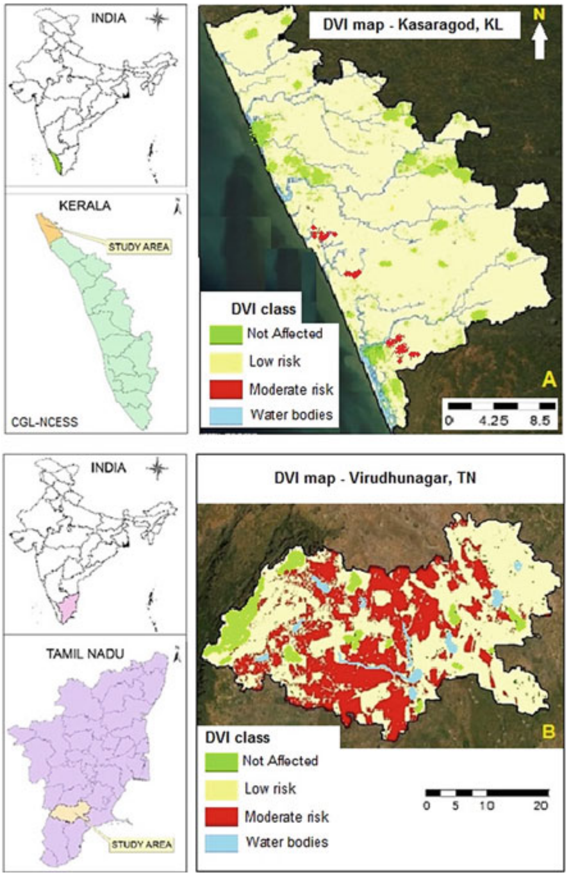

Fig. 3 GIS-based DVI model shows the desertification vulnerability for two districts of South India: Kasargod (**a**) and Virudhunagar (**b**)

GIS-based DVI model. The result shows that the Kasargod district in Kerala is not identified with a higher category of desertification vulnerability, and 8.3% of the total area has no significant exposure. Table 1 shows the estimated rate of desertification vulnerability index (DVI) and its area extend in Kasargod district (Kerala) and Virudhunagar district (Tamil Nadu). Meanwhile, 91.4% of the land was found under low vulnerability and 0.23% under moderate vulnerability to land degradation in site-specific areas, including Kodakkad, Timiri, Kilalode, Pullur, Panayal Pallikere, and Bare due to human-induced activities like deforestation and LULC changes.

In the Kasargod district, the various LULC features are noted as environmentally vulnerable areas due to human-induced activities, which gradually produce significant changes in landscapes and socio-economic conditions. In the Virudhunagar district, many spots face land degradation issues mainly due to severe erosion and soil salinization that adversely impact human society and surrounding environmental ecosystems. Major factors inducing land degradation are caused by various interrelated factors like soil erosion, vegetation degradation, land use change, climate

Table 1 Estimated rate of desertification vulnerability index (DVI) and its area extend in Kasargod district (Kerala) and Virudhunagar district (Tamil Nadu)

DVI rating	Kasargod (KL)		Virudhunagar (TN)		DVI vulnerability class
	Area (km^2)	Percentage	Area (km^2)	Percentage	
100–125	61	1.42	167	8.33	Not affected
126–150	2817	65.42	1834	91.43	Low risk
151–175	1428	33.16	5	0.25	Moderate risk
176–200	NA	NA	NA	NA	High risk

variability, and socio-economic issues, besides the natural and human-induced activities. Impacts of land degradation increased in various parts are drastically decreased crop productivity due to several factors like increasing land surface temperature, soil dryness, morphological deformations, soil erosion, human encroachments, and over-exploitation of water resources.

The Virudhunagar district in Tamil Nadu state has prevailing sub-tropical condition that shows 1.4% has not fallen under land degradation; however, 65.4% of the area falls under low vulnerability and 33.2% under the moderately moderate vulnerable zone. The site is estimated at 1428 km^2 (33.2%) with moderate vulnerability to land degradation in various parts of the landscape that including Vembakottai, Panaikudi, Narikudi Sivakasi, Virudhunagar urban proximity, and Aruppukottai, due to severe soil erosion and soil salinization. The 65.42% of the area is noticed as low vulnerability to land degradation; however, the land resources of the various sites are gradually undergoing degradation status due to both natural and anthropogenic activities that become causing adverse impacts on environmental ecosystems.

Across the Virudhunagar district, the LULC features, especially dryland agriculture, drastically degrade soil fertility and food production due to soil infertility and salinity. In this region, the massive lands are used for dryland agriculture, whereas land degradation is one of the major issues due to soil erosion and soil salinity. In these two districts, the various landscapes fall under desertification and land degradation at different degree levels. It is mainly due to increasing pressure on natural settings that drive erosion, infertility, salinity, etc. For example, removing upland vegetative increases surface runoff (or) overland flow followed by flooding and landslide, eroding topsoil and nutrients from downslope and plan surfaces. The process of land degradation is increasing in various parts due to improper land management practices. The landscapes of those areas accompanied by uplands and rivers/streams are seen as highly productive zones due to prevailing favorable climate and soil conditions. Likewise, the LULC around human-intervening locations is highly sensitive to land degradation due to altering the natural settings of the biophysical and environmental systems.

However, in many areas of these two districts, the agricultural lands are being used for multiple crop cultivation during the northeast and southwest monsoons. It is noted that increasing land degradation silently coupled with impacts of natural and socio-economic factors in these districts may be causing severe effects on the livelihood of the local people.

5 Conclusion

The GIS-based DVI model is used to map potential vulnerability to desertification and land degradation by analyzing the multiple influencing factors at a site-specific scale. The DVI map shows that the various parts of both districts fall under higher vulnerability to land degradation due to increasing adverse impacts that alter regular mechanisms of biophysical and environmental factors. LULC features at various parts are significantly degraded in both districts due to overexploitation of land resources and improper land-use practices. Specifically, in many locations, LULC features around the human-intervening proxy are susceptible to land degradation and desertification due to frequently altering biophysical and environmental systems. However, the massive areas are found with no apparent changes towards land degradation. The increase in land degradation is commonly coupled with impacts of biophysical and socio-economic factors in these districts, causing severe effects on the socio-economic status of local people. It is concluded that the assessment and mapping of desertification vulnerability using integrated remote sensing and GIS techniques provides a primary database for preparing combating plans and sustainable developmental activities.

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