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Using remote sensing technology to detect, model and map desertification: A review

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Abstract

Desertification is a serious global environmental problem that affects many people directly in countries with semi-arid or arid climates. The causes of desertification are diverse and complicated, ranging from international economic activities to unsustainable land use practices of local communities. The consequence of desertification reduces the ability of the land to support life and decreases biodiversity. Natural processes and artificial forces initiate this process. Natural causes of desertification include climatic factors drought, and water or wind erosion. Human induced activities that can cause desertification include over-cultivation, overgrazing, deforestation, and poor water management.The aim of this paper is to analyse how remote sensing and GIS have been used to monitor desertification globally. Remote sensing has proven to be efficient in detecting desertification processes including changes in natural vegetation, land use, and soil. Multi-temporal coverage provided by satellite data facilitates the use of remote sensing imagery to monitor changes in land coverage and usage over time. Remote sensing data and GIS are critical for extracting reliable information important for assessing environmental changes and land quality in any given region. Various techniques in remote sensing combined with analytical methods such as NDVI or classification provide primary data that can be used to assess desertification processes. Several key indicators of the processes of desertification are identified where remote sensing can be used to detect, monitor, and map affected areas. Changing vegetation and land use, drought, soil, erosion, and urbanization are the most common indicators of desertification used by researchers. Results of studies can be used to make important management, environmental, and political decisions. Therefore, care, must be taken to use recent imagery, select the appropriate technique, and to include as much additional data as possible so that reliable and robust results are obtained.

Key words: Land use, land cover, desertification, soil degradation, drought, erosion, remote sensing, vegetation indices, urbanization, GIS.

Introduction

Desertification, where the areas of desert are expanding, is a serious environmental problem that continues to threaten biodiversity and human inhabitants of third world countries with semi-arid or arid climates in particular [1]. The fight against desertification is crucial at this time of climate change if the long-term productivity of drylands is to continue. Efforts to combat desertification are difficult due to increasing anthropogenic activities, with inadequate attention and commitment from the international community to halt the process. While deserts occur naturally, desertification is accelerated by a combination of human and natural causes. Many countries lack adequate financial resources to prevent the causes of desertification, or monitor the processes involved. Understanding the causes and implications of desertification must be a priority before any monitoring of desertification can take place. Remote sensing techniques are used across various environmental and anthropogenic aspects of studies, providing an effective tool for mapping and to support the decision-making process.

The aim of this manuscript is to review the current techniques used in remote sensing as a tool for detecting the process of desertification globally from natural and human induced causes. The gaps in the current knowledge and techniques are highlighted.

Desertification: definition, causes and impact: Desertification is variously defined. The United Nations Convention to Combat Desertification defined desertification broadly as land degradation in arid, semi-arid, and sub-humid regions [2]. More recent definitions include aspects that deal with soil components [3] and refer to the processes that alter productive areas into non-productive areas due to unsustainable and poor land-management practices [4]. More than 250 million people are directly affected by desertification and about a billion people are at risk of desertification [5, 6]. Lack of action could cause many people worldwide to be displaced by land degradation and desertification in the future [1].

Desertification is caused by natural factors (e.g. drought) and human induced activities (e.g. agricultural) [7]. Since the early 1920s desertification has been identified as an environmental problem globally, however, major adverse social and economic impacts over the last two decades have emphasised the serious environmental issues [8]. The impacts of desertification lead to serious threats worldwide, especially populations of affected developing countries [9]. Poor agricultural practices lead to serious consequences of drought and famine [10] causing long-term economic problems, human health, famine, and food security. Desertification can be devastating for environments, economies, and political stability of the countries in which they occur. Unsustainable practices in developed nations also pose problems, where poor land management and weak government policies are employed in agriculture and forestry [11]. As stated by the UNCCD [12] 'desertification, exacerbated by climate change, represents one of the greatest environmental challenges of our times'.

Desertification processes are well known, but are not fully understood [10]. The consequence of desertification reduces the ability of the land to support life and decreases biodiversity. Natural processes and artificial forces initiate this process [2, 13]. Natural causes of desertification include climatic factors (e.g. low rainfall and high temperatures), drought, and water or wind erosion. Human induced activities that can cause desertification include over-cultivation, overgrazing, deforestation, and poor water management [6, 14]. Williams and Saunders [15] noted that natural factors, such as geological orientation of land and processes that lead to global warming, may facilitate land degradation. Abahussain *et al.* [16] provide a clear outline of the major driving forces (natural and human induced) for desertification in the Arab region that can be applied to other regions (Fig. 1). As the process of desertification reduces the potential of land to support life, identifying the processes of degradation is vital if productive lands are to be preserved and lands rehabilitated irrespective of the extent of degradation [17, 18].

Remote sensing used for detecting and monitoring: Remote sensing (RS), with the ability to cover wide areas, is valuable for assessing the key indicators of desertification [4, 19]. Monitoring and mapping desertification is the best way to control and halt the processes. Remote sensing techniques have been applied to monitor trends of land degradation as well as to identify and characterize sand dunes and their temporal dynamism [20, 21]. In the last two decades satellites have provided data for global monitoring that is important for improving our understanding of desertification [20,22-28].

The ongoing problem of desertification is increasing annually [25], generating numerous studies using remote sensing techniques to aid the detection of processes globally [4, 19, 20, 25-29]. Advantages of using RS technology include saving time, wide coverage (satellite remote sensing provides the only source when data is required over large areas or regions), are faster than ground methods, and facilitate long term monitoring of land coverage and land usage [29-33]. These techniques provide image resolutions that can be low (NOAA-AVHRR), medium (Landsat TM, Landsat MSS, and IRS-I, ISS-II), and high (SPOT, IKONOS, QuickBird, GeoEye-1, Worldview-1, and WorldView-2).

Landsat imagery is frequently used to demonstrate the impact of desertification on people and the environment due to image availability and accessibility [4, 14, 19, 33-35]. Higher resolution imagery is able to detect greater detail for better precision, thereby, providing more accurate image analysis. Remote sensing data can be used as input into a geographic information system (GIS) for further analysis and comparison with other data gathered spatially or temporally. Selecting the band or bands required for particular needs (e.g. soil, water, or vegetation) and integrating GIS with remotely sensed data provides valuable information on the nature of land cover changes, especially for large areas and spatial distribution of different land cover changes [29, 32].

Remote sensing data and GIS techniques are becoming a vital component of the primary analysis and extraction of information including proportion of drifting sand areas, urban land use mapping, dynamics of the ecosystem, and geological monitoring of natural hazards such as global warming [19, 36-38].

Desertification key indictors: There are several key indicators of the processes of desertification that remote sensing can be used to detect, monitor, and map over affected areas. Changing vegetation and land use, drought, soil, erosion, and urbanization are the most common indicators used by researchers.

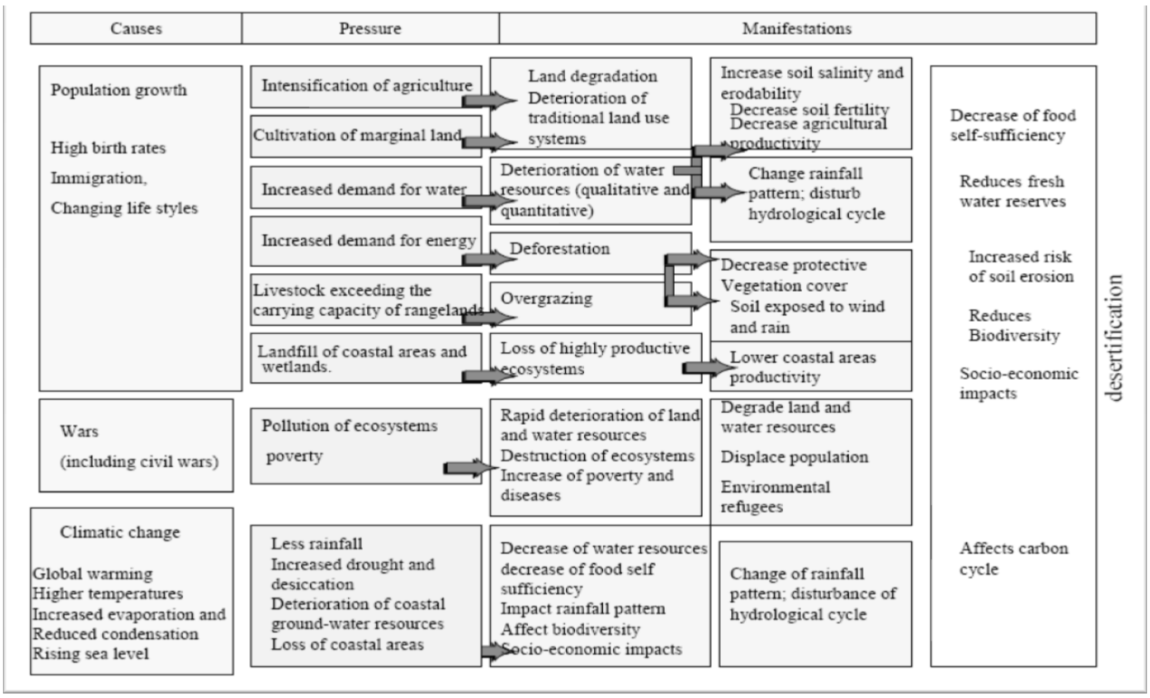

Figure 1. Major driving forces for desertification in the Arab region and their impacts [16].

Land cover/agricultural land use: Satellite data have proven to be useful for vegetation studies, whether it be for composition or land use. Expanding agricultural areas pose potential environmental impacts on water reserve and quality, plus chemical and physical properties of soil [4, 7, 20, 27, 34].

Remote sensing techniques are increasingly used to monitor agricultural land use changes, and therefore aid-monitoring desertification processes in semi-arid and arid areas. Land use and agricultural land are effective indicators because they are easy to identify from satellite imagery. For example, changes in the composition of the topsoil as well as vegetation cover composition can be identified through analysis of the colour composites. The assessment of vegetation changes using remote sensing techniques, estimates desertification processes [36]. Many studies have discussed land cover and land use changes in semi-arid and arid areas of Africa [39], Sudan [36], Egypt [29, 34], Saudi Arabia [27] and China [33] associated with land degradation and desertification. Decreasing areas of natural vegetation are directly related to increases in agriculture land use [27, 29, 40].

Mismanagement of land use farming practices in fragile land, including over-grazing [7, 20, 25, 27, 29 ,41], irrigation [34], mining [42] and woodcutting for domestic use [27] impact the land and can lead to desertification; such mismanagement can be detected using remote sensing. For example, studies showing overgrazing in Argentina[20], North China [25], Saudi Arabia [7, 27], and the Sahel [23] used imagery from Landsat-2, Landsat TM, NOAA--AVHRR, Landsat TM5 and SPOT respectively (Table 1).

The normalised difference vegetation index (NDVI) derived from RS imagery has been used to monitor changes in vegetation cover, patterns, and condition in desertification studies [7, 43]. There is increasing evidence that the addition of the Red-Edge spectral band can improve the accuracy and sensitivity of plant studies, especially in areas with low vegetation cover [23, 28, 43] such as in semi-arid and arid areas. Detecting decreases relative to the baseline as an indicator for drought intensity, is necessary for estimating desertification [44].

Satellite imagery can be used to assess ecosystem degradation by measuring rain-use efficiency (RUE), which is often used as an indicator for the state of the vegetation cover [23]. A decrease in RUE reflects a reduced capacity of the vegetation to transform water (and nutrients) into biomass [23, 45]. The resultant loss of vegetation cover decreases nutrient availability and increases run off due to soil compaction. Hein and De Ridder [23], however, noted that many RS studies using RUE ignored the relation between

Table 1. Some studies and techniques used in remote sensing to detect desertification processes over the last 10 years.

Author	Country	Sensor	Study period	Technique
Collado et al. 2002	Argentina	Landsat-2 MSS Landsat-5 TM	1982, 1992	Change detection using spectral mixture analysis (SMA) – derive the proportions of different basic land cover types that compose a mixed pixel; appropriate to monitor desertification processes, since the mixture of vegetation and soil is very common in arid areas, Water to indicate rainfall (water bodies), bare soil (dunes)/vegetation (green crops) to indicate degraded areas.
Sun et al. 2005	Minqin County, China	Landsat 5 TM	1988, 1992, 1997	Land use map, Cluster sampling, Multi-criteria evaluation derived from remotely sensed data, 4 general desertification types (and 4 general desertification grades (NDVI & albedo (reflectivity sum method) – vegetation change, Ecological system stability.
Hein & De Ridder 2006	Sahel, Africa	RUE		NDVI (net primary production) + RUE (decline in RUE indicates ecosystem degradation)
Pannenbecker 2006	North of the Republic of Lebanon	Landsat 5 TM Landsat ETM+	1987, 2000	3 bi-temporal change detection methods: Change Vector Analysis (CVA), Iterative Principal Components Analysis (IPCA), Multivariate Alteration Detection (MAD) in combination with Maximum Autocorrelation Factor (MAF).
Khiry 2007	North Kordofan State, Sudan	Landsat MSS Landsat 5 TM Landsat ETM+	1976, 1988, 2003	Detection change in fraction images, Spectral Mixutre Analysis (SMA) – direct measure of different land cover, Linear mixture model (LMM) – endmembers with Principal component, analysis (PCA) to aid selection, CVA (change vector analysis), determine/analyse land cover change, EMI (Eolain mapping index) – to assess areas vulnerable to wind erosion
Shalaby & Tateishi 2007	Northwestern coastal zone of Egypt	Landsat 5 TM Landsat ETM+	1987, 2001	Maximum likelihood supervised classification, Change detection, CROSSTAB – compares categories in 2 images and cross classification: shows all combinations of categories in the original image
Fang et al. 2008	Western Jilin Province, North China.	Landsat 5 TM	1986, 2000	Land use and land cover (12 classes), Supervised classification approach, analysed human and natural driving forces, Dynamic degree of land degradation (SD)
Al-Harbi 2010	Tabuk, Saudi Arabia	Landsat 5 TM SPOT 5	1988, 1999, 2008	Supervised classification, Soil properties, Hydrological parameters: Measured % change in bare soil/irrigated areas
Kundu & Dutta 2011	Churu, Thar Desert, Rajasthan, India	NOAA-AVHRR		Long term study NOAAAVHRR data 1983-2003, NDVI time trend + long term rainfall, Changes in vegetation conditions (growth depends entirely on rainfall) indicates ongoing desertification processes
Yanli 2011	Northern Shaanxi Province, China	Landsat 5 TM Landsat ETM+	1987, 2002	Image differencing, Change vector analysis, NDVI, Supervised classification: 5 land use land cover (LULC) classes (urban area, water bodies, unused land, sand area, vegetation area), Natural and anthropogenic factors included.
Shafie et al. 2012	Sistan Plain, Iran	Landsat 5 TM Landsat ETM+ Quickbird	1990-2006	Evaluated 83 vegetation indices, Change detection

annual rainfall variation and RUE.

Remote sensing techniques cannot replace the need for ground-sourced data. In agricultural studies remote sensing and ancillary data are complementary. Providing fast and effective results can aid farmers in their planning and decision making to develop ongoing comprehensive management plans [46].

Drought: Drought occurs when an area continuously suffers from lower precipitation than normal and is often associated with land degradation, hence, is a vital factor in the process of desertification [4, 47, 48]. Satellite remote sensing has the ability to monitor plant available moisture, land cover type and condition at regional scales over extended periods. Remote sensing provides an effective tool for monitoring to assess the level of vegetation stress as an indicator of drought, providing a means of determining responses at regional scales [47, 48].

Remote sensing techniques have been used to detect and assess meteorological drought [37, 49]. NOAA–AVHRR is the most widely applied spaceborne sensor for investigating drought, using the combined power of NDVI (reflectance bands) and Land Surface Temperature (LST) (thermal bands) [48]. Other drought related indices commonly used to identify and monitor areas affected by drought are NDVI anomaly, integrated or standardized NDVI, Global Vegetation Index (GVI), and Vegetation Condition Index (VCI). Bayarjargal *et al.* [37] and Palmer and van Rooyen [39] used Change Vector Analysis (CVA) to show the direction and magnitude of change in drought and desertification studies, as CVA has an advantage in time series data compression over other change detection methods.

Soil: Remotely sensed imagery has been used for soil properties in desertification studies [50-54]. Fragile soils are made vulnerable to erosion and, therefore, desertification due to climatic variations [55, 56]. The processes that cause the rise and fall in the level of essential components of soil can lead to soil degradation and consequently, desertification. Mapping soil degradation using Grain Size Index (GSI) of topsoil has potential as a tool for assessing land degradation and desertification processes, through change detection. Hill [51] identified abundant fine-sand areas in China Using GSI, and Xiao *et al.* [52, 53] detected the source area of sand/dust storms in Mongolia using this index. The GSI index must be used on imagery captured prior to the germination of ephemerals in spring to be effective [51, 52].

Soil salinity is a major problem for agricultural development in dry and semi-dry regions, making soils unproductive [57], causing land degradation and desertification [40]. For example, on the Albatinah coast in Oman the main reasons for desertification are soil salinity, and soil types played an important role in speeding up the desertification process [40]. Remote sensing techniques provide an effective tool for detecting and mapping soil salinity [40, 58, 59]. Salinity indices such as Soil Salinity Index (SSI), Soil and Sodicity Index (SSSI), and Brightness Index (BI) were used by Abbas and Khan [32] to detect salinity in degraded land using the multi-temporal IRS-1B LISS-II images; noting that determining soil salinity was difficult in semi-arid and arid areas with low vegetation and low soil moisture. Surrogate indicators of soil salinity (e.g. vegetation cover, vegetation health) are often employed for low/medium spatial and spectral multispectral resolution imagery (e.g. Modis and Landsat imagery).

Erosion: Desertification reduces vegetation and increases soil erosion, as the bare soil is exposed to wind and water erosion [29, 60]. Soil erosion is the process of eroding including weathering, dissolution, abrasion, corrosion, and transportation, by which material is worn away from the earth's surface. In the detection of erosional forces and the extent of desertification, modern methods employ remotely sensed satellite imagery for accurate methods of monitoring vegetation cover and dry land [61]. Human induced forces including cultivation and deforestation from poor economic development is a major source of erosion in semi arid/arid areas such as seen in China, and the Middle East [42]. Remote sensing is a vital component for monitoring the dynamic processes of wind erosion. The forces of the seasonal wind changes are factors contributing to the dynamic nature of sand dune movements as part of the wind erosion process in China [19].

Urbanization: Urban encroachment is an irreversible desertification process [34]. Expanding urbanization due to economic development and increasing population is pushing agriculture into ecologically fragile land that can lead to desertification [29, 34]. Increasing human population creates high demand on resources such as groundwater reserves, plus domestic food and water supplies, which leads to severe degradation of the environment [1, 4, 14].

Remote sensing techniques are used to classify land use and urban development to detect the impact of urban growth and desertification [22, 28, 62]. By monitoring environmental change using SPOT and Landsat imagery over a 15-year period, major increases in areas of erosion were detected with the main cause of land degradation being urban growth [22, 28]. Shalaby *et al.* [34] reported that 20 000 ha of highly fertile agricultural land are lost yearly due to urban encroachment in Egypt, putting more pressure on fragile areas.

Indices used to detect key desertification indicators: Vegetation indices are most commonly used for consistently detecting desertification [31] (Table 2), measuring plant growth (vigor)/stress, vegetation cover, land cover, and biomass production using multispectral satellite data. Changes in the vegetation index can reflect the changing processes of land degradation and desertification. The NDVI is commonly used for detecting vegetation cover and to assess vegetation condition [28, 63, 44] (Table 2). Time series analysis of NDVI allows establishment of a baseline for normal vegetation productivity for a region. Low NDVI values mean there is little difference between the red and NIR signals, indicating stressed vegetation that is relatively inactive photosynthetically. Shafie *et al.* [64], however, criticized using land plant cover to detect desertification. There are many factors that can affect NDVI index (e.g. total plant cover, plant and soil moisture, plant stress and photosynthetic activity). Semi-arid and arid environments tend to have more bare ground and exposed rock than temperate or tropical habitats, therefore, indices such as soil-adjusted vegetation indices (SAVI, SAVI1 and SAVI2) include a soil brightness correction factor [65] to minimize the effect of the background sensitivity in analysis [63]. Kundu and Dutta [43], using NDVI time trend plus long term rainfall, showed that their study area in Rajasthan was gradually desertifying as a complex consequence of both climate and anthropogenic factors.

Table 2. Vegetation indices commonly used to detect change in desertification studies.

Vegetation Index (VIs)	Advantages	Disadvantages
$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$	Simple atmospheric, Monitor phenology, quantity, and activity of vegetation, Long time series, Simple transformation, No assumptions (land cover classes, soil type or climatic conditions)	Background reflectance sensitivity, Plant canopy sensitive (changes in water content), Over estimate vegetation in semi-arid & arid regions, Low-resolution vegetation maps, Nonlinearity (ratio based index) soil surface light over detection
$EVI = 2.5 * \frac{(NIR - RED)}{(NIR + C_1 * RED - C_2 * BLUE + L)}$	Tolerates background reflectance, High aerosol loads, Biomass, biophysical leaf area index, Quantification of evaoptranspiration or water-use Efficience, change over large areas	Blue wavelengths, Difficult to extract from broadband radiation measurements, Nonlinearity (ratio based index), Lower ranges over semiarid sites, Is not a structural property of a land surface areas, Requires surface reflectance measurements from blue, red, and near-infrared bands, sensitive to plant canopy
$SAVI = \frac{NIR - RED}{(NIR + RED + L)} * (1 + L)$	Semi-arid & arid regions	Sensitive to atmospheric differences, Less sensitive to changes in vegetation
$WDVI = R_{nir} - R_{vis}\left(\frac{Rs_{vis}}{Rs_{nir}}\right)$	Effectively by enhancing canopy reflectance component	Detailed atmospheric correction, Distance based index
$MSAVI = (1 + L)\frac{R_{NIR} - R_{red}}{R_{NIR} + R_{red} + L}$ where $L = 1 - 2a \times$ NDVI $\times$ WDVI	Rangeland studies correlated to field data on vegetation cover/desertification, Requires red and a near infrared band to calculate	Sensitivity to changes in vegetation amount/cover to correct for the soil surface brightness, Sensitive to differences in atmospheric conditions between areas or times

Shafie *et al.* [64], however, found Weighted Difference Vegetation Index (WDVI) produced more accurate maps of their study in Iran, than did TSAVI2, MSAVI1 and NDVI, with NDVI still in the top four.

Problems using remote sensing: Remote sensing technology involves using automated devices mounted on an elevated platform (e.g. satellite) to provide image data [66]. Data collected from remotely sensed imagery, such as satellite imagery, requires corrective processing (e.g. atmospheric, image alignment, etc.) and appropriate analysis prior to using data to assess a specific issue or problem [67]. It is important that remotely sensed data be combined with ancillary data, with both data sources accurately aligned and integrated [68]. Data accuracy is important if the findings are to be used for environmental monitoring, inventory analysis, and quality thematic mapping [26] to aid policy change and new management structures essential for controlling desertification processes [69]. Currently, satellite images alone do not provide enough information to draw a strong conclusion; hence, including qualitative methods is essential [70]. Each imaging sensor has its own limits on scene recognition in the sense of thematic, temporal, and other interpretation [63]. Remote sensing has been recommended as a technique for timely, up-to-date, and relatively accurate information for sustainable and effective management of vegetation [71].

Conclusions

Remote sensing techniques can aid the complex task of assessing and monitoring desertification. While desertification is a natural process, human induced activities such as expanding urbanization and agriculture, are speeding up the desertification process. The remote detector from satellite systems allows for mapping of the vegetation cover, vegetation stress, drought, area under irrigation, areas of soil degradation, and other aspects that can be used as key indicators of desertification. While all remote sensing systems are capable of providing image data, not all remotely sensed data have the same capabilities needed for identifying and monitoring desertification. Higher resolution images offer greater detail for analysis, however, medium resolution Landsat imagery is commonly used since it is readily available. A major setback of using remote sensing imagery to detect aspects of desertification is that it gives primary data, therefore, further analysis is required using ancillary data before substantial conclusions can be made. Remote sensing has accelerated the study on desertification, enabling the enactment of policies to take steps towards reducing polarity of the land to degradation. However, as studies can be used to make important management, environmental, and political decisions, care must be taken to include as much additional data as possible so that reliable and robust results are obtained.

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