DETECTION AND MAPPING OF LONG-TERM LAND DEGRADATION AND DESERTIFICATION IN ARAB REGION USING MODESERT

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(Received 17 June 2014 - Accepted 12 August 2014)

ABSTRACT

This paper presents the definition and formulation of a remotely sensed based monitoring system for land degradation and desertification. The main objective of this system is to identify processes of land degradation and desertification sensitive areas at regional scale. The proposed methodology relies on the use of time series NDVI images generated from remote sensing satellites for the regional assessment and monitoring of vegetation dynamics. Parametric model based on ordinary least-squares regression was developed and implemented through the use of MODESERT, an open-source software developed by the National Council for Scientific Research in Lebanon (CNRS). The study area covers the entire Arab World. Long term trends were derived using the GIMMS NDVI data set over the time period between 1982 and 2006. It is the longest series of NDVI product covering our regions. Three main classes, subdivided into seven groups, were established representing: moderately to highly sensitive areas, areas with no-significant change, moderately to highly developed areas. Mean absolute percentage error (MAPE) was used to estimate the accuracy of the trend model; it generated a mean error at 5-10%. Results indicated that more than 40% of the total MENA region were sensitive to land degradation and desertification. In contrast, only less than 5% of the region had witnessed positive changes in vegetation cover. The major drivers of land degradation were mainly linked to climate variability and recurring drought and to less extent their sub-drivers such as forest fires and the poor socioeconomic development. Development in vegetation cover was found to occur at larger scales in Southern Somalia, Sudan and Southern Iraq marshlands. This method could be applied to national scale assessment. Using others satellites images (e.g. SPOT Vegetation, MOD13Q1, etc…) has also potential. This monitoring system is operational since 2007 and was validated through the publication of the biennial Arab Desertification Bulletin.

Keywords: land degradation, sensitivity assessment, trend analysis, NDVI, MENA, monitoring system, MODESERT

INTRODUCTION

The United Nations Convention to Combat Desertification (UNCCD) defines land degradation as “the reduction or loss in the capability of the land to support biological or economic productivity and complexity of rain-fed cropland, irrigated cropland, or range, pasture, forest, and woodlands”. Desertification, on the other hand, depicts "land degradation in arid, semiarid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities" (UNCCD, 1994). Processes of land degradation and desertification are considered among the most serious, widespread and complex environmental problems of the 21st century.

The main driving forces for land degradation and desertification are associated with climate variability and anthropogenic factors. Usually these processes occur simultaneously or as a combination of processes, such as:
(i) Extended droughts, attributed to shifts in precipitation and increased temperature, influence the distribution of vegetation and constitute the main driver for initiating or exacerbating desertification;
(ii) Soil erosion caused by wind and/or water and the deterioration of the physical, chemical, and biological soil properties;
(iii) Poor land use practices and human activities such as unsustainable agricultural practices, overgrazing, and deforestation.

Despite the impact of land degradation and desertification on the environment and the sustainability of life, estimates of land degradation are generally presented in separate contexts. It remains difficult to present the extent and severity of land degradation in a single framework for regional scale. Broad approximations are generally presented due to the lack of unified local and regional monitoring networks. In fact, few countries have sound information on the progress of land degradation and desertification. So far, most research on the status of land degradation has involved local investigation for the exploration of specific driving forces. Other research had focused on investigating vegetation dynamics as they are considered the key components for the understanding of land surface models, especially when assessing and monitoring land degradation and desertification (Symeonakis & Drake, 2004; Tian *et al*., 2013). The combination of vegetation dynamic models and remote sensing time-series images is being used in the assessment of land use, land cover, vegetation changes as well as in the prediction of temporal variations in canopy cover, primary production, crop yield, crop growth, and crop production. Among most important remote sensing products is the normalized differentiated vegetation index (NDVI) data sets used for large-area mapping and monitoring (Diouf & Lambin, 2001; Bestelmeyera *et al*., 2006; Hill *et al*., 2008; Giannini *et al*., 2008; Luo *et al.*, 2013; Tian *et al*., 2013). The main advantages of NDVI are associated with its global coverage, high temporal resolution (daily to monthly), and their availability at medium spatial resolution (1 to 10 km) suitable for regional mapping. Many researchers using NDVI emphasize on quantifying spectral characteristics and include phonological analysis of vegetation cover (Zhou *et al*., 2001; Julien & Sobrino, 2009), land-cover mapping and classification (DeFries & Townshend, 1994; Friedl *et al*., 2002; Tucker *et al*., 2005) crop yield forecasting (Benedetti & Rossini, 1993; Quarmby *et al*., 1993). The assessment of time series NDVI data sets is mainly used for capturing seasonal, inter-seasonal and annual variability (Rasmussen, 1997; Balaghi *et al*., 2008). Few researchers had focused on formulating a methodology for quantifying land degradation and desertification risk areas, which are approaches less proposed for the evaluation of trend of changes.

GIS and allied technologies, namely RS, contributions in the field of vegetation exploitation and forecasting are not only due to their capabilities to support spatial dimension but also to their ability to capture, store, organize, process, analyze, and create outputs. In this context, MODESERT software was developed to fulfill the necessity to integrate a variety of data sources (time series and geospatial data), parameters, and outputs. The main objective behind MODESERT is to create an integrated monitoring, modeling, and assessment system.

MODESERT is a combination of graphical user interfaces (GUI's) and time series and statistical tests. In addition, the software supports both raster and vector GIS data. MODESERT has a set of multi-variable and multi-objective linear and nonlinear (parametric and non-parametric) statistical tests to solve the optimization of the software (*e.g.* Trend detection, change assessment, *etc*…). The software is developed and tested for optimizing NDVI variation (vegetation dynamics) as part of a long term project aiming to develop a desertification monitoring and early warning system.

In this study, the development of MODESERT was investigated; it included the theory and methodology used to represent the proposed software and to verify its functionalities and how NDVI time series can be used as a monitoring tool for land degradation and desertification over the Arab World. NDVI derived from GIMMS data over the time period between 1982 and 2006 are used for the analysis.

STUDY AREA

The MENA region in this paper refers largely to the territories of the Arab countries. The study area is inhabited by more than 350 million, putting increasing pressures on the natural systems which are currently beyond the system's ability to regenerate, causing the unsustainable use of the natural resources, and increased land degradation (UN, 2009; UNEP, 2013).

According to the Köppen climate classification system the MENA region is mostly dominated by hot and arid climate with exceptions that exist in the coastal areas and highlands. The North African and West Asia regions are dominated by the desert climate where the Sahara desert covers 90 per cent of the total North African region (UNEP, 2013). The prevailing temperature usually exceeds 50°C and the precipitation annual average is less that 25mm. The arid steppe climate with cold winters prevails in Morocco, Algeria and Tunisia, except in the region of the Atlas mountains where the climate is cooler and has higher precipitation. Regions including the southern part of Sudan and Somalia are characterized by the Equatorial climate where average annual precipitation exceeds 1500 mm, and the average temperature is around 20°C. The warm temperate climate (*i.e.* Mediterranean climate) dominates the coastal North Africa and the eastern Mediterranean countries. The Mediterranean climate is characterized by mild to cool, wet winters with hot, dry summers. Annual average temperature ranges between 7 and 25°C and the annual precipitation is around 520 mm. The inland areas of Syria, Jordan and Iraq are dominated by the arid steppe Climate (UNEP, 2013). The arid to hyper-arid climate prevails in the Arabian peninsula, where the average annual precipitation does not exceed 150 mm and the average temperatures varies drastically between winter and summer seasons (ranges between 5 to 15°C during winter and between 40 and 50°C during summer).

According to UNEP (UNEP, 2013) most of the MENA region is desertified and/or highly vulnerable to desertification. Of the total 14.1 million km^2 land area, 89.3 per cent is arid or hyper-arid land. Agricultural lands cover around 2 million km^2 (~14.5 per cent of total area), of which only 4.2 per cent are cultivated (AOAD, 2009). Forest areas are largely limited to Sudan (~62000 km^2) and Somalia (~7500 km^2) and to a less extent in regions of Morocco and Algeria and the coast of the western Mediterranean countries (UNEP, 2007; AOAD, 2009; UNEP, 2013). Nevertheless the poor management of agricultural practices and increased deforestation are significantly exacerbating desertification and land degradation

(UNEP, 2006). Based on the past 30 year trends, it is expected that the MENA region will continue to suffer from severe degradation of lands resulting from anthropogenic drivers, namely from deforestation, agricultural and industrial pollution, and the increase in urban and infrastructural development at the expense of agricultural lands (UNEP, 2013). Existing natural hazards contribute further to land degradation and desertification in the MENA region. Currently drought is the most prevailing natural hazard in the MENA region. Extreme temperatures, wildfires, flooding, landslides, sand and dust storms are also among the natural events that negatively impact land and contribute to its degradation. Climate change further impacts vegetation in the region. According to IPCC (IPCC, 2008) it is expected that precipitation will decrease and temperature will increase, as well as the magnitude and frequency of drought that will consequently increase over the MENA region over the coming decades.

At present many countries in the MENA region are aware of the status of land degradation and desertification. Different measures are being proposed to adapt and mitigate their adverse impact. Despite this fact, little knowledge on the regional scale is available as many countries are oriented towards addressing local and site specific problems. There is a necessity for a regional monitoring system that highlights the land scarcity and establishes the link between land degradation and land vulnerability to desertification and the main driving forces.

METHODOLOGY

Data Background

NDVI trend maps were generated for the period extending from 1982 to 2006 as derived from the National Oceanic and Atmospheric Administration–Advanced Very High Resolution Radiometer NOAA/AVHRR NDVI satellite imageries. This long-term bimonthly global NDVI data sets are available from the University of Maryland Global Land Cover Facility (GLCF). The GIMMS NDVI product is comparable to other global data sets, despite fundamental issues with the sensor (spectral, spatial, atmospheric correction, *etc*...) compared to MODIS and SPOT. However, it remains the only long term data sets available for NDVI calculation and assessment.

Model

Time series NDVI variable exhibit a trend when there is a significant change in vegetation over time. Long term NDVI time series function is a combination of trend line component, stochastic component, seasonal component and noise. The effects of annual vegetation cycles (crop yields, cultivated lands, *etc*…) are reduced in this case due to the long duration.

Therefore NDVI model is written as follows:

$$NDVI_t = a_0 + \beta_0 t + \sum_{i=1}^{n} (\beta_i \text{ x } NDVI_{t-i})$$

With “a_0” and “β_0” representing the coefficients of the linear trend component, “t” the corresponding time, “n” is the duration of time-lag and “β_i” the lag coefficient. “$NDVI_{t-i}$” is the NDVI for the time-lag i months, respectively.

Parametric approach based on ordinary least-squares (OLS) regression was used to estimate the trend of NDVI slope (β_0). Jarque-Bera (JB) test (Jarque & Bera, 1987) was used to verify the normality of data, with an assumption that the error terms are independent. Significant slope was tested by a t-test to show if the trend exists.

To validate our model, mean absolute percentage error (MAPE) was applied. It was calculated using over 100 specific points over different countries such as Lebanon, Syria, Yemen and Iraq. The outcome generated a mean error between 5 and 10% (Fig. 1-A). Figure 1-B illustrates an approximately normal distribution of residuals produced by a model for a calibration process.

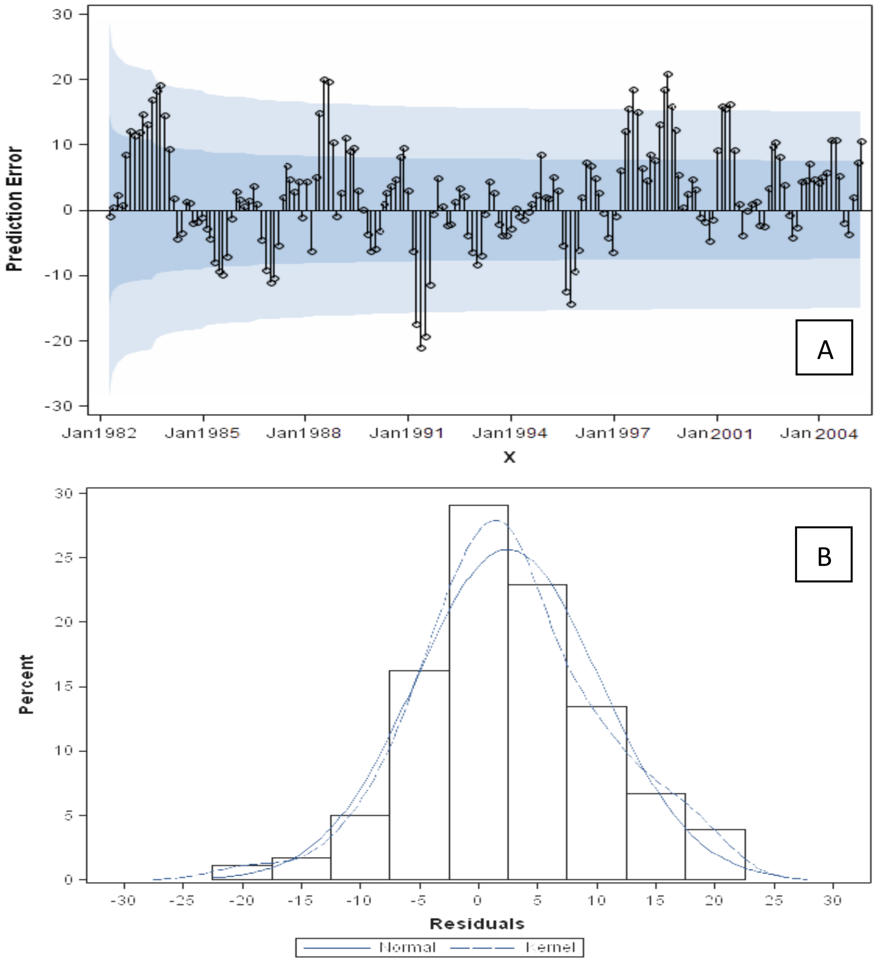

Figure 1. Calculation of the mean absolute percentage error (MAPE) (A) and residual error (B).

The NDVI trend maps are categorized in several classes, which are subdivided into other categories as follows:

1- Moderately to highly sensitive areas (vegetation decrease from -5% to less than -25%). The expression “hot spot” is used to flag areas which are suffering from various types of degradation processes; subcategories are moderate decrease (vegetation decrease between -15% and -5%), severe decrease (between -25% and -15%) and hot spot (less than -25%);
2- Areas with no-significant change (-5% < vegetation values < +5%);
3- Moderately to highly developed areas or bright spot (vegetation increase between 5% and 25%); Subclasses are moderate increase (vegetation increase between 5% and 15%), advanced increase (between 15% and 25%) and bright spot (between 15% and 25%).

Software development

MODESERT (monitoring desertificiation) allows for the assessment of parametric models for trend detection over the entire time series spatial images. It is basically conceived as a tool for monitoring land degradation and desertification. This software is built using ArcObjects and thus it has one advantage over other software such as Timestat that it supports GIS analysis, including the support of GIS data (both raster and vector data) and data editing in a GIS environment.

The main objective of this software is to deliver operationally feasible algorithms and statistical tests to assess large NDVI data set in the framework of a monitoring system for the assessment of land degradation and desertification on a regional scale (*i.e*. MENA region). In particular, the software embraces: (i) A number of mathematical models for the adjustment of time series data; (ii) Statistical properties and tests for the assessment of seasonality and trends; (iii) Coupled methods for the analysis of time series data; (iv) Ability to evaluate the performance NDVI data sets for the assessment of vegetation dynamics based on major land type classes and/or geographic regions; and (v) Detection of land degradation and desertification on regional scale. MODESERT capabilities: (i) allows easy statistical testing using different tests; (ii) supports various raster image time series data input formats; (iii) provides outputs in raster format of trends and tests; (iv) provides simple statement of the test result; (v) displays statistical test and critical values for various statistical significance levels.

MODESERT (Figure 2) allows visual interpretation of time-series trend images and time series data (*i.e*. signals for each pixel) and statistical characteristics of each time series. Visual interpretation using images and graphs to explore, understand, and present data offer a greate advantage in the field of remote sensing image processing and the assessment of trend and statistical significance level.

RESULTS AND DISCUSSIONS

Analysis of the GIMMS NDVI (1982 - 2006) data allowed for the assessment of long term changes in land degradation and desertification vulnerability. The results obtained through the interpretation over the time period between 1982 and 2006 revealed a critical increase in land degradation in northern African countries especially along the coastline extending from Morocco to Egypt.

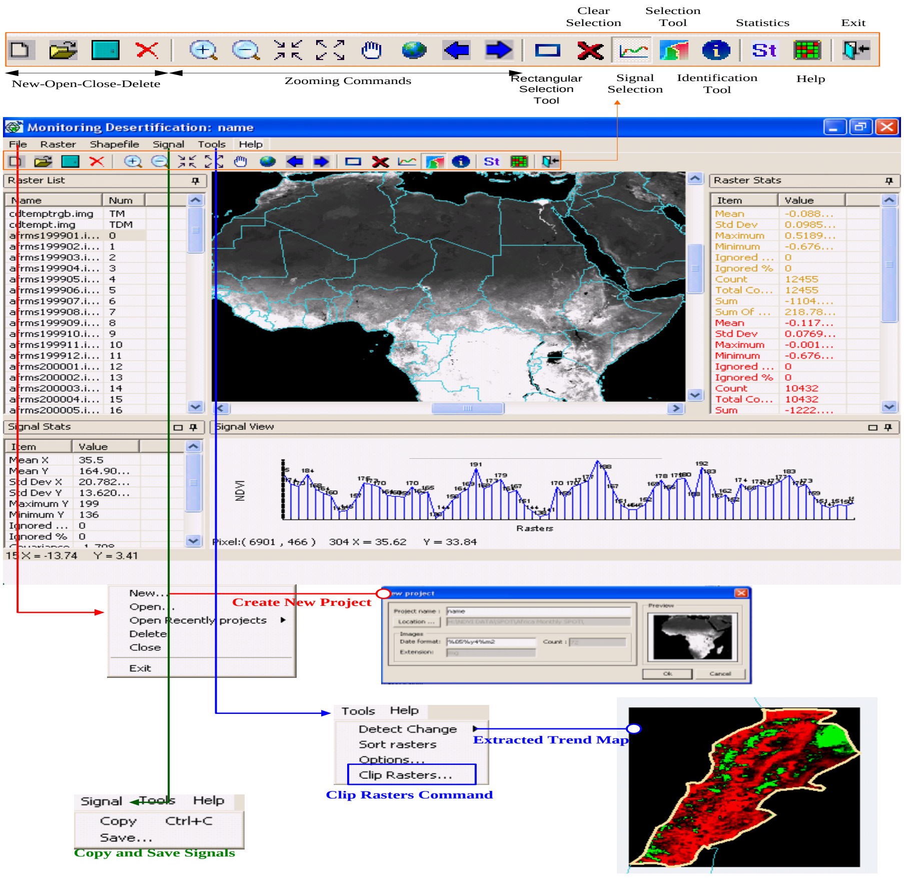

Figure 2. MODESERT main frame and toolbars.

As illustrated in Figures 3 and 4, land degradation accounted for 45% to 60% decrease in Morocco, Algeria, Libya, and Egypt (land improvement accounted for around 5% on average for most countries). The situation is most noticeable in the northwestern parts of Morocco, the northern part of Algeria, and the northern part of Libya. Tunisia experienced less degradation estimated at around 25% (with an estimated increase of around 6%).The southern and northern parts of Tunisia showed an important increase in vegetation cover. Same applies to the Western African region of Mauritania where the land degradation impacted around 63% of the country's total area. In Egypt, parts in the eastern part of the country, at the Nile banks and delta showed land development. East African countries experienced less land degradation among African countries where it was estimated that land degradation and land development in Sudan were between -38% and 25% respectively, for Djibouti the situation was not better (-42% decrease and 4% increase in vegetation covers), in Somalia vegetation showed much more development (-13% land degradation and around 26% increase in vegetation cover). In the Middle East, the situation was characterized by mutual changes in vegetation covers. It was clear that Lebanon is undergoing moderate land degradation estimated at 32% *versus* 10% in land development. In Syria, the situation was much more critical, especially in the northern part of the country where drought prevails. It was estimated that around 57% of the country's area were subject to degradation *versus* around 5% land development. The same applies to Iraq, where land degradation accounted for around 35% especially in the southern parts of the country and more precisely in the Mesopotamian wetlands (Iraq's marshlands). The northern part of the country experienced land development of around 8%. In Jordan the situation is critical where it was estimated that around 81% of the country's total area is subject to land degradation. Stabilizing trends are more common in the Arabian Peninsula. The region had witnessed several developments in irrigation practices at the expense of the overuse of the groundwater resources for desert agricultural projects. Land development accounted for around 5 to less than 10% in most countries (Figures 3, 4). Despite this development part, land degradation remains the most dominant factor in this particularly arid to hyper arid region of the MENA region. Land degradation was estimated at around 35% in Saudi Arabia (KSA) and Yemen and to a less extent in Kuwait, Qatar and Emirates (around 5%).

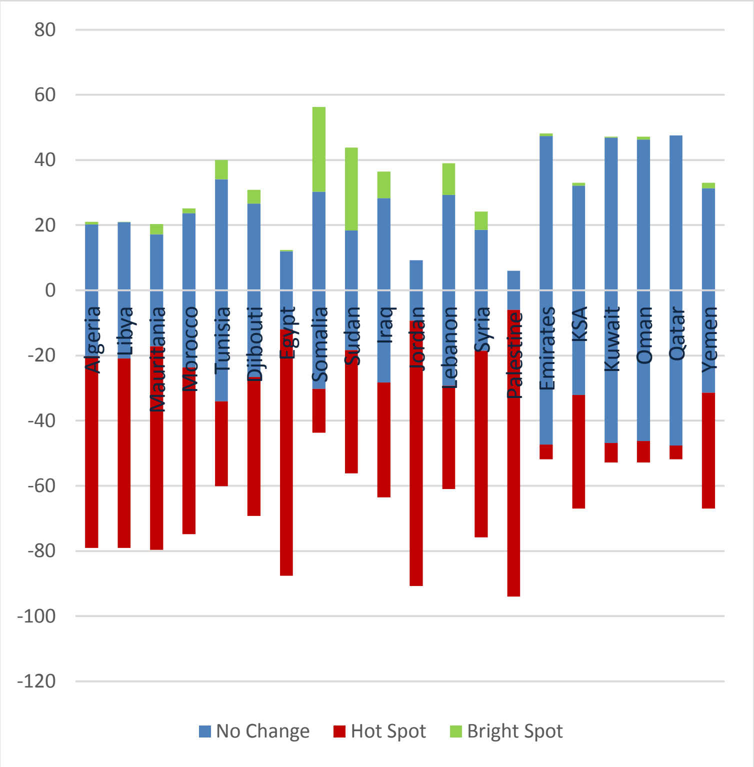

Figure 3. Hot spot, bright spot and no change vegetation areas derived from long time GIMMS data (1982-2006).

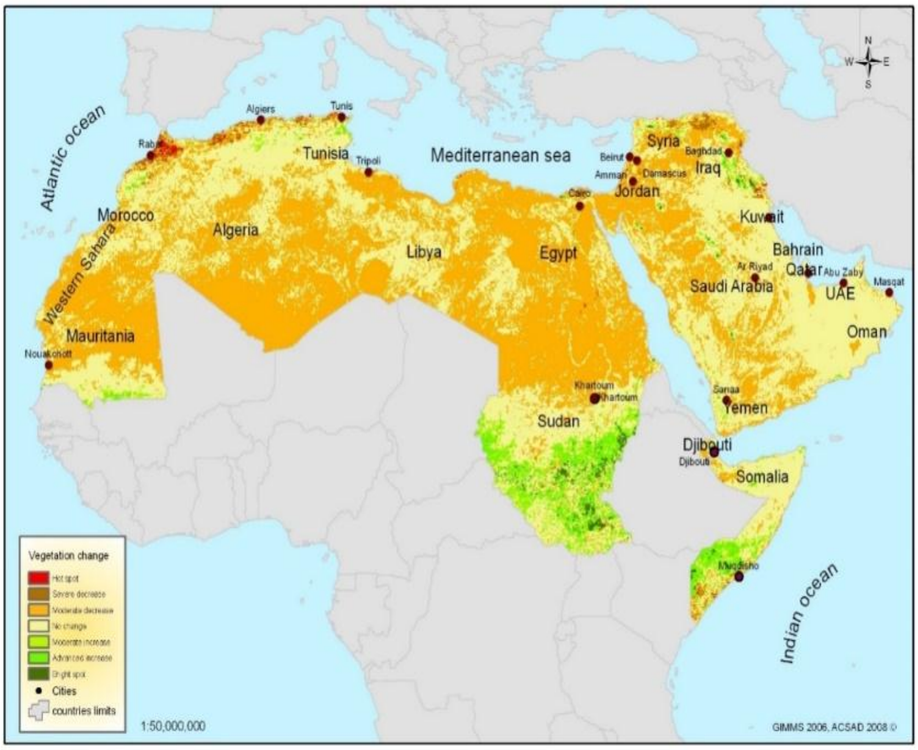

Figure 4. Monitoring vegetation changes in the Arab world using GIMMS NDVI images during the period extending from 1982 to 2006.

Among the most vulnerable lands in the MENA region are the wetlands of Mesopotamia (Iraq's marshlands). It is believed that these wetlands have been decimated between the 1970's and throughout the 21 century through damming and the development of canals and reservoirs for agricultural irrigation across the Tigris and Euphrates Rivers and for a political pawn in the 1990's. In the 1970s, the marshland covered up to 9000 square kilometers (Figure 5, Plate A1 top). However, by the early 2000 the marshlands were reduced to around few hundred square kilometers (Figure 5, Plate A1 bottom). The overexploitation of natural water resources is among the key drivers of land degradation in the MENA region. Starting early 2004 different efforts have been made to restore the Iraqi marshlands to its former extent. Despite the fact that marshes were recovering over the last 10 years they now face new threats, including new dam construction upstream and increased vulnerability to drought as illustrated in the MODIS Image of February 2005 (Figure 5, Plate A2 top) and the drought during 2009 (Figure 5, Plate A2 bottom). It is now believed that the marshes are shrinking again at the expense of extensive irrigated agricultural areas.

Regions where natural water resources have been over-exploited at the expense of agriculture development are mostly established in many parts of the MENA region. In the

Sahara where rainfall is only a few centimeters a year, water available in aquifers is a non-renewable resource (take thousands of years, or longer, to recharge). Despite this fact, many countries such as Tunisia, Morocco, Algeria, Sudan, Libya, Jordan, and Saudi Arabia are among the nations irrigating with fossil water.

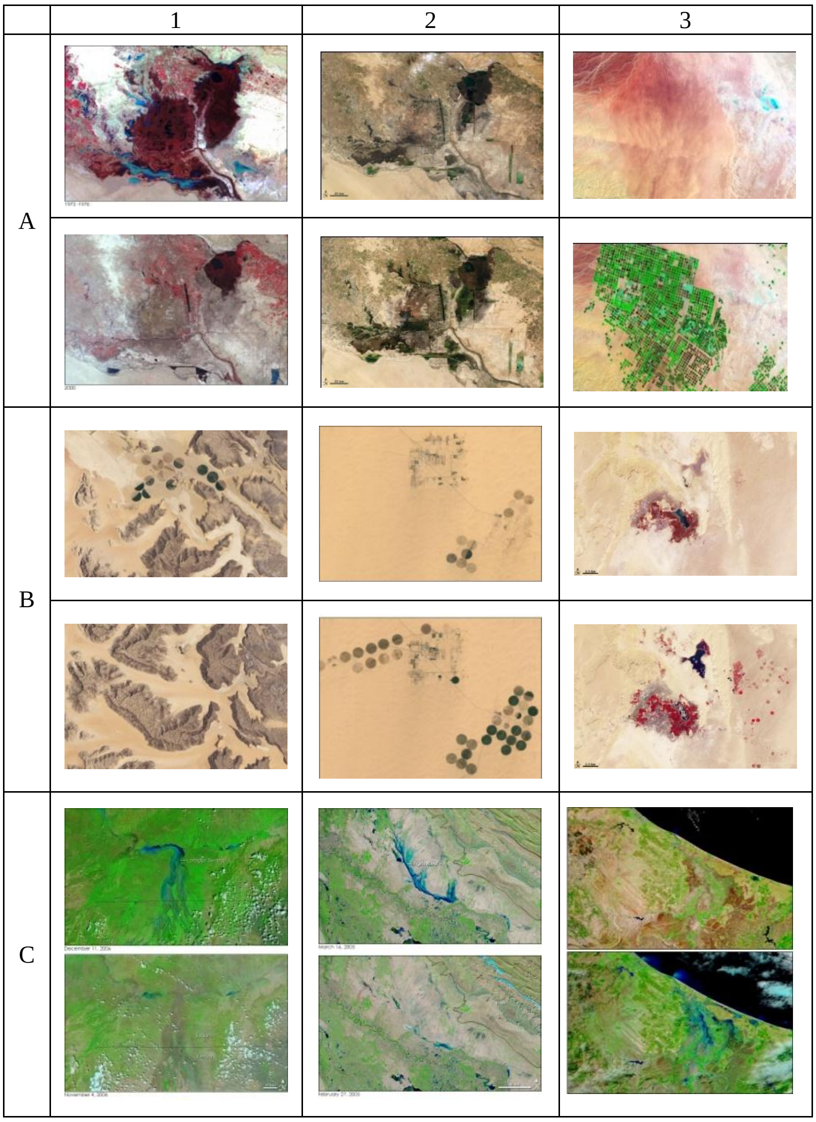

Figure 5. Main drivers of land degradation in the MENA region (courtesy of NASA Earth Observatory).

In fact, over the past three decades, Saudi Arabia has been drilling non-renewable groundwater resources for the production of grains, fruits, and vegetables in the desert. Figure 5 illustrates two Landsat images of the desert agriculture development at two time frames between February 1987 (Plate A1 top) and January 2012 (Plate A1 bottom). Desert agriculture is also present in parts of southwestern Jordan, in the Rum Wadi. The images captured by NASA's Earth Observing-1 (EO-1) satellite on July 27, 2001 depicted fields with center-pivot irrigation that make circles of green and brown (Figure 5, Plate B1 top) and the naturally arid granite and sandstone rise of the mountains (Figure 5, Plate B1 bottom) where little annual precipitation does support sparse vegetation. Figures show the development of small central-pivot irrigation (each about just a kilometer in diameter) north of the border between Egypt and Sudan captured by Landsat ETM+ on October 31, 1999 (Figure 5 Plate B2 top) to December 23, 2001 (Figure 5, Plate B2 bottom). In Southern Algeria, where precipitation is low, most agriculture is fed by the underlying north-west Sahara aquifer. The false-color images captured by Landsat-2 on January 16, 1972 (Figure 5, Plate B3 top) and Landsat-7 2000 (Figure 5 Plate B3 bottom) show the Ouargla Oasis in southern Algeria, where the agricultural expansion is shown in red.

Flood is among the natural hazards that occur in the MENA region. It is usually associated with heavy rain. Floods are mostly common in regions like Somalia and Sudan and usually occur after heavy rains. For different floods in Sudan in December 2006 see Figure 5, Plate C1. Floods are also less common in Iraq. Figure 5 Plate C2 illustrates the March 2005 flood over the Tigris River in Iraq. Flood as depicted in Figure 5, Plate C3 represent the November 2002 flash flood near the city of Rabat, located on Morocco's west coast. This is considered among the worst floods in the region as it washed away loose sediment from the surrounding countryside and carried it to the Atlantic ocean. Noting that the rain that caused the floods also brought streaks of green vegetation to the surrounding desert.

CONCLUSION

This paper presents a methodology for the characterization and assessment of land degradation and vulnerability to desertification based on remote sensing approaches. Satellite-images of NDVI derived from GIMMS data sets were evaluated and assessed. Significant regions were discussed. While almost 52% of the total Arab region show no change in its vegetation cover, 40% of this region reflect high decrease in vegetation areas. It is an alarming situation and require a fast action. Some regions such as north of Morocco, Syria and South of Iraq show an important hotspot regions, whereas south of Sudan and Somalia represent an important bright spot areas.

The significance of this research lies in its ability to provide useful information on the status of land degradation and its vulnerability. The integration of the outputs with different forcing variables would help in the proper understanding of the impact of these drivers on the land in one of the most vulnerable areas in the world. The successful outcomes of this research require continuing improvements in the development of adaptation and mitigation measures to protect the land as well as the population and the economy. In particular, it is recommended that future models include other meteorological, environmental, and economical inputs such as rainfall (including amount, frequency, duration, and intensity), water resources availability (both surface and groundwater), and population (distribution and density) in order to assess future potential impacts. The model output which provided valuable information on the regional scale should be used as valuable indicator for land management and improved decision making.

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