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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Impact of land cover change on soil erosion hazard in northern Jordan using remote sensing and GIS

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Abstract

Jordan is dominated by arid ecosystems that are vulnerable to human interventions and activities. It receives little rainfall with high intensity, which renders land degradation, soil erosion and desertification imminent threats of the ecosystem balance. Several changes in land cover have also occurred during the last decades. The above mentioned processes and changes can be mapped using remotely sensed satellite images and modeled in a Geographic Information System (GIS) environment. This study aims at assessing the impact of land cover change on the erosion in agricultural areas of northern Jordan. It was achieved by quantifying and analyzing the soil erosion in the study area between the years 1992 – 2009, and by comparing it with land cover changes. The Revised Universal Soil Loss Equation (RUSLE) was employed in a GIS environment to create soil erosion maps of the specific years using data from meteorological stations, soil surveys, topographic maps, Landsat satellite images and results of other relevant studies. The mean soil loss in the study area was 9.53 t/hr and 8.97 t/hr in 1992 and 2009 respectively. This was subsequently reclassified to erosion risk levels. By comparing the change of the erosion risk levels with the land cover change map of the study area using geographic overlay analysis, it was evident that the main reason for soil erosion change was the abandonment of rainfed crops and their conversion to rangelands. The differences in soil erosion risk between the two years were considerable indicating that changes in land cover affects significantly the soil erosion rate.

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Keywords: Soil erosion; land cover change; RUSLE; NDVI

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1. Introduction

Since the last century, soil erosion accelerated by human activities has become a serious environmental problem. It has a manifold environmental impact by negatively affecting water supply, reservoir storage capacity, agricultural productivity, and freshwater ecology of the region. Soil erosion risk varies from case to case depending on the configuration of the watershed (topography, shape), the soil characteristics, the local climatic conditions and the land use and management practices implemented.

However, estimation of soil erosion loss is often difficult due to the complex interplay of many factors, such as climate, land cover, soil, topography, and human activities. Erosion models can provide a better understanding of natural phenomena such as transport and deposition of sediment by overland flow and allow for reasonable prediction and forecasting. Many different models have been proposed to describe and predict soil erosion by water and associated sediment yield. They vary considerably in their objectives, time and spatial scales involved. The models can be categorized into physical process based models and empirical models. The physical based models include AGNPS , ANSWERS , WEPP [1] and SHE. Empirical models include the Universal Soil Loss Equation (USLE) [2], the Modified Universal Soil Loss Equation (MUSLE) [3], the Revised Universal Soil Loss Equation (RUSLE) [4], and the Erosion Productivity Impact Calculator (EPIC).

One of the major drawbacks in the application of erosion models is the low availability of input data. The conventional methods proved to be too costly and time consuming for generating this input data. With the advent of remote sensing technology, deriving the spatial information on input parameters has become more handy and cost-effective [5]. Multi-temporal satellite images provide valuable information related to seasonal land use dynamics, erosional features, such as gullies, rainfall interception by vegetation, and vegetation cover factor. The application of the Normalized Difference Vegetation Index (NDVI) derived from remotely sensed images has been proved to be useful in providing an estimate of the vegetation cover management factor (C-factor). It can express the condition of vegetation in different seasons, thus providing a reliable temporal dimension in soil erosion risk assessment, which is of great importance in Mediterranean regions [6, 7].

Besides that, the powerful spatial processing capabilities of Geographic Information System (GIS) and its compatibility with remote sensing data have made the soil erosion modeling approaches more comprehensive and robust [5]. GIS can be used to scale up to regional levels and to quantify the differences in soil loss estimates produced by different scales of soil mapping used as a data layer in the model [5]. The integrated use of remote sensing and GIS could help to assess soil loss at various scales and also to identify areas that are at potential risk of soil erosion. Several studies showed the potential utility of GIS technique for quantitatively assessing soil erosion hazard based on various models. The combined use of GIS and USLE/RUSLE has been proved to be an effective approach for estimating the magnitude and spatial distribution of erosion [8, 9].

Land use - land cover (LULC) change has been an important research field and it is one of the most sensitive indicators of the interactions between human activities and natural environment. It is associated with climatic and geomorphologic conditions of the area have an accelerating impact on the land degradation. Natural as well as human-induced LULC change has significant impacts on regional soil degradation, including soil erosion, soil acidification, nutrient leaching, and organic matter depletion. In recent years, a number of studies have been carried out to estimate the potential effects of LULC change on soil erosion at different spatio-temporal scales. These include the scale of small watersheds [10] and global scale. Similarly, effects of LULC change have been studied at temporal scale of few years to number of decades [11]. All these studies identified a strong influence of land use changes on soil erosion and sediment transport rates.

The main objective of this work was to assess the impact of land cover change on the erosion in agricultural areas in north Jordan. The specific objectives were: 1) estimation the C factor values using the normalized difference vegetation index (NDVI), 2) adjustment and implementation of RUSLE erosion model using existing data in 1992 and 2009, and 3) detection of the differences in the proportion of the area of LULC classes in the erosion hazard maps.

2. Materials and methods

2.1. Study area

The study area (Fig. 1) is located in the northern part of Jordan, over an area of 1400 km2 from Mafraq to Irbed, which is the main source of surface water for the country. The elevation of the study area ranges from 310 to 1022 m above sea level. The Badia region, which covers large part of the study area, is the main region for livestock production in Jordan, and the income of many people depends on these rangelands. Facing a loss of their livestock, many of the farmers in Badia tend to move into the cities looking for work thus putting more pressure on urban areas. In the area, heavy withdrawal of groundwater, rapid urbanization and industry growth has resulted in accelerating land degradation and reduction of available water resources. Most of the area is threatened from high rates of soil loss by wind and water, which can lead to desertification. The LULC mapping of the study area revealed changes that include reduction of irrigated areas from 9 % in 1992 to 7.7 % in 2009, and growth of urban areas which nearly doubled between 1992 and 2002. Additionally, maps of LULC showed that the open rangeland is about half of the area in 2009, increasing from 38% in 1992 to 48% in 2009, indicating that the land use of the area is changing from agricultural to non-cultivated lands. The major changes in the land use in the study area were in the mixed rain fed areas, decreasing from 24.6% of the study area in 1992 to 13.9 % in 2009. This decline also reflects the frequent drought and rainfall irregularity in the last two decades.

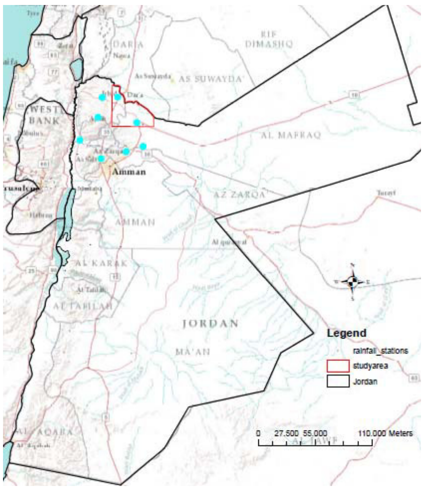


Fig. 1.(A) Location and meteorological stations in the study area.

Fig. 1.(B) the study area

2.2. Data and preprocessing

In order to predict soil erosion, the following spatial and temporal datasets were used:

- DEM (Digital Elevation Model) of 90 m resolution (source: http://www.earthexplorer.usgs.gov). The DEM shows that the elevation of the study area ranges from 310 to 1022 m. From the DEM the flow accumulation and the slope gradient in degrees, which are used in slope length and steepness factor (LS), were derived.
- Two Landsat TM images (source: http://www.earthexplorer.usgs.gov). The Landsat series of satellites has the most comprehensive archive of earth observation satellite imagery to date and provides an excellent baseline resource for moderate resolution land cover change detection studies. The dates of acquisition for the images are May 1st 2007 and on the 31st of May 1992. Two NDVI were derived from Landsat TM images acquired on May 1992, 2007. Due to the lack of available images on 2009 the NDVI, derived in 2007, is assumed to be the same in 2009.
- Two land cover maps of 1992 and 2009. (source: Dr. Jawad Al-Bakri, University of Jordan, Assessment and Monitoring of Desertification in Jordan Using Remote Sensing and Bioindicators project). In this project mapping of LULC was carried out using visual interpretation of satellite images of ASTER for 2009 and one TM image for 1992. These maps were classified into 11 land use land cover classes.
- Long term annual precipitation of 8 meteorological stations in 1992 and 2009. (Source: Jordan meteorological stations) In this study, records of 8 rainfall gauge stations were used to estimate the R factor. For each station, the mean values were calculated for 1992 and 2009 in order to make this factor stable in the study in 1992 and 2009 and make the C factor the only variable factor in the study.
- K factor map of Jordan (source: Lubna Al Qaryouti ministry of agriculture – Jordan).

2.3. RUSLE

The RUSLE is an erosion model designed to predict the long term average annual soil loss caused by runoff from specific field slopes in specified cropping and management systems including rangeland [4]. The RUSLE model groups the many influences on the erosion process into five categories including climate, soil profile, relief, vegetation and land use, and land management practices. These categories are well known as the erosion factors, R, K, LS, C and P, respectively. The product of these factor values gives the expected soil loss in t/ha/yr, depending on the dimensions used in the climate and soil factor [4]. The RUSLE equation is:

$$A = R \times K \times LS \times C \times P \qquad (1)$$

where:

A is the computed spatial average soil loss and temporal average soil loss per unit area, expressed in t/ha/yr,

R is the rainfall runoff erosivity factor which is the rainfall erosion index calculated as an average annual value. In their study, El Taif et al. [12] equation R = 23.61 x e0.0048P was used to estimate the R factor in the study area expressed in MJmmyr/ha/h,

K is the soil erodibility factor which is the soil loss rate per erosion index unit for a specified soil as measured on a standard plot (22.1 m in length of uniform 9% slope in continuous clean tilled fallow) In this study the K factor used was calculated by Lubna al Qaryouti using the nomograph developed by Wischmeier and Smith [2] based on soil texture, organic matter, soil structure and soil permeability obtained from national soil map and land use project in Jordan,

L is the slope length factor which is the ratio of soil loss from the field slope length to soil loss from a 22.1 m length under the same conditions,

S is the slope steepness factor which is the ratio of soil loss from the field slope gradient to soil loss from a 9% slope under the same conditions In this study we used the DEM of 90 m resolution to calculate the LS factor based on the model offered by Simms [13]. As described in Simms [13], the LS equation is: T = (A/22.13)0.6 x (sinβ/0.0896)1.3 and for ArcGIS use he used the following map algebra expression:

LS = ((flow accumulation) x cell size)/22.13)$^{0.6}$ x ((sin(slope of DEM) x 0.01745) / 0.0896)$^{1.3}$

C is the cover management factor which is the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow. The traditional method for spatial estimation of C factor is assigning values to land cover classes using classified remotely sensed images of study areas. Researchers developed many methods to estimate C factor using NDVI for soil loss assessment with USLE/RUSLE. The normalized difference vegetation index (NDVI) is generally used to derive the C factor used in erosion modeling. The Normalized Difference Vegetation Index (NDVI), one of the vegetation indices, measures the amount of green vegetation. The spectral reflectance difference between Near Infrared (NIR) and red is used to calculate NDVI. The formula can be expressed as: NDVI = (NIR – RED) / (NIR + RED). In this study the equation used to derive C factor from NDVI was [14]: C= exp [-a((NDVI/(b-NDVI))], where α-value is 2 and β-value is 1. The α, β parameters determine the shape of the NDVI curve.

P is the support practice factor which is the ratio of soil loss with a support practice such as contouring, strip cropping, or terracing to soil loss with straight row farming up and down the slope, In this study the values of P factor were not evaluated as part of calculation because of unavailability of data and all the P factor values were assigned to be 1.

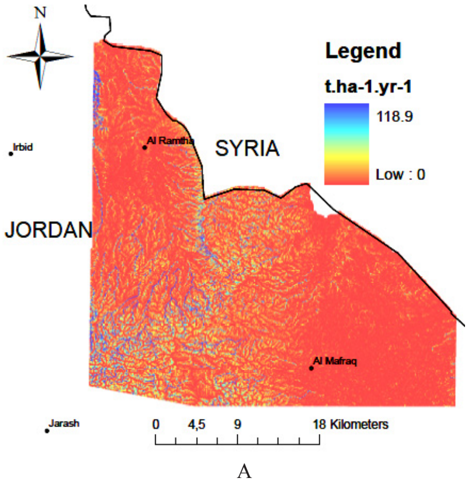
2.4. Geographic and statistical analyses

In this study, ArcGIS version 9.2 was used in the whole process since it provides all the functions needed to estimate the soil erosion using RUSLE model. In order to analyze the area of LULC classes in each erosion hazard map, the zonal statistics (ArcGIS Spatial Analysis) was used; the differences in the proportion of the area of LULC classes for the erosion hazard classes were compared between 1992 and 2009.

3. Results and discussion

3.1. Soil erosion hazard and changes

Two soil erosion maps of the study area based on the Revised Universal Soil Loss Equation (RUSLE) was obtained (Fig. 2). The erosion maps of the study area show that the erosion loss varies from 0 – 118.9 t/ha/yr in 1992 and from 0 – 121.6 t/ha/yr in 2009.



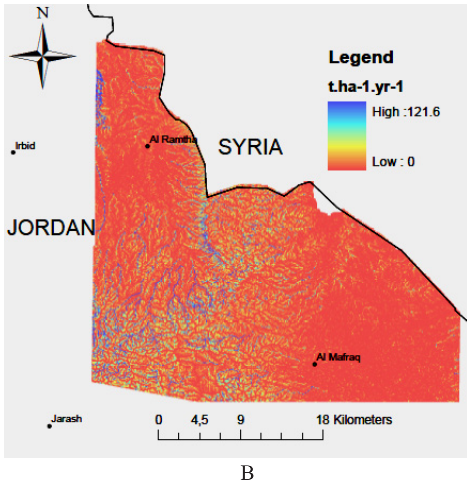


Fig. 2. Soil erosion hazard map of (A) 1992 and (B) 2009

Fig. 3 shows the change between these erosion maps. The mean erosion loss is 9.53 and 8.97 t/ha/yr in 1992 and 2009 respectively. The change of soil erosion between 1992 and 2009 is due to the change of the vegetation cover in this time period, as the other parameters were kept constant. The areas with mainly increase of soil erosion are located in the central and western parts of the study area (red hues), while the areas with decreased soil erosion are located in the north and southwest parts (blue hues) and are characterized by high slope and rainfall. The eastern part shows no major change between the two years, and is characterized with low rainfall, low slope and poor plant coverage.

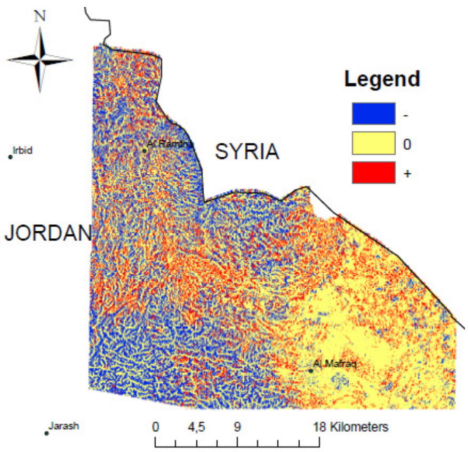


Fig. 3. The change of soil erosion between 1992 and 2009

The soil erosion hazard classes in 1992 and 2009 are compared in table 1, where the "high" and "very high" soil loss classes are decreased and the "low" and "moderate" soil loss classes increased in 2009.

This could be interpreted due to the change in the land use land cover in the study area from agricultural land to uncultivated lands which reduced the agricultural practices in these areas and decreased the soil loss. Another reason may be due to the differences in acquired time of the satellite images that were used to derive the NDVI, the image of 1992 acquired on May 31st and the 2009 image acquired on the 1st of May. With difference in these times the plant coverage could have big changes which affect the C factor and finally the soil loss in the study area.

Table 1. The area percent of the soil erosion hazard classes of 1992 and 2009.

Erosion risk	Area percent in 1992	Area percent in 2009
Low	70.01	71.86
Moderate	9.34	9.51
High	8.61	7.83
Very high	12.03	10.79

3.2. Soil erosion changes per land cover

Table 2 shows the mean soil erosion per each LULC class in the study area. Both in 1992 and 2009 the highest erosion rates were observed in "quarries" class (24 and 26 t/hr respectively). The lowest average soil loss was 2.10 t/ha/yr in 1992, 2.16 t/ha/yr in 2009, and it was observed in "protected areas". On the other hand, the "forest" class in 1992 and 2009 are expected to have low erosion rates but the results showed that the erosion rates were 17 and 14 t/ha/yr in 1992 and 2009 respectively. These results can be explained due to poor coverage of trees in the forest classes and the high slopes which increase the soil erosion rates in these areas.

In the study area, there were several changes among the LULC classes. The mean soil loss estimated from each LULC class varies based on its characteristics like the vegetation coverage and type, slope and management practices. Results of LULC mapping (Table 3) showed that the area had important changes. Among these changes was the decrease of "irrigated" areas from 9 % in 1992 to 7.7% in 2009. Also, "rainfed" areas declined with time. One important change was the increase of "urban" areas which nearly doubled between 1992 and 2002. The "open rangeland" increased from 38% in 1992 to 48% in 2009, which indicated that the area was changing from agricultural areas into non-cultivated lands. The major changes in the LULC in the study area were in the "mixed rainfed" areas. The "mixed rainfed" areas have decreased about 40% from 1992 to 2009. This decline could also reflect the frequent drought and rainfall irregularity in the last two decades.

Table 2. Mean soil erosion (t/hr) in 1992 and 2009 per each LULC class.

LULC	MEAN soil loss in 1992	MEAN soil loss in 2009
Quarries	23.95	26.70
Commercial and industrial	4.10	4.06
Educational	3.18	2.91
Forest	17.44	14.78
Open rangeland	11.12	10.13
Protected areas	2.10	2.16
Rainfed barley	9.62	12.85
Residential areas	6.21	5.22
Mixed rainfed areas	10.92	7.54
Irrigated areas	2.13	3.39

Table 3. The land use area change between 1992 and 2009.

LULC	Area percent in 1992	Area percent in 2009
Quarries	0.4	0.36
Commercial and industrial	0.28	0.41
Educational	1.7	1.75
Forest	0.8	0.6
Open rangeland	37.5	48.0
Protected areas	1.65	1.65
Residential areas	4.9	10.0
Mixed Rainfed areas	24.6	13.9
Irrigated areas	9	7.7
Rainfed barley	18.5	15.5
Water bodies	0.4	0.1

3.3. Discussion

In our study the mean soil loss was decreased from 9.53 t/ha/yr in 1992 to 8.97 t/ha/yr in 2009. The main reason for the changes in soil erosion between the LULC types are due to the changes in land cover which are reflected by NDVI, and in turn changing the C factor values which effect strongly the soil erosion. This could be interpreted due to change in LULC caused by human activity and climate changes that occurred in Jordan in the last decades. The main reason of this decline is the progressive decrease of the agricultural areas, a huge percent of the cultivated area changed to uncultivated areas in the study area. The declining of the cultivated areas can be considered one of the desertification consequences in Jordan. Threats of desertification, which is one of the climate change aspects in Jordan, were well-summarized and portrayed by the LULC change, and showed that the area is dynamic and adversely changing.

It is clear in our study that with increasing "rangeland" areas and decreasing "mixed rainfed" areas the erosion was decreased in 2009. This is a clear indicator that the LULC change affects soil erosion losses. Many researchers found that the LULC affects soil erosion positively and negatively, among them is Wijitkosum [15], who studied the impact of LULC change on soil erosion in Pa Deng Sub-district, Thailand. He found that the soil erosion decreased when the LULC are changed in some classes, for example the soil erosion risk decreased when the land use changed from bare land in 1990 to forest in 2010. The mean soil loss estimated from each land use varies from land use class to another based on the characteristics of each LULC class like the vegetation coverage and type, slope and management practices. In the study area, some land use land cover areas are increased and others are decreased. The change of LULC in the case of "rangeland" (from agricultural lands to uncultivated lands) reduced the soil erosion in these areas (most of these areas are in the east of the study area) which is characterized by low rainfall, high evaporation rates due to hot summers, strong winds and cold winters [16].

The mean soil loss from the "mixed rainfed" areas decreased from 10.92 t/hr in 1992 to 7.52 t/hr in 2009. This is due to large areas of "mixed rainfed", which cover the high lands in the study area in 1992 that decreased in 2009. In Jordan, rainfed agriculture is the most sensitive sector to climate change (the decreasing precipitation and increasing temperature) and the most prominent impact of climate change on rainfed agriculture is the reduction in crop productivity [17]. Beside this reason, the low yields due to the reduction in productivity drove many farmers to leave their fields and search for other jobs. All above factors lead to a decline in the "mixed rainfed" areas in the study area. Climate change directly affects precipitation amount and intensity and potential evapo-transpiration, and it indirectly affects plant water use efficiency through altering plant growth rate and species composition, which result in change of land cover [18]. In Jordan, several studies showed that the country is affected by climate change [19]. The analysis of climate trends in his study showed a negative trend in total rainfall and positive trend in mean maximum temperature in the time period from 1976 to 2005 in three sites in Jordan; one of them is Irbed.

By comparing the LULC maps with soil hazard maps in 1992 and 2009 the relation between the LULC and soil erosion is clear. "Mixed rainfed" was one of the major covers of high and very high erosion in 1992, and it was the dominant class in the southwest part of the study area. In 2009 and in the same area, the high and very high erosion hazard decreased remarkably with declining of the "mixed rainfed" areas. On the other hand the low and moderate erosion hazard increased in the east part of the study area in 2009 due to the changes in LULC in these areas. Our study showed that the differences in soil losses between LULC classes and their contribution area in each soil erosion hazard in 1992 and 2009 years were notable. This gives a clear indication that changes in LULC in the study area affect considerably the soil erosion rate.

Our results could have a meaningful value to the decision makers in Jordan to best understand the impact of climate change that has been taking place in the last two decades, and its impact on agricultural lands in Jordan; it could help them to apply plans to reduce this impact. Also they can use the results as a contributing factor to help them apply LU plans in Jordan to decrease the unfavorable impact of humans in land degradation. By using the results of soil erosion in the study area, local agronomists could suggest to the farmers some practices that reduce soil erosion risk.

4. Conclusion

This study assesses the impact of land cover on the erosion in agricultural areas in northern part of Jordan in 1992 and 2009. The overall methodology involved the use of the RUSLE model in a GIS environment to create and compare soil erosion maps of 1992 and 2009 aiming at the identification of soil erosion changes that occurred due to land cover change. The RUSLE model was combined with GIS techniques to analyze the soil loss rates and their distribution under different land uses. The RUSLE model was successfully applied and the C factor was successfully derived from NDVI, resulting in mean erosion loss of 9.53 and 8.97 t/ha/yr for 1992 and 2009 respectively. The differences in soil loss between years were notable giving a clear indication that changes in LULC affect considerably the soil erosion rate. A series of satellite images in time and more rainfall data, if available, would result in more accurate estimations from the model.

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