Study of desertification sensitivity in Talh region (Central Tunisia) using remote sensing, G.I.S. and the M.E.D.A.L.U.S. approach

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Abstract

Background: Tunisia is one of countries most affected by desertification. Sustainability of its resources, particularly agricultural ones, is closely dependent on it. Studies have multiplied to understand this phenomenon and consequently try to reduce its consequences on society. In recent decades, attempts have been made to find methods of forecasting and predicting desertification. Today, with significant progress made in remote sensing and GIS techniques, there is a better control of data from field, environment and society. This now makes it possible to produce documents that are much more accurate and reliable than before. This paper aims to assess sensitivity to desertification in a region of central Tunisia using remote sensing tools, GIS and guidelines of MEDALUS (Desertification and Land Use in the Mediterranean) model. Integration of different parameters with weighted values in a GIS system resulted in indices of climate, soil, vegetation and management.

Result: In almost all cases, indices reveal the preponderance of soils, vegetation, climate and management of moderate and especially poor quality. Overlaying the four indices by multiplying them according to model equation yields the final sensitivity index map. This index shows that study area is in an advanced stage of desertification since most of its surface area (82%) is in critical class. The rest is considered as fragile. Whole region is therefore placed in of high sensitivity classes of desertification. This situation is linked to a very poor vegetation cover, unstructured and low-developed soils, cultural practices based on tillage and high livestock numbers in regard to low natural grazing resources. It is also due to a farming system not taking into account soil natural vulnerability.

Conclusion: As natural resources, in current context of exploitation, cannot regenerate so quickly, pressure on environment is remarkable, exacerbating at the same time desertification problem. Continuing with current practices with clear signs of degradation may make situation irreversible in near future. Therefore, immediate action is necessary to stop degradation and preserve future generations’ resources.

Keywords: Desertification sensitivity, GIS, Remote sensing, Medalus, Tunisia
**Introduction**

Desertification is a transformation of land that was not desertic into land recalling desert landscapes. It is a scourge that affects many of world’s countries. Its occurrence is closely linked to population growth, remarkable expansion of crops sometimes on naturally fragile environments and inadequate farming practices in relation to soil conditions. Desertification occurs in a region because of lack of water reserves, soils are humus-depleted and rather destructured, and vegetation has become scarce and sparse. But also, because poor soils have been forced to produce by repeated and harmful ploughing. Desertification’s consequences can be disastrous for societies and can impact stability of affected countries. Tunisia has experienced an intensification of desertification in recent decades, which is made more noticeable particularly during dry periods.

According to national institute of strategic studies, 96% of Tunisian territory is directly or indirectly affected by desertification (Institut national des études stratégiques (Tunisie) 2017). In addition, a study conducted by INRA (France), a 2°C increase in global average temperature by 2050 will cause North African countries to lose half their cultivable land (Le Mouël et al. 2015). In these rather alarming perspectives, research has multiplied to understand underlying causes and attempt to predict phenomenon’s evolution.

Originally steppic and covered by formations based on *zizyphus lotus* and *acacia raddiana*, study region is currently suffering from erosion phenomena, especially eolian, which is damaging soil reserves and seriously threatening sustainability of crops. Environmental sensitivity to desertification can be defined, in this context, as a response of an environment, or part of it, to a change in one or more factors (Basso et al. 1999). These factors are climate, vegetation, soils and management. Sensitivity of a region to desertification can be assessed by several methods. But with advent of remote sensing and GIS, it is now possible to integrate an infinite number of parameters interacting in emergence and evolution of desertification. Therefore, MEDALUS model allows an assessment of desertification sensitivity to be performed (Kosmas et al. 1999). And this is obtained by calculating weighted values of soil characteristics (texture, parental material, depth,
drainage, etc.), vegetation (cover, fire resistance, etc.), climate (rainfall, evapotranspiration, aridity, etc.) and management (land use, overgrazing, etc.) to have values at the end that are geometric mean of all these parameters and that will reflect sensitivity state.

Since model’s guidelines were published, several studies in Mediterranean countries and in others have been carried out to assess desertification risks. In addition, this model allows modifying parameters according to basic data availability for each case. Therefore, Sepehr et al. (2007) tried to assess desertification sensitivity in southern Iran, Lahlaoi et al. (2017) in Wadi Melah basin (northern Morocco), Boudjemeline and Semar (2018) and Bouhata and Kalla (2014) in Algeria, Basso et al. (1999) in southern Italy, Kamel et al. (2015) in Lebanon, Budak et al. (2018) in Turkey, Momirović et al. (2018) in Serbia, Vieira et al. (2015) in north-eastern Brazil and Malhue and Isabel (2018) in Chile. In these studies, authors have in each case added or excluded parameters concerning soils, climate or management and sometimes even added new indexes that did not exist in initial document, such as physical quality index including geomorphological, geological and pedological data (Vieira et al. 2015). Results are in correlation with physical and climatic conditions in each region, but it is appropriate to note that adopting same parameters, following model’s weighting values and properly assigning values in first steps are very important in an evaluation or comparison process between studies using this model.

Study region
Study area is in central Tunisia between 9° 20’ to 9° 52’ East and between 34° 15’ to 34° 29’ North (Fig. 1). It is composed mainly of plains that rises slightly on north and west sides only because of slight slopes at neighboring relief piedmont. Altitudes are less than 100 m in 90% of region’s terrain but can reach 341 m on foothills of northern and western reliefs (Fig. 2). To south-east extends the Naouel sebkha (salt flat), which represents a local base level for region’s temporary watercourses. Study region corresponds to two synclines. The first is in western part and is bounded to north by the Large Bouhedma

![Fig. 2 Terrain elevation in study area](image-url)
Fig. 3 Geomorphological map with legend ((Source: National office of mines, Geological map at 1/50000 sheets n° 120, 113. Geological map at 1/500000 southern part (National office of mines n.d.). Office of Topography and Cartography, Tunisia. topographical map, 1/50000 sheets n°113,120,121 (Office of Topography and Cartography n.d.). My own field knowledge (work in progress))
Anticline and to south by the Small Chemsi and Belkhir Anticlines. The second, located in eastern part and corresponds to the Naouel sebkha. It is bordered only by small anticlinal convexities. Geological formations outcropping in study area are varied. But since these are often low plains, surface formations are of miopliocene and quaternary age. Piedmont of northern reliefs is site of chaotic accumulations of alluvial fans of various ages (Fig. 3). To east, Pleistocene limestone crusts cover pediments or old alluvial fans. To west, limestone and gypsum crust predominate on surface. But most of study region corresponds to alluvial layers from Upper Pleistocene to Holocene. On surface, sand dunes built by *Ziziphus lotus* trees are scattered all over the field, including on land of the natural reserve. Small sand dunes created by perennials are also very frequent on flat areas.

Study region is constituted of salty soils with 42% of total area, 43% of poor or mineral soils and only 21% of valuable soil usable in agriculture (Fig. 4) (Table 1). Natural vegetation is composed of a steppe of *Acacia raddiana*, *Ziziphus lotus* for trees and shrubs category. Perennials are composed in most areas by *Astragalus armatus*, *Rantherium suavolens*, *Arthrophytum schmittianum*, *Pegnum harmala*, *Salsola vermiculata*, *Lycium arabicum*, *Artemisia campestris* and *Artemisia herba-alba*. Stream beds are occupied by riparian species such as *Tamarix gallica* and *Nerium oleander*.
Materials and methods

Data sources can be summarized in following table (Table 2):

Data source | Parameter | Reference
--- | --- | ---
Merra_2 | Rainfall, temperature (to calculate evapotranspiration and aridity index) | © MERRA. (http://www.soda-pro.com/web-services/meteo-data/merra) (NASA n.d.-b)
Carte Agricole (digital database) | Soil texture, soil depth, soil parental rock, drainage, rock fragment, natural reserve boundary. | Ministry of agriculture, Tunisia (2001) (Ministry of agriculture 2001)
Sentinel_2_1c 10 m resolution satellite image | Cropland, fire resistance, drought protection, erosion protection, plant cover (by using NDM index) | © Copernicus open access hub (Copernicus open access hub n.d.) https://scihub.copernicus.eu/dhus/4/home
28 m resolution DEM | Aspect, slope. | © NASA: ASTER GDEM Digital Elevation Model (NASA n.d.-a) https://lpdaac.usgs.gov/dataset_discovery/aster/aster_products_table
Socio-economical data | Population density, livestock data | Office for Development of the Centre, Office for Development of the South, the National Institute of Statistics: Statistics of governorates of Sidi Bouzid and Gafsa (Institut national des statistiques 2014; Office de développement du Centre ouest (ODCO) 2017; Office de développement du Sud (ODS) 2017)
Google earth imagery | Conservation practice (digitalization) | ©Google earth Pro. app.

Table 2 Data sources

| Data source            | Parameter                                                                 | Reference                                                                 |
|------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Merra_2                | climatological gridded data                                              | © MERRA. (http://www.soda-pro.com/web-services/meteo-data/merra) (NASA n.d.-b) |
| Carte Agricole         | Soil texture, soil depth, soil parental rock, drainage, rock fragment,   | Ministry of agriculture, Tunisia (2001) (Ministry of agriculture 2001)    |
|                        | natural reserve boundary.                                                 |                                                                           |
| Sentinel_2_1c 10 m     | Cropland, fire resistance, drought protection, erosion protection, plant | © Copernicus open access hub (Copernicus open access hub n.d.) https://scihub.copernicus.eu/dhus/4/home |
| resolution satellite    | cover (by using NDM index)                                                |                                                                           |
| image                  |                                                                           |                                                                           |
| 28 m resolution DEM    | Aspect, slope.                                                            | © NASA: ASTER GDEM Digital Elevation Model (NASA n.d.-a)                   |
|                       |                                                                           | https://lpdaac.usgs.gov/dataset_discovery/aster/aster_products_table      |
| Socio-economical data  | Population density, livestock data                                        | Office for Development of the Centre, Office for Development of the South, |
|                        |                                                                          | the National Institute of Statistics: Statistics of governorates of Sidi   |
|                        |                                                                          | Bouzid and Gafsa (Institut national des statistiques 2014; Office de      |
|                        |                                                                          | développement du Centre ouest (ODCO) 2017; Office de développement du    |
|                        |                                                                          | Sud (ODS) 2017)                                                           |
| Google earth imagery   | Conservation practice (digitalization)                                    | ©Google earth Pro. app.                                                   |

Climate quality index

Climate quality index was calculated from climatological data from MERRA-2 platform (Modern-Era Retrospective analysis for Research and Applications, Version 2) downloadable here (http://www.soda-pro.com/web-services/meteo-data/merra). Data range from 2008 to 2017 (NASA n.d.-b) (Table 3). These are gridded data including precipitation and temperatures among others. Temperatures in Kelvin have been converted to °C. From these data, evapotranspiration values were obtained according to Thornthwaite equation (Thornthwaite 1948) (Eq. 1, 2 and 3) and then aridity index according to UNESCO equation (UNESCO – United Nations Educational: Scientific and Cultural Organization 1979; Sampaio et al. 2003) (Eq. 4) (Thornthwaite 1948):

\[ ETP = 16 \times \left(10^\left(-\frac{T}{P}\right)\right)^a \times F \]  \quad (1)

Where: ETP is mean evapotranspiration for a month, in mm; T is mean temperature for a month, in °C. F is latitude corrective factor (Thornthwaite 1948).

\[ a = 0.016 \times I + 0.5 \]  \quad (2)

Where: I is annual thermic index (Thornthwaite 1948).

Table 3 Main climatological data for study area (NASA n.d.-b)

| Long. | Lat. | Station      | Rainfall | Evapotranspiration | Aridity |
|-------|------|--------------|----------|--------------------|---------|
| 9.555 | 34.259 | Sidi Mansour | 166.9    | 1018.15            | 0.16    |
| 9.39  | 34.414 | Haddej-village | 186.54   | 998.78             | 0.18    |
| 9.6   | 34.465 | Elboua-village | 189.38   | 996.5              | 0.190   |
| 9.699 | 34.481 | Station parc  | 189.78   | 997.49             | 0.19    |
| 9.843 | 34.572 | Mezzouna      | 136.31   | 1016.95            | 0.13    |
| 10.096| 34.741 | Bir Ali       | 208      | 997.5              | 0.20    |
| 8.784 | 34.422 | Gafsa         | 161.21   | 1017.03            | 0.15    |

Table 4 Assigned weighing indices for various parameters used for assessment of Climate quality (Kosmas et al. 1999; Vieira et al. 2015)

| Parameter | Class | Description | range      | Weight |
|-----------|-------|-------------|------------|--------|
| Rainfall  | 1     | High        | > 300 mm   | 1      |
|           | 2     | Moderate    | 150-300 mm | 1.5    |
|           | 3     | Low         | < 150 mm   | 2      |
| Aridity   | 1     | High        | AI ≥1      | 1      |
|           | 2     | Moderate    | 0.1 < AI < 1 | 1.5  |
|           | 3     | Low         | AI ≤0.1   | 2      |
| Aspect    | 1     | Wet         | North      | 1      |
|           | 2     | Dry         | South      | 2      |
$I = \sum_{m=1}^{12} i(m) = \left[ \frac{T(m)}{5} \right]^{1.514}$  

**Aridity Index (UNESCO – United Nations Educational: Scientific and Cultural Organization 1979):**

$$\text{AI} = \frac{P}{\text{Etp}}$$

Where $P$ is mean annual precipitation and Etp is mean annual potential evapotranspiration.

Land exposition (Aspect) was generated from a DEM of 28 m resolution and simplified in only two directions which are north and south. Then three climate parameters were weighted according to scores proposed by Medalus model (Table 4). Calculation of climate quality index is achieved by multiplying these three layers as follows (Eq. 5):

$$\text{CQI} = (\text{rainfall} \times \text{aridity} \times \text{aspect})^{1/3}$$

**Table 5 Assigned weighing indices for various parameters used for assessment of soil quality (Kosmas et al. 1999)**

| Class  | Description                                      | Weight |
|--------|--------------------------------------------------|--------|
| Texture | Good                                             | L, SCL, SL, LS, CL | 1     |
|        | Moderate                                         | SC, SCL, CL | 1.2   |
|        | Poor                                             | Si, C, SCL | 1.6   |
|        | Very poor                                        | S      | 2     |
| Slope  | Very gentle to flat                              | < 6%   | 1     |
|        | Gentle                                           | 6–18%  | 1.2   |
|        | Steep                                            | 18–35% | 1.5   |
|        | Very steep                                       | > 35%  | 2     |
| Parent material | Good                                 | Shale, schist, basic, ultra-basic, Conglomerates, unconsolidated | 1     |
|        | Moderate                                         | Limestone, marble, granite, Rhyolite, Ignimbrite, gneiss, siltstone, sandstone | 1.7   |
|        | Poor                                             | Marl, Pyroclastics | 2     |
| Soil depth | Deep                               | > 75    | 1     |
|          | Moderate                                         | 75–30   | 2     |
|          | Shallow                                          | 15–30   | 3     |
|          | Very shallow                                     | < 15    | 4     |
| Drainage | Well drained                                      | 1     |
|         | Imperfectly drained                              | 1.2    |
|         | Poorly drained                                    | 2     |
| Rock fragments | Very stony                              | > 60    | 1     |
|         | Stony                                             | 20–60   | 1.3   |
|         | Bare to slightly stony                           | < 20    | 2     |

$\text{SQI} = \text{texture} \times \text{parent material} \times \text{rock fragment} \times \text{depth} \times \text{slope} \times \text{drainage}^{1/6}$

**Soil quality index**

Soil quality index was calculated from data provided by Carte Agricole (agricultural map) of Ministry of Agriculture (Fig. 4). These are soil texture, depth, parent rocks, rock fragments and drainage. Scores were assigned according to Medalus guidelines (Table 5). Map is obtained by multiplying different scores with following equation (Eq. 6):

**Vegetation quality index**

Vegetation quality index was calculated using data from Sentinel_2_1c satellite image with a resolution of 10 m. First, land cover map was obtained from calculation of NDVI index, which shows vegetation density by intersecting the two red and infrared channels of Sentinel_2_
### Fig. 5 Land use in study area

### Table 6

| Parameter               | Class | Description                                                                 | Type of vegetation                                                                 | Weight |
|-------------------------|-------|------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------|
| Fire risk               | 1     | Low                                                                          | bare land, perennial agricultural crops, annual agricultural crops (maize, tobacco, sunflower) | 1      |
|                         | 2     | Moderate                                                                     | annual agricultural crops (cereals, grasslands), deciduous oak, (mixed), mixed Mediterranean, macchia/evergreen forests | 1.3    |
|                         | 3     | high                                                                         | Mediterranean macchia                                                                | 1.6    |
|                         | 4     | Very high                                                                    | pine forests                                                                         | 2      |
| Erosion protection      | 1     | Very high                                                                    | Mixed Mediterranean macchia/evergreen forests                                         | 1      |
|                         | 2     | high                                                                         | Mediterranean macchia, pine forests, Permanent grasslands, evergreen perennial crops | 1.3    |
|                         | 3     | Moderate                                                                     | Deciduous forests                                                                    | 1.6    |
|                         | 4     | Low                                                                          | Deciduous perennial agricultural crops (almonds, orchards)                           | 1.8    |
|                         | 5     | Very Low                                                                     | Annual agricultural crops (cereals), annual grasslands, vines,                       | 2      |
| Drought resistance      | 1     | Very high                                                                    | Mixed Mediterranean macchia/evergreen forests, Mediterranean macchia                  | 1      |
|                         | 2     | high                                                                         | Conifers, deciduous, olives                                                          | 1.2    |
|                         | 3     | Moderate                                                                     | Perennial agricultural trees (vines, almonds, ochrand)                                | 1.4    |
|                         | 4     | Low                                                                          | Perennial grasslands                                                                  | 1.7    |
|                         | 5     | Very Low                                                                     | Annual agricultural crops, annual grasslands                                         | 2      |
| Plant cover             | 1     | high                                                                         | > 40%                                                                                | 1      |
|                         | 2     | Low                                                                          | 20–40%                                                                               | 1.8    |
|                         | 3     | Very Low                                                                     | < 20%                                                                                | 2      |
Table 7  Main management indicators in study area source: INS, ODCO, ODS (Copernicus open access hub n.d.; Office de développement du Centre ouest (ODCO) 2017; Office de développement du Sud (ODS) 2017)

| Delegation (administrative subdivision) | Population (2017) (inhabitant) | Area (km²) | Population density (inhabitant/km²) | Livestock density (heads/km²) | Grazeland area (km²) | Livestock density (heads/km²) |
|-----------------------------------------|---------------------------------|------------|------------------------------------|-----------------------------|---------------------|-----------------------------|
| Mezzoune                                 | 25535                           | 1119       | 22.81                              | 39250                       | 161.41              | 35.07                       |
| Belkhir                                  | 14882                           | 8395       | 17.72                              | 22350                       | 817.02              | 26.62                       |
| Melnassy                                 | 24327                           | 625        | 38.92                              | 24380                       | 124.195             | 39.00                       |
| Menzel Bouzayane                         | 26012                           | 590        | 44.08                              | 26240                       | 149.2               | 44.47                       |
| Guettar                                  | 20466                           | 910        | 22.49                              | 18850                       | 887.03              | 20.71                       |

Management quality index
Calculation of management index was obtained after land use map was completed to assess land use intensity. Data on population density in study area were provided by National Institute of Statistics and assigned according to an administrative subdivision followed by an extraction of study region (Institut national des statistiques 2014). Overgrazing data were obtained using statistics from regional development centers in central west and south (Office de développement du Centre ouest (ODCO) 2017; Office de développement du Sud (ODS) 2017). Calculation of overgrazing was done according to head rate per square kilometer based on sheep head as a calculation unit. Bovine heads have been multiplied by four to equal sheep heads (Table 7). Water erosion conservation facilities have been digitized from ©Google earth app. Bouhedma natural reserve extension was provided by Carte Agricole (Ministry of agriculture 2001). After weighted scores were assigned, the four

Table 8  Assigned weighing indices for various parameters used for assessment of management quality (Kosmas et al. 1999; UNESCO – United Nations Educational: Scientific and Cultural Organization 1979; Vieira et al. 2015))

| Parameter                     | Description                        | Range                                      | Weight |
|-------------------------------|------------------------------------|--------------------------------------------|--------|
| Cropland (land use)           | low land use intensity             | < 10 inhabitants per square km             | 1.00   |
|                               | Medium land use intensity          | 10–20 inhabitants per square km            | 1.33   |
|                               | high land use intensity            | 20–50 inhabitants per square km            | 1.66   |
|                               |                                    | > 50 inhabitants per square km             | 2.00   |
| population density            |                                    | < 10 inhabitants per square km             | 1.00   |
| Policy (conservation practices)| High                               | Complete: > 75% of area under protection   | 1.00   |
|                               | Moderate                           | Partial: 25–75% of area under protection   | 1.5    |
|                               | low                                | Incomplete: < 25% of area under protection | 2.00   |
| Overgrazing                   | Low                                | < 20 heads per square km                   | 1.00   |
|                               | Moderate                           | 20–60 heads per square km                  | 1.33   |
|                               | High                               | 60–100 heads per square km                 | 1.66   |
|                               | Very high                          | > 100 heads per square km                  | 2.00   |
parameters were multiplied according to following equation (Eq. 9) (Table 8):

\[
MQI = \left( \frac{\text{cropland} \times \text{population density} + \text{overgrazing} \times \text{policy}}{C_0} \right)^{1/4}
\]

Desertification-sensitive areas index
Map of final index of desertification-sensitive areas is based on multiplication, in a GIS system, in this case ArcGis software (Fig. 6). Superimposition of different layers in vector format is done by Overlay_union tool. Equation is applied in final integration field through field calculator box (eq. 10):

\[
ESAI = (SQI \times CQI \times VQI \times MQI)^{1/4}
\]

Where ESAI is desertification-sensitive areas index, SQI is soil quality index, CQI is climate quality index, VQI is vegetation quality index and MQI is management-quality index.

| Class                  | Value  | Area sq. km | %     |
|------------------------|--------|-------------|-------|
| Unclassified (sebkha)  | 0      | 139.26      | 14.26 |
| Moderate quality       | 1.15–1.81 | 389.22      | 40.03 |
| Low quality            | > 1.81 | 443.69      | 45.63 |

| Class                  | Value  | Area | %     |
|------------------------|--------|------|-------|
| Unclassified (sebkha)  | 0      | 139.26 | 14.26 |
| Moderate quality       | 1.13–1.45 | 606.02 | 62.08 |
| Low quality            | > 1.45 | 230.81 | 23.64 |
Results and discussions

Climate quality index

By examining this index, areas of study region are almost divided between moderate quality (40%) and low climate quality (45%) (Fig. 7) (Table 9). This map is strongly influenced by terrain exposition map (Aspect) which assigns a value to each set of pixels with same exposition. All climatic parameters included in this index inputs prove that study area is in an arid zone. Only exposure to North has somewhat reduced aridity of some areas.

Soil quality index

Soil quality map shows that 62% are in moderate quality class and 23% in low quality one. Most of land (85%) in region is therefore of moderate or low quality, which makes it particularly fragile (Fig. 8) (Table 10). It also shows that low-quality soils are in central plain where cropping activities in region are concentrated, resulting in degradation of superficial soil horizons due to tramping, deep tillage (seed) or surface tillage (grass cleaning). Continued pressure in this area affects soils that have become fragile, thin and impoverished. Remaining areas, of moderate quality, are due to complexity of their development because of parent rocks that are still very close, crop-unfriendly crusting and presence of steeper slopes.

### Table 12 Spatial distribution of management quality index classes

| Class                  | Value | Area sq. km | %    |
|------------------------|-------|-------------|------|
| Unclassified (sebkha)  | 0     | 139.26      | 14.26|
| High quality           | < 1.25| 61.59       | 6.19 |
| Moderate quality       | 1.5–1.50 | 546.10   | 54.95|
| Low quality            | > 1.50 | 247.01      | 24.85|
Vegetation quality index
This map shows that 40% of land in study region is in moderate quality and 45% in low quality (Fig. 9) (Table 11). As a result, these areas are poorly or not covered by protective vegetation, exposing them to erosion factors. Medium-quality vegetation terrain corresponds to unprotected grasslands, extensive arboriculture, often young and with very poor covering for soil. Irrigated plots, therefore intensive, are too isolated and are not significant areas to change situation. Areas of poor vegetation quality are zones without vegetation other than xerophilous or annual species with very low coverage.

Management quality index
On management quality and land use map, 6% of land has good protection and management quality, 54% is in moderate class and 24% has a low management quality (Fig. 10) (Table 12). Only area that benefits of good management and therefore protection is that of Bouhedma natural reserve where forest authorities have set up a strict system to prohibit any illegal grazing or illegal use of wood from rare shrub species of *acacia raddiana*. Areas of moderate quality correspond to zones that have been protected by conservation practices against water erosion. Remaining areas, of low management quality, are all simply unprotected rangelands.

Desertification sensitive areas index
Desertification sensitivity map produced by overlaying the four thematic maps shows high sensitivity values affecting most of the study area. Thus, 0.29% of the
land belongs to class F2 (Fragile 2), 2.87% of the land to class F3 (Fragile 3), 8.56% to class C1 (Critical 1), 60% to class C2 and 13% to maximum class C3 (Fig. 11) (Table 13). Critical class covers 82% of surface area with its three subclasses. This clearly shows that study region is extremely sensitive to desertification given its physical and management characteristics. As shown on this map we can distinguish:

- Areas of the fragile class:

  * Relatively less sensitive areas (but which remain in the fragile class) correspond to lands in the natural reserve where grazing, cutting wood, ploughing, etc. are strictly forbidden. Trampling is also low since entry is also prohibited, except for the wild fauna living there.

  * Areas in south-western part of the map that are poorly cultivated by man due to slopes or crusting unfavorable to crops, or areas with conservation practices to prevent water erosion.

- Areas of critical subclasses 1 and 2:

  Critical subclass 1 and 2 areas cover most of study area. Their degradation is in progress and requires rapid intervention, notably by creating rangelands closed to use for a period of time allowing natural vegetation to regenerate and soil to stabilize. A multiplication of land conservation facilities to prevent water and wind erosion, but also by initiating an ambitious reforestation program, which paradoxically is still lacking, would be salutary for the region.

- Areas of critical subclass 3:

  Subclass C3 covers the entire eastern half of study region and corresponds to sectors with poor quality soils but which are paradoxically heavily used in farming and the least protected against erosion. These lands are very sensitive to desertification due to cultural practices used, particularly dry farming requiring repeated ploughing. The latter proves to be damaging to soil because it releases particles and makes available to wind and water erosion the best soil elements which are organic matter and fine fraction. Their protection would start with a profound change in
farming methods, which must take into account soil weakness. Generalization of conservation techniques to prevent erosion would also help to reduce loss of essential soil elements.

**Conclusion**

In this study, objective was to use physical and human parameters integrated in a GIS environment and following MEDALUS model guidelines, in order to assess desertification sensitivity of a steppe region in south-central Tunisia. All parameters were first weighted and calculated individually to produce indices of climate, vegetation, soil and management. They were then superimposed to produce final desertification sensitivity index. Study region is characterized primarily by a substantially arid climate. This was reflected in calculation of this index by 85% of its area with a moderate or low-quality climate (45% for the latter category). Low rainfall and water deficit, exacerbated by high evapotranspiration during most months of year, often explain this situation. Poor and low-structured soils predispose region to desertification. Most of land in region (85%) has soils of moderate or low quality (including 23% for the latter category), indicating an increased sensitivity to degradation. Thin depth of soils, their destruction by livestock and use of ploughing are often behind their current state. Rare and sparse vegetation contributes to fragility of the region. 85% of lands have moderate to low quality vegetation (45% of which is of low quality). Except for protected natural reserve, which allows vegetation regeneration and soil stabilization, area’s land suffers from poor protection by vegetation. This is due to scarcity of trees and xerophilic aspect of shrubs and perennials which are still under threat of illegal cutting despite cutting being prohibited for certain species (*acacia raddiana*). Human management in this vulnerable region is highly responsible for desertification extension. 78% of land has human management of moderate or poor quality (including 24% for the latter). This shows that human management is clearly not compatible with current environmental conditions. Analysis of desertification sensitivity index of study area shows that it is at an advanced stage of desertification since most of its...
surface area (82%) has been classified in critical category. Remaining part is considered as fragile. This place the entire region in high desertification sensitivity classes. This state is linked to a combination of multiple factors, including a lack of vegetation cover, unstructured and poorly developed soils, tillage-based cropping practices and livestock heads numbers in regard to low natural grazing resources. As a result, there is a remarkable pressure on natural resources, especially since they are not able to regenerate as quickly in the current context of exploitation.

Abbreviations
MEDALUS: Mediterranean Desertification and Land Use; GIS: Geographic information system; MERRA: Modern-Era Retrospective analysis for Research and Applications; ETP: Evapotranspiration; DEM: Digital elevation model; NDVI: Normalized difference vegetation index; EASAI: Environment-sensitive areas index; CQI: Climate quality index; SQI: Soil quality index; VQI: Vegetation quality index; MQI: Management quality index

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Competing interests
The author declare that he has no competing interests.

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