Geoenvironmental Disasters

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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

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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,

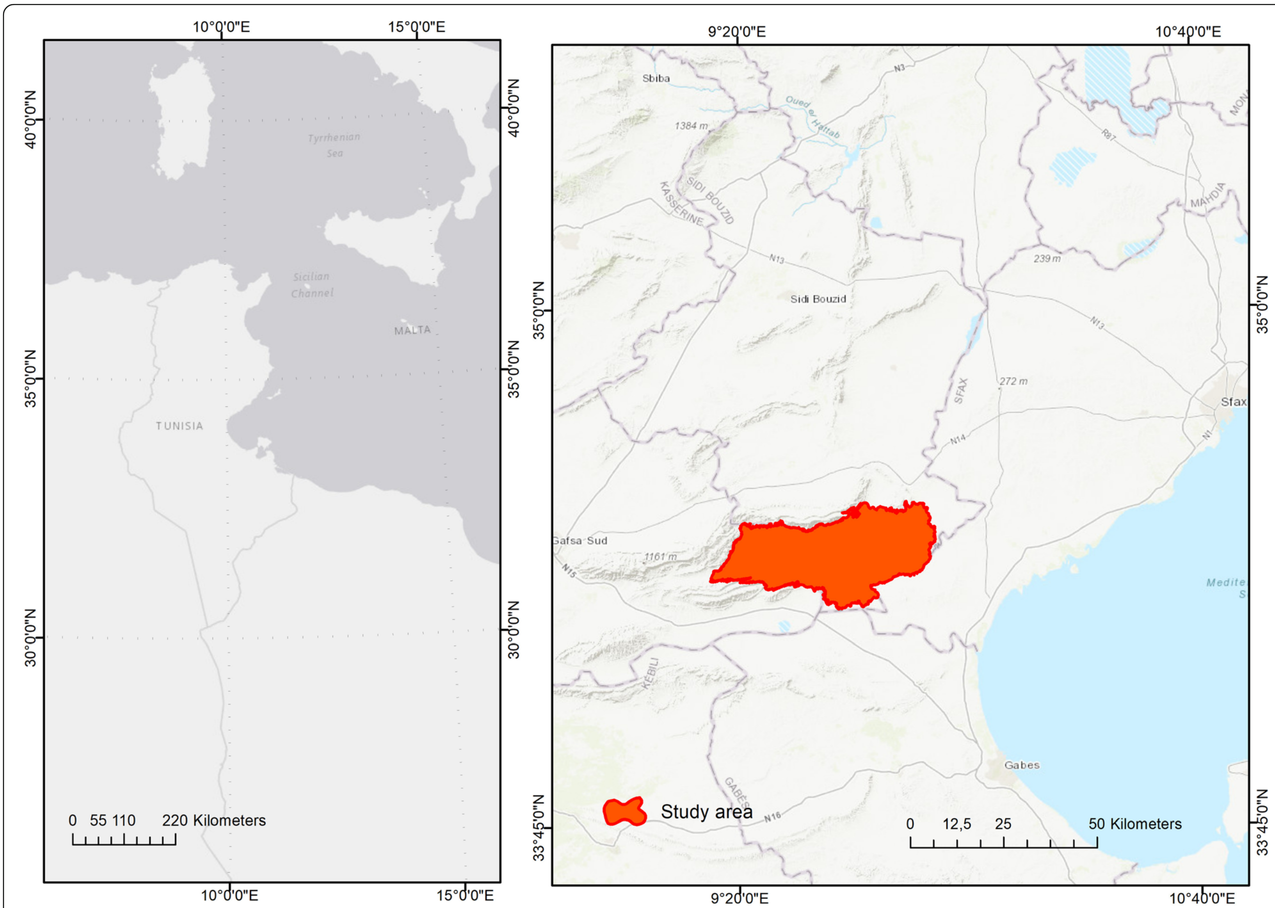

Fig. 1 Location map

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), Boudjemline 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

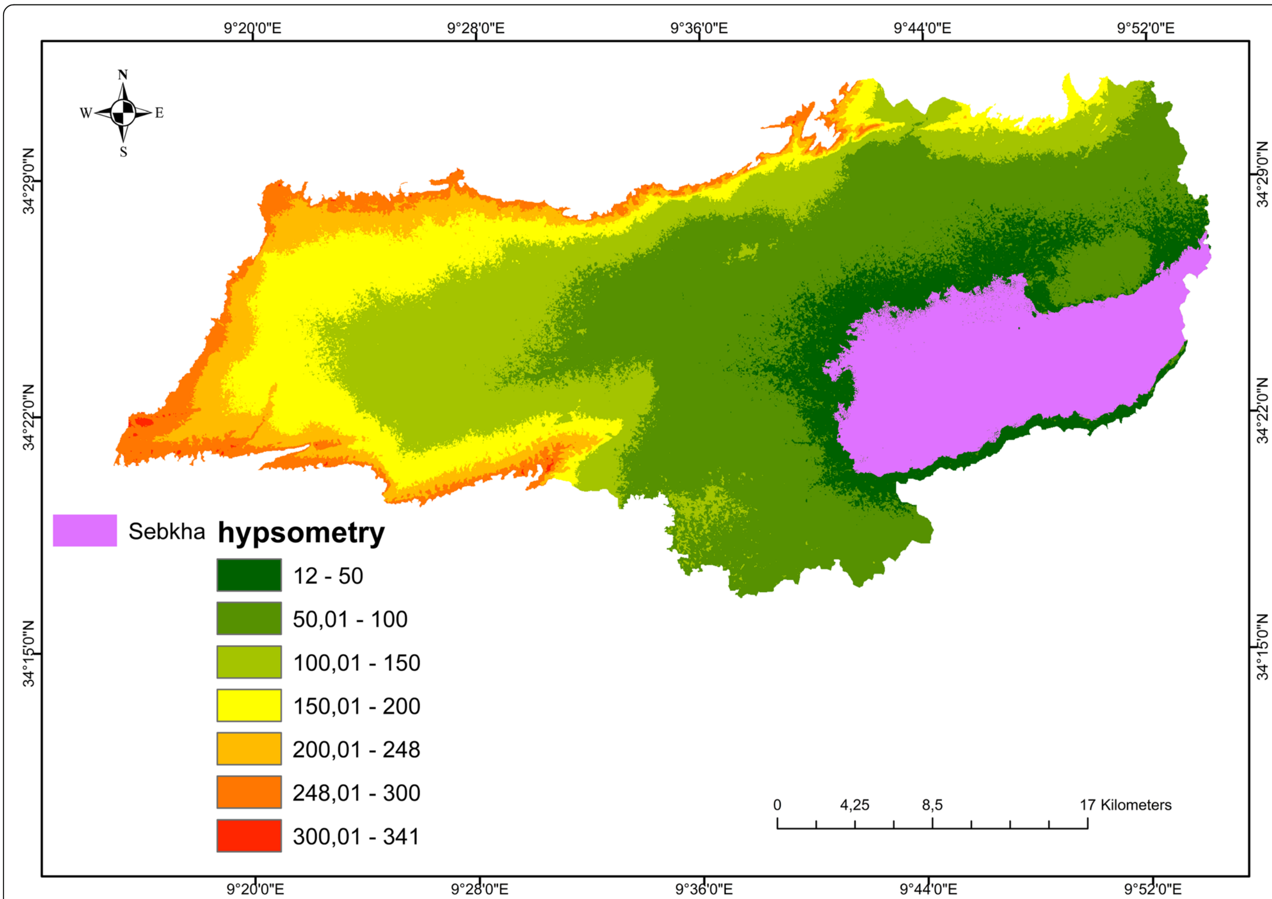

Fig. 2 Terrain elevation in study area

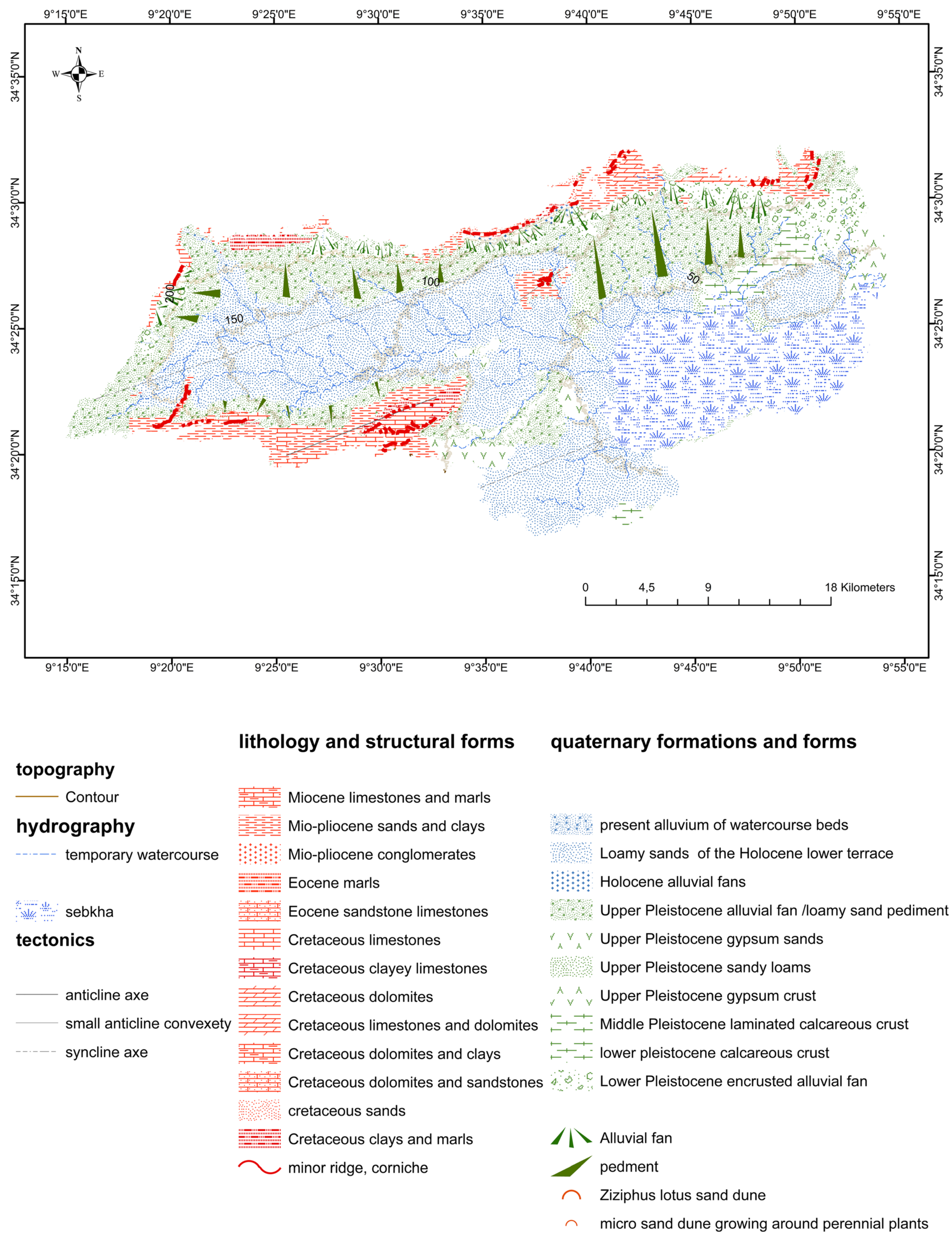

Fig. 3 Geomorphological map with legend ((Source: National office of mines, Geological map at 1/50000 sheets n° 120, 113. Geological map at 1/500000 southern part (National office of mines n.d.). Office of Topography and Cartography, Tunisia. topographical map, 1/50000 sheets n°113,120,121 (Office of Topography and Cartography n.d.). My own field knowledge (work in progress))

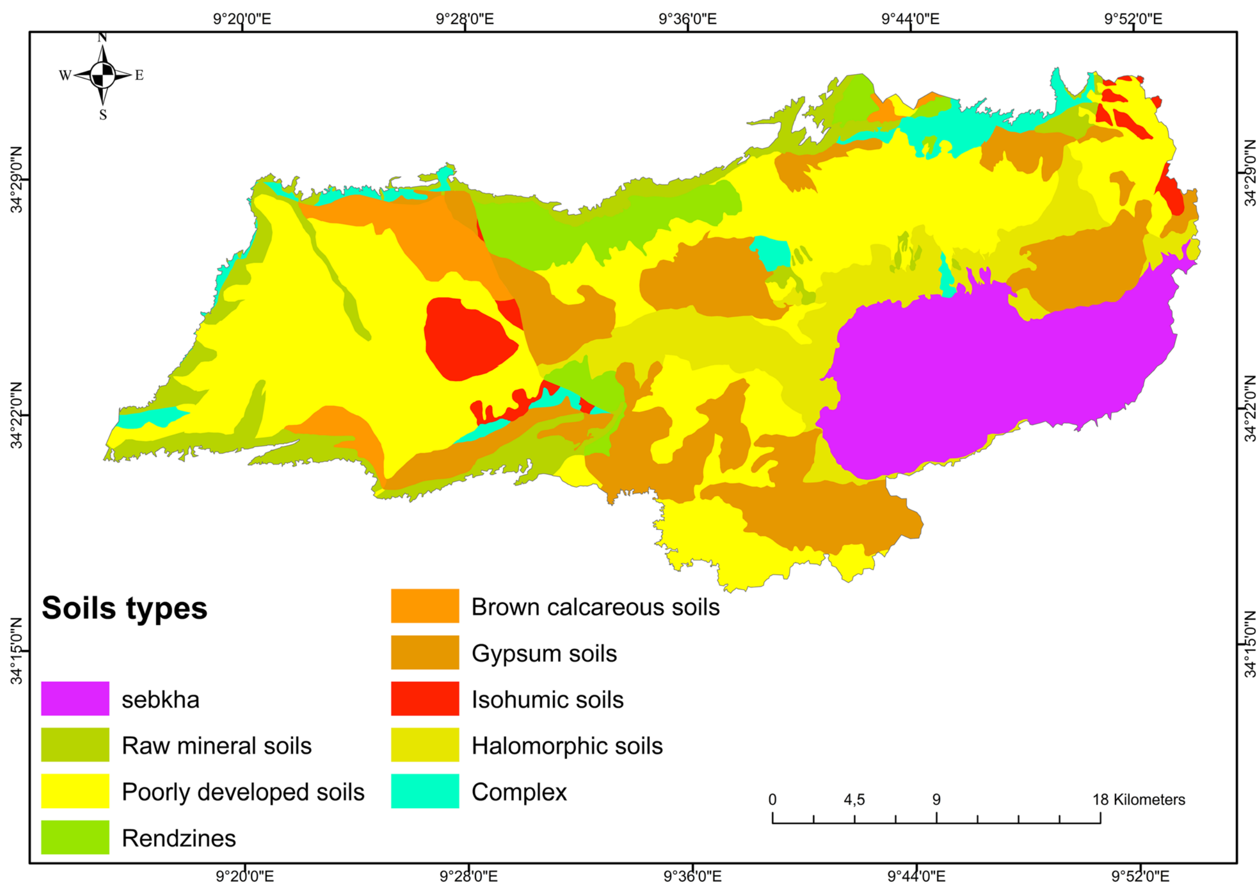

Fig. 4 Soil types in study area

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.

Table 1 Soil types in study area

Category	Soil type	%	% category
Salty soils	Gypsum soils	18.69	42.4
	Halomorphic soils	9.45	
	Sebkha	14.26	
Poor soils	Raw mineral soils	8.09	43.02
	Poorly developed soils	34.93	
Valuable soils	isohumic soils	2.74	21.14
	Rendzine	4.80	
	Complex soil	3.25	
	Brown calcareous soils	3.55	

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*, *Zizyphus 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*.

Table 2 Data sources

Data source	Parameter	Reference
Merra_2 climatological gridded data	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 NDVI index)	© Copernicus open access hub (Copernicus open access hub n.d.) https://scihub.copernicus.eu/dhus/#/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 développent du Sud (ODS) 2017*)*
Google earth imagery	Conservation practice (digitalization)	©Google earth Pro. app.

Materials and methods

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

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):

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

$$\mathrm{ETP} = 16 * \left[10 * \frac{\mathrm{T}}{\mathrm{P}}\right]^{\mathrm{a}} * \mathrm{F} \tag{1}$$

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*).*

$$\mathrm{a} = 0.016 \times \mathrm{I} + 0.5 \tag{2}$$

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

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

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

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

L loam, *SCL* sandy clay loam, *SL* sandy loam, *LS* loamy sand, *CL* clay loam, *SC* sandy clay, *SiL* silty loam, *SiCL* silty clay loam, *Si* silt, *C* clay, *SiC* silty clay, *S* sand

$$I = \sum_{m=1}^{12} i(m), = \left[\frac{T(m)}{5}\right]^{1.514} \quad (3)$$

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

$$\mathrm{AI} = \frac{\mathrm{P}}{\mathrm{Etp}} \quad (4)$$

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):

$$\mathrm{CQI} = (\mathrm{rainfall} * \mathrm{aridity} * \mathrm{aspect})^{1/3} \quad (5)$$

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):

$$\mathrm{SQI} = (\mathrm{texture} * \mathrm{parent\ material} * \mathrm{rock\ fragment} * \mathrm{depth} * \mathrm{slope} * \mathrm{drainage})^{1/6} \quad (6)$$

Vegetation quality index

Vegetation quality index was calculated using data from Senitinel_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_

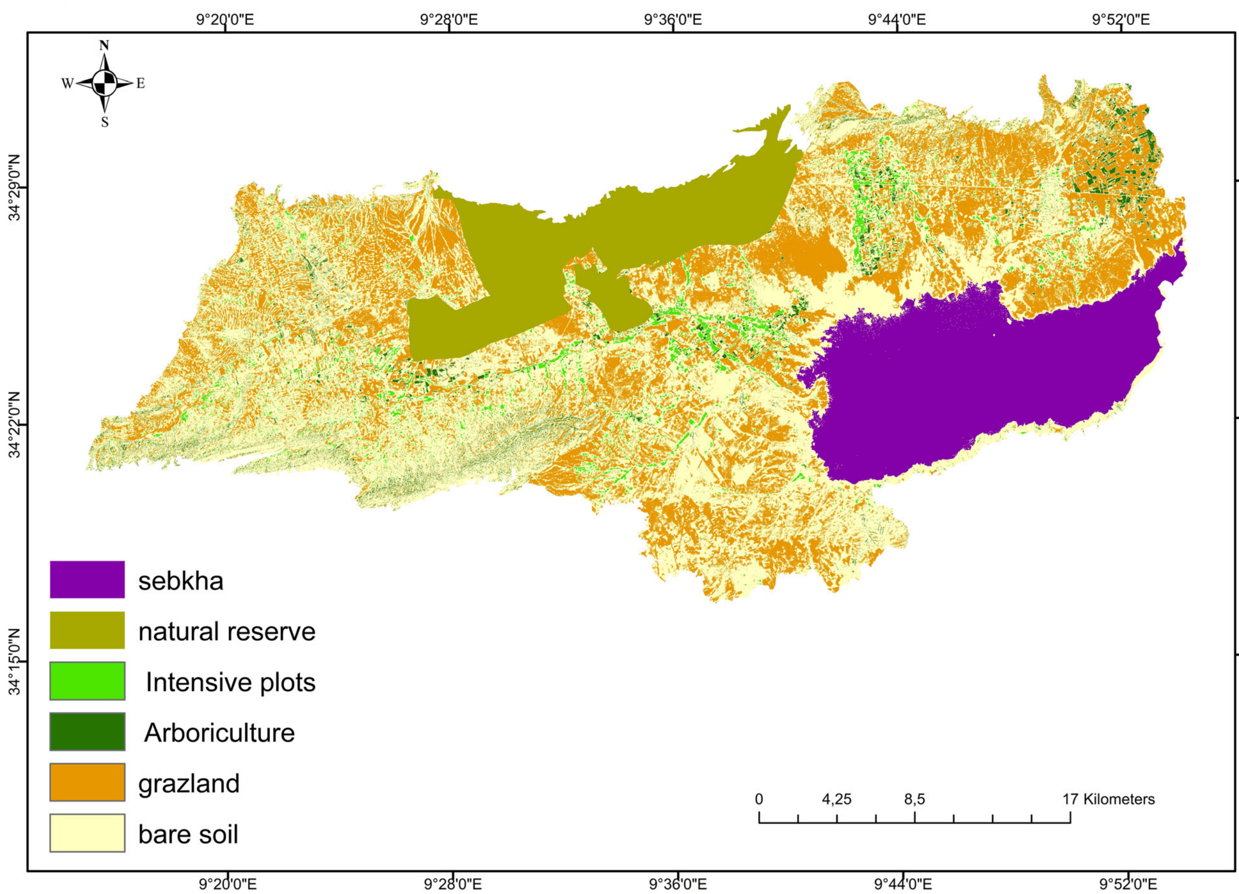

Fig. 5 Land use in study area

Table 6 Assigned weighing indices for various parameters used for assessment of vegetation quality (Kosmas et al. 1999)

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 développent du Sud (ODS) 2017)

Delegation (administrative subdivision)	Population (2017) (inhabitant)	Area	Population density	Livestock (head)	Grazeland area	Livestock density
Mezzouna	25535	1119	22.81	39250	161.41	35.07
Belkhir	14882	8395	17.72	22350	817.02	26.62
Meknassy	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

1c image 5, in this case band 8 and 4 (eq. 7) (Copernicus open access hub n.d.).

$$\mathrm{NDVI} = \frac{(NIR - R)}{(NIR + R)} = \frac{(BAND\ 8 - BAND\ 4)}{(BAND\ 8 + BAND\ 4)} \tag{7}$$

Where NIR is the near infra-red band and R is the red band.

Then, a supervised classification of image produced a land use map that was a basis for calculating parameters of drought resistance, fire resistance and erosion protection (Fig. 5). All four parameters were weighted with scores provided in model and multiplied with following equation (Eq. 8) (Table 6):

$$\mathrm{VQI} = \left(\text{fire risk} * \text{erosion protection} * \text{drought resistance} * \text{vegetation cover}\right)^{1/4} \tag{8}$$

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 développent 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		1
	Medium land use intensity		1.5
	high land use intensity		2
population density		< 10 inhabitants per square km	1.00
		10–20 inhabitants per square km	1.33
		20–50 inhabitants per square km	1.66
		> 50 inhabitants per square km	2.00
Policy (conservation practices)	High	Complete: > 75% of area under protection	1
	Moderate	Partial: 25–75% of area under protection	1.5
	low	Incomplete: < 25% of area under protection	2
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

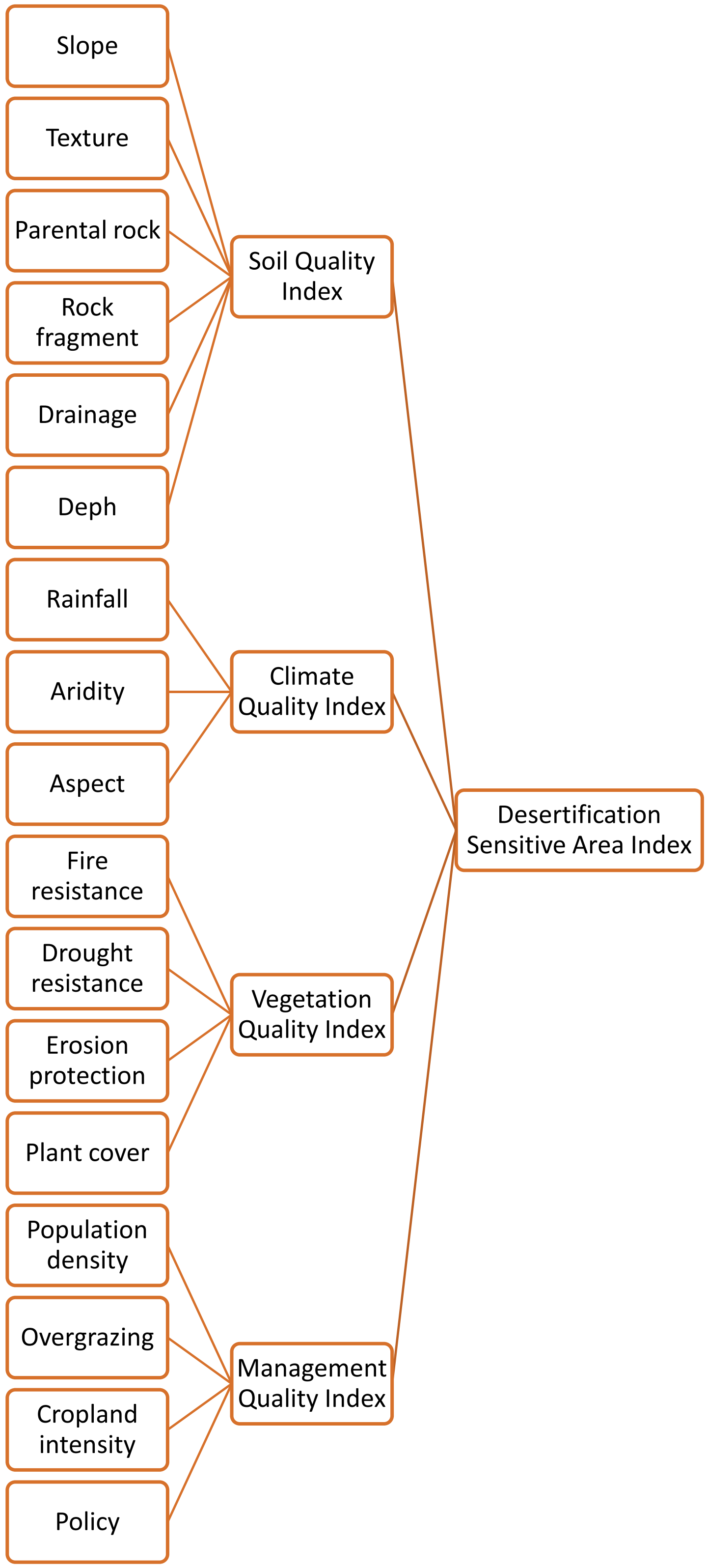

Fig. 6 Methodology flowchart

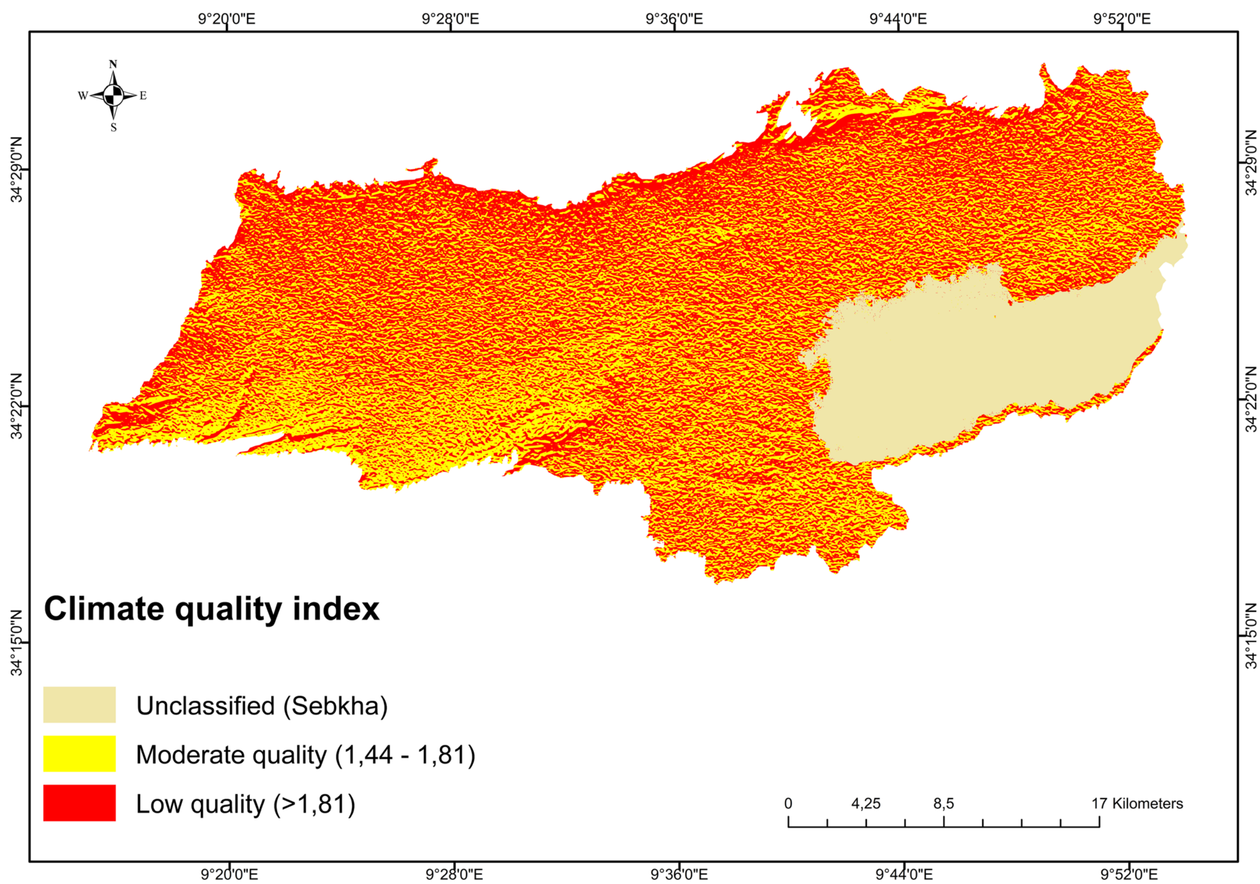

Fig. 7 Climate quality index map

parameters were multiplied according to following equation (Eq. 9) (Table 8):

$$MQI = (cropland*population\ density*overgrazing*policy\ )^{1/4} \quad (9)$$

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):

$$ESAI = (SQI*CQI*VQI*MQI)^{1/4} \quad (10)$$

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

Table 9 Spatial distribution of climate quality index classes

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

Table 10 Spatial distribution of soil quality index classes

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

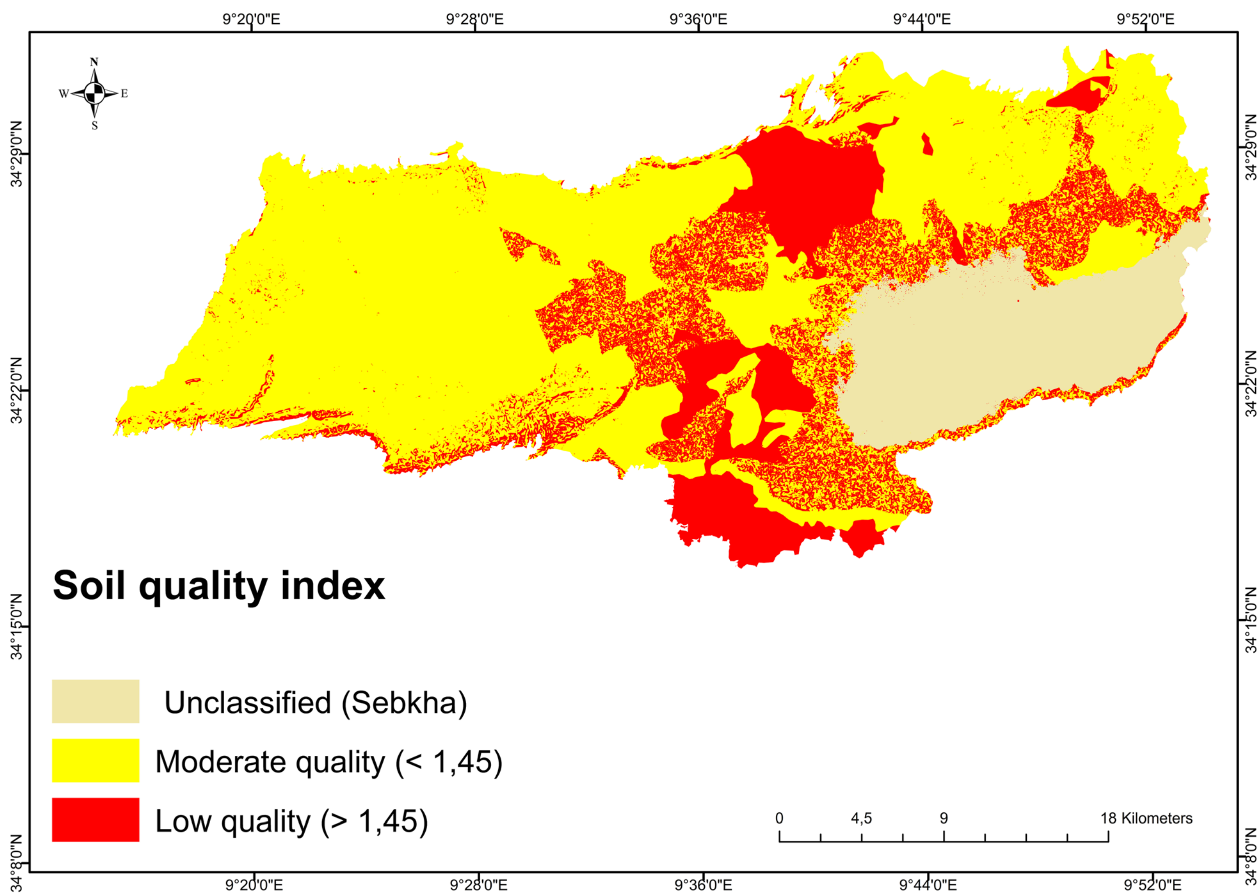

Fig. 8 Soil quality index map

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 trampling, 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 11 Spatial distribution of vegetation quality index classes

Class	Value	Area	%
Unclassified (sebkha)	0	139.26	14.26
Moderate quality	1.2–1.6	394.84	40.01
Low quality	> 1.6	450.88	45.68

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

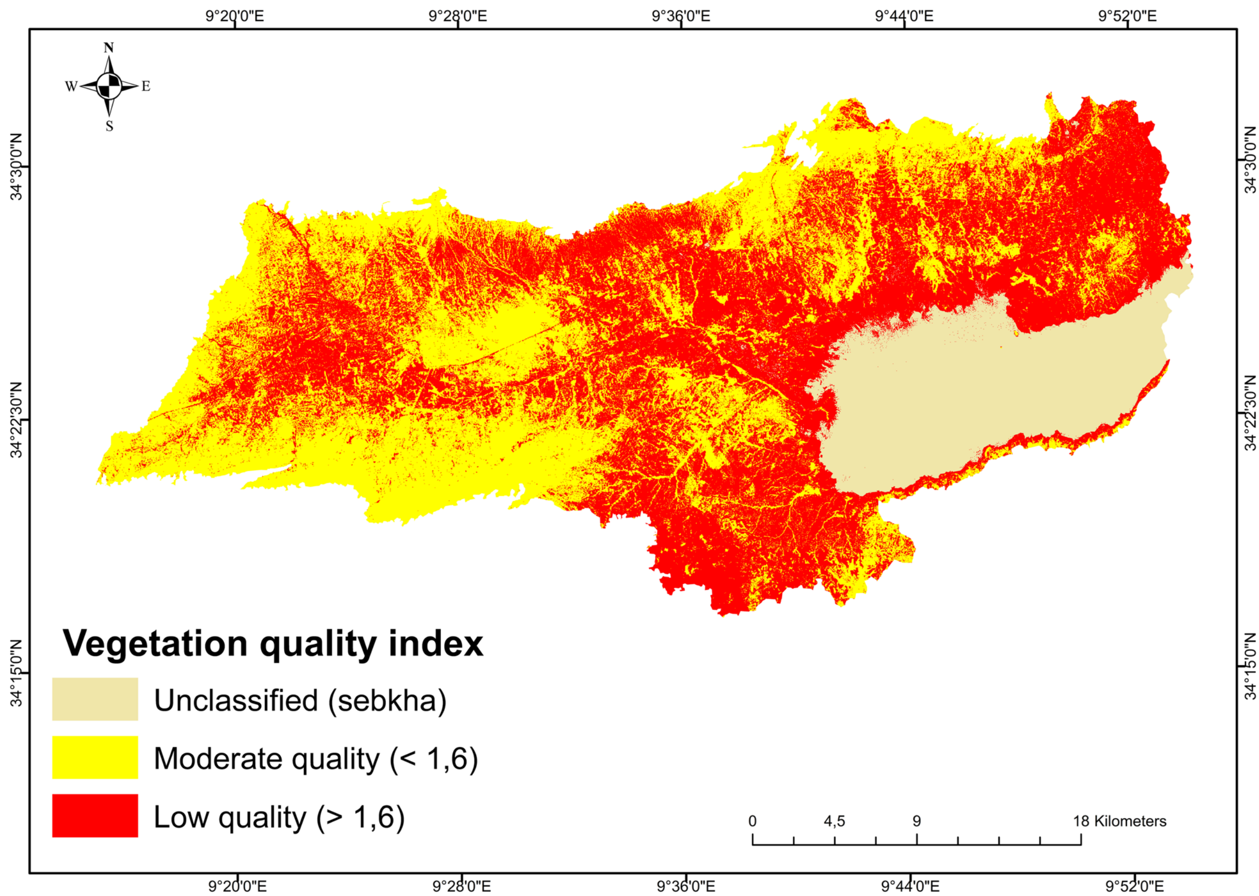

Fig. 9 Vegetation quality index map

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.

Table 13 Spatial distribution of desertification sensitivity areas index classes

Class	Value range	area sq. km	%
Unclassified (Sebkha)	0	139.26	14.26
Fragile 2	< 1.2	2.86	0.29
Fragile 3	1.32–1.37	27.93	2.87
Critical 1	1.37–1.41	83.09	8.56
Critical 2	1.41–1.53	583.03	60.09
Critical 3	> 1.53	133.97	13.81

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

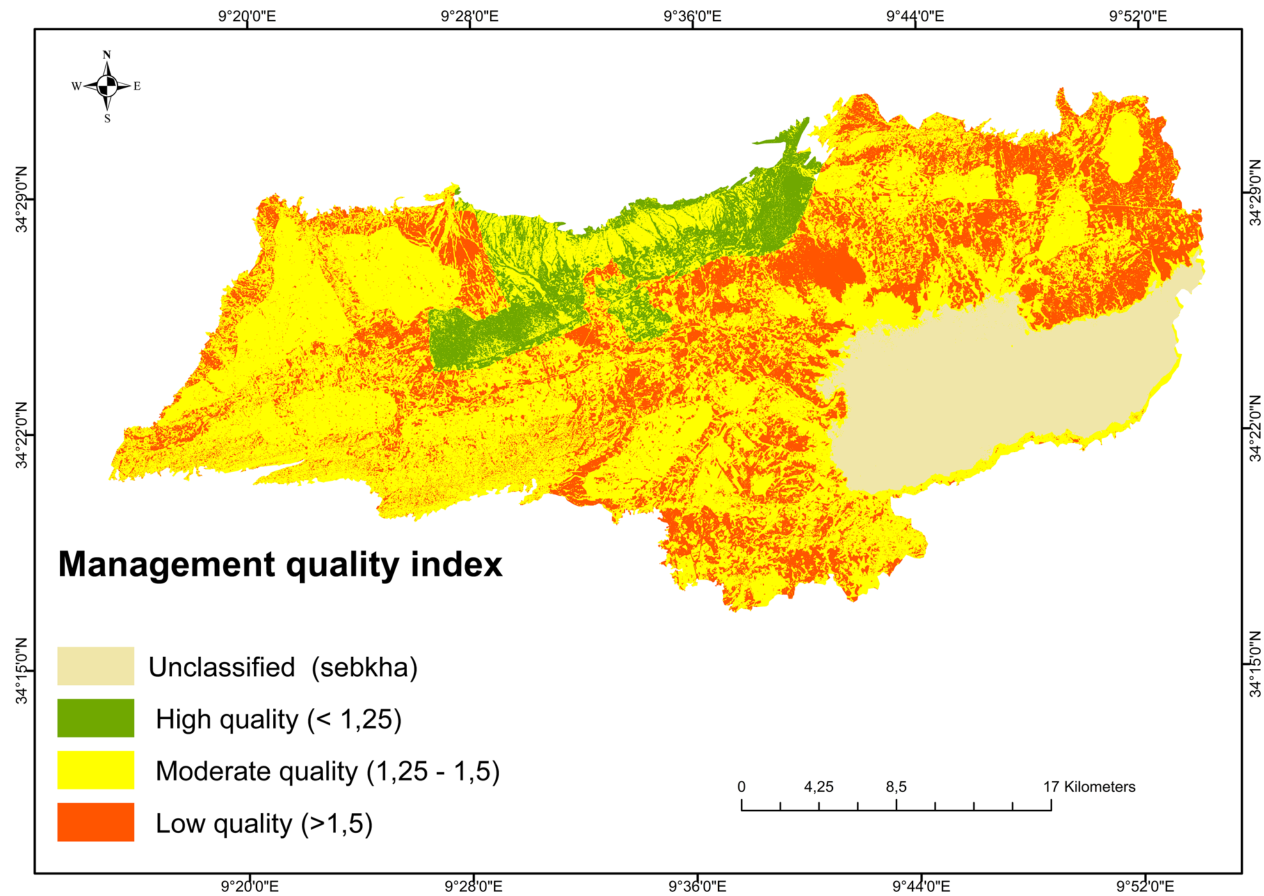

Fig. 10 Management quality index map

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

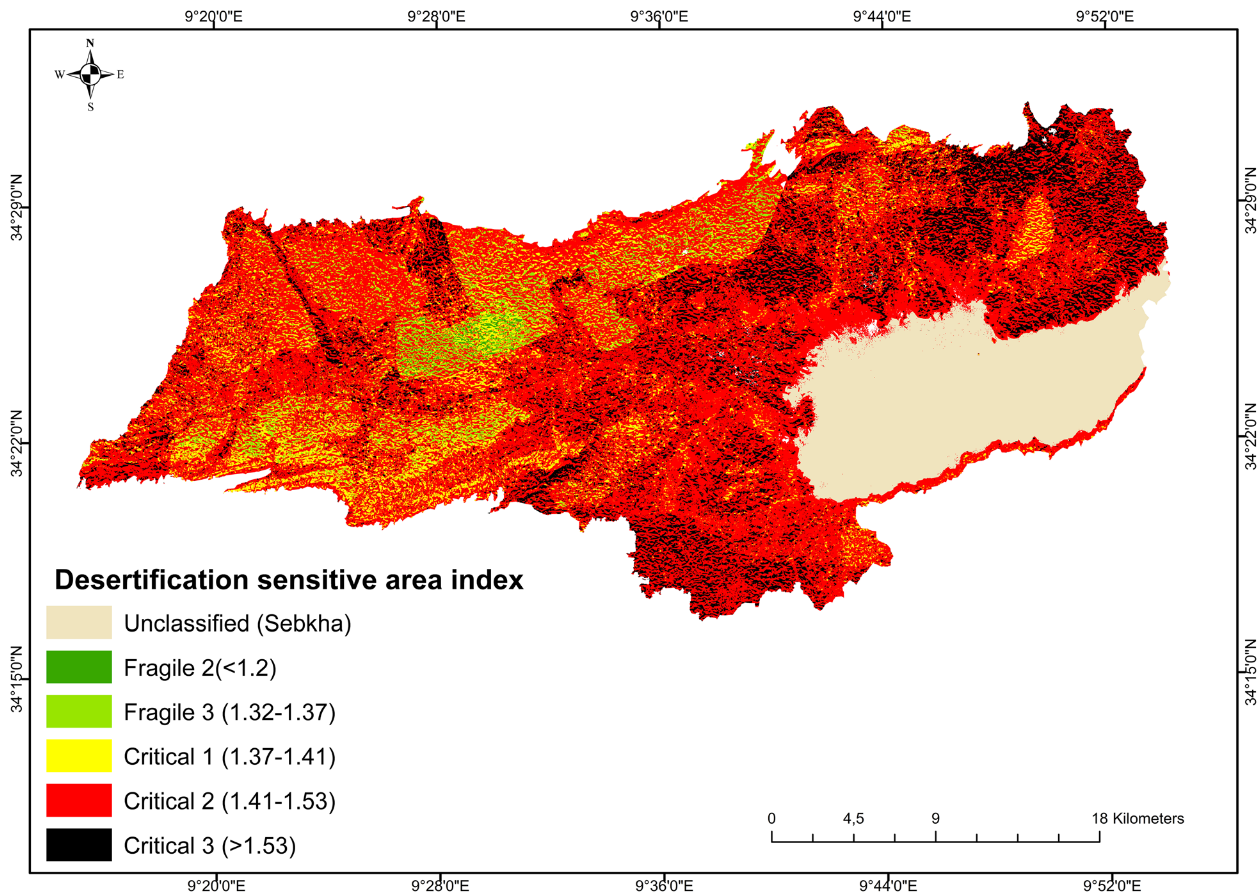

Fig. 11 Desertification sensitive areas map

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; ESAI: 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
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References
Basso F, Belloti A, Fareta S, Ferara A, Marino G, Pisante M, Quaranta G, Tabemer M (1999) The Agri Basin In: Basso et al, 1999. Mediterranean desertification and land use. manual on key indica- tors of desertification and mapping environmentally sensitive areas to desertification, in: ftp://ftp.Fao.Org/agl
Boudjemline F, Semar A (2018) Assessment and mapping of desertification sensitivity with MEDALUS model and GIS—case study: basin of Hodna, Algeria. J Water Land Dev:17–26 [CrossRef]
Bouhata R, Kalla M (2014) Mapping of environmental vulnerability of desertification by adaptation of the MEDALUS method in the endoreic area of gadaine (eastern Algeria). Geogr Tech 09:1–8
Budak M, Günal H, Çelik I, Yıldız H, Acir N, Acar A (2018) Environmental sensitivity to desertification in northern Mesopotamia; application of modified MEDALUS by using analytical hierarchy process. Arab J Geosci 11:481
Copernicus open access hub (n.d.). Sentinel-2 1c 10m resolution imagery. https://scihub.copernicus.eu/dhus/#/home
Institut national des études stratégiques (Tunisie) (2017) Revue stratégique de la sécurité alimentaire et nutritionnelle en Tunisie, p 246 https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwjGrt24ruTjAhUPYVAKHd7HBogQFjAAegQIARAC&url=http%3A%2F%2Fwww.onagri.nat.tn%2Fuploads%2FEtudes%2Fsecurite%2520alimentaire.pdf&usg=AOvVaw0rdbLfSPaymfiw1dMo6fOd
Institut national des statistiques (2014) Recensement général de la population et des ménages. Gouvernorat de Sidi Bouzid et de Gafsa
Kamel A, Ali H, Ghaleb F, Mario M, Tony G (2015) GIS-based mapping of areas sensitive to desertification in a semi-arid region in Lebanon. South-Eastern Eur J Earth Obs Geomat 4:91–103
Kosmas C, Kirkby MJ, Geeson N (eds) (1999) Medalus project: Mediterranean desertification and land use. Manual on KEY INDICATORS of desertification and mapping environmentally sensitive areas. Publication of European Union, Brussels ISBN 9282863492. https://www.researchgate.net/publication/262374822_Methodology_for_mapping_Environmentally_Sensitive_Areas_ESAs_to_desertification
Lahlaoi H, Rhinane H, Hilali A, Lahssini S, Moukrim S (2017) Desertification assessment using MEDALUS model in watershed Oued El Maleh, Morocco. Geosciences 7:50 [CrossRef]
Le Mouël C, Forslund A, Marty P, Manceron S, Marajo-Petitzon E, Caillaud M-A, Schmitt B (2015) Le système agricole et alimentaire de la région Afrique du Nord – Moyen-Orient à l'horizon 2050 : projections de tendance et analyse de sensibilité. Rapport final de l'étude réalisée pour le compte de Pluriagri, Paris et Rennes : INRA-DEPE & INRA-SAE2, p 133 https://www.google.fr/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=2ahUKEwjt5KfrteTjAhUKWZoKHQ9xAlIQFjABegQIBRAC&url=https%3A%2F%2Fwww6.paris.inra.fr%2Fdepe%2Fcontent%2Fdownload%2F3862%2F36656%2Ffile%2FR%25C3%25A9sum%25C3%25A9_8_pages%2520Etude_Inra_Pluriagri_28_10_2015.pdf&usg=AOvVaw0cBafdjs-jn_YHSgI9rFin
Malhue H, Isabel A (2018) Análisis de la evolución de las áreas ambientalmente sensibles a la desertificación en la cuenca del Puangue en Chile. Idesia 36(4):61–70. https://doi.org/10.4067/S0718-34292018005002801 ISSN 0718-3429
Ministry of agriculture (2001). *La carte agricole* (the agricultural map), governorate of Sidi Bouzid (digital database as shapefiles), 480 megabytes
Momirović N, Kadović R, Perović V, Marjanović M, Baumgertel A (2018) Spatial assessment of the areas sensitive to degradation in the rural in the rural area of the municipality Čukarica. Int Soil Water Conserv Res. https://doi.org/10.1016/j.iswcr.2018.12.004
NASA (n.d.-a): Digital Elevation Model 28m resolution accessible at https://lpdaac.usgs.gov/dataset_discovery/aster/aster_products_table
NASA (n.d.-b): Solar radiation data (Soda), (Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2)), Merra_2 climatological gridded data accessible at (http://www.soda-pro.com/web-services/meteo-data/merra)
National office of mines (n.d.), Geological map at 1/50000 sheets n° 120, 113. Geological map at 1/500000 southern part
Office de développement du Centre ouest (ODCO) (2017): Le gouvernorat Sidi Bouzid en chiffres
Office de développent du Sud (ODS) (2017): Le gouvernorat de Gafsa en chiffres
Office of Topography and Cartography (n.d.), Tunisia. Topographic map, 1/50000 sheets n°113,120,121)
Sampaio EVSB, Araújo MSB, Sampaio YSB (2003) Propensão à desertificação no semi-árido brasileiro. Rev Geogr 22:59–76
Sepehr A, Hassanli AM, Ekhtesasi MR, Jamali JB (2007) Quantitative assessment of desertification in south of Iran using MEDALUS method. Environ Monit Assess 11134(1–3):243–254
Thornthwaite CW (1948) An approach toward a rational classification of climate. Geogr Rev 38:55–94. https://doi.org/10.2307/210739
UNESCO – United Nations Educational: Scientific and Cultural Organization, Map of the world distribution of arid regions: map at scale 1 : 25 000 000 with explanatory note, MAB technical notes 7, UNESCO, 1979. https://www.google.fr/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwjD9LipoenjAhXJb1AKHWXhAZsQFjAAegQIARAC&url=https%3A%2F%2Funesdoc.unesco.org%2Fin%2Frest%2FannotationSVC%2FDownloadWatermarkedAttachment%2Fattach_import_58623115-6143-4260-ae6d-3fa9bd0fbe1f%3F_%3D032661engo.pdf&usg=AOvVaw0lYc2zRF53MRPclWNLIPET
Vieira RMSP, Tomasella J, Alvala RCS, Sestini MF, Affonso AG, Rodriguez DA, Barbosa AA, Cunha APMA, Valles GF, Crepani E, De Oliveira SBP, De Souza MSB, Calil PM, Carvalh MA, Valeriano DM, Campello FCB, Santana MO (2015) Identifying areas susceptible to desertification in the Brazilian northeast. Solid Earth 6:347–360 https://www.google.fr/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=2ahUKEwiozeKloenjAhVKKlAKHV6AC5AQFjAAegQIABAB&url=https%3A%2F%2Fwww.solid-earth.net%2F6%2F347%2F2015%2Fse-6-347-2015.html&usg=AOvVaw1OYRpv-i6hzbILQJgaGxJ8

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