Are long-term vegetation dynamics useful in monitoring and assessing desertification processes in the arid steppe, southern Tunisia

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Abstract

A vegetation-focused diachronic study to monitor and assess desertification processes in the southern Tunisian steppes was carried out between 1975 and 2000. Climatic variability and land use changes have caused considerable changes in vegetation units and in the structure of ecological systems during the past 25 years. About 10% of the steppe area has been taken over by agriculture, shrinking perennial plant cover has led to the appearance and dominance of a highly degraded vegetation class (perennial plant cover <5%), and floristic composition transformation has occurred as unpalatable species encroached the area. Studies to monitor the ecosystem dynamics in arid southern Tunisia during the past three decades provided reliable indicators of steppe degradation and the need for long-term ecological monitoring to assess desertification processes.

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Keywords: Arid land; Ecological change; Land degradation; Land use/land cover; Steppe

1. Introduction

According to the definition proposed at the 1992 Rio Summit (UNCED), sustainable development incorporates economic, social and environmental spheres, once considered isolated on a global scale (Benhayoun et al., 1999), and places human beings, notably those of future generations, at the heart of actions to preserve resources. This concept has been combined with the concept of desertification control, which aims to protect natural resources against degradation in order to secure the life of future generations. In arid zones,
long-term ecological changes and desertification during the past few decades have imposed a real need to monitor vegetation dynamics. Vegetation, long threatened by degradation, needs to be preserved and managed so as to curtail desert encroachment and encourage sustainable development of rural societies.

1.1. Vegetation dynamics and long-term ecological changes

From a scientific viewpoint, stresses and disturbances, as defined by Grime (1977), play a key role in vegetation dynamics characterised by succession processes. Since the pioneering study by Clements (1916), many theoretical ideas about succession have been put forth (Odum, 1969; Whittaker, 1972). Succession refers to the replacement of one biological community by another, i.e. primary succession occurs on new substrata (bare rock or soil) never before colonised while secondary succession occurs on colonised land that has experienced disturbance and thus reverted back to an earlier state. Succession begins with the arrival of a pioneer species and gradually leads to the establishment of an initial community. To study succession processes and understand ecological changes requires long-term data and systematic observations of the type that help decision-makers manage natural resources (desertification control, biological conservation, ecological restoration, watershed management and global environmental change; Pickett et al., 1994). Hence, long-term approaches and protocols have been developed to monitor and assess ecological changes and vegetation dynamics and evaluate the impact of stresses and disturbances on the structure and functioning of ecosystems. Since the 1970s, many long-term monitoring studies have been established world-wide through networks such as the American LTER network, the African ROSELT/OSS network for the circum-Saharan region, the Canadian EMAN, and the MAB/UNESCO reserves network. Moreover, numerous diachronic studies are now focusing on specific goals to build on available knowledge (Rees et al., 2003; Tong et al., 2004). In the past, these studies have been difficult to maintain because of the prevalence of short-term funding programs and the misconception that long-term studies were nothing more than monitoring; thus explaining the emphasis on short-term experimentation or hypothesis testing of specific interactions or processes (Likens, 1988).

1.2. Monitoring long-term ecological changes to assess desertification processes

In Africa, following recurrent droughts since the mid 1960s, political awareness and efforts by the scientific community to curtail desertification and mitigate the effects of drought have emphasised the need to monitor and evaluate natural resources in order to ensure their sustainable management in the semi-arid and arid regions of the circum-Saharan belt. Considerable research and numerous studies have been devoted to drought and aridity, and to their ecological features and socio-economic impacts (Bennouna et al., 2004; Casenave and Valentin, 1989; Floret et al., 1982). The early adoption of an action plan to combat desertification, developed during the United Nations Conference on Desertification in Nairobi (1977) and the entry in force of the UNCCD (Anon, 1994), further raised the need for reliable data and indicators of long-term change to better assess and monitor land degradation and desertification using systematic observation tools capable of collecting, analysing and exchanging relevant short-term and long-term data and information. The aim was to improve knowledge on the mechanisms, causes, consequences and scope of desertification and land degradation, i.e. the reduction or loss of biological or economic productivity of ecosystems resulting from land use practices and a combination of processes such as, soil erosion, deterioration of soil properties and long-term vegetation loss (UNCCD, Anon., 1994).

1.3. A case study in arid southern Tunisia

Our research was developed in “steppic” Tunisia, within the global framework of UNCCD in North Africa. The primary vegetation was described as arboreal steppe, viz. *Acacia tortilis* ssp. *raddiana*\(^2\), *Pistacia atlantica*, *Juniperus phoenicea* and *Stipa tenacissima* (Floret et al., 1978; Le Houérou, 1959), characterised by tall to medium *malacophyllous* species with high palatability. This arboreal steppe has been gradually replaced by

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\(^2\)We will use in this text the species nomenclature proposed by Le Floc’h and Boulos (in prep.).
treeless steppe with co-dominant chamaephytes and perennial grasses, and small and medium malacophyllous species with high palatability, and due to selective grazing and harvesting, the latter has further been replaced by dwarf-shrub steppe (Rhanterium suaveolens, Artemisia campestris, Seriphidium herba-alba and so on). The present-day steppe is characterised by medium malacophyllous and/or tall evergreen chamaephytes and annuals (Jauffret and Lavorel, 2003). Vegetation dynamics are responses to the combined effects of stresses (edaphic and climatic) and disturbances (grazing and clearing/ploughing) (extensively described by Jauffret and Visser, 2003).

In order to assess vegetation dynamics and long-term ecological changes in southern Tunisia, we compared two vegetation maps: the first was constructed in 1975 (Floret et al., 1978) and the second in 2000 (Hanafi, 2000). We focused our comparison on land use/land cover changes to define indicators of long-term changes that could be used to monitor desertification processes.

Inspired by the four basic guidelines for developing integrated soil-vegetation systems for rangelands (Havstad and Herrick, 2003), we addressed the following two questions: (1) using a GIS tool, is it possible to monitor and assess spatial and temporal variability and changes in land use/land cover, and to define indicators representing these ecological changes? (2) Can we identify specific vegetation indicators that are consistently correlated to stresses and disturbances by studying the evolution of qualitative and quantitative vegetation features (cover, floristic composition and palatability)?

2. Materials and methods

2.1. Study area: a region with strong abiotic stresses and disturbances

Our work was conducted in the ROSELT/OSS Observatory of Menzel Habib (80,000 ha), located in the Tunisian arid region (34°02’ and 34°19’N latitude and 9°33’ and 9°58’E longitude). The bioclimate is defined as lower arid Mediterranean (Emberger, 1955) and has a short humid season (4–5 months) and long dry season (7–8 months). Yearly precipitation is very variable; the mean annual rainfall is less than 200 mm (Fig. 1) with a very high coefficient of variation reaching 70% (Ferchichi, 1996; Floret et al., 1982). The annual rainfall regime is bimodal, being characterised by both autumn and spring peaks). Fig. 1 shows two major climatic periods: the first period, during the seventies, was humid and the second, during the eighties and nineties, was relatively dry. This tendency to drought could contribute to and explain the vegetation changes in the region.

The mean annual temperature is about 22 °C, the mean daily minimum temperature of the coolest month is about 5 °C and the mean daily maximum temperature of the hottest month is about 32 °C with 4 months of summer drought (Ferchichi, 1996). The daily and yearly thermal amplitudes are very high, reaching 20 °C.
Hot and dry south-westerly wind (sirocco) blows frequently, dominating the area during the spring and summer. Evapotranspiration (ETP) is very high, reaching 1311 mm/year (Ferchichi, 1996), and the water balance (Pm-ETP) is always negative, reaching 830 mm in most years. The most important consequence of these conditions is both climatic and edaphic aridity.

This climatic aridity, aggravated by dry edaphic conditions and low soil fertility, plays a key role in limiting primary production in the Tunisian arid region. Sandy-loamy and gypsum soils of quaternary Mio-Pliocene determine different edaphic groups and associated vegetation types (Le Houérou, 1959). Determination of these vegetation units has been based mainly on perennial species in order to avoid the high seasonal rainfall variability of the arid climate. This variability has a greater effect on the annual species than the perennials, and thus, these units were characterised by specific soils, perennial plant cover, floristic composition and land use. Nine vegetation types were described in the Menzel Habib region in 1975 (Floret et al., 1978):

- *Stipa tenacissima* vegetation units (SD) on calcareous mountains (elevation 150–290 m) characterised by lithosols that contribute to very strong water erosion. The land is used for extensive grazing.
- *Gymnocarpos decander* vegetation units (GD) on calcareous crusted glacis (elevation 100–150 m) characterised by regosoils that contribute to very strong water erosion. The land is used for extensive grazing.
- *Anarrhinum brevifolium–Zygophyllum album* vegetation units (AZ) on glacis upslope of the foothills (elevation 80–120 m) characterised by gypsum crusted shallow silty soils contributing to very high hydro-eolian erosion. The land is used for extensive grazing.
- *Seriphidium herba-alba–Haloxylon scoparium* vegetation units (AA) on calcareous glacis and on plains (elevation 80–120 m) characterised by deep loamy soils with low to medium hydro-eolian erosion. The land is used for grazing and woodcutting on the pastureland but most of the steppe has been cleared for cereal cropping and orchards (aa). As a result, this steppe now carries vegetation dominated by post-cultivated species, especially *Artemisia campestris*.
- *Rhanterium suaveolens* vegetation units (RK) on sandy plains (elevation 70–90 m) characterised by deep sierozem with medium to high hydro-eolian erosion. A gypseous crust on the sandy plains also favours *Lygeum spartum–Rhanterium suaveolens* facies (LK), characterised by low to medium hydro-eolian erosion. *Thymelaea hirsute–Rhanterium suaveolens* facies (HK), which are favoured by overgrazing, also grow on sandy-loamy plains characterised by low hydro-eolian erosion. The land is used for intensive grazing, cereal cropping and orchards (rk).
- *Stipagrostis pungens* vegetation units (AR) on sand dunes in the sandy plains (elevation 70–90 m) characterised by very high eolian erosion. The land is used for extensive grazing and plantations developed to fix the dunes.
- *Ziziphus lotus–Retama raetam* vegetation units (ZR) on wadi depressions with fixed dunes (elevation 70–90 m) characterised by alluvial sandy-loamy soils that are temporarily flooded. The land is used for a combination of woodcutting, grazing and cereal cropping (zr).
- *Nitraria retusa–Suaeda mollis* vegetation units (NS) on depressions with fixed dunes (elevation 60–80 m) characterised by salty soils that are temporarily flooded. The land is used for extensive grazing, cereal cropping and orchards (ns).
- *Pulicaria laciniata–Verbena supina* vegetation units (PV) on depressions (elevation 60–80 m) characterised by alluvial and hydromorphic soils that are temporarily flooded. The land is only used for cereal cropping and orchards (pv).

An increase in the rural population density, from 5.3 inhabitants per km² in 1881 to 24.2 inhabitants in 1985, (Le Floc’h et al., 1999) has intensified human pressure on natural resources through “disturbances” such as grazing and wood harvesting, land clearing and ploughing, which depend largely on the annual rainfall. In 1985, using aerial photographs obtained using field recognition, the same authors reported that the proportion of land reclaimed for cultivation increased from 13.9% in 1948 to 41.6% in 1985 (Floret et al., 1978); the remaining rangelands have been consistently used for grazing.
2.2. Data collection and processing in 1975

In 1975, vegetation units in the Menzel Habib region were mapped (Floret et al., 1978) using (1) aeriels photographs to define landscape units combining topographical units with plant communities, and (2) field data based on phytocommunity relevés obtained using the Quadrats points method (Daget and Poissonet, 1971). The authors measured only perennial plant cover and determined an exhaustive list of species, soil types, soil surface properties and land uses (Floret et al., 1978). These data enabled determination of a nomenclature for degradation states characterised by three soil-vegetation orders classified as follows:

- **Class 1**: A highly degraded state with low edaphic potential due to erosion processes; perennial plant cover (PPC) as high as 10%.
- **Class 2**: A medium degraded state with degraded edaphic potential due to erosion processes; PPC as high as 20%.
- **Class 3**: A good state with high edaphic potential; PPC as high as 40%.

This also enabled classification of nine vegetation types, divided into 22 sub-units representing degradation states and characterised by dominating species, PPC, soil types and land uses (Floret et al., 1978). The map was digitised and integrated into a Geographical Information System using Arc View 3.2 GIS software (Hanafi, 2000).

2.3. Data collection and processing in 2000

In 2000, in order to re-map the vegetation units and compare them with data on the first map obtained in 1975, we observed the same region and used the same design and terminology to describe the vegetation units.

2.3.1. Photo-interpretation

To define homogeneous reflectance areas, a Landsat/TM satellite image taken in March 1999 was geo-referenced and integrated into the GIS. Based on colour and texture differences, we visually interpreted this image using a combination of information sources, including topographic features, geomorphological data, soil characteristics and the spatial extent of the vegetation units in 1975. This work enabled determination of a cartographic layer with 579 polygons.

The sampling design was then elaborated to determine 304 test sites. The sites were geo-located in the centre of the polygons using hand-held GPS receivers so that they could subsequently be related to satellite imagery. Site locations were selected on the basis of earlier maps of morphological, soil and vegetation features (Floret et al., 1978). The boundaries of major vegetation types were identified mainly through satellite imagery, while the detailed floristic composition and plant cover were determined from field survey records.

2.3.2. Field data collection and analysis

Field data was collected between September 1999 and January 2000 (humid season) and Braun-Blanquet vegetation relevés (Braun-Blanquet, 1949) were made in every test site. Each relevé included a careful and detailed description of all accessible biophysical parameters (topography, geomorphology, geology, soil, perennial vegetation, climatic parameters, etc.). These test site descriptions also included an estimation of the anthropo-zoogenic impact on vegetation, soil, perennial plant cover, and soil surface characteristics, as well as an exhaustive list of species characterised by abundance and frequency indices. The relevés were statistically analysed (Benzecri, 1964) using Statbox software and multivariate analysis on the correlation matrix of a data set composed of 120 species and 304 sites was performed. Two types of analysis were conducted using, firstly, the presence-absence of species in each of the 304 sites to define vegetation units and, secondly, the abundance of species to determine vegetation sub-units and their dominant species.

Many correlations were determined between species and between species and environmental factors (climatic, edaphic, land-use). These analyses made it possible to (1) recognise the main vegetation units, as described in detail by several plant ecologists (Floret et al., 1978; Le Houérou, 1959), and (2) identify several
new vegetation sub-units. Moreover, some relevés realised in transition areas were characterised by mixed vegetation units called mosaics. The integration of physical and anthropo-zoogenic data collected in the relevés with the vegetation data made it possible to determine a significant decrease in the PPC, and soil erosion that resulted in a greater decrease in the edaphic potential than expected. Hence, we established a new nomenclature for the PPC, better adapted to the new states, with four classes (Hanafi, 2000; Jauffret, 2001; Jauffret and Visser, 2003):

- **Class 0**: PPC $<5\%$.
- **Class 1**: PPC $5–15\%$.
- **Class 2**: PPC $15–25\%$.
- **Class 3**: PPC $>25\%$.

Using the new nomenclature, we reclassified the units and sub-units described in 1975 and updated the previous vegetation map. All units were then integrated into the GIS database, giving our 2000 vegetation map. The results have since benefited from both numeric and field data (Ben Hamouda et al., 1998).

### 2.3.3. GIS and database processing

GIS is considered a powerful tool for mapping land use/land cover changes thanks to its capacity to correlate cartographic data with field data (Rees et al., 2003; Tong et al., 2004). A combination of GIS tools and satellite images offers the possibility to locate spatial phenomena on a medium scale (geomorphological features, vegetation types and degradation, etc.), which are determined not only by their spectral signature but also by their structure (wadi beds, sand dunes, human settlements, etc.). As a result, GIS allows creation of a database and mapping of quantitative and qualitative data, extracted from both numeric and field data.

In this study, GIS was used to (1) establish a spatial representation of land use/land cover changes from 1975 to 2000, and (2) quantify these changes using a GIS database constructed using field data. Moreover, GIS allowed elaboration of new item maps that highlighted special ecological changes concerning crop evolution and the extension of *Astragalus armatus* ssp. *tragacanthoides*. The crop map was obtained by quantifying the percentage of cropland in all 579 polygons, but only including those crops that represented up to 25% of the total area of each polygon. The *Astragalus armatus* ssp. *tragacanthoides* map was made to represent the spatial and quantitative distribution of this species in the rangelands because of its growing abundance in the field. Indeed, there is clear evidence that, since the 1970s, arid Tunisian steppes have tended to be invaded by previously unseen species, many of which are of low pastoral interest (Le Floc’h, 2001); e.g., *Astragalus armatus* ssp. *tragacanthoides*, a chamaephyte belonging to the *Fabaceae* family. This species has eco-physiological characteristics that promote its rapid proliferation on the steppes (good germinative aptitude especially in comparison with *Rhanterium suaveolens*, rooting capacity enabling it to develop soil-water reserves, and abundant aboveground production), but it is unpalatable (Chaieb, 1997). The mapping exercise was preceded by an evaluation of the specific abundance level to determine the percentage of this species in each vegetation sub-unit. It was mapped when its spatial and quantitative distribution reached 16%.

### 3. Results

#### 3.1. Steppe dynamics and land use changes

Using the GIS database, the area of each vegetation unit was calculated in order to assess their evolution over a 25-year period. First, between 1975 and 2000, the steppe area shrank from 62% to 52% as the crop area (aa, rk) grew from 38% to 48%. During this period, the steppe lost 0.4% of its area annually to the benefit of cropland (Hanafi, 2000), leading to an important spatial heterogeneity; although the steppe area is generally characterised by annual fluctuations caused by climate variability and human pressure.

Second, the diagnosis was completed by studying changes in the area of the vegetation units (Table 1). *Rhanterium suaveolens* steppe suffered significant degradation ($-10.9\%$) due to the strong pressure of cropping and the subsequent proliferation of sandy dunes (the increase in *Stipagrostis pungens* sandy units was
about 0.4%). A significant decrease in *Stipa tenacissima* unit area was also observed (−1.2%) and was replaced in 2000 by *Gymnocarpos decander* units.

As the steppe area regressed, agriculture made important advancements in the Menzel Habib region, as can be seen from the 2000 cropping map (Fig. 2). In the past, cropping systems were adapted to the climate characteristics (droughts and rainfall variability) and topography (the cropping systems were only located on wadi beds, which are rich in water and consist of fertile soil). Now, however, many water harvesting techniques (*jessour*, *tabias*, ... ) exploit areas in between the wadi beds, thus allowing for the extension of arid agricultural systems (cereal cropping, orchards and so on).

Marginal cereal cropping and olive tree plantations, which were also observed before the 1990s (Le Floc’h et al., 1995), are also increasing, especially in the RK sandy units. The agricultural replacement of steppe thus

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**Table 1**

Changes in the area (%) of the main vegetation units and sub-units between 1975 and 2000 in the Menzel Habib region (Hanafi, 2000)

<table>
<thead>
<tr>
<th>Vegetation units and sub-units</th>
<th>Area in 1975 (%)</th>
<th>Area in 2000 (%)</th>
<th>Rate of change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Rhanterium suaveolens</em></td>
<td>29.27</td>
<td>18.32</td>
<td>−10.95</td>
</tr>
<tr>
<td><em>Stipa tenacissima</em></td>
<td>4.06</td>
<td>2.85</td>
<td>−1.21</td>
</tr>
<tr>
<td><em>Anarrhinum brevifolium</em></td>
<td>12.09</td>
<td>11.89</td>
<td>−0.19</td>
</tr>
<tr>
<td><em>Stipagrostis pungens</em></td>
<td>0.33</td>
<td>1.21</td>
<td>0.89</td>
</tr>
<tr>
<td><em>Seriphidium herba-alba</em></td>
<td>10.43</td>
<td>11.82</td>
<td>1.38</td>
</tr>
<tr>
<td>rk sub-unit</td>
<td>20.91</td>
<td>23.85</td>
<td>2.94</td>
</tr>
<tr>
<td>aa sub-unit</td>
<td>9.55</td>
<td>17.18</td>
<td>7.63</td>
</tr>
</tbody>
</table>

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*Fig. 2. Spatial distribution of croplands in the Menzel Habib region in 2000 (Hanafi, 2000).*

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3The *tabias* and *Jessur* are small runoff water harvesting techniques (earthen dams in wadi beds) employed in the south Tunisian mountains to save surplus water and soil coming from impluviums for use in agriculture. A *Jesser* (singular) is composed of an impluvium, the wadi bed and earthen dams also known locally as *tabia* or *katra* (Bonvallot, 1979).
threatens the region as a result of desertification due to its sandy soil. The proliferation of *Stipagrostis pungens* steppe could be considered a direct consequence of this phenomenon. Similarly, marginal cropping is also important in the AZ units, which are characterised by gypsum-crusted shallow silty soils and, consequently, major hydro-eolian erosion. Furthermore, the pattern of land use here is extensive grazing. As a result, land productivity is very low and very variable from year to year.

3.2. Long-term ecological changes

3.2.1. Fragmentation of vegetation units

In 2000, thanks to multivariate statistical analyses and an updated nomenclature, we were able to recognise nine existing vegetation units (1975) and complete our classification of the vegetation sub-units so that they better matched the reality:

- Five sub-units characterised by high PPC disappeared (SD2, GD2, rk2, and AR2) in addition to PV units that were totally replaced by agricultural sub-units (pv).
- The previous sub-units were reclassified from 22 to 28, as a result of the introduction of cover class 0, which accommodates high degradation of the PPC, thus generating 10 new sub-units.
- Eight sub-units characterised by *Astragalus armatus ssp. tragacanthoides* appeared on *Rhanterium suaveolens* sandy units (AK3, AK2, AK1, AK0), *Seriphidium herba-alba* loamy units (SA1, SA0), and *Anarrhinum brevifolium* gypsum-crusted units (ZA1, ZA0).
- Two sub-units characterised by *Deverra tortuosa* were observed on *Seriphidium herba-alba* loamy units (PA1, PA0).

The nine vegetation units were further subdivided into 38 sub-units, forming an impressive mosaic and showing high landscape heterogeneity. This phenomenon was also noted in 1975 (Fig. 3) but is more pronounced at present.

![Main vegetation units in the Menzel Habib region in 1975 (Floret et al., 1978).](image-url)
The spatial distribution of the sub-units has not been marked by notable change except concerning mixture between the two agricultural sub-units (aa and rk) and the presence of agricultural sub-units throughout the region (Fig. 4). This phenomenon is due to changes in the soil surface state (Escadafal et al., 1996). Indeed, wind deflation of sand in the RK units after it has been ploughed and cropped, and emergence of the underlying loamy level promotes the proliferation of *Artemisia campestris* and *Deverra tortuosa* from the aa sub-units. This is particularly obvious in the northwestern corner of the region where the area of AA-aa units has expanded at the expense of RK-rk units. Unit fragmentation is one answer to the diversification and intensification of human activities that have taken place since 1975, leading to notable transformation in the are of each unit, the dominant species and land uses.

### 3.2.2. Degradation of vegetation cover

Table 2 shows the high degradation of PPC in 2000 characterised by strong spatial representation of sub-units within class 0. This class, not represented in 1975, is an excellent indicator of PPC degradation. As a result, the rate of representation of the remaining classes (1, 2, and 3) decreased, respectively, by 26.4%, 20.7%, and 6.3% between 1975 and 2000. The extension of the sub-units characterised by class 3 has been very limited, representing only 0.3% of the total area; the rate of degradation was about 95% between 1975 and 2000. Class 3 now characterises only the RK units and AK sub-units.

Table 2
Overview of changes in perennial plant cover (PPC) classes between 1975 and 2000 in the Menzel Habib region (Hanafi, 2000)

<table>
<thead>
<tr>
<th>Class</th>
<th>PPC (%)</th>
<th>Degradation level</th>
<th>Area in 1975 (%)</th>
<th>Area in 2000 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0–5</td>
<td>Very high degraded</td>
<td>0</td>
<td>52.7</td>
</tr>
<tr>
<td>1</td>
<td>6–15</td>
<td>High degraded</td>
<td>52.6</td>
<td>26.2</td>
</tr>
<tr>
<td>2</td>
<td>16–25</td>
<td>Medium degraded</td>
<td>26.0</td>
<td>5.3</td>
</tr>
<tr>
<td>3</td>
<td>&gt;25</td>
<td>Good state</td>
<td>6.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Crops</td>
<td>–</td>
<td></td>
<td>14.8</td>
<td>15.5</td>
</tr>
</tbody>
</table>

Today, almost 79% of the total area has a PPC < 15%, inducing steppe physiognomy changes. The Menzel Habib region therefore not only depicts a mosaic between vegetation units, but also a mosaic between PPC...
classes. This mosaic is characterised by the dominance or presence of class 0 in the whole region and in the overall vegetation units. The new sub-units were originally characterised by a highly degraded PPC (class 0) and relatively homogeneous floristic composition. Class 0 was shown to be present in almost all the vegetation units and is characterised by important spatial extension throughout the region. This is especially the case for some overgrazed sub-units derived from units such as AK, SA, and ZA, which are essentially represented by their degraded sub-units (AK0, SA0, and ZA0).

3.3. Changes in floristic composition

3.3.1. Changes in dominant species

In addition to the appearance of new sub-units, there have also been changes in the floristic composition of the units described in 1975 and observed again in 2000 (Table 3), especially with regard to the dominant species (Hanafi, 2000). In the 1975 study, the authors established a list of four dominant species for each sub-unit, the first one being the most dominant. Now, changes in this list can be reported according to four dynamics-related pathways:

- The disappearance of some dominant species in 1975, especially with regard to *Pulicaria laciniata* and *Verbena supina* in PV sub-units.
- The disappearance of some species from the dominant species list such as *Anarrhinum brevifolium* in the AZ1 sub-units, and *Launaea nudicaulis* and *Plantago ovata* in the aa sub-units. However, this change does not mean that they have totally disappeared from the units.
- A switch in species dominance; for example, in the RK1 sub-units, *Stipa lagascae* was the second dominant species in 1975 but the fourth in 2000. This kind of switch also occurred with respect to *Helianthemum kahiricum* and *Gymnocarpos decander* in AZ1, and *Plantago albicans* and *Argyrolobium uniflorum* in AR1.
- The appearance of new dominant species such as *Astragalus armatus* ssp. *tragacanthoides* in RK3, RK2, and RK1 sub-units, *Thymelaea hirsuta* and *Deverra tortuosa* in aa sub-units, and *Zygophyllum album* in AZ1 sub-units.

<table>
<thead>
<tr>
<th>Vegetation units</th>
<th>Dominant species in 1975</th>
<th>Dominant species in 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ</td>
<td><em>Atractylis serratuloides</em></td>
<td><em>Atractylis serratuloides</em></td>
</tr>
<tr>
<td></td>
<td><em>Helianthemum kahiricum</em></td>
<td><em>Zygophyllum album</em></td>
</tr>
<tr>
<td></td>
<td><em>Gymnocarpos decander</em></td>
<td><em>Helianthemum kahiricum</em></td>
</tr>
<tr>
<td></td>
<td><em>Anarrhinum brevifolium</em></td>
<td><em>Gymnocarpos decander</em></td>
</tr>
<tr>
<td>AA</td>
<td><em>Haloxylon scoparium</em></td>
<td><em>Haloxylon scoparium</em></td>
</tr>
<tr>
<td></td>
<td><em>Asteriscus pygmaeus</em></td>
<td><em>Artemisia campestris</em></td>
</tr>
<tr>
<td></td>
<td><em>Erodium glaucophyllum</em></td>
<td><em>Erodium glaucophyllum</em></td>
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<td></td>
<td><em>Stipa retorta</em></td>
<td><em>Seriphidium herba-alba</em></td>
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<tr>
<td>RK</td>
<td><em>Rhanterium suaveolens</em></td>
<td><em>Rhanterium suaveolens</em></td>
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<td><em>Stipa lagascae</em></td>
<td><em>Astragalus armatus</em></td>
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<td><em>Plantago albicans</em></td>
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<td><em>Stipa lagascae</em></td>
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<td><em>Stipagrostis pangens</em></td>
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<td><em>Cleome amblyocarpa</em></td>
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<td><em>Cutandia dichotoma</em></td>
<td><em>Argyrolobium uniflorum</em></td>
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<td><em>Verbena supina</em></td>
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<td><em>Tamarix sp.</em></td>
<td><em>Polygonum equisetiforme</em></td>
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<td><em>Malva aegyptiaca</em></td>
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3.3.2. Reduction in species palatability

The physiognomic changes in the Menzel Habib region have also been characterised by a decrease in highly palatable species. In the SD, AZ and GD units, several pastoral species disappeared or became very rare, e.g. *Periploca laevigata* and *Rhus tripartitum* in the SD units, *Anarrhinum brevifolium* in the AZ units, *Helianthemum lippii* var. *sessiliflorum* and *Gymnocarpus decander* in the GD units, and *Stipa lagascae* in the RK units.

Finally, the highly palatable species are gradually being replaced by unpalatable species such as *Astragalus armatus* ssp. *tragacanthoides*, *Cleome amblyocarpa*, *Peganum harmala*, *Haplophyllum tuberculatum*, *Deverra tortuosa*, *Zygophyllum album*, *Carduus getulus*, and *Thymelaea hirsuta*.

3.3.3. *Astragalus armatus* ssp. *tragacanthoides* case study

The eco-physiological peculiarities of this species have allowed its fast spatial extension and increasing abundance (Fig. 5). According to Fig. 5 and Table 1, extension of this species has been particularly significant in the *Rhanterium suaveolens* units and in the *Seriphidium herba-alba* (AA) and *Anarrhinum brevifolium* (AZ) units. Besides its spatial extension, *Astragalus armatus* ssp. *tragacanthoides* has increased in dominance in eight sub-units (ZA1, ZA0, SA1, SA0, AK3, AK2, AK1, and AK0), showing the capacity of this species to proliferate under different edaphic conditions. However, its low palatability also allows it to grow better, thus improving trapping and, in turn, soil conditions and plant cover, which protect the ecosystem against desertification (Jauffret and Lavorel, 2003). *Astragalus armatus* ssp. *tragacanthoides* also has a positive role in the restoration of ecological balance and the maintenance of species required by animals that take refuge inside its tufts. This species enables them to achieve their life cycle and disseminate their seeds for germination after rainfall (Chaieb, 1997). Accordingly, this species could play a pioneer role during succession, and thus, temporal and spatial monitoring may well be important for land managers.

4. Discussion

4.1. Land use/land cover changes: causes and ecological consequences

In Africa it is common to observe land use/land cover changes in response to changes in land tenure/settlement policies (Reid et al., 2000). In Tunisia, significant long-term changes have been made in the
settlement policies since the 1950s. These changes, particularly those affecting the vegetation, have made it possible to understand the different steps in ecosystem trajectories. The main results of the steppe dynamics described in this study (a decrease in steppe area and perennial plant cover, fragmentation of vegetation units, changes in floristic composition and palatability) and elsewhere (Jauffret and Visser, 2003), can be considered good ecological indicators, thus providing a better understanding of two important ecological consequences.

The first is the increase in the spatial heterogeneity of units. In the Menzel Habib region, this consequence is due to the deep socio-economic changes that have occurred especially since the 1960s. Indeed, the population growth rate was close to 0.8% per annum between 1956 and 1994 (Auclair et al., 1996), increasing pressure on natural resources, which has been further aggravated by the privatisation of collective lands. Once the lands were privatised, the Useful Farming Area rose from 10.7% in 1970 to 67.5% in 1996, and the region was progressively integrated into the national economy (Auclair et al., 1996). These factors have led to accentuated steppe clearing to the benefit of croplands.

Since the 1970s, agriculture has gained popularity in the best watered areas, i.e. wadi beds and depressions (Floret et al., 1978). The alluvial areas, which received most water thanks to runoff and had the best soils, were already being cultivated in 1948, and cropping history indicates they were farmed as far back as 1902 (Floret et al., 1992). Now, land cultivation has spread, essentially in the sandy-loamy plains (RK) (Jauffret, 2001) where the erosion-prone lands are not suitable for modern agriculture methods. Moreover, land appropriation has encouraged land clearing and ploughing, without agricultural improvement of the steppes, thus destroying the natural vegetation, particularly the perennial plants. It has also led to spatial fragmentation of steppe units, characterised by the formation of numerous sub-units. Furthermore, the fragmentation of spatial units and the absence of perennial plants together with changes in soil properties has resulted in a dangerous increase in wind erosion. However, from an agricultural viewpoint, the pressure seems to have slowed down since 1985, with only a 6% increase in cropland in 15 years (Floret et al., 1992). This suggests that the decrease in steppe area has been caused by the harvesting of perennial plants for domestic use. This was also pointed out by Le Floc’h (1976) who suggested that this phenomenon has prevented the regeneration of natural vegetation.

Since the land privatisation in the 1990s (Floret et al., 1992), there has been significant development of orchards, especially olive tree orchards, and cereal harvesting on plain sandy soils occupied by Rhanterium suaveolens steppe lately, using mechanical methods to work the soils. Further, recent access to mechanisation has allowed the population to (1) accentuate ploughing and clearing on steppes, and (2) convey water using tractor drawn cisterns to irrigate the croplands.

Moreover, the impact of human activities on the heterogeneity of spatial units has been aggravated by the variability that typifies the lower arid Mediterranean climate. Generally in southern arid Tunisia, a positive correlation can be observed between rainfall, rural activities and population mobility, as was demonstrated in the Menzel Habib region (Auclair et al., 1996). Population behaviour affects pressure on vegetation and determines agriculture/pastoral activities, explaining why some lands remain fallow for between 1 and 3 years (Floret et al., 1978) to allow for regeneration of natural vegetation, while others (main cropping areas and also the steppes) are cultivated continuously for several years.

These important consequences of human activities (a decrease in steppe area, fragmentation of the landscape and heterogeneity of spatial units) should be investigated in the future to better understand their effects on the functioning of both ecological and agricultural systems. Research should also be developed to better understand the impact of landscape fragmentation on exchanges and fluxes (genes, seed dissemination, etc.) and biodiversity (habitat loss, changes in and wealth of wild fauna and flora, etc.).

The second ecological consequence is the increase in the homogeneity of vegetation features. This consequence is due to the decrease in PPC, and changes in both floristic composition and vegetation palatability. These ecological indicators of steppe degradation can be explained by human activity disturbances such as overgrazing and land clearing, which have been aggravated by the droughts observed since the end of seventies.

Indeed, grazing, like agriculture, is known to play a key role in rangeland dynamics (Westoby et al., 1989). In the Menzel Habib region, steppe areas decreased from 86.1% in 1948 (Jauffret, 2001 adapted from Floret et al., 1992) to 52.4% in 2000 (Hanafi 2000), and the remaining steppes have been subjected to extensive grazing. Nowadays, grazing pressure has increased and is now estimated at 0.25–0.70 sheep equivalents/ha.
(Genin, 1999), while the carrying capacity is estimated at 0.15–0.20 sheep equivalents/ha (Chaieb et al., 1991). Overgrazing, combined with woodcutting and cropping, can be considered the main cause of the floristic changes and the decrease in PPC.

The floristic homogeneity of some units and sub-units is demonstrated by the dominance or presence of certain species in different units and sub-units, e.g. Astragalus armatus ssp. tragacanthoides, Atractylis serratuloides, Helianthemum kahiricum, Atractylis flava, and Asteriscus pygmaeus. This also applies to some post-cultivated sub-units (aa, rk, zr) characterised by the same species, especially Deverra tortuosa, Artemisia campestris, Kickxia aegyptiaca and Polygonum equisetiforme. Furthermore, the dominant species characterised by high or medium palatability in 1975 (Cenchrus ciliaris, Stipa lagascae, Argyrolobium uniflorum, Anarrhinum brevifolium, Gymnocarpus decandcr, and Rhanterium suaveolens), were, by 2000, replaced by low palatable species (Atractylis serratuloides and Astragalus armatus ssp. tragacanthoides) or unpalatable species (Cleome amblyocarpa, Haplophylhum tuberculatum, and Peganum harmala) (cf. acceptability indices in Waechter, 1982). The Astragalus armatus ssp. tragacanthoides sub-units highlight steppe degradation due to overgrazing while Deverra tortuosa characterises the post-cultivated sub-units.

4.2. Limits of diachronic studies

Inspite of the above results, we hereafter underline the limits of our diachronic study. First, although GIS is recognised as a powerful tool for improving the capability of land use/land cover monitoring over space and time, the interpretation of changes using early and actual field data observations and measurements has to be argued. That is, several methodological and technical limits can be underlined. Indeed, the 1975 map was based on aerial photographs whereas the 2000 map was essentially based on satellite imagery; these tools are different especially in their precision level (spatial resolution, colour and so on). We addressed this problem by systematically visiting the whole area, choosing sites in the middle of the polygons and using the same methodology to collect field data.

Second, in arid regions, good comparison of vegetation data requires examination of vegetation relevés in spring, because of the high vegetation activity and varying climatic conditions throughout the year especially in precipitation. In 1975, these conditions were ignored, while in 2000 data were collected between September 1999 and January 2000. This period is known in arid regions for its weak vegetation activity, which can have negative effects on reflectance on satellite images and on photo-interpretation. Furthermore, this period follows the dry summer, during which there is no annual vegetation and the perennial species are very degraded (drought, overgrazing, woodcutting, etc.). These conditions are likely to have had an effect on data collection, especially on the determination of complete plant lists, which included information on annual species and the vegetation units, as well as on the mapping exercise. The solution adopted was to map only the perennial species, which can survive these stresses and/or disturbances.

Finally, the Tunisian arid region is known for its great climatic variability, which includes a long dry season (7–8 months). The climate is more suitable for perennial species than for annual ones, particularly trees and shrubs and for cereal cropping and olive trees. Moreover, the very uncertain distribution of rain contributes to vegetation degradation. Despite this, however, Ferchichi (1996) showed that Tunisian arid vegetation is theoretically able to sustain itself under natural conditions; 40% of the annual rainfall is around 200 mm, with conditions being improved thanks to soil-water reserves. However, this situation supposes the total absence of disturbances, which is impossible in the Menzel Habib region. Rainy years are usually followed by an increase in cropping and ploughing (Floret et al., 1978), and the high temperatures, especially in the summer, and frequency of dry winds during the spring, reduce water efficiency and negatively impact vegetation production. As a result, this variability influences ecological conditions (erosion, land use, etc.) and makes it difficult to compare vegetation maps. This was addressed by only checking the perennial species and adopting a specific scale for the vegetation units.

Lastly, the scope of the study was limited to ecological items. We believe that new data on socio-economic features (main sedentarisation nuclei, water points, etc.) would help better understand the spatial impact of human activities on the vegetation. Overlaying all these GIS data could contribute to better monitoring of environmental change in the future. The pertinence of diachronic comparison at both the landscape (land use/land cover changes) and ecosystem level (vegetation features) should also be discussed to help...
highlight hot spot changes to be monitored by the long-term monitoring networks (ROSELT/OSS) in arid southern Tunisia; this would be truly helpful for decision-makers.

5. Conclusion

This paper presents the results of a diachronic comparison of ecological changes that occurred between 1975 and 2000 in the Menzel Habib region. Field data collection and processing were completed by a GIS-based approach, allowing biophysical features to be mapped and compared spatially and temporally.

At the landscape scale, the extent of clearing and ploughing of crops in the rangelands has brought about significant regression in steppe area. In 1948, for example, steppes represented 86.1% of the total land area. Since then, however, the progressive sedentarisation of the population has resulted in increased pressure on natural resources (overgrazing, clearing and ploughing, harvesting and wood cutting). At present, steppes are overlapped by croplands and represent only 52% of the total area. These results allowed us to identify the first ecological indicator: the decrease in steppe area.

At the vegetation unit scale, ecological analysis based on 304 relevés allowed confirmation that since 1975 land degradation has been characterised by floristic composition and structure changes. The following changes are considered good ecological/vegetation indicators:

- A decrease in perennial plant cover in each vegetation unit. “Good state” vegetation sub-units do not exist anymore in the main vegetation units where “very highly degraded” vegetation sub-units have taken over.
- Floristic homogeneity with the presence and/or dominance of certain species in the main vegetation units and sub-units.
- Gradual disappearance (or extreme scarcity) of the most palatable species (perennial grasses and palatable chamaephytes), and their replacement by unpalatable ones.

It is obvious that in the Menzel Habib special case study the survival of the *Rhanterium suaveolens* steppe is being threatened due to land use changes. A new dynamic is being engaged (olive tree orchards expansion), the monitoring of which is important for understanding the underlying processes and their consequences on ecological systems. Land use changes, characterised by the replacement of rangelands by croplands, gives rise to questions concerning the impact of these recent changes on natural resources, the viability of croplands in such a constraining context (climate, soil quality, water quality and quantity, salinisation, etc.), and whether monitoring the evolution of the above four ecological indicators could be useful for decision-makers and land managers.

Our study demonstrated that field data collections are essential for observing ecological changes and identifying correlated vegetation indicators, which, in turn, are correlated to the main stresses and disturbances occurring in the region. Even if no specific data were collected to quantify the impact of these stresses and disturbances on vegetation, further research would still be needed to characterise and assess their frequency and intensity and their effects on the structure and functioning of ecosystems. Plant functional types can also be defined and associated to these stresses and disturbances, as indicated previously (see Jauffret and Lavorel, 2003). This development of field research contributes to our understanding of an ecosystem’s responses to disturbances and of biodiversity dynamics at the landscape scale. This could have strong implications for biological conservation and for the maintenance of vegetation diversity and the “goods and services” of such ecosystems.

GIS allows the mapping of vegetation indicators and facilitates spatial and temporal monitoring and assessment. Updating land use/land cover data and using GIS will make it possible to further evaluate changes and spatial and temporal variability more frequently. Making full use of GIS (spatial analysis) to integrate all items, including social- and economic-related features, could help explain the complex linkage between societies and the environment; i.e., by showing how socio-economic systems and their dynamics interact in the structure and functioning of ecosystems and their biodiversity, and vice versa; and by highlighting the effects of ecological and socio-economic changes on the evolution of societies (household strategies, people’s responses to these changes, adaptation strategies, and so on).
To model the evolution of agro-ecosystems in a changing world unquestionably requires studies on biodiversity dynamics and models of the impact of land use and climate changes at the local scale. Such studies make it possible to predict changes in floristic composition and the functioning of ecosystems (stability, resilience, invasion, competition, etc.). The main challenge, however, lies in defining a holistic, interdisciplinary conceptual framework for analysis of population-environment relationships. Ecological science could make a major contribution if studies were to focus on the interactions between society and the environment, particularly the “social trajectories” in relation to the latter. The answer could be to model the interaction between land uses and natural resources, predict the dynamics of ecological systems, propose evolution scenarios for the future and provide new decision-making tools to improve land management.

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