


VEGETATION DYNAMICS OF NORTH AFRICAN STEPPE (CASE STUDY OF THE MOULOUYA PLATEAU IN MOROCCO)

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Abstract

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The North African steppe areas represent a heritage of great economic and ecological importance. These areas, which were once prosperous, are currently experiencing significant degradation and a decrease in productivity due to several factors. The objective of this study was to evaluate the dynamics of the steppe vegetation, identify the responsible factors, and present perspectives for their management and restoration. The methodological approach adopted for the characterization of climatic and socioeconomic conditions and the analysis of vegetation dynamics combined classical geomatics methods with a data mining method by mobilizing several sources and on important temporal horizons. This study was optimized by using the Google Earth Engine platform. Results showed that steppe areas are characterized by their plant richness and great potential for resilience despite their low vegetation cover. The analysis of the dynamics of change has highlighted a regressive trend in steppe vegetation during the study period (1995–2020). This study has been able to highlight the extent of the dynamics of the steppes in the study area during the last 26 years and to identify the human activity as the main trigger for the transformation that steppe areas are currently undergoing. Such results improve our knowledge of these areas and open perspectives for their management.

Key words: LULC, degradation, *Stipa tenacissima*, remote sensing, GEE.

Introduction

Arid zones comprise highly specialized ecosystems that cover 47% of the global land surface and where over a third (39%) of the world's population live (Cherlet et al., 2018), 90% of which is in developing countries. The area of arid zones could increase by 7% by 2100 under the extreme climate change scenario (Koutroulis, 2019). The vulnerable ecosystems of these areas are also subject to desertification and land degradation, resulting in reduced productivity and complexity of underlying terrestrial ecosystems (Stavi, Lal, 2015). This degradation process has consequences for natural capital and the populations that depend on it (Conacher, 2009), which are amplified by the pressures induced by climate change and sociodemographic and territorial dynamics (Khan et al., 2009).

In North Africa, steppe areas fall exclusively within arid zones and represent an important economic and ecological her-

itage (Aïdoud et al., 2006). They are characterized by a great ecological diversity with an important socioeconomic role (forage resources, PAM, game...) (Hachmi et al., 2023; Koutroulis, 2019) and a strategic ecological role in safeguarding natural resources and combating desertification (Le Houérou, 2000). These once prosperous areas have experienced significant productivity degradation due to several factors (Hanafi, Jauffret, 2008). Major influences on land cover change include unfavorable climatic conditions, ecological processes, and human land use, which modify the pace of certain geomorphological processes such as soil erosion (Hanafi, Jauffret, 2008; Rhanem, 2009). Other influencing factors include inter-annual climate variability and climate change (Huang et al., 2017a), natural disasters (Mharzi Alaoui et al., 2017), changes in biodiversity composition, and biotic interactions within these ecosystems (Aïdoud et al., 2006; Rhanem, 2009).

The evaluation and monitoring of changes in vegetation cover can thus help clarify the state, health, and quality of resources

in a specific area. Various studies have addressed this issue by using opportunities offered by remote sensing (Greiner et al., 2021; Timm Hoffman et al., 2018).

In Morocco, these areas cover nearly 90% of the national territory. The ecosystems that develop there have been shaped over time by conditions associated with water scarcity and human practices underlying the valorization of natural capital and ecosystem services provided. Current practices, characterized by a proven tendency toward overexploitation, lead to degradation trends in these ecosystems and compromise their future capacity to provide essential services for human well-being (Benabou et al., 2022a).

The study area selected for this work is located on the plateau of the Moulouya basin. These areas are more vulnerable than elsewhere to climate fluctuations and unsustainable land use. Without an appropriate response, this situation of vegetation degradation in the study area could exacerbate the desertification process, posing socioeconomic and security issues (Rhanem, 2009). Additionally, by reducing the productive capacity of spaces, vegetation degradation can contribute to increasing poverty and food insecurity (Derderi et al., 2022). In this regard, this research focuses on investigating the dynamics of vegetation in steppe areas over 26 years (1995–2020) and identifying the key factors driving these changes. This work aims to enhance the rationale behind managing and conserving these areas with a tailored approach, ultimately bolstering the resilience of steppe ecosystems amidst the backdrop of acknowledged climate change (Hallegatte et al., 2015; Huang et al., 2017a). This work is based on the exploitation of Earth observation products, optimized by the use of processing tools of the Google Earth Engine platform (Gorelick et al., 2017).

Material and methods

Study area

The study area is located in the central-eastern part of Morocco and includes the territory of the El Orjane rural commune, which belongs to the Fes-Meknes region. This commune is situated in the southern part of the Moulouya plateau and covers an area of 45,943 ha between the parallels 33.34 and 33.57N and the meridians 3.62 and 3.92W. It is considered as arid zone with particular ecological characteristics and significant dynamics of land occupation, where natural vegetation formations are subject to multiple forms of degradation. The area is characterized by its homogeneous vegetation dominated by steppes, which make up over 90% of the vegetation. Those steppes provide a wide range of environmental, social, and economic services. The main species is generally *Stipa tenacissima* L. associated in some places with other stands based on *Chenopodiaceae* and *Artemisia* spp. Also, in limited areas at high altitudes, forest species are encountered. Agriculture is mainly subsistence farming. Some crops, such as market gardening and fruit growing, particularly in the vicinity of the Moulouya river and urban areas, are irrigated. The altitude varies between 705 and 2533 m with an average of around 1090 m. The main type of soil is calcareous-magnesium soil resulting from the weathering of carbonate rocks.

The average annual precipitation in the study area ranges from 171 to 538 mm, with an average of around 240 mm. The

maximum is recorded in the northern part, which is characterized by high altitudes. The average annual temperature is around 14.5 °C, ranging from 8.7 to 16 °C (Fick, Hijmans, 2017; Funk et al., 2015). Calculation of various formulas selected by naturalists, foresters, and geographers for the characterization of the bioclimatic environment (De Martonne, 1942; Emberger, 1955) positions the study area in a semi-arid to arid cool variant climate. The dry season extends between six to eight months in most of the territory, making this zone particularly vulnerable to drought risks (Bagnouls, Gaussen, 1957).

The total population of the study area is 7,740 inhabitants, organized in 1,332 households, with a density of around 16.8 inhabitants/km², significantly higher than the average for rural municipalities in the province. Additionally, the average population growth rate was 1.06% between 1994 and 2014, compared to 1.01% at the provincial level. Significant disparities in human development are recorded, and the development deficit is 43.2%, reflecting the isolation of the area (ONDH, 2017). According to the RGA report (2016), livestock farming is extensive with a total of 17,765 animals, dominated mainly by sheep (13,012 head). A significant increase in the number of heads (+96%) between 1996 and 2016 are recorded, which reflects the magnitude of pastoral pressure.

Monitoring the evolution and dynamics of the arid steppe vegetation

The methodological approach adopted for analyzing vegetation dynamics combined classical geomatic methods with methods using data mining by mobilizing several sources and important temporal horizons (Gorelick et al., 2017). To monitor the state of vegetation and detect changes in space and time caused by human and/or natural disturbances (Luo et al., 2022), we used free data from Earth Observation (EO), which offer better opportunities and allow for a solid evaluation of different dynamics (Kruasilp et al., 2023) agricultural practices, and agriculture expansion. This study evaluated the usefulness of multi-sensor Landsat-5 (LS5). To better characterize the vegetation cover of the area, two well-tested and suitable indices for relatively sparse vegetation areas, called Normalized Difference Vegetation Index (NDVI) (Rouse, Haas, 1973) and Enhanced Vegetation Index (EVI) (Huete et al., 2002), were used. The values of the different vegetation indices were calculated from the spectral reflectance values of satellite image bands. The annual median of the values recorded during the vegetation season (from March 15 to May 15) was adopted to reduce the various biases associated with extreme values. The study of the median value of vegetation indices for the selected period is interesting because this period remains representative of the climate of the studied region and coincides with the maximum of steppe vegetation.

The availability of a time series of Landsat and Sentinel satellite images covering the period from 1995 to 2020 facilitated the monitoring of trends and major changes over time. These images were used after a series of preprocessing procedures (radiation correction, cloud correction, spatial resolution harmonization, image clipping, etc.) and calculation of the different selected vegetation indices. In addition, other satellite data (CHIRPS¹) were

¹ Climate Hazards group InfraRed Precipitation with Station data

used to calculate precipitation (Funk et al., 2015). To evaluate the intrinsic response of vegetation to rainfall variability, the NDVI and rainfall relationship (Olsson et al., 2005) were used. Thus, the Rain Use Efficiency (RUE) coefficient, defined as the ratio between net primary production and approximated by NDVI and precipitation (Le Houérou, 1984), was developed. This parameter has been used to monitor vegetation degradation and to provide information on the degree of resilience of this vegetation in relation to climatic conditions. The precipitation period that is best correlated with $NDVI_{April}$ (April is the period selected for vegetation monitoring) is the cumulative rainfall recorded between December and March (Mokhtari et al., 2013). Subsequently, land-use maps between the two dates 1995 and 2020 and changes in vegetation cover, on the selected time step, were made based on the spectral information of different land uses. For the classification validation, a verification process was carried out based on the authors' expertise and field data, sometimes coupled with validation by photo interpretation using satellite images from the archives of Google Earth Pro and ESA platforms, and even consultations with managers in the field. A grouping of certain classes was adopted in order to have classes with more or less distinctive spectral behavior. Forested areas and arboriculture zones were grouped into a single "woody vegetation" class, while crops (rainfed and irrigated) were grouped into the two variants of steppe classes (dense and medium). Thus, four land-use classes were retained, namely, i, the "Dense Steppe" class; ii, the "Moderately Dense Steppe" class; iii, the "Sparse Steppe/Bare Soil" class; and iv, the "Woody Vegetation" class.

The spatiotemporal evolution of each land-use class was evaluated through a series of transformations. The relationship between the same class at two different dates made it possible to extract "stable" or "change" areas, and statistical indicators were calculated to quantify changes in land use at the level of these classes. In particular, global change rates between 1995 and 2020 and the transition matrix were calculated, which highlight the different trends and changes in land-use classes between the two selected dates (Kruasilp et al., 2023; Rifai et al., 2018) agricultural

practices, and agriculture expansion. This study evaluated the usefulness of multi-sensor Landsat-5 (LS5). The process of downloading, viewing, processing, and analyzing time-series satellite images has been greatly facilitated by the use of the Google Earth Engine (GEE) platform (Gorelick et al., 2017) and by the capabilities of certain spatial analysis tools (such as R and QGIS software, 2020) that have features enabling the automation of various tasks. This has enabled the handling of a multitude of satellite data covering the study period for the execution of various analyses.

Results

Vegetation indices and degree of vegetation resilience

The evolution of different vegetation indices is illustrated in Figure 1. The values of these indices vary annually, and their overall trend seems to follow a slight increase since 2009. The average values of NDVI and EVI are around 0.134 and 0.215, respectively, as shown in Figure 1.

Calculation of the total precipitation ($Rain_{December-March}$) appears to be relatively irregular from year to year (Fig. 2a). However, over the last decade (2011–2020), there has been a decrease in total precipitation during this period from December to March. The combination of the annual evolution of precipitation ($Rain_{December-March}$) between December and March (Fig. 2a) and the evolution of the NDVI (Fig. 1) allowed us to estimate the RUE (Fig. 2b). The results showed that the annual values of the RUE vary from year to year. However, the overall trend in the evolution of this ratio between 1995 and 2020 remains relatively stable, with a very slight trend toward improvement in recent years (since 2010), despite differences between dry and humid years. Additionally, calculating the Pearson-correlation coefficient (r) between NDVI and the cumulative precipitation ($Rain_{December-March}$) through the RUE also shows both positive and negative values (from -0.71 to $+0.77$), with the majority of values being of low intensity.

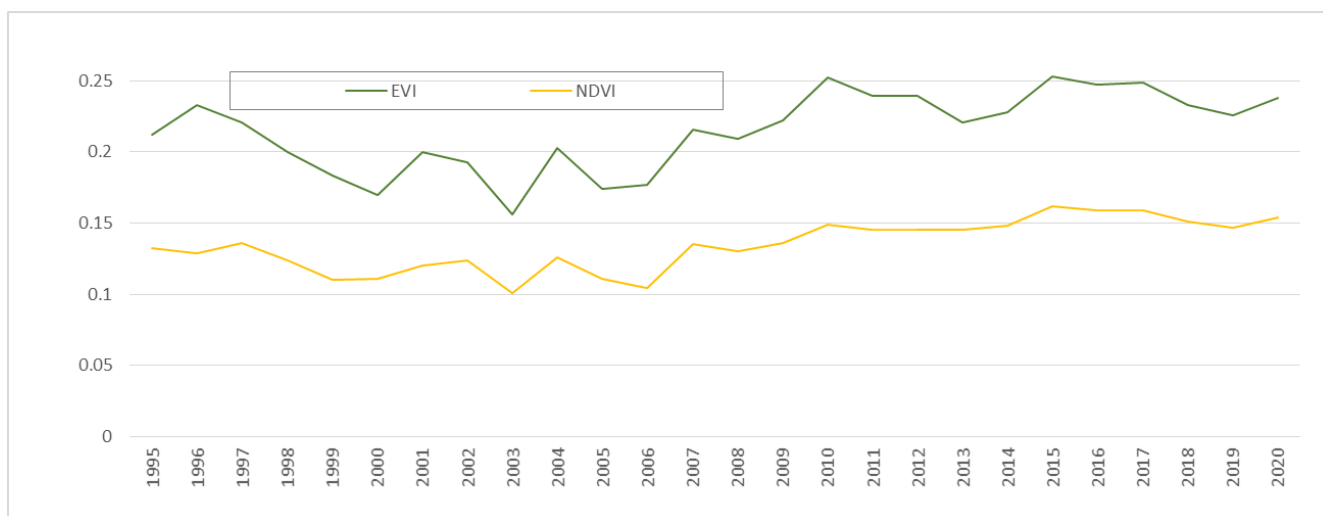


Fig. 1. Evolution of vegetation indices over the period 1995–2020.

Evaluation of the dynamics of steppe vegetation

Land-use mapping

After identifying and spectrally recognizing land-use classes based on the 2020 image, the classification of the 1995 image was mainly done by spectral correspondence. Also, correspondence verifications were carried out using Google Earth Pro and ESA archive images and even consultations with local managers. More specifically, in the different classes, the following vegetation units can be distinguished:

- The “Dense steppe” class is characterized by the clear dominance of *Stipa tenacissima*. It occurs at medium altitudes and dominates the landscape to form more extensive and consistent carpets (below 1500 m), often mixed with *Artemisia inculta* and graminoids. However, at higher altitudes, *Stipa tenacissima* is mixed with *Rosmarinus officinalis* and even with some woody species, in some limited areas, such as *Pinus* spp., *Juniperus phoenicea*, and *Cistus libanotis*. This class also includes some irrigated cropland areas usually located around rural settlements (*douars*) and along the *Moulouya* river.
- The “Moderately dense steppe” class is characterized by the presence of *Stipa tenacissima* with moderate coverage mixed with other species, particularly those of the family *Chenopo-*

diaceae and *Cistaceae*, spread between depressions and regs. These annual herbaceous grasslands include *Noaea mucronata*, *Asphodelus cerasiferus*, and some cultivated fields mainly in depressions.

- The “Sparse steppe /Bare soil” class includes areas with degraded vegetation dominated by *Chenopodiaceae* with very low coverage rates. Bare lands are also included in this class.
- The “Woody vegetation” class includes areas characterized by the presence of natural forests based on *Juniperus phoenicea* and *Pinus halepensis*. These groups are usually mixed with other species, particularly *Pistacia lentiscus*, *Fraxinus dimorpha*, *Cistus libanotis*, *Cytisus balansae*, *Buxus balearica*, *Bupleurum spinosum*, and sometimes with *Artemisia mesatlantica* and *A. campestris*. Forest formations are located at the northern part of the study area, inserted into an altitude range exceeding 1800 m. This class also includes orchards located along the Moulouya river and near “douars,” based on apple, olive, apricot, plum, fig, pomegranate, etc.

For 1995, the land-use map clearly shows the dominance of the “Moderately dense steppe” class with 26,043 ha (56.68% of the total area), followed by the “Dense steppe” class with 10,864 ha (23.65%), then the “Sparse steppe /Bare soil” class with 7,764 ha (19.9%), and finally, the “Woody vegetation” class with 1,272 ha (approximately 2.77% of the total area). The “Dense steppe” class was mainly located in the northwest part of the study area,

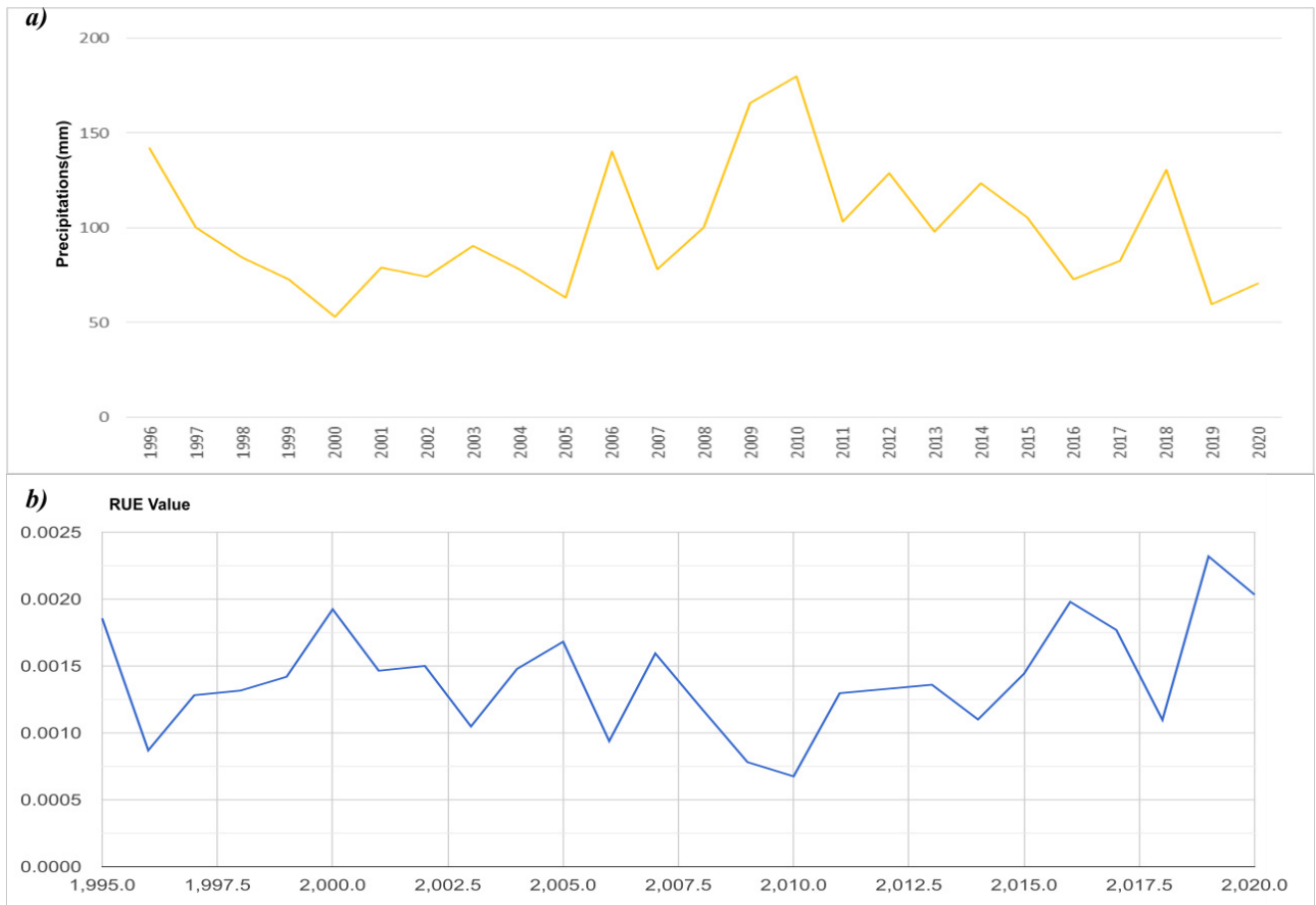


Fig. 2. a) Annual evolution of cumulative precipitation between December and March; b) evolution of RUE.

around agglomerations, and on the outskirts of the Moulouya river (Fig. 3a). For the year 2020, the results of this classification show the dominance of the “Moderately dense steppes” class, occupying an area of about 28,080 ha (on about 61.12% of the study area). The rest is occupied by the “Dense steppe” class with 9,274 ha (20.19%), the “Sparse steppe/Bare soil” class with 7,120 ha (15.5%), and finally, the “Woody vegetation” class with 1,469 ha (3.2%) (Fig. 3b).

Spatiotemporal evolution of land use

The spatiotemporal evolution of land use in the study area between 1995 and 2020 shows that the four identified land-use classes have undergone changes. On one hand, there is a significant decrease in the area of the “Dense steppe” class (-1,590 ha) and a slight decrease in “Sparse steppe/Bare soil” (-644 ha). On the other hand, there is an increase in the areas occupied by the “Moderately dense steppe” (+2,037 ha) and “Woody vegetation” (+197 ha) classes. Thus, the recorded global evolution rates are approximately -14.6, +7.8, -8.3, and +15.5%, respectively, for the land cover classes of “Dense steppe,” “Moderately dense steppe,” “Sparse steppe/Bare soil,” and “Woody vegetation.” The overlap of the land cover maps of 1995 and 2020 (Fig. 3) allowed for the development of a map illustrating changes in land cover between the two dates, an assessment of vegetation dynamics, and the

specialization of the changes that occurred (Fig. 4). The development of the transition matrix revealed the various dynamics that occurred (Table 1). 18.4% of the surfaces changed to other classes between 1995 and 2020. The most significant conversions remain those related to the transition from dense steppes to moderately dense steppes (2,954 ha) and from primarily forested woody vegetation to dense steppes (481 ha). Additionally, it highlights that only 68% of the surfaces in the “Dense steppe” class did not undergo any variation during the 1995–2020 period. For the “Moderately dense steppe” class, a significant area (92%) did not undergo any variation, and only 2,180 ha were converted to other classes, mainly to the “Sparse steppe/Bare soil” class (1,419 ha). For the other classes, the initial surfaces that did not experience any change are around 71% (5,516 ha) and 61% (718 ha), respectively, for “Sparse steppe/Bare soil” and “Woody vegetation.” However, it should be noted that the “Woody vegetation” class underwent significant transformations with the expansion of arboriculture and the shrinking of areas occupied by natural forests.

Discussion

The bioclimatic and socioeconomic syntheses allowed the characterization of the generally arid bioclimatic environment of the area (De Martonne, 1942; Emberger, 1955) and the high magni-

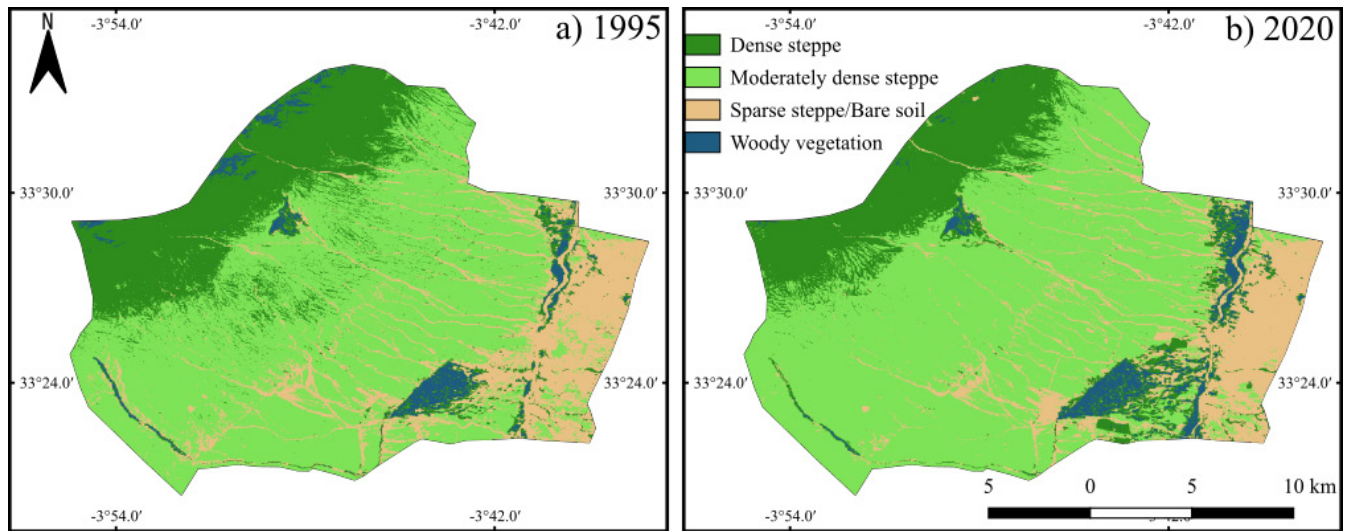


Fig. 3. Land-use maps: a) 1995 and b) 2020.

Table 1. Transition matrix between 1995 and 2020 (ha).

	Dense steppe	Moderately dense steppe	Sparse steppe/Bare soil	Woody Vegetation	Total 1995
Dense steppe	7,357	2954	179	375	10,864
Moderately dense steppe	693	23,862	1419	68	26,043
Sparse steppe/Bare soil	743	1261	5,516	245	7,764
Woody Vegetation	481	3	6	781	1272
Total 2020	9,274	28,080	7120	1,469	45,943

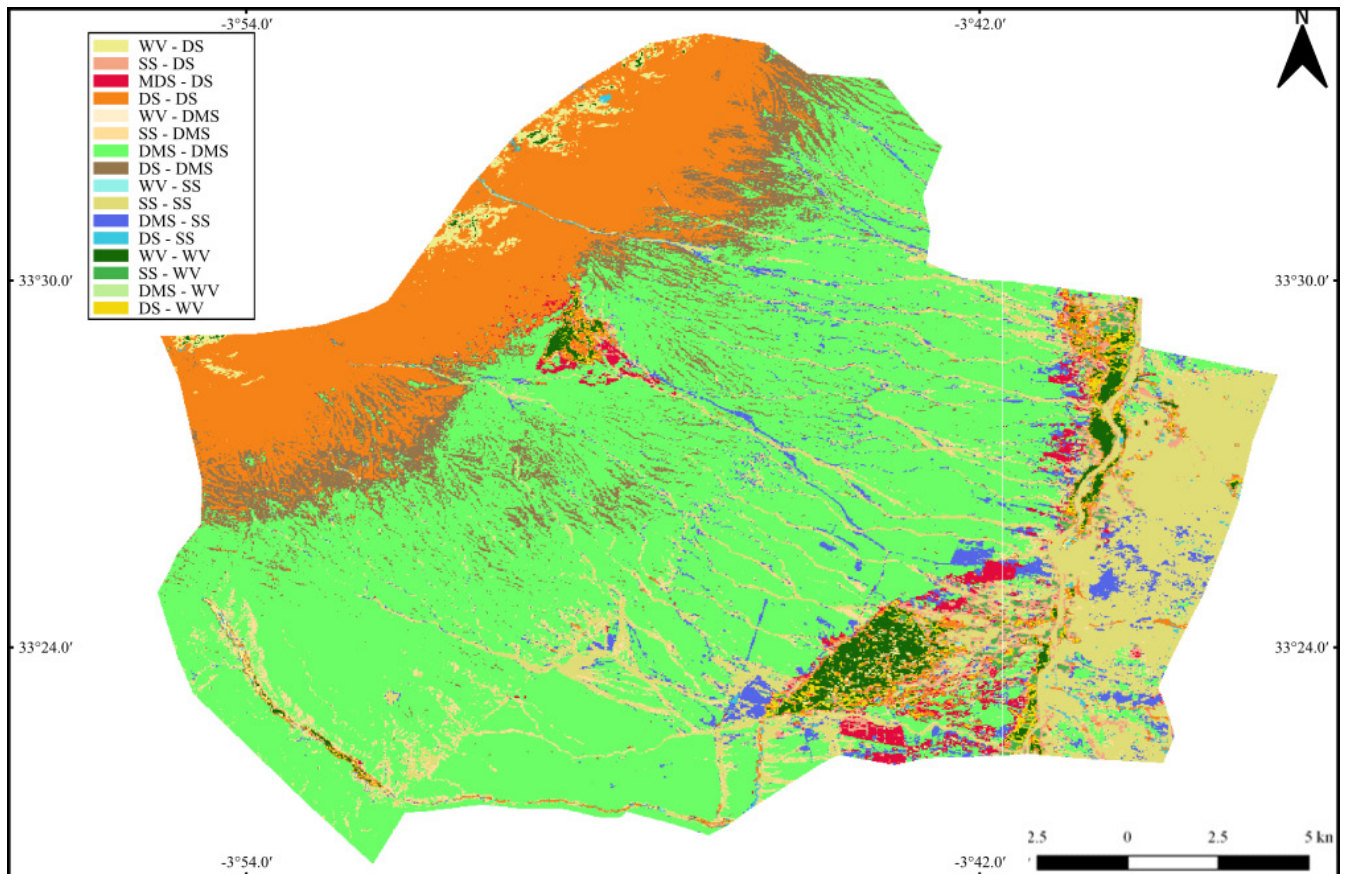


Fig. 4. Land-use classes changes between 1995 and 2020.

Note: DS - Dense steppe; MDS - Moderately dense steppe; SS - Sparse steppe/Bare soil; WV - Woody Vegetation.

tude of anthropogenic pressures with high dependence of populations on natural resources (Kamil, 2009). The spatiotemporal analysis of vegetation indices revealed low vegetation cover in the area, while the correlation between rainfall and NDVI showed the insignificance of the relationship between these two parameters and the great potential for resilience of the vegetation to different precipitation conditions. This allows vegetation in the area to recover adequately during favorable years (Aïdoud et al., 2006). Certainly, the duration (26 years) of the analysis of the RUE results and the correlation between rainfall and vegetation indices are short to identify long-term trends, and these results suggest, at this stage, the presence of other parameters that influence the health and vigor of vegetation in the study area, such as anthropogenic factors that have recorded a clear evolution and can surely be aggravated by climatic conditions (Huang et al., 2017a).

The analysis of the dynamics of change highlighted the different evolution processes that occurred within the study area during the period 1995–2020. Two major processes (de-densification and/or steppe transformation) were observed in the landscape over 26 years. These processes were elucidated using the transition matrix, field knowledge, and discussions with local managers and local populations. The recorded conversions from i, “Dense steppe” class to of low densities classes (3,133 ha); ii, “Moderately dense steppe” to “Sparse steppe/bare soil” (1,419

ha); and iii, “Woody vegetation” class (mainly forests) to classes of steppes with different densities (490 ha) highlighted the regressive dynamics of vegetation in the study area and provided an overview of the level of de-densification of steppe vegetation. This may indicate a long process of diffuse degradation of natural steppe ecosystems in the study area, similar to some other steppe (Bechchari et al., 2014a; Mahyou et al., 2016). The conversions of “Moderately dense steppe” class (693 ha) to “Dense steppe” and “Sparse steppe/Bare soil” (2,004 ha) to higher density steppes highlighted positive vegetation dynamics and transformations in steppe spaces. However, the transitions of “dense, medium, sparse” steppe classes (608 ha) to the “Woody vegetation” class should be taken with caution, especially since most of the areas concerned by these conversions were located around settlements and on the banks of the Moulouya river. This suggests that these are mainly transitions to agricultural/orchard lands instead of densification and improvement of natural steppe vegetation. This observation, also noted during field trips, is supported by the clear evolution of agricultural areas since the advent of the agricultural strategy “Green-Morocco-Plan” (Sraïri, 2021).

Also, the regressive trends have been observed in terms of pastoral potential, with a decline in appreciable formations in favor of those with lesser pastoral values, leading to an alteration of the physiognomy of these areas (Bechchari et al., 2014a,b). Thus, the spatial distribution of perennial species has narrowed,

and the climatic species of the study area “*Stipa tenacissima*” is increasingly being replaced by indicator species of degradation, notably *Noaea mucronata*, *Asphodelus* sp., and *Peganum* sp., which is consistent with the literature in other high plateaus steppe areas (Bechchari et al., 2014a; Mahyou et al., 2016). *Asphodelus* sp. and *Peganum* sp., which are gaining ground, are also postcultivation species, which may testify and reflect the practice of cultivation in these steppe areas (Bechchari et al., 2014a; Mahyou et al., 2018) covering various rangeland categories during autumn (November).

The assessment of land-use dynamics has shown that the study area contains dynamic environments and that the ecological balances of steppe ecosystems have been severely disrupted. Although there are natural factors that favor the regressive dynamics of natural environments (Wang et al., 2015), human activities have been the main trigger for the transformation that these steppe areas are currently undergoing for some time now (Rhanem 2009; Rotenberg, Yakir, 2010; Bechchari et al., 2014a) Maroc. This regressive trend in steppes can be largely explained by increasing anthropogenic pressures, mainly those related to extensive livestock breeding (Moukrim et al., 2019) and the modification of the primary vocation of steppe areas (from grazing to cultivation and orchard establishment). The development of inappropriate exploitation systems and the adoption of unsustainable management practices can lead to disturbances in the ecological balances of steppe areas and ultimately to a dysfunction of this ecosystem, increasing the vulnerability of local populations and aggravating the desertification process in these vulnerable areas (Hanafi, Jauffret, 2008; Bechchari et al., 2014a; Derderi et al., 2022). The regressive trend recorded in the study area, as well as in other spaces in North Africa (Bouazza et al., 2004; Bechchari et al., 2014a; Mahyou et al., 2016; Derderi et al., 2022), is likely to worsen in the coming years if effective protection measures are not implemented, especially in the context of proven climate change (Benabou et al., 2022b; Huang et al., 2017b; Moukrim et al., 2020, 2022).

Conclusion

The North African steppe areas are characterized by ecological diversity that gives them an important socioeconomic role and ecological functions for the preservation of natural resources. They represent a regional heritage of great importance, both in terms of the extensive space they occupy and the wealth they contain, which is one of the main sources of life for the neighboring populations. This work, whose methodology can easily be duplicated in other areas, was able to highlight the extent of the dynamics of the steppes in the study area during the last 26 years, and the factors of this degradation help to identify priority areas for natural resource conservation. Indeed, the steppe areas are subject to enormous constraints that have led to the increasing deterioration of the integrity of these ecosystems and their productivity. The fragility of these environments is exacerbated by uncontrolled and increasingly intense human pressure that has various impacts on the stability and maintenance of ecological balance. It would be judicious to define and implement, in a participatory manner, strategies and management rules for these spaces and the resources they contain. This is in order to slow down the initiated degradation process, reverse trends, and initi-

ate a development dynamic that is harmonious with the conservation of natural capital.

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