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Digital detection of steppe vegetation change over time in Naâma (Algeria), using the soil-adjusted vegetation index

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Abstract. Remote sensing has allowed us to analyse changes in land use over 42 years in a steppe zone located in south-western Algeria, covering most of Naâma Province (wilaya) and the western part of El Bayadh Province. The main economic activity is pastoralism there. The society faces many challenges, including complex social and environmental interactions, climatic factors, and anthropogenic actions that cause major degradation of the natural ecosystems, leading to desertification and erosion. Our spatio-temporal study of plant cover dynamics was conducted using 4-period Landsat scenes (1977-1987, 1987-1998, 1998-2008, and 2008-2019). The soil-adjusted vegetation index (SAVI) images were classified into 3 classes to detect changes in land cover. The results show varying degradation of steppe vegetation, as the plant cover decreased from 4.37% in 1977 to only 0.20% in 1987, followed by an increase to 8.80% in 1998, a decline to 1.05% in 2008, and a rise to 3.89% in 2019. Restoration measures should be taken in the areas classified as sensitive to desertification by using remote sensing.

Key words: desertification, remote sensing, Landsat, SAVI, land use, Naâma, Algeria, pastoralism, steppe

1. Introduction

Desertification is a major and often irreversible problem that causes abrupt and unnatural degradation of an ecosystem's biotic and abiotic potential (Le Houérou 1996). It affects 2/3 of the world's semi-arid and arid countries (Nahal 2004). Steppe regions with arid and semi-arid climates cover nearly 40% of the Earth's surface and support over one billion people (Reynolds *et al.* 2007a). The Mediterranean region is heavily impacted by desertification due to demographic and climatic imbalances (Le Houérou 1996; Alados *et al.* 2011; Vicente-Serrano *et al.* 2012). In Algeria, about 200 000 km^2 extending from the north-east to the south-west form a band between the desert and northern lands, which is losing fertility. Semi-arid areas are highly sensitive to desertification resulting from combined human activity, overexploitation of natural resources (Zhou *et al.* 2015) by grazing etc., climate change, and droughts (Lundholm 1976; Manière & Chamignon 1986; Le Houérou 1993, 1996, 2005). This leads to massive degradation of plant cover, loss of biodiversity and biological potential (Nedjraoui & Bédrani 2008; Sitayeb 2016), and depletion of water resources (Bakr *et al.* 2012).

Failure to take adequate measures to stop degradation often leads to alarming changes, such as soil erosion and impoverishment, threatening plant cover regeneration. This can result in the displacement of pastoralist populations and nomadism, exerting pressure on new areas and entering a vicious cycle of degradation. Knowledge of local ecosystem characteristics is necessary to manage better and restore the lands affected by desertification (Jacket 2005). Studies have been conducted to address the problem of desertification, as it is the main cause preventing development in arid and semi-arid areas (Adeel *et al.* 2007).

The Algerian administration's High Commission for the Development of the Steppe (HCDS) implemented strategies to limit damage and restore the steppe. In Naâma, the HCDS limited the grazing season for better management of rangelands and to address degradation caused by human or natural actions (Saïdi & Gintzburger 2013). Vegetation dynamics were monitored

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using modelling techniques to understand interactions between landscape elements (Favier 2003). Remote sensing vegetation indices were used to model changes in plant cover over time and across ecosystems (Sitayeb & Benabdeli 2008). These detection techniques are a cost-effective and useful alternative to older, more expensive methods that require more time for large-scale systematic control (Chen *et al.* 2013; Higginbottom & Symeonakis 2014).

Since 1972, Landsat images have been a key resource for conducting diachronic studies (Williams *el al.* 2006). The studies compare multi-temporal vegetation indices to characterize the terrestrial surface and differentiate land use classes (Javzandulam *et al.* 2005; Jiang *et al.* 2008; Lambin & Linderman 2006). The goal is to provide decision-makers with information to understand the state of the target territory and develop long-term strategies and restorations (Fernandez *et al.* 2002; Reynolds *et al.* 2007b) using geographic information systems (Ludwig *et al.* 2007).

Our study aimed to analyse changes in land use since the 1970s in a steppe zone of south-western Algeria, in order to facilitate the development of restoration plans.

2. Material and methods

2.1. Study area

Our study area is located in south-western Algeria on the high steppe plain, about 1170 m asl, extending from 31°40'N to 34°00'N and from 1°00'W to 1°30'E. It covers an estimated 27 090 km^2, mostly in Naâma Province (wilaya) and the western part of El Bayadh Province. It is bordered by the communes of Bogtob and Rogassa to the north, Moghrar and Elbiodh Sidi Sheikh to the south, Sfissifa, Machria, and Makman ben Amar to the west, and Brezina and Boualem to the east (Fig. 1). The area lies between the Tell Atlas and the Saharan Atlas Mountains, with sheep farming as the main activity and a major cause of natural ecosystem degradation.

The study area is classified as semi-arid Mediterranean, with annual precipitation ranging from 150 mm to 300 mm, and the gradient is due to 2 phenomena. Firstly, the Spanish Sierra Nevada and Moroccan Atlas in the west act as a screen, eliminating the Atlantic influence (Le Houérou 1996). Precipitation is spatially and temporally irregular, sometimes causing damage due to soil nature. Secondly, the average annual temperature also affects climate aridity, with high temperatures in summer and low temperatures in winter, including frost during winter months.

2.2. Available data

Five Landsat scenes were selected for this study (Table 1), involving Multispectral Scanner (MMS), Thematic Mapper (TM), and Operational Land Imager (OLI) sensors. The scenes cover the same area and were taken at intervals of 10-11 years: on 9 March 1977, 8 March 1987, 6 March 1998, 18 April 2008, and 16 March 2019. The images were taken under similar atmospheric conditions with no cloud cover. The image season was chosen to coincide with maximum vegeta-

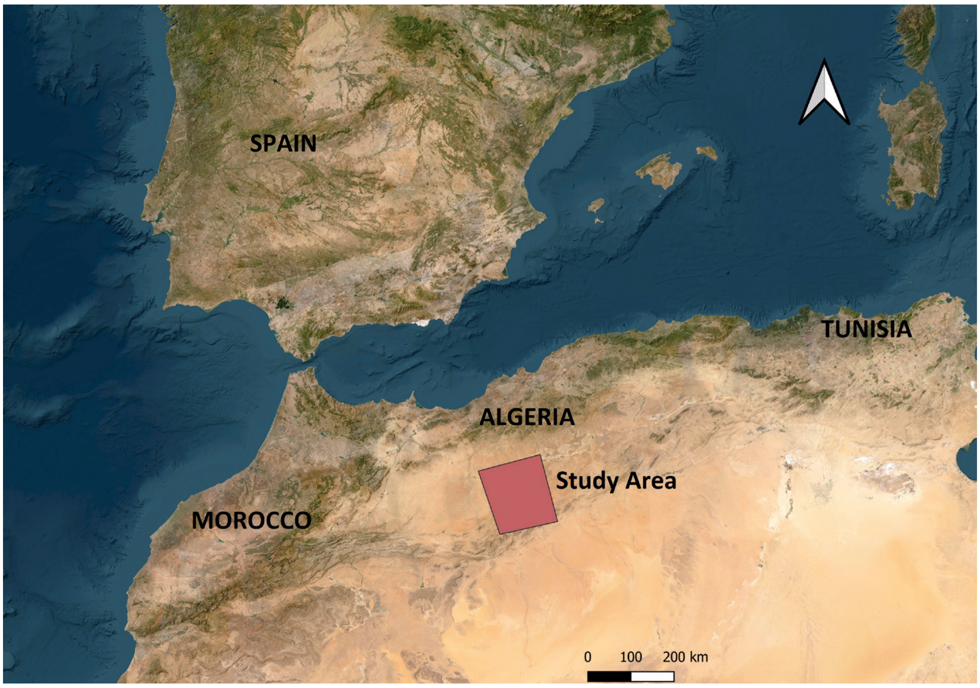

Fig. 1. Location of the study area

Table 1. Image conditions and characteristics in this study

Date	Satellite	Sensor	Satellite scene	Hour	Solar elevation	Solar azimuth	Pixel size [m^2]
9 March 1977	Landsat 2	MSS	212/37	9h38	37°99	18°282	68 × 83
8 March 1987	Landsat 5	TM	197/37	9h54	40°15	133°49	30 × 30
6 March 1998	Landsat 5	TM	197/37	10h09	41°73	137°83	30 × 30
18 April 2008	Landsat 5	TM	197/37	10h22	58°78	129°51	30 × 30
16 March 2019	Landsat 8	OLI	197/37	10h32	48°46	142°53	30 × 30

tion production (March to April). Images were obtained from https://earthexplorer.usgs.gov/.

2.3. Data processing

Satellite images of the area must be carefully processed to eliminate geometric and atmospheric effects due to the presence of anomalies. These images are taken in spring, when vegetation is at its peak. Change detection helps us understand the interactions between biotic and abiotic elements (Pu *et al.* 2008). The soil-adjusted vegetation index (SAVI) is commonly used to detect changes in vegetation, as it is less influenced by topography and can explain variations in shade relative to the solar elevation angle. This helps to distinguish between different land use classes, such as sparse or dense vegetation and bare soil (Stefanov *et al.* 2001). The index is based on mathematical combinations of spectral bands from the visible to near-infrared electromagnetic spectrum (Viña *et al.* 2011).

Change detection is subject to spatial and radiometric constraints, as atmospheric conditions and lighting can vary in space and time. Therefore, both atmospheric and geometric radiometric corrections are necessary to harmonize multi-spectral and multi-date data. The data must be as homogeneous as possible to avoid false results or interpretations due to errors unrelated to actual changes. Careful processing is mandatory to avoid confusing image errors with actual changes.

2.3.1. Resampling

To achieve accurate change detection and facilitate image superposition and visual interpretation, resampling the MSS sensor image is necessary to match the spatial resolution of the TM and OLI images. The MSS sensor image from 9 March 1977 has a pixel resolution of 60 m × 83 m, which is coarser than the resolutions of the TM (30 m) and OLI (30 m) sensors. Resampling involves adjusting the pixel size of the MSS image to match the 30 m × 30 m resolution of the TM and OLI images.

Nearest-neighbour resampling method was used to assign the value of the nearest pixel in the original image to the corresponding pixel in the resampled image. This means that each new pixel in the resampled image takes on the value of the nearest pixel in the original image.

Nearest-neighbour resampling is a straightforward method that preserves the original pixel values, making it suitable for applications where maintaining sharp edges and details is crucial, such as in certain types of remote sensing analysis or when resampling raster datasets for compatibility in geographic information systems (GIS). However, its blocky appearance and potential for aliasing effects should be considered, depending on the specific requirements of the analysis.

2.3.2. Geometric correction

The Universal Transverse Mercator (UTM) and World Geodetic System 1984 (WGS 1984) are used for georeferencing images. A mean square error of 0.2 pixels between images is indicated, which is acceptable as it does not exceed the 0.5 pixel threshold for change detection between images (Jensen 1996). This involves geometrically rectifying one image relative to another. All images have been georeferenced relative to the OLI image taken on 16 March 2019, ensuring that ground elements and their coordinates are identical across all images.

2.3.3. Radiometric calibration

The radiometric data in a raw Landsat image are digitally encoded in 8 bits, ranging from 0 to 255. To analyse the spectral behaviour of the objects being studied, it is essential to convert these digital numbers into physical quantities, such as luminance or reflectance (Sitayeb & Benabdeli 2019). For this study, the Landsat-5 and Landsat-2 images were converted to at-satellite radiance according to the formula:

$$L\lambda = (\text{Gain}\lambda \cdot \text{DN}) + \text{Bias}\lambda,$$

where $L\lambda$ is the radiance at the sensor, while DN is the digital number. The gain and bias values are provided in the header file attached to the images, while the coefficients for other variables can be found on the Landsat 7 Science Data User's Handbook website (Chander &

Markham 2003). To account for sensor degradation, the impact on the gain parameter was assessed using data published by Teillet *et al.* (2001) and Thome *et al.* (1997). For images acquired and processed after 5 May 2003, the revised gain parameters published in 2003 were used. The bias values reported by Markham *et al.* (2006) were applied to all images.

Landsat 7 data were converted to at-satellite radiance using the formula:

$$L = (L_{max} - L_{min})/(\mathrm{DN}_{max} - \mathrm{DN}_{min}),$$

where L_{max} and L_{min} denote the spectral radiance of the measured band of DN_{max} and DN_{min} (W m^{-2} sr^{-1} µm^{-1}), respectively, while DN_{max} and DN_{min} are maximum and minimum values of the digital number.

Then conversion to reflectance followed the formula:

$$\rho\lambda = \frac{\pi \cdot L\lambda \cdot d^2}{\mathrm{ESUN}\lambda \cdot \sin(\theta)},$$

where $\rho\lambda$ is the reflectance at the sensor, λ is the number of the spectral band, $L\lambda$ is the radiance at the sensor, d is the distance between the Earth and the Sun in astronomical units, ESUN is mean solar exo-atmospheric irradiance, and θ is the solar zenith angle.

Landsat 8 Level-1 data can be converted to the top of the atmosphere (TOA) spectral radiance by using the radiance rescaling factors in the MTL file:

$$\mathrm{L}\lambda = \mathrm{M_L\,Q_{cal}} + \mathrm{A_L},$$

where L_λ is the TOA spectral radiance (W m^{-2} sr^{-1} µm^{-1}), M_L is the band-specific multiplicative rescaling factor from the metadata (RADIANCE_MULT_BAND_x, where x is the band number), A_L is the band-specific additive rescaling factor from the metadata (RADIANCE_ADD_BAND_x), and Q_{cal} is the quantized and calibrated standard product pixel value (DN).

Besides, reflective band DNs can be converted to TOA reflectance by using the rescaling coefficients in the MTL file:

$$\rho\lambda' = M\rho\ Qcal + A\rho,$$

where $\rho\lambda'$ is the TOA planetary reflectance, without correction for solar angle (note that ρ_λ' does not contain any correction for the sun angle), $M\rho$ is the band-specific multiplicative rescaling factor from the metadata (REFLECTANCE_MULT_BAND_x), $A\rho$ is the band-specific additive rescaling factor from the metadata (REFLECTANCE_ADD_BAND_x), and Q_{cal} is the quantized and calibrated standard product pixel value (DN).

TOA reflectance with a correction for the sun angle is then:

$$\rho\lambda = \frac{\rho\lambda'}{\cos(\theta sz)} = \frac{\rho\lambda'}{\sin(\theta se)},$$

where $\rho\lambda$ is the TOA planetary reflectance, θ_{SE} is the local sun elevation angle (the scene centre sun elevation angle in degrees is provided in the metadata: SUN_ELEVATION), and θ_{SZ} is the local solar zenith angle, calculated as $\theta_{SZ} = 90° - \theta_{SE}$

2.4. The soil-adjusted vegetation index (SAVI)

Huete (1998) proposed this index to track green plant cover from reflectance measurements. The SAVI equation includes an adjustment parameter (L) for the soil. Huete demonstrated that the soil line and vegetation isolines are not parallel, and that L should be set to 0.5 in areas with moderate plant cover due to the intermediate density of the cover.

$$\mathrm{SAVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red} + L}(L + 1),$$

where L is the amount of green plant cover, NIR is the pixel reflectance value from the near-infrared band, and Red is the pixel reflectance value from the near-red band.

SAVI values range from -1 to 1, but Sobrino and Raissouni (2000) distinguished 2 classes: values from -1 to 0.1 (class 1) represent bare soil or water surfaces, urban areas, etc., while values from 0.1 to 1 (class 2) indicate the presence of plant cover.

2.5. Change detection

Digital change detection is a technique used to analyse changes in images of the same area over time and space. This technique allows pixel-to-pixel comparison of images (Othman *et al.* 2014) and is commonly used to detect changes in multi-source and multi-date data (Jensen 2004; Mundia & Aniya 2006). This method has the advantage of eliminating analytical difficulties related to comparing images from different dates and sensors (Alphan 2003; Coppin & Jonckheere 2004; Yuan *et al.* 2005). Post-classification analysis can address issues related to the nature and quantity of changes (Howarth & Wickware 1981). A quantitative and comparative analysis of the SAVI images from 1977-1987, 1987-1998, 1998-2008, and 2008-2019 was performed using automatic classification with ENVI 4.5 software. This analysis allowed the detection and mapping of vegetation dynamics in the steppe area between 1977 and 2019.

3. Results and discussion

3.1. Distribution of plant cover

The difference in SAVI values between the various sensors is entirely due to the unique response of each sensor. It is well established and documented that comparing reflectance and vegetation indices from different sensors, whether for the same or different dates, should not be done without cross-calibration. Each sensor processes atmospheric reflected light differently, influenced by factors such as lens type, sensor type, sensor sensitivity, angle of light incidence, and the off-nadir angle of the sensor

A comparison of the distribution of plant cover in the Naâma steppe between 1977 and 2019 shows changes in the area of each class over time (Table 2). The net changes for each class were calculated by taking the difference between the area estimates, showing losses and gains for each class (Figs. 2-3). During the first period (1977-1987), the distribution of plant cover varied across space and time. The results show that the area with plant cover decreased dramatically from 1183.46 km^2 in 1977 to 53.5 km^2 in 1987 (Table 2). This change can be attributed to a combination of drought and anthropogenic actions, such as clearing, over-exploitation of alfalfa for paper mills, overgrazing, and cutting in 1984, which led to degradation of steppe vegetation (Bensaïd 2007).

Table 2. Spatial evolution of plant cover in the study area

Year	Bare soil		Plant cover	
	[km²]	[%]	[km²]	[%]
1977	25906.42	95.63	1183.46	4.37
1987	27036.38	99.80	53.50	0.20
1998	24706.39	91.20	2383.49	8.80
2008	26804.63	98.95	285.25	1.05
2019	26037.16	96.11	1052.72	3.89

Between 1987 and 1998, there was an increase in the area covered by vegetation from 53.5 km^2 to 2383.5 km^2 (Table 2). During that period, the Algerian government implemented measures and rehabilitation projects to restructure the Algerian steppe, such as the Special Wilaya Program (PWS) (Bensaïd 2007). Those efforts had a positive impact, resulting in an increase in plant cover.

From 1998 to 2008, there was a sharp decrease in the area of plant cover again, from 2383.49 km^2 to 285.25 km^2 (Table 2). That period was marked by years of drought and a population explosion that put pressure on the steppe area through overexploitation of natural resources, mainly overgrazing.

The most recent period, from 2008 to 2019, saw an increase in the area of plant cover from 285.25 km^2 to 1052.72 km^2. This increase can be attributed to a slight rise in precipitation and a change in lifestyle, with the population shifting towards economic activities other than grazing (Sitayeb 2016), thus reducing human pressure on the natural ecosystem.

3.2. Disruption of plant cover

It is evident that the steppes of Naâma (Algeria), in particular, exemplify a harmful and continuous ecological imbalance resulting from the combination of strong human impact but low production and pastoral value. This often leads to the reduction or disappearance of fertile pastures, an increased contribution of less palatable species, and soil erosion, which indicates progressive desertification. Persistent overgrazing further accelerates the degradation of these areas. Vegetation damage becomes more pronounced near human settlements. Rangeland degradation is influenced by the interaction of 2 types of factors: (1) natural factors related to the physical environment; and (2) socio-economic factors, including human actions that often disrupt the ecosystem in an uncontrolled manner. In practice, degradation refers to the loss of pastoral resources and subsequent decrease in their value. While decision-makers are aware of the risks, the actions taken to address them, despite their significance, fall short of meeting the expressed needs and mitigating the risks involved. Therefore, the issues and challenges at hand are of great

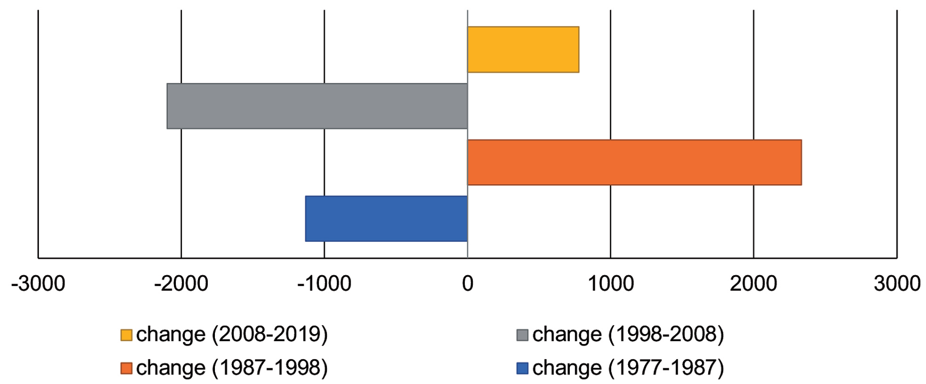

Fig. 2. Steppe cover change over time during the study periods

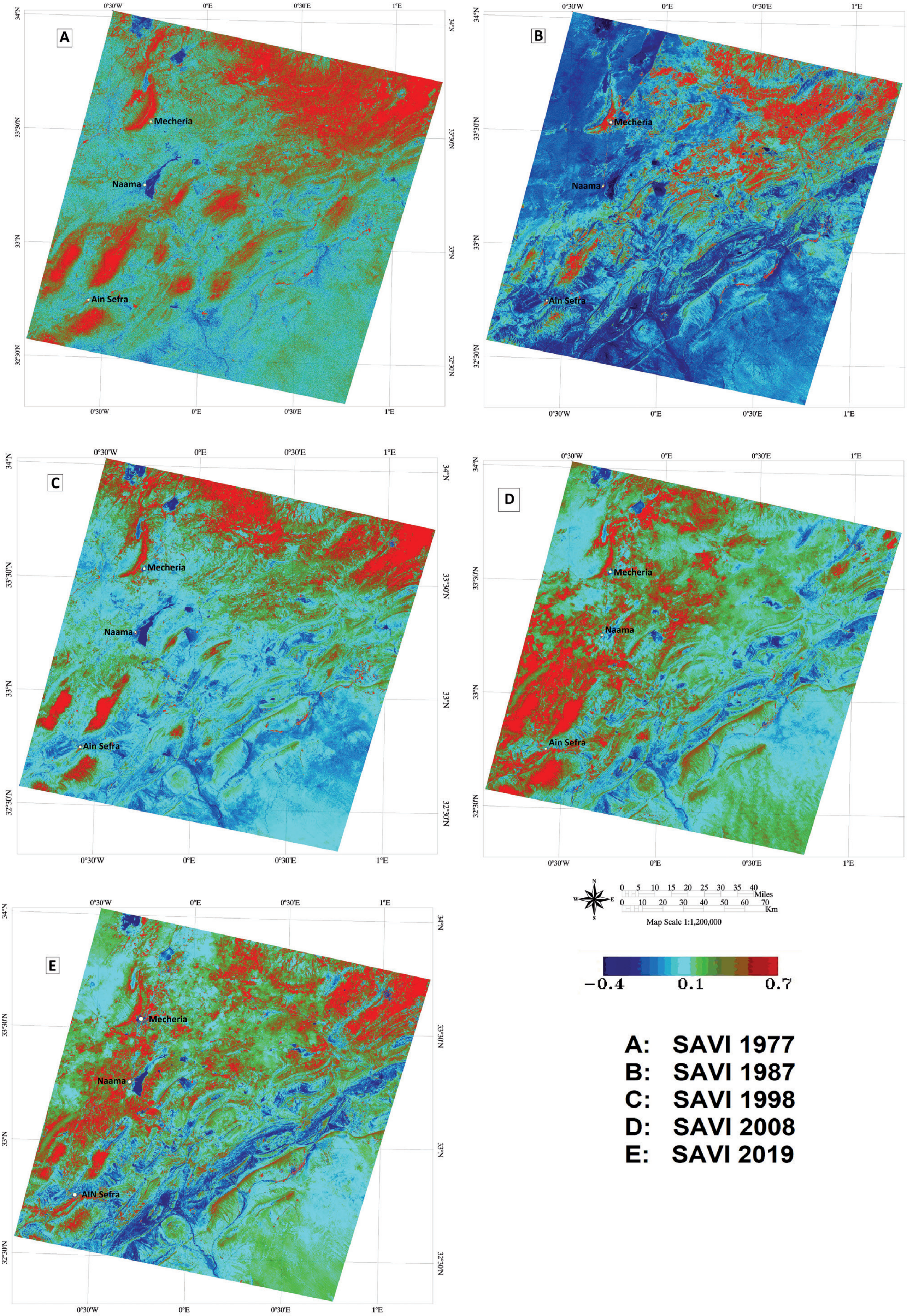

Fig. 3. Soil-adjusted vegetation index (SAVI) images of the study area

importance. These observations raise the fundamental question of rigorously identifying the specific problem affecting the south-eastern Oranian steppe-a region currently undergoing significant processes of change that impact both its natural and anthropogenic ecosystems (Sitayeb & Belabbes 2018).

Various ecological, social, and economic factors have more or less contributed to the decline in pastoral production and the degradation of pastures.

- Gradual sedentarization, leading to increased pastoral pressure on routes, as the herds have less mobility (Haddouche 2009).
- Conversion of pastoral land to cereal and tree cultivation, which undermines the pastoral viability of certain areas (Haddouche 2009).
- Clearing and expanding agriculture on fertile land, resulting in the loss of optimal grazing areas for livestock and further intensifying pressure on already degraded pastures (Nedjraoui & Bédrani 2008).
- Growth in livestock populations, exacerbating the existing high pastoral pressure and resulting in chronic forage deficits (Aidoud 1994).
- Decline in perennial species, as they are increasingly consumed by sheep as a supplement to concentrated feed, which dominates their diet (Benabdeli 1996).
- The absence of perennial plant cover for a significant part of the year leads to soil erosion and degradation of edaphic (soil-related) and water resources (Haddouche 2009).
- Genetic erosion has resulted in a decline in the performance of pastoral species, as the most productive plant populations have experienced a loss of genetic diversity (Nedjraoui & Bédrani 2008).
- Climate change is evident through a decrease in annual average rainfall, increased thermal fluctuations, aridity, and climate crises (Hirche *et al.* 2007).
- Human population growth has played a significant role in resource decline. The number of inhabitants of the region rose from 62 510 in 1966 to 246 692 in 2013, with an average annual growth rate of 2.77%. This demographic change has increased the demand for food resources (Khalid *et al.* 2015).
- The complexity of socio-economic factors contributing to the degradation of the steppes is often overlooked due to limited knowledge. Previous studies on environmental degradation have neglected the socio-economic aspect (Khalid *et al.* 2015; Aidoud & Touffet 1996).
- The region heavily relies on pastoralism as the primary economic sector, while crop production is only marginal, as 99% of agricultural land is designated for grazing (HCDS 2005).
- Bipolarization is observed around the 2 main cities in the region: Mécheria and Ain Sefra. Despite occupying only 7% of the area, these cities concentrate 1/3 of the population. This phenomenon has led to socio-economic imbalances due to the influx of rural populations seeking employment and better living conditions. Moreover, the availability of amenities in these cities has encouraged rural exodus, which needs to be addressed in other urban areas (HCDS 2005).

4. Conclusions

Remote sensing is an essential tool for monitoring natural ecosystems, allowing general diagnostics and identification of target areas requiring intervention. The research plays a crucial role in combating desertification by providing satellite images that cover the area. From a theoretical and technical standpoint, remote sensing provides valuable data for the management and utilization of natural resources. Using multi-date images (MSS, TM, OLI) spanning 42 years and estimating the soil-adjusted vegetation index (SAVI) suitable for the moderate plant cover of the study area during each period, we cartographically presented the quantity and quality of change data between 1977 and 2019, divided into 4 periods. The results reveal phases of plant cover degradation and slight recovery in certain areas due to protective measures implemented by the government. However, small variations have been observed, attributed to the combined influence of climate change and anthropogenic activities, which contribute to the degradation of steppe plant cover. This situation is alarming and calls for a strategic approach and policies that properly identify and manage pastoral, other agricultural, urban, and forestry activities in a sustainable manner. Thus the data from the Landsat programme have facilitated the assessment of long-term spatial dynamics in steppe vegetation and provided a deeper understanding of the driving forces behind the dynamics in each period. To obtain actionable results for land use planning and the management of steppe ecosystems, it is crucial to incorporate environmental knowledge and conduct field validation.

Author contributions
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Critical revision of the article: I. Belabbes, T. Si Tayeb
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