TEMPORAL CHANGES IN COASTAL DUNE VEGETATION IN ALGIERS (ALGERIA) BASED ON AERIAL PHOTOGRAPHY

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Abstract. The dune systems in the Algiers region (Algeria) are scarce and often relict, making them highly vulnerable to disappearance. They face numerous pressures, mainly linked to human activities, and benefit from few effective protection measures. It is important to note that these habitats are at risk of disappearing due to both drastic natural conditions and human activities. The aim of this study is to evaluate alterations in vegetation status and the usefulness of airborne remote sensing, which is more cost-effective than very high-resolution satellite imagery, in studying these delicate environments, specifically in the region of El Kadous as a study area. The multi-temporal aerial imagery (1959, 1980, 2003, 2015 and 2019) is used to monitor the spatio-temporal dynamics of vegetation units. The methodology is based on a qualitative and quantitative analysis of diachronic mapping and field surveys. The results obtained are consistent with the Normalized Difference Vegetation Index (NDVI), extracted from the Quick Bird satellite images. Also, the Chi-Square Test of Independence is applied to demonstrate the effectiveness of aerial photography in monitoring and analyzing coastal dune vegetation. The findings indicate a decline in vegetation from the 1980s onwards, with an 87.14% reduction in overall plant cover and changes in the spatial structure. Additionally, there has been a decrease in key species such as the Oyat. It should be noted that the causes of this degradation are mainly attributed to climate change, coastal erosion, and human activity.
Keywords: *El Kadous, Ammophila arenaria, diachronic mapping, NDVI, Chi-square test*

Introduction

Coastal zones worldwide are subject to natural phenomena, including waves, rising sea levels, climate change, and flooding (Sallaye et al., 2022; Cantasano, Boccalaro and Ietto, 2023). These factors, along with human pressures, are causing an increase in coastal erosion (Cantasano, Boccalaro and Ietto, 2023) which is accompanied by a loss of biodiversity (Pioch and Desse, 2023). Dune belts are crucial to the coastal system as they restrict erosion and prevent the coastline from retreating (Pioch and Desse, 2023). To fulfil this role, the dune cordon must be colonized by vegetation, which in turn stabilizes it (Duffaud, 2021).

Coastal plant communities are arranged in a specific pattern, from the beach to the wooded dune, based on their adaptation strategies (UICN, 2020). The pattern of this phenomenon is mainly influenced by ecological factors, such as wind, sand mobility, and salinity. These factors decrease in intensity as one moves from the shore inland (Hasnaoui-Slimani, Dahmani-Megrerouche and Djebbar, 2014; Duffaud, 2021). Several successive and interconnected habitats are defined based on substrate mobility and vegetation physiognomy: the upper beach, mobile dunes (embryonic dunes and white dunes), and fixed dunes (grey dunes and wooded dunes) (Khennouf et al., 2018; Lafon and Hardy,

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2019; UICN, 2020). Observing this pattern in the field is the best indicator of the integrity of the dune cordon as a whole (UICN, 2020), as each plant community requires a very specific sector of the area. The vegetation of the coastal dunes is increasingly vulnerable because it is subject to two types of stress: edaphoclimatic and anthropozoogenic (Carter, 1988; Bouchetata and Bouchetata, 2005; Rabehi, Guerfi and Mahi, 2018).

In that context, coastal biodiversity in Algeria is being eroded due to both anthropogenic and natural causes. Abusive extraction of sand from beaches and wadi beds, as well as the development of coastal areas, are the main anthropogenic causes. To prevent further damage, it is important to address these issues (Environnement, 2015).

As a consequence, erosion is a significant environmental issue in Algeria, particularly affecting sandy beaches. The loss of beaches is the primary consequence of this phenomenon. Algeria has responded to this threat by implementing management programs for 15 coastal towns and establishing national commissions dedicated to coastal zones (Ghodbani and Bougherira, 2019). As part of its coastal development plan for the Algiers area, the Algerian authorities have analyzed the sediment budgets of three pilot beaches on the east coast of Algiers: Surcouf, El Kadous and Decaplage. The results indicate negative balances, which suggest a loss of surface area on these beaches (Environnement, 2015) with consequences never before present in plant communities.

This study analyses the spatio-temporal dynamics of the vegetation of the dune cordon at El Kadous site, located approximately 32 km east from Algiers. The aim is to assess the kinetics of biodiversity degradation on this beach, which is already suffering from coastal erosion.

Due to the narrowness of its dune strip and the low density of its plant communities, aerial photography was chosen as the study material due to its large scale. In this case, aerial photography provides a more accurate qualitative and quantitative assessment of dune vegetation units compared to satellite imagery. The methodology is based on ortho rectification, which involves geometric correction using LPS ERDAS IMAGINE software on multi-date photos (1959, 1980, 2003, 2015, and 2019) obtained from the National Institute of Cartography and Remote Sensing in Algiers. Ortho rectification eliminates distortions caused by photo-taking conditions and altitude. Dune vegetation features were manually digitized using ArcGIS. A field validation was conducted to ensure correspondence between the screen and reality.

The study applied the Chi-square test to quantify the relationship between the reality on the ground and the photo interpretation. Additionally, a comparison was made between the results of manual digitization using Orthophotography and the results of the normalized difference vegetation index (NDVI) applied to the very high-resolution Quick Bird satellite image (year 2003). The statistical test and NDVI can be used to evaluate the effectiveness of aerial photography as a tool for studying and monitoring vegetation in this ecosystem.

The aim of this work is to trace the evolution of dune vegetation at El Kadous site and identify the causes of its degradation. Remote sensing is crucial in retrospectively studying this type of ecosystem. Recommendations will be made to preserve the remaining biodiversity, which is now at risk of extinction.

Material and methods

Study area presentation

Our work was carried out in a portion of the coastline to the east of Algiers (Algeria). It is positioned approximately 32 km east of Algiers and 14 km from the town of Boumerdes,

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spanning two communes, Reghaia and Heuraoua. El Kadous site extends between 36°47’3.98” and 36°47’0.87” north latitude and 3°20’8.04” and 3°20’45.18” longitude, to the north of Algeria (*Fig. 1*).

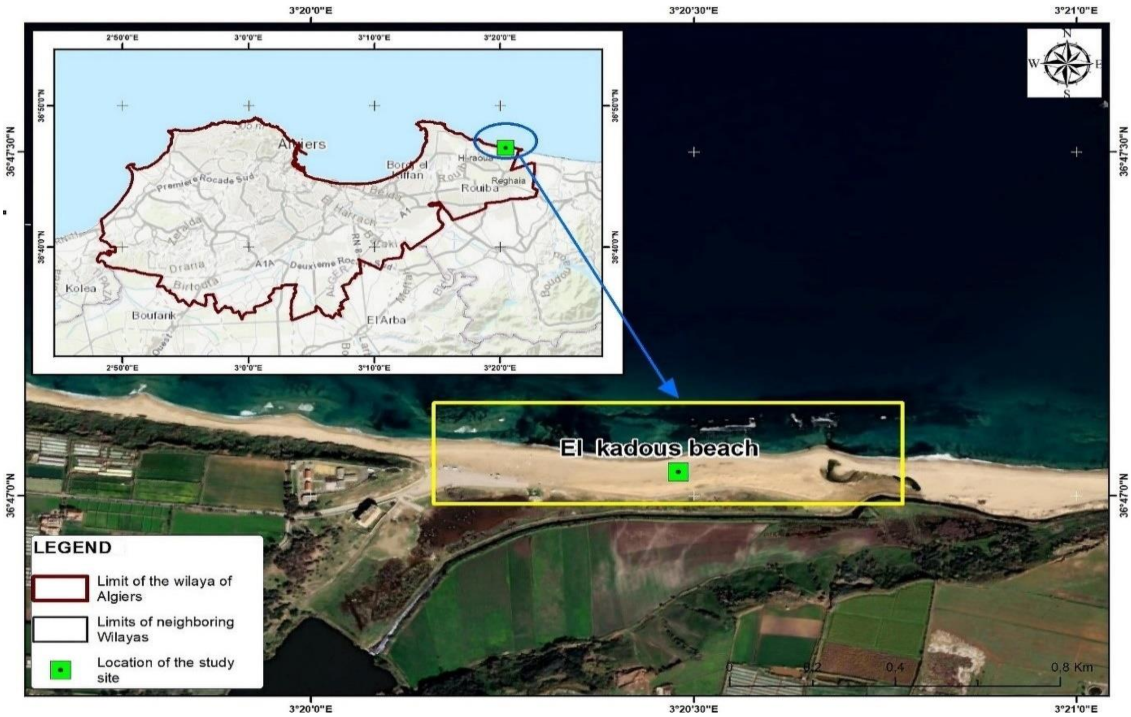

Figure 1. *Location of El Kadous site (https://earth.google.com/web/ – accessed: 3 May 2023)*

The site comprises various ecological sub-systems, including the marine environment, the dune belt, the marshy, forest, agricultural, and lake ecosystems, which collectively give it a bio-strategic role (MATE, 2015). The Reghaia Lake, situated on the site, has been listed on the Ramsar list of Wetlands of International Importance since 2003. Additionally, it has been designated as a Nature Reserve since 2016 (Ouarab et al., 2017).

The study area has a temperate subhumid bioclimate with an average annual rainfall of 585.6 mm/year and an average annual temperature of 18.53°C (with a minimum of 5.4°C and a maximum of 32.4°C). The seasonal regime is of the H.A.P.E. type, and there is a dry period of 5 months (from mid-May to the end of October) (Hanifi, 2007; Hasnaoui-Slimani, Dahmani- Megrerouche and Djebbar, 2014). The soil has a sandy texture and is well aerated. The humidity increases with depth, and the pH ranges from 7.6 to 8.8, becoming less saline as you move from the sea to the scrubland (Hanifi, Kadik and Guittonneau, 2007; Hasnaoui-Slimani, Dahmani-Megrerouche and Djebbar, 2014).

The site is under various pressures, primarily due to human activity (Otmani et al., 2019). The study area experiences an annual population growth rate of 1.9% and urbanization rates exceeding 50% (Rabehi, Guerfi and Mahi, 2018).

Acquisition and data nature

The study utilizes data from various sources, including multi-date aerial photographs from 1959, 1980, 2003, 2015, and 2019, which were made available by the *Institut National de Cartographie et de Telédétection d’Alger* (INCT). These

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photographs cover the entire coastal fringe of the study area, specifically El Kadous beach. Additionally, a Quick Bird (2003) satellite image with a resolution of 2.5 m for the visible and infrared spectral bands was used to extract the normalized difference vegetation index (NDVI). Note that this is the only image of this resolution in our possession. Additionally, we tested NDVI extraction for other years (for 2015 and 2019) using Landsat 8 OLI imagery.

The aerial photographs from 1959, 1980, and 2003 were taken at different scales: 1:25 000, 1:10 000, and 1:10 000, respectively. The 2003 photographs show a 30% overlap in the direction of flight. Digital aerial photographs with a ground resolution of 50 cm were used for 2015 and 2019.

The climatic data used in this study were provided by the National Meteorological Office (Dar El Beida, Algiers, Algeria) and cover the period from 1999 to 2019. The measurements were taken at the professional station closest to the study area, named Algiers Dar El Beida (3°13’ E, 36°41’ N).

Image processing and ortho-rectification

In our study, Aerial imagery processing is crucial, due to the variations in scale and geometric distortions of aerial photography (Crowell, Leatherman and Buckley, 1991). Our approach aimed to find a distortion model to rectify these faults and ensure that the images were spatially consistent with the terrain (Thieler and Danforth, 1994). The implementation of these processes was carried out systematically and accurately using LPS ERDAS Imagine 9.2 software, following the best practices defined by previous studies (Dolan, Hayden and Heywood, 1978; Smith and Zarillo, 1990; Shoshany and Degani, 1992; Jimenez et al., 1997; Aubie and Tastet, 2000; Heathfield and Walker, 2011; Ford, 2013).

To ensure accuracy, it is essential to calculate the root mean square error (RMS) for the internal orientation of the aerial photographs. This statistical measurement assesses the quality of the match between the estimated position of a point on the rectified image and its actual position on the ground. It is also important to maintain objectivity in technical writing and avoid some subjective evaluations (Lejeune and Cornet, 2010; Courchay, 2012; Motet et al., 2019). The steps involved in calculating the coordinates of the points of interest are executed with precision to ensure accurate estimates.

Once the image block has been prepared, the projection parameters are precisely specified. These parameters include the type of projection, which is Universal Transverse Mercator (UTM) Zone 31N associated with the World Geodetic System 1984 (WGS 84). The details of the camera, such as its name, focal length, principal points (x, y), fiducial points, and radial distance, are then entered. These details are usually extracted from the camera’s calibration file.

The photos contain fiducial marks, which are clearly identified points. The first three fiducial marks are used for initial calibration, and the LPS module automatically calculates the positions of the remaining fiducial marks. Finally, calculate the root mean square error using the following formula:

$$RMS = \sqrt{\sum_{i=1}^{n} (Xi + X'i)2 + (Yi + Y'i)2/n} \qquad \text{(Eq.1)}$$

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where *n* represents the number of control points, specifically 13 points extracted from the Quick Bird reference image. *Xi* and *Yi* denote the actual coordinates, while *X'i* and *Y'i* represent the coordinates calculated after orthorectification.

In this study, the critical threshold was to maintain the root mean square error below 0.33 pixels, a value deemed acceptable (Indra and Lalu Muhamad, 2016; Dechaicha and Alkama, 2021). This approach ensures that the images are transformed while respecting the geometric characteristics of the aerial photographs. This guarantees an accurate analysis of the study area's evolution over time.

Photo-interpretation and digitization

The criteria for texture, structure, and color are defined by Girard and Girard (1975, 1999) and Ray and Izard (1969). With this information, it is now possible to define isochromatic zones on the screen. The areas were digitized using ArcGIS 10.4.1 Desktop from the Environmental System Research Institute (ESRI). The 'tasks' were then photo-interpreted exhaustively by a single operator, the first author of the article, who has a good knowledge of the terrain.

The process of digitization was accompanied by the assignment of a "vegetation class" code to each polygon. This code was based on achromatic greyscale nuances and resulted in the identification of three classes (A, B and C), which correspond to three thematic layers (*Fig. 2*). For the year 1959, the photographic document (1:25 000) is of insufficient quality to identify vegetation classes with precision. Therefore, we have only considered one global layer, the "dune vegetation class".

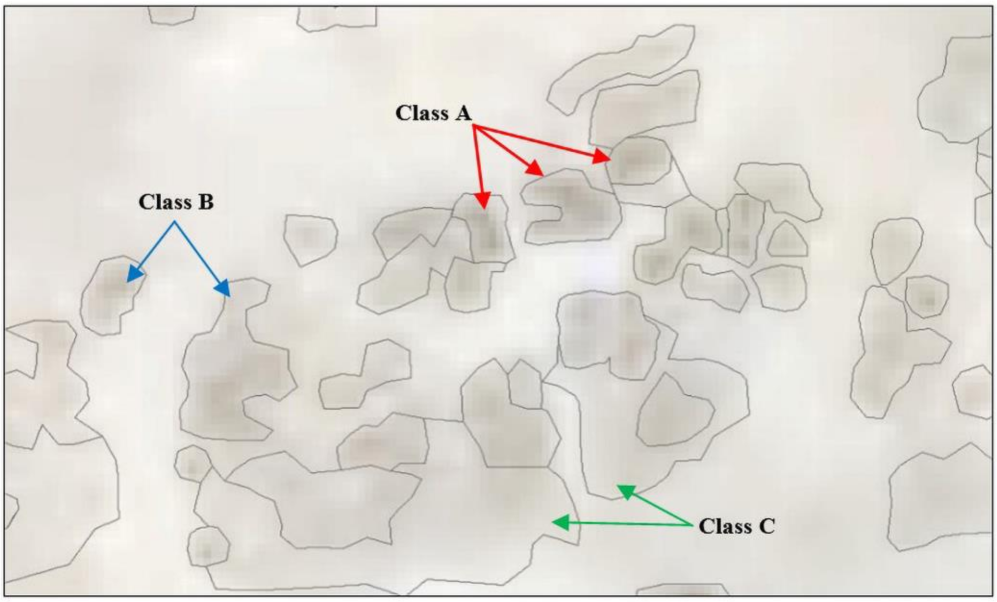

Figure 2. *Example of selection of three classes A, B and C on the screen and their digitization on orthophotography*

The data from photo interpretation and field surveys were compiled in a Geographic Information System (GIS) environment. This information was then used to calculate the area lost or gained by dune vegetation.

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Checking correspondence between "field surveys" and "screen points"

To assess the efficacy of aerial photography as a tool for studying dune vegetation, a random on-screen selection of points distributed throughout the non-wooded dune was made: 105 points for image 2003, 79 for 2015 and 73 for 2019, 257 points in total for the three studied images. The points covered all the digitized entities, and their number therefore depended on the relative importance of each class of vegetation on the image.

In the field, verification was conducted during three campaigns in 2009, 2017, and 2019. The screen points were identified using a GPS. Initially, the type of dune formation was determined (embryonic dune, mobile dune or semi-fixed dune), followed by the altitude and, subsequently, the type of plant formation (dominant species and floristic list).

It is also important to highlight that the flora and vegetation of the study site are being monitored using appropriate sampling techniques, including systematic sampling (linear and surface survey) in order to assess qualitative and quantitative biodiversity parameters. This work will be presented in greater detail in a forthcoming article.

The data was processed using chisq. test function to perform the chi-square test of independence in the stats package in R statistical software (v 4.3.2; R Core Team, 2023). This test is suitable for measuring the strength of the relationship between two qualitative variables (Pottier, 1994; Dieme, 2022). In our case, these variables are the screen points and the field surveys.

We also assessed the accuracy of the manual digitization of the orthophotographs by comparing the results of the NDVI (standardized differential vegetation index) applied to Quick bird satellite imagery from 2003. NDVI provides a clear extraction of vegetation, offering a highly accurate estimate of its presence (De la Iglesia Martínez and Labib, 2023; Wang et al., 2023). The aim is to compare the results obtained from vegetation mapping and NDVI.

Calculating surface areas

Real double type fields were created in the attribute tables of the shape layers in ArcGIS. The areas of the digitized polygons were then calculated using the "Calculate Geometry" function, selecting "Area" as the property and hectare (ha) as the unit.

To estimate changes in vegetation cover over time, we calculated the rate of change from one period to the next using MS-Excel 2019. We then compared these rates to those of 1959, which is considered the reference year for maximum cover. This approach allows us to determine variations in vegetation cover by class.

Results and discussion

A diachronic assessment of plant diversity at El Kadous site

For the year 1959, only one zone, corresponding to "vegetation class", has been considered, given the scale of the photo (1/25 000) which does not allow for precise distinction of the shades of grey (*Fig. 3*). For the years 1980, 2003, 2015, and 2019, the zones were divided into three classes (A, B, and C) corresponding to three main plant formations (*Figs. 4, 5, 6* and *7*). It is important to note that the photo-interpretation work was conducted for the year 2019 to establish a relative resemblance with the current state. Due to the lack of old reference documents, this was then extrapolated to other years.

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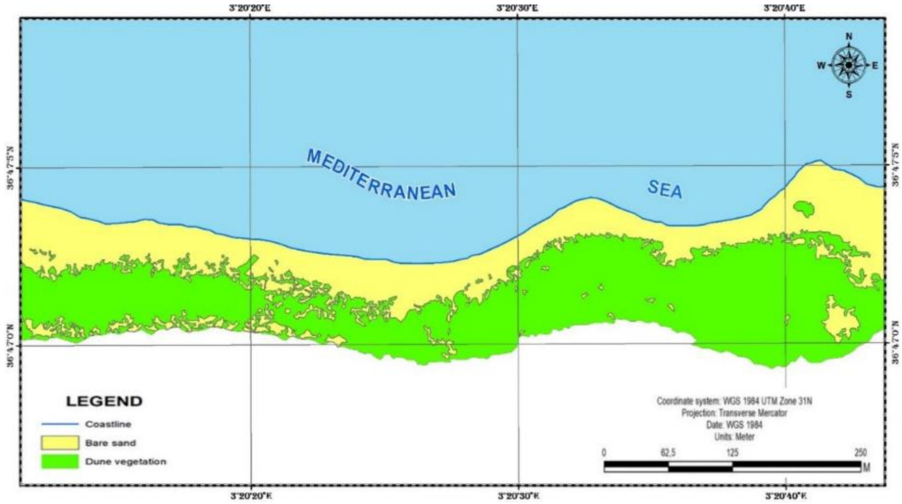

Figure 3. *Map of vegetation cover on the dunes at El Kadous in 1959*

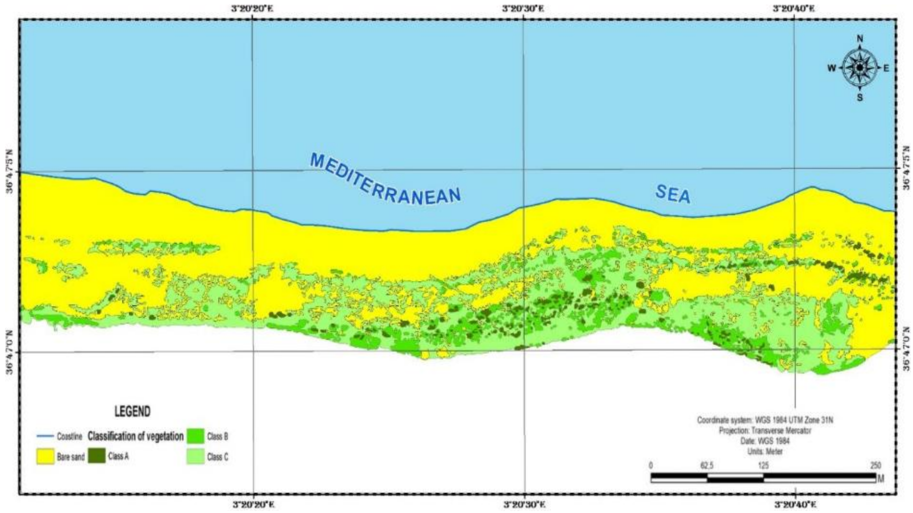

Figure 4. *Map of the dune vegetation cover of EL Kadous site (1980)*

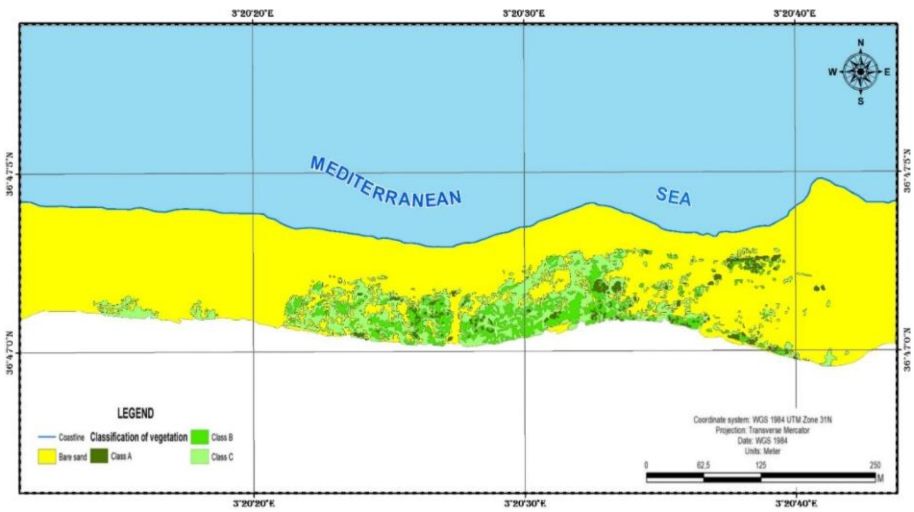

Figure 5. *Map of the dune vegetation cover of EL Kadous site (2003)*

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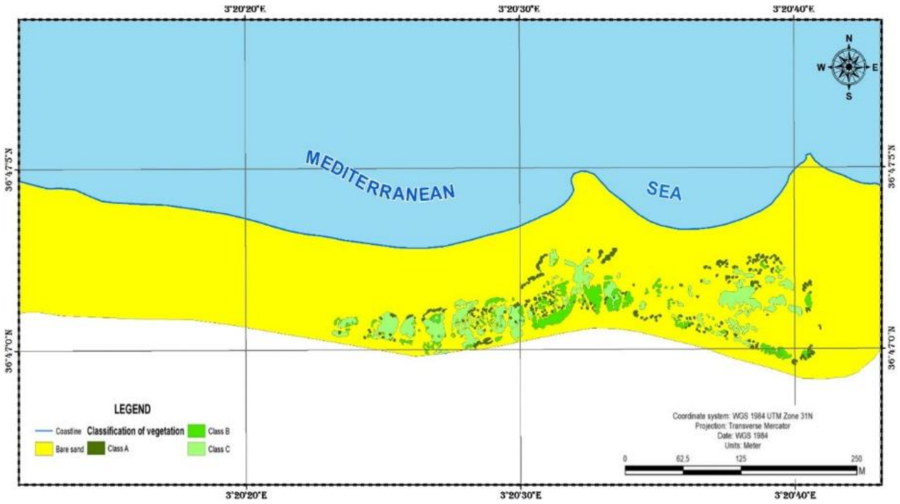

Figure 6. *Map of the dune vegetation cover of EL Kadous site (2015)*

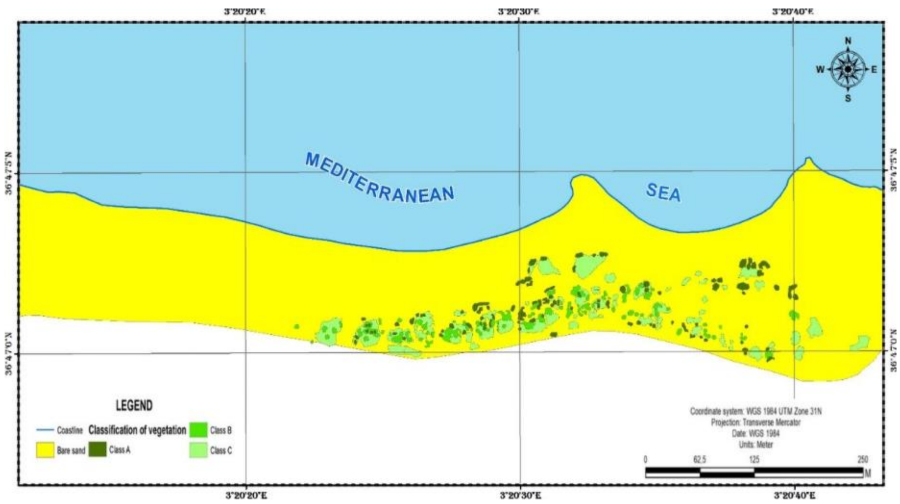

Figure 7. *Map of the dune vegetation cover of EL Kadous site (2019)*

Meaning of the three classes

The El Kadous site survey reveals that the current dune vegetation differs significantly from the classic coastal physiognomy. The concentric zonation previously described by the authors is no longer clearly observed.

The non-wooded dune at the study site has only two main vegetation formations, which can be observed successively from the shore to the scrubland:

- The bordering dunes are dominated by Oyat (*Ammophila arenaria* (L.) Link), forming the “remains” of a formation that was supposed to be denser.
- The area consists of fixed dune grasslands, where the vegetation is low and fragmented, revealing areas of bare sand.

The sampling campaigns conducted on the site have identified the ecological significance of the three classes displayed on the screen:

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(i) Class A corresponds to the darkest areas on the orthophotographs. These formations are dominated by *Ammophila arenaria* (L.) Link and *Pancratium maritimum* L. They are located on the first coastal dunes (*Fig. 8*).

Figure 8. *General appearance of class A on coastal dunes represented in the field by Ammophila arenaria and Pancratium maritimum (Original photo)*

The presence of *Pancratium maritimum* L. “mixed” with *Ammophila arenaria* (L.) Link on the first bordering dunes would indicate:

- Due to the significant erosion of its habitat, the Oyat has retreated towards the semi-fixed dunes, which are the natural habitat of the *Pancratium maritimum* L. (Parisod and Baudière, 2006);
- Or a “colonization” by *Pancratium maritimum* L. of what remains of the Oyat habitat (MATE, 2005).

In both cases, the situation indicates a confusion of habitats, resulting in a structural and functional imbalance in the non-wooded dune of the site. On the other hand, Class A includes more occasional elements dominated by *Salsola kali* L. or *Chamaerops humilis* L., scattered here and there on the fixed dune behind the aforementioned dune (*Fig. 9*).

(b)

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(a)

Figure 9. *General aspect of class A ground specifically the back dune which is represented in the field by elements of Chamaerops humilis and Salsola kali. The first photo (a) shows a closer look of the lawn while the second photo (b) provides a zoomed-out view (Original photos)*

The analysis of the 1980 and 2003 maps shows that class A formed a fragmented narrow band in the right foreground, possibly corresponding to Ammophilaie. It was also more present in the background at the edge of the scrubland.

This location suggests a possible disappearance of the first belts corresponding to the upper beach elements and the embryonic dune dominated by *Elytrigia juncea* L. (=*Agropyron junceum* (L.) P. Beauv.). According to Duffaud (1998), Khelifi (2008), Parisod and Baudière (2006), Thomas (1968) and Zaffran (1960) *Elytrigia juncea* L. colonises the embryonic dunes of the Mediterranean, allowing other species that are less adapted to sandy transit to become established. Thomas (1968) describes it as an "edificator". During our fieldwork at El Kadous, we did not find any upper beach features or clearly individualized embryonic dunes.

Duffaud (1998) confirms that on most of the evolved profiles, the front part of the profile is truncated due to marine erosion. This leads to the disappearance of the extension zone of the *Agropyretum*. In addition, beaches are often cleaned for tourism purposes using heavy machinery, which can cause damage to the communities located at the top of the beach (Forey, 2007).

Regarding the groupings of *Ammophila arenaria* (L.) Link, they require significant amounts of sand for their growth and development. These groupings always correspond to the optimal phase of construction of mobile coastal dunes by wind accumulation (Géhu, Biondi and Géhu-Franck, 1988). Once the dunes have been consolidated, *Pancratium maritimum* L. can establish itself (Thomas, 1968; Parisod and Baudière, 2006).

The presence of scattered *Chamaerops humilis* L. plants, which are anthropogenic heliophiles, in the fixed dune grassland provides information about the openness of the shrub layer of these pre-forest groups. This differs from the surrounding scrubland of *Pistacia lentiscus* L. and *Phillyrea angustifolia* subsp. *Angustifolia* L. (Khelifi, 2008) following the dune vegetation belts of chamaephytic and therophytic plants (Géhu, Biondi and Franck, 1994). The old photos (*Fig. 10*) suggest that these dune grasslands originated from the degradation of the coastal scrubland. However, due to a

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lack of old documentation describing the groupings at the time, any conclusions can only be speculative.

In addition, *Salsola kali*, characteristic of the *Salsolo kali-Cakiletum aegyptiacae* Costa and Manzanet, 1981, is a therophyte of the upper beach with *Cakile maritima* Scop., *Polygonum maritimum* L. or *Euphorbia peplis* L. …. (Meziani, 1984; Géhu, Kaabache and Gharzouli, 1992; Géhu, Biondi and Franck, 1994; Géhu and Biondi, 1996). The presence of the species outside its natural habitat on the consolidated dune suggests a reorganization of species arrangement on the beach, likely caused by human activity. Destruction of the frontal dunes due to sand over-exploitation and over-frequentation forces the species to develop further from the shore, away from passing traffic (Khelifi, 2008).

(ii) Class B is represented on aerial photographs by areas of intermediate shades of grey between classes A and C. In the field, this class is characterized by perennial grass vegetation or vegetation dominated by back-dune annual plants with a dense cover (as shown in *Figure 11*). The dominant species in this class are *Centaurea spherocephala* L. and *Lotus creticus* L., along with numerous other species such as *Echium sabulicola* Pomel, *Sporobolus pungens* (Schreb.) Kunth, and *Scolymus hispanicus* L.

This group corresponds to the *Loto-Centaureetum sphaerocephalae* (Géhu and Sadki, 1994; Nègre, 1964), between and behind the dunes, the overall coverage varies from 50% to 80% (Khelifi, 2008). The development of this grouping, to the detriment of *Ammophiletum*, on the edges of dune systems, is linked to moderate trampling and eutrophication, as noted by Géhu and Sadki (1994). This association is not affected by the breaking of the waves but remains under the influence of sea spray (Khelifi, 2008).

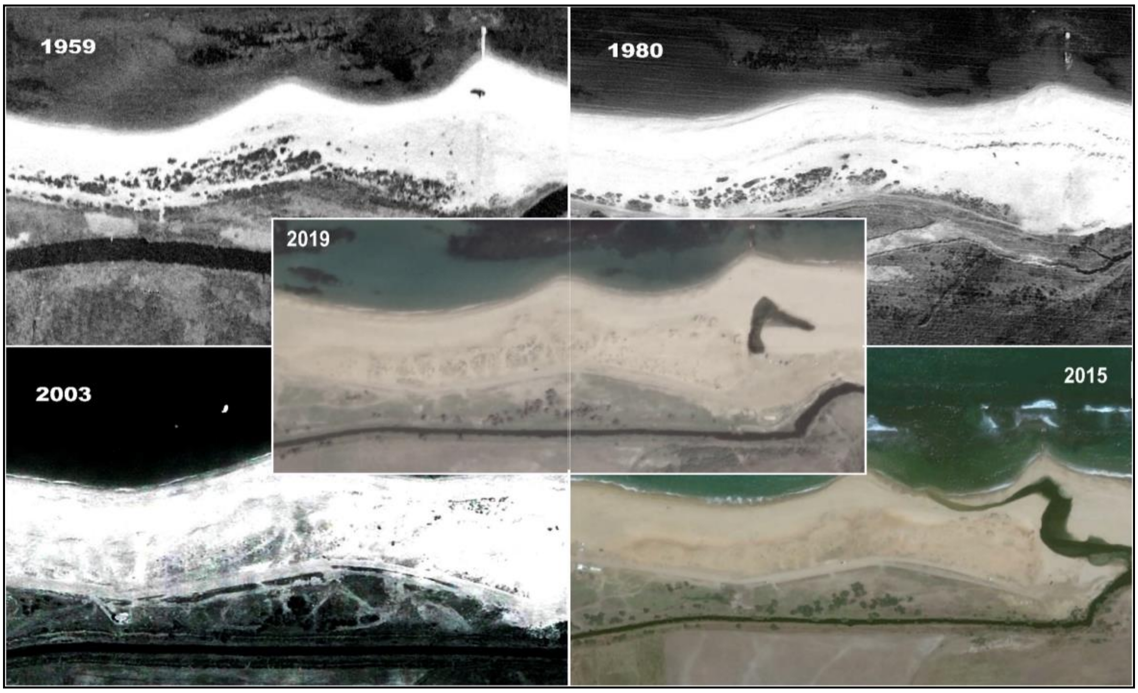

Figure 10. *Changes in the dune landscape of the study site between 1959 and 2019 (After 1980 the vegetation lost its concentric structure and the overall plant cover decreased. In 2015 a watercourse originating from the overflow of the Reghaia marsh to the southwest divided the beach. In 2019 the Algerian authorities initiated development work to correct the diverted course)*

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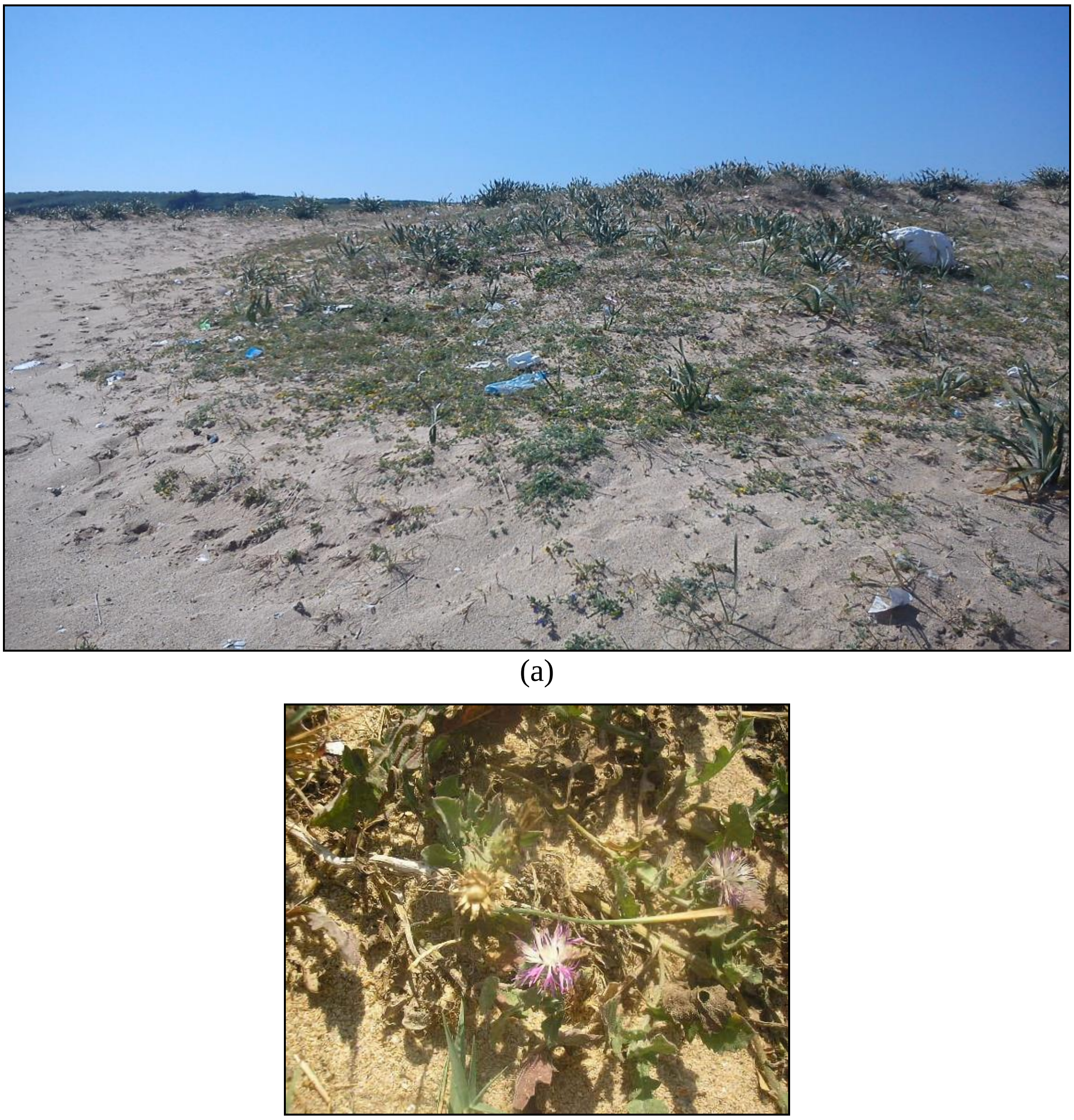

Figure 11. *General appearance of class B, represented in the field by a dense and patchy lawn. The first photo (a) shows a zoomed-out view of the lawn while the second photo (b) shows a closer look (Original photos)*

These grasslands are located in the central regions of the dunes and are described as “dense, low, and very uniform grassland” (Chevassut, 1956). According to Ducellier (1911), the area is characterized as a lush lawn where many therophytes thrive during the spring. Our field observations reveal the presence of densely covered “patches” (80%) of these lawns, which would indicate a fragmentation of the *Loto- Centaureetum sphaerocephalae* previously described by Ducellier (1911) and Chevassut (1956) as “fairly dense blankets”.

(iii) Class C: represented on aerial photographs by a light shade of grey. On the ground it corresponds to light pelous vegetation (*Fig. 12*). It should be noted that this

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class has a double meaning. On the one hand, it corresponds to an open grassland with *Sporobolus pungens* (Schreb.) Kunth, located on the edges of the adjacent dunes (embryonic dunes) and occasionally on the fixed dune. On the other hand, it reflects the formations dominated by *Echium sabulicola* Pomel and *Lotus creticus* L., ... of the *Loto-Centaureetum sphaerocephalae* (Nègre, 1964; Géhu and Sadki, 1994), with low cover, located on the solid dune.

The *Sporoboletum arenarii* Arènes, 1924 characterized by *Sporobolus pungens* (Schreb.) Kunth, is part of a Mediterranean syntaxon that includes: perennial vegetation of dune sands, communities of foredunes and loose to semi-fixed dunes, and even perennial vegetation of sandy beach tops (Khelifi, 2008). This is a low-growing perennial grassland due to the grassy form of *Sporobolus pungens* (Schreb.) Kunth. with a variable cover between 40 and 80% (Khelifi, 2008).

The "intrusion" of *Sporobolus pungens* (Schreb.) Kunth. into the group of class B species, with very low cover, behind the dune, explains the very similar floristic composition of the field surveys corresponding to classes B and C. This species can be found in a wide range of topographical situations and in contact with a variety of plant communities (Piazza and Paradis, 1997). Here, the presence of *Sporobolus pungens* (Schreb.) Kunth. in the same place as the *Loto-Centaureetum sphaerocephalae* species would indicate a regressive stage linked to the erosion of the dune cordon (UICN, 2020).

The vegetation on El Kadous beach is classified into three classes, forming a variable mosaic. Changes in the spatial distribution of these classes can be observed from one map to another, both in terms of quality (spatial structure and composition) and quantity (density). In addition to the floristic composition, the density of the plant cover also appears to be a determining factor. This was observed during our various field surveys. Classes B and C are similar in terms of floristic composition, particularly in the back dunes. The only distinguishing factor between them is the density of their plant cover. On the screen, areas with high density were classified as class B, while those with lower density were classified as class C.

(a)

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(b)

Figure 12. *General appearance of class C, represented in the field by an open lawn with Echium sabulicola, Lotus creticus and Sporobolus pungens. The first photo (a) shows a zoomed-out view of the lawn, while the second photo (b) provides a closer look (Original photos)*

Statistical verification of the significance of screen points

Table 1 shows the percentages of field surveys and screen points for each vegetation class, along with the results of the Chi-square test of independence. The initial digit in each cell of the table represents the number. The subsequent digit indicates the percentage of the entire table that is represented by this cell. To illustrate, there are 29 values in the first row and column. This represents 11.284% of the 257 values in the table.

The table analysis indicates the reliability of the screen points concerning the significance of the three classes.

Table 1. *Occurrences of field surveys and screen points by vegetation class in a statistical study*

	GS[a] 2003	**GS 2015**	**GS 2019**	**Total**
SP[b] Class A	29 11.28%	14 5.45%	14 5.45%	57 22.18%
SP Class B	47 18.29%	24 9.34%	24 9.34%	95 36.96%
SP Class C	29 11.28%	41 15.95%	35 13.62%	105 40.86%
Total	105 40.86%	79 30.74%	73 28.40%	257 100.00%

Test	Chi-square	Df[c]	Probability
Results	13.148	4	0.0106

[a]Ground survey
[b]Screen point
[c]Degree of freedom

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NDVI extraction

The Normalized Difference Vegetation Index (NDVI) was extracted from Landsat 8 OLI imagery for 2015 and 2019. However, the results were inconsistent due to the narrow study area and the 30 m spatial resolution of the multispectral bands. However, the Normalized Difference Vegetation Index (NDVI) extracted from the Quick bird very high-resolution satellite image (*Fig. 13*) that covers the El Kadous area for the year 2003 is in perfect agreement with the results obtained by manual digitization on orthophotographs.

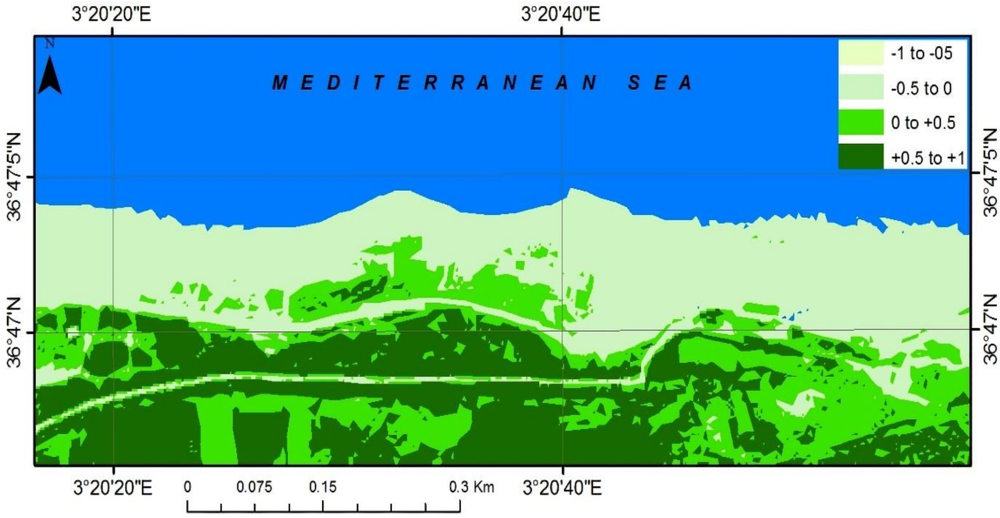

Figure 13. *Highlighting the vegetation cover of the study area by applying the Normalized Difference Vegetation Index (NDVI) to very high-resolution Quick bird satellite images from 2003*

Analysis of vegetation cover areas

Figure 14 analysis reveals a significant alteration in land cover. The vegetation cover has regressed towards bare sand, decreasing from 50.04% in 1959 (4.879 ha) to only 6.43% (0.602 ha) in 2019.

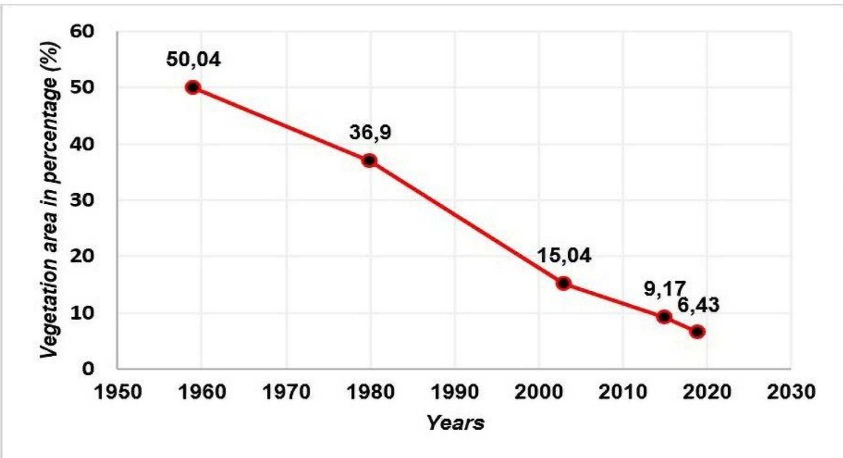

Figure 14. *The evolution of the dune vegetation cover surface area (in percentage of the total area) at El Kadous site between 1959 and 2019*

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Since the 1980s, there has been an apparent deterioration. These findings align with Grainger's (1988); Lepers et al.'s (2005) global research, and MATE's (2003) study of the Algerian coastline. There has been a significant trend towards the fragmentation and destruction of dune vegetation. This is primarily due to climate change, urban and tourist development, and the over-exploitation of natural resources such as sand removal, intensive trampling, grazing, and attempts to reshape the landscape. The change in vegetation cover is a result of alterations in the surface areas of the different classes A, B, and C (*Fig. 15*).

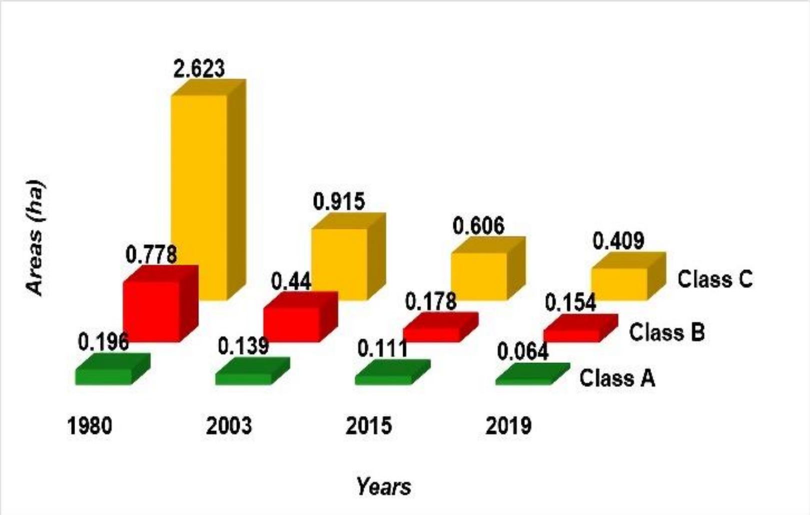

Figure 15. *Evolution of the surface area (in hectares) of the dune vegetation cover of El Kadous site from 1959 to 2019*

The rate of change in overall vegetation cover (*Table 2*) indicates that between 1959 and 2019, the overall area decreased by 87.1%. The most concerning rate was recorded between 1980 and 2003, with a value of -59.2% over a period of only 23 years (*Fig. 16*).

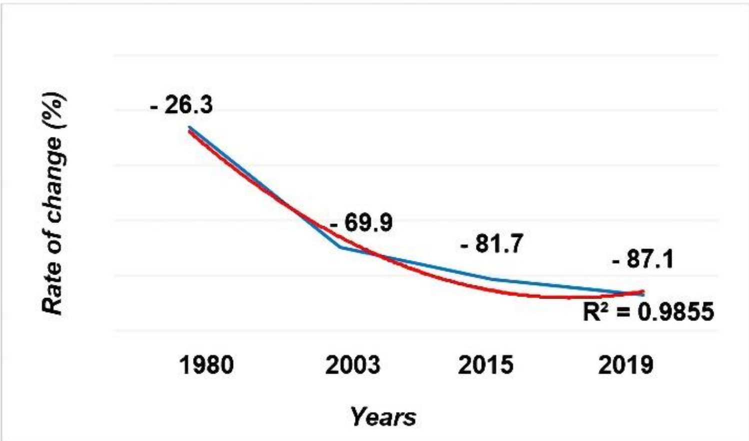

Figure 16. *Rate of change over time of the overall vegetation cover of the site El Kadous (Period 1959-2019). Blue line: rate of change from base year (1959). Red line: second degree polynomial curve (rate of change from base year (1959))*

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Table 2. *Rate of change in overall vegetation cover*

	1980	2003	2015	2019
Rate of change compared to the reference year of 1959	-26.3%	-69.9%	-81.7%	-87.1%

Additionally, the trend curve for the second-order polynomial is decreasing with a coefficient of determination R^2 of 0.9855, which corresponds to a correlation coefficient of 0.993. This suggests a consistent decrease from 1959 to 2019.

The analysis was refined by calculating the rates of change for each vegetation class. However, it should be noted that the reference year used in this study is 1980, rather than 1959. This is due to the fact that the 1959 photograph has a low resolution and does not display all three vegetation classes.

The rate of change in vegetation cover for class A (*Table 3*) indicates a decrease of 67.3% between 1980 and 2019 (*Table 3*; *Fig. 17*). It is worth noting that the most concerning rate was recorded between 2015 and 2019, with a value of -42.3%.

For Class B, the calculations indicate that the area decreased by 80.2% between 1980 and 2019 (*Table 4; Fig. 18*), with the most significant reduction occurring between 2003 and 2015, i.e. - 59.5%.

Table 3. *Rate of change in vegetation cover for Class A*

	2003	2015	2019
Rate of change compared to the reference year (1980)	-29.1%	-43.4%	-67.3%

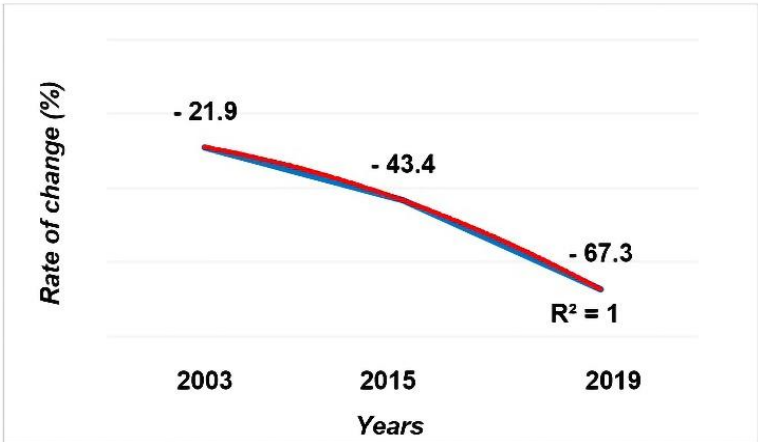

Figure 17. *Rate of change over time of class A vegetation cover (Period 1980-2019). Blue line: rate of change of class A compared to the reference year (1980). Red line: second degree polynomial curve (rate of change of class A with respect to the reference year (1980))*

Table 4. *Variation of vegetation cover in Class B*

	2003	2015	2019
Rate of change compared to the reference year (1980)	-43.4%	-77.1%	-80.2%

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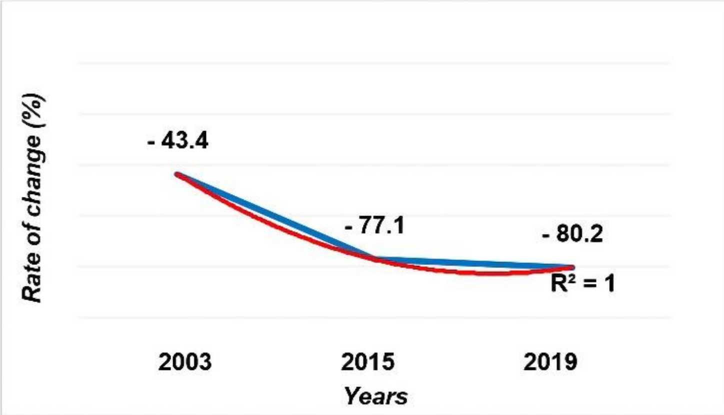

***Figure 18.** Rate of change over time of class B vegetation cover (Period 1980-2019). Blue line: rate of change of class B compared to the reference year (1980). Red line: second degree polynomial curve (rate of change of class B with respect to the reference year (1980))*

Furthermore, for class C, the rates of change calculation show an 84.4% decrease in vegetation cover between 1980 and 2019 (*Table 5*; *Fig. 19*). The highest decrease recorded between 1980 and 2003, i.e. -65.1%.

The results for classes A, B, and C indicate that the variations from year to year do not follow the same pattern:

- Class A experienced the maximum decline between 2015 and 2019
- Class B experienced the maximum decline between 2003 and 2015
- Class C experienced the maximum decline between 1980 and 2003

However, the trend curves in relation to the reference year of 1980 demonstrate a consistent pattern of decline. The R^2 coefficient of 1 indicates a strong correlation between decreasing vegetation and time passing from 1980 to 2019.

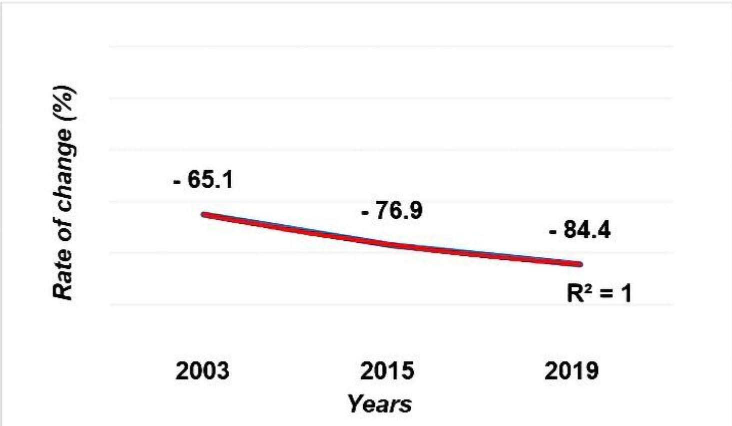

***Figure 19.** Rate of change over time of class C vegetation cover (Period 1980-2019). Blue line: rate of change of class C compared to the reference year (1980). Red line: second degree polynomial curve (rate of change of class C with respect to the reference year (1980))*

***Table 5.** Rate of change of vegetation cover in class C*

	2003	2015	2019
Rate of change compared to the reference year (1980)	-65.1%	-76.9%	-84.4%

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Causes of degradation

Climate change

A comparison of the average annual of precipitations at El Kadous site for 1980 (731.1 mm/year), 2003 (736 mm/year), 2015 (438 mm) and 2019 (446 mm) shows a drying trend. Weather data for 1959 were not available. Nevertheless, the diachronic analysis of the rainfall pattern for the two periods "1913-1938" and "1999-2019" showed a decrease in the amount of rainfall per season and a "seasonal shift" (Saidi, Sai and Hasnaoui- Slimani, 2021). Not only the quantity of water available, but also the quality and frequency of its distribution during the growth period affects vegetation phenology (Hassini, Abderrahmani and Dobbi, 2008).

A comparison of the average annual temperatures at the El Kadous site for the years 1980 (17°C), 2003 (18.46°C), 2015 (18.32°C) and 2019 (18.37°C) shows an increase in temperature of more than one degree Celsius.

The average minimum temperatures "m" has also fluctuated: 1980 (5.3°C in December), 2003 (5.4°C in February), 2015 (2.6°C in November) and 2019 (4.1°C in February). The lowest value of "m" was recorded in the autumn of 2015.

In addition, the average maximum temperatures "M" has increased alarmingly: 1980 (31.9°C in August), 2003 (34.8°C in August), 2015 (34.6°C in July) and 2019 (37.7°C in August). The peak will be in the summer of 2019. *Figure 20* summarizes the temperature variations within the study area.

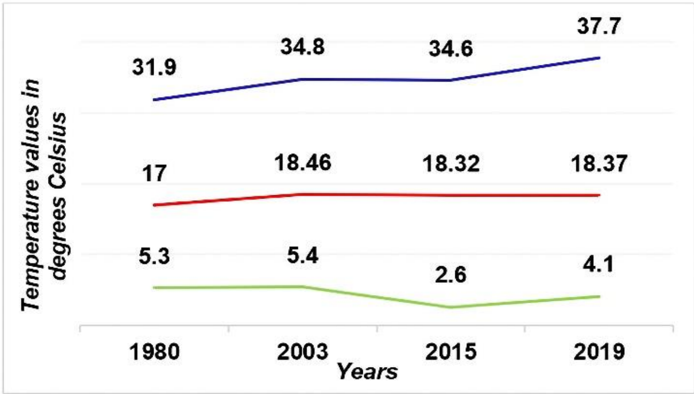

***Figure 20.** Variation of temperatures at El Kadous site by year of observation. Red line: average temperature (°C). Green line: average minimum temperature of the coldest month (°C). Blue line: average maximum temperature of the hottest month (°C)*

Saidi, Sai and Hasnaoui- Slimani (2021) report a warming of the climate along the coast of Algiers over the last twenty years. A comparison with the old values of Seltzer (1946) for the period (1913-1938) shows that the average monthly temperatures are higher for the most recent period (1999-2019). The largest differences (2.71°C) are observed in the average maximum temperatures "M". In the Mediterranean region, maximum temperatures seem to be increasing more than minimum temperatures and more than average temperatures (Rifai, Khattabi and Rhazi, 2014).

Nouaceur, Laignel and Turki (2013) note that the number of violent storms along the Algerian coast has increased since 1990, affecting groundwater recharge and amplifying runoff and flooding.

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Coastal erosion

According to Aoudj et al. (2020), the beaches of eastern Algiers have been the most affected by coastal erosion over the last half century. El Kadous beach, for its part, has experienced several scenarios depending on the period:

- A retreat of the coastline varying from -0.6 to -1.2 m/year (period 1972-1993) and from -0.5 to -2.0 m/year (period 2003-2010)
- An increase in sedimentation, with an average rate of progradation (EPR) of 1.13 m/year (period 1993-2003) and 0.9 m/year (period 2010-2017)

The natural causes of erosion on El Kadous beach are mainly due to the repeated and cumulative effects of storms and the relative rise in average sea level. Records from tide gauges indicate that the Mediterranean Sea has been rising at a rate of between 1.2 and 1.5 mm per year over the last century, resulting in the loss of habitat for many ecosystems (Haddad, 2017; Madelenat, 2019; Otmani et al., 2019; Sallaye et al., 2022). Moreover, the findings of Nouaceur, Laignel and Turki (2013) revealed a clear and statistically significant correlation (r = 0.93) between the rise in daytime temperatures and the increase in the number of storms recorded along the Algerian coast. This relationship illustrates a causal relationship between the two phenomena. Indeed, an increase in maximum temperatures results in greater evaporation and thermo-convective processes, which are accompanied by storms and intense precipitation, thereby promoting erosion.

The anthropogenic causes of coastal erosion may be due to the massive, uncontrolled and illegal extraction of minerals for urban development in the wilaya of Algiers since the early 1970s (Otmani et al., 2019).

Based on our observations, it is clear that the removal of sand directly from beaches and dune cordon has had a serious impact on the ecosystem balance of the beaches of the east coast of Algeria, and in particular El Kadous (*Fig. 21*). Khelifi (2008) points out that the Ammophilaie is seriously threatened on the east coast of Algeria due to encroachment (illegal sand mining, development of car parks and campsites, etc.).

Figure 21. *Sand scavengers on El Kadous beach (Original photo)*

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There has also been a reduction in the solid flows in the wadis (Corso, Isser, Boumerdes, etc.) in recent decades due to excessive sand extraction from the beds of these oueds (Otmani et al., 2019).

Trampling and attendance

The beach of El Kadous is a victim of its own reputation, with a high level of tourist attendance makes it very fragile (*Fig. 22*). The dune vegetation on the site is very sensitive to the effects of trampling due to the low cohesion of the sandy substrate. According to Duhamel et al. (2017), visitor numbers generate trampling, which is unfavorable for the maintenance of the dune habitat in general and the Oyat belts on the top part of the coastal dune in particular, leading to their sharp decline in the Mediterranean.

Figure 22. *White dunes at the study site transformed into a shelter for summer visitors (Original photo)*

The white (mobile) dune would be the most important ecosystem in the dune belt, ensuring its resilience to disturbance.

Apart from the mobile dunes “in distress”, the El Kadous site no longer has any upper beach elements or well individualized embryonic dunes as described in previous works. Indeed, in his “*Excursion internationale de phytosociologie*”, Wojterski (1985) observed an upper beach element containing *Cakile maritima* Scop. and embryonic dunes with *Achillea maritima* (L.) Ehrend. & Y.P.Guo, which obstructed the mouth of the Oued Reghaia. However, this element has since disappeared due to the local authorities’ beach cleaning efforts to accommodate more summer visitors.

The beach top element exhibits a natural coastal sedimentary pattern, which is characterized by seasonal cycles of sediment accumulation (fertilization) and depletion (demaigration). This pattern is beneficial for the dune habitat (Duhamel et al., 2017).

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Grazing

During field visits, it was observed that El Kadous site had been transformed into a grazing area, damaged by cattle and goats brought in by pastoralists for economic purposes. There was no evidence of any restoration or conservation strategy (*Fig. 23*).

Figure 23. *Some goats grazing in the dunes of El Kadous (Original Photo)*

Pollution

The area closest to the beach is facing several pollution-related problems. For several years, untreated sewage has been discharged into Lake Reghaia, which is located just opposite the beach. The source of this wastewater is the industrial zone in the same locality, and it also comes from neighboring towns (MATE, 2015). This pollution is carried by Oued of Reghaia, which crosses the beach and ends up in the sea, superimposed on other pollution. Agricultural activities, through the use of fertilizers, are also a source of nitrate and phosphate pollution.

Devèze and Sigoillot (1978) confirmed the phytotoxic role of sea spray on vegetation. The dieback of vegetation is directly linked to sea spray polluted by surfactants (detergents from industrial or domestic wastewater discharges) and fuel oil (from maritime traffic).

Garrec (2021), explains that surfactants can impact leaf permeability by changing cuticles, leading to the degradation of waxes. This can promote the penetration of NaCl from sea spray into leaf tissue, which is the primary cause of necrosis and dieback. Additionally, the author notes that concentrations of detergents and fuel oil are significantly higher in sea spray than in seawater.

Artificialization

Over the last six decades, artificial development has caused damage to the dune zone. The eastern part of the Bay of Algiers has lost approximately 69% of its dune massifs, with the highest rate of clearing occurring between 1960 and 1985 during the country’s post-independence economic urbanization, at a rate of 24 hectares per year (Otmani et

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al., 2019). According to the same source, the rate of land clearance has decreased from 13.4 Ha/year between 1985 and 2000 to 13.6 Ha/year between 2000 and 2015. However, it is still considered very high. This is likely due to demographic pressure on land, such as rural exodus and precarious housing in the 1990s, as well as national housing policy in the 2000s.

Conclusion

The issue addressed in this study concerns the evaluation of the contribution of aerial photography as a tool for monitoring dune vegetation at El Kadous site (on the eastern coast of Algiers). The main objective is to measure, over a period of more than half a century (60 years), the qualitative and quantitative changes in these plant communities using aerial photographs supported by a very high-resolution Quick bird satellite image taken as a reference.

The methodology used involves using geographic information systems to produce diachronic cartography from aerial photographs. This allows for the analysis of the spatiotemporal evolution of dune vegetation. Additionally, the effectiveness of aerial photography as a tool for studying and monitoring the vegetation of non-wooded coastal dunes was assessed using the Chi-square Test of Independence.

The study of changes over time shows a clear decline, particularly from the 1980s onwards, in both the overall plant cover and the spatial structure of this type of vegetation. The reduction in vegetation cover has been significant, reaching -87.14% in just 60 years. Consequently, the concentric zonation that is typical of dune vegetation can now only be observed in isolated areas. The traditional pattern of the unwooded dune has been altered into a mosaic of elements due to the disappearance of the upper beach element and the first clearly individualized embryonic dunes.

Furthermore, the statistical test results demonstrate the efficacy of aerial photography as a means of studying non-wooded coastal dune vegetation. In the field, photo-interpretation was employed to identify vegetation units, with density classes corresponding to the main plant formations. This is a noteworthy finding, as it allows users to substitute aerial photography for very high-resolution satellite imagery, when it is not available due to its high cost. However, the effectiveness of the obtained results depends on the quality of available aerial photographs, the accuracy of geospatial data, and the user’s familiarity with the terrain. Additionally, the complexity of coastal ecosystems makes it challenging to consider all factors that influence dune vegetation.

Also, this study highlights the degradation of dune vegetation due to climate change, coastal erosion, and anthropogenic factors. Urgent recommendations are needed to develop a conservation strategy adapted by Algeria to mitigate the negative impacts affecting the coastal fringe, which is crucial both ecologically and socio-economically. The establishment of protected areas that incorporate these coastal ecosystems and the implementation of concrete measures to counteract tourist pressures, urbanization, and pollution should be included.

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