

New Insights in Seagrass Mortality Patches at the Arguin Bank in the Perspectives of Climate Change

Anne Littaye^{1*} and Mohamed Ahmed Sidi Cheikh²

¹Deutsche Gesellschaft für Internationale Zusammenarbeit, GIZ/CIM, Nouakchott, Mauritania

²Doctorant, University of Groningen, The Netherlands

*Corresponding author: Anne Littaye, Expert, Deutsche Gesellschaft für Internationale Zusammenarbeit, GIZ/CIM, Nouakchott, Mauritania, Tel: +22245254423; E-mail: anne.littaye@orange.fr

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Abstract

All over the world, seagrass beds are key natural habitats for their ecosystem services. Those in the Gulf of Arguin, in Mauritania, have been monitored for more than twenty years; their conservation status is considered good despite very variable climatic conditions. In the absence of anthropogenic stress, the abiotic conditions have given rise to a number of hypotheses explaining temporary patches of mortality. These observations and hypotheses were revisited during the analysis of the evolution over 20 years of the total vegetation cover in Arguin Bay, evaluated by the NDVI index. This change over the medium term is consistent with wind conditions, drivers of sediment transport and hydrodynamics. The chronological contextualization of field observations by climatic conditions provides a new understanding of short-term variations. The importance of ongoing monitoring of this ecosystem is demonstrated; additional guidance is suggested to assess the specific resilience of each of the species that make up this seagrass beds.

Keywords: Climate impact; Seagrass bed; Mauritania; Resilience

Introduction

Seagrass beds are a globally monitored and protected habitat for its multiple ecosystem functions [1]. The shallow and extended continental shelf of the Gulf of Arguin harbours two species *Zostera noltii* and *Cymodocea nodosa*. This seagrass habitat extends over approximately 500 km² in the intertidal zone [2]. Coverage in the subtidal zone has not yet been estimated. Seagrass beds have been degraded throughout the world for many years, mainly as a result of anthropogenic activities and also climatic impacts [3]. On the contrary, the seagrass beds on the central area of the Gulf of Arguin is in a good state of conservation and expanding since the first estimates were made in 1985. They are preserved from activities by the protected area status of the Banc d'Arguin National Park. However, the effects of climatic events or stress from other sources are not excluded. In 2005, following the detection of mortality patches, several pressure assumptions were made [4].

A lethal temperature threshold was sought to explain mortalities of *Zostera noltii* in the Formosa lagoon [5,6]. Temperature could affect the symbiosis between a mollusk linked with *Zostera noltii* and a sulpho-reducing bacterium on the Banc d'Arguin [7]. The degradation of this symbiosis would lead to an increase in the sulphur content of the sediments in contact with rhizomes, which would constitute chemical stress.

Several field and laboratory experiments have also been implemented on the burial effect of sedimentary deposits on leaves and rhizomes; stress on several marine phanerogamous species was compared. The thickness of the sedimentary cover and its duration would lead to changes in leaf growth and post-stress recovery time or mortality [8-10]. Sediment deposition is a consequence of strong hydrodynamics, which in itself is a source of stress [11-13]. These

studies analyzed one-off *in situ* observations, supplemented by experiments. In order to provide new elements, these mortality hypotheses are tested by comparing a series of vegetation coverings by the intertidal meadows of the Banc d'Arguin and climatic wind series between 1985 and early 2017. Two temporalities are examined, the inter-annual variation of seagrass cover and the medium-term variation over the entire series.

Materials and Methods

Study system

The study area lies about 200 km north of Nouakchott at 19°53'N and 16°18'W (Figure 1). The waters of Banc d'Arguin are shallow. At low tide, extensive mudflat surfaces emerge and are covered by seagrass of *Zostera noltii*. At Iwik Bay, tides have an average diurnal range of 2.0 m and a normal maximum range of 3.1 m (personal measurement). The Banc d'Arguin is protected by a sandstone bank at its western boundaries from the high energy of the oceanic influence.

Data collection

Through the Earth Explorer website <http://earthexplorer.usgs.gov/>, we identified a series of satellite images available and their quality status regarding cloud cover. We have also taken into account the usability of images taken in high tide. Any scene that does not allow distinguishing seagrass meadows has not been downloaded. Our analyses cover the period spanning from 1984 through 2014 with a data gap over between 1993 and 1998.

Pre-processing data

The biggest concern to which we granted much of our time is the calibration processing. Because the use of a generation of 3 sensors of Landsat TM/ETM +/OLI requires finding a means of comparison for tracking over time the seagrass coverage by analyzing the satellite signal. For this purpose, we used the calibrated products offered by the USGS.

The georegistration of the images has already been done by the USGS on the reference system of UTM/28 N and datum WGS84.

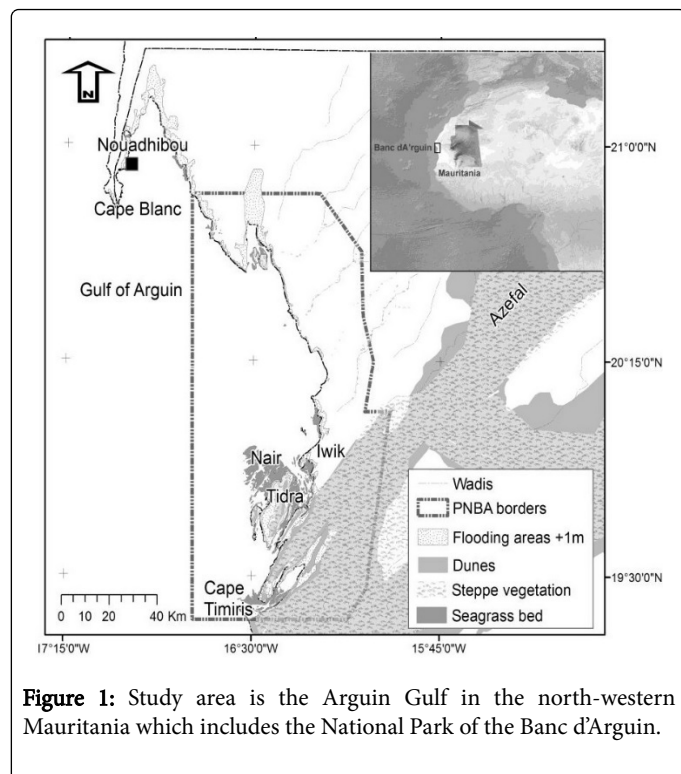


Figure 1: Study area is the Arguin Gulf in the north-western Mauritania which includes the National Park of the Banc d'Arguin.

Sampling design

To investigate seagrass coverage, we identified representative sites allowing us to quantify the density of seagrass over time. In order for the monitoring to be efficient in detecting possible changes in seagrass distribution, we selected 11 transects divided into 51 stations distributed over sampling area and taking into account the exposed areas and those sheltered. We considered also the site factor by including longitudinally located dots. The selected points serve to compare the high sites and those at the bottom because the transects are distributed on a topographic gradient from inner channels rim, central and towards outer parts of the mudflats.

Seagrass cover

Seagrass cover describes the fraction of sea floor covered by seagrass, thereby provides a measure of seagrass abundance, and subsequently reflects the spatial distribution in the same investigated area. To estimate the coverage of seagrass meadows, we used the vegetation index extracted from remote sensing products as a proxy for vegetation abundance and biomass. Normalized Difference Vegetation Index, NDVI, is widely used for monitoring intertidal seagrass [14]. Seagrass abundance and biomass data are expressed in NDVI which

can take theoretically the range of values between -1 and 1. Healthy seagrass can have a value of 0.4 to 0.6. Bare area is around 0.1. That is why in our analysis we exclude all values less than 0.1 as considered not belonging to seagrass or bare soil.

Thus, to calculate the NDVI on selected sampling points, we used GIS techniques to facilitate the analysis. First, we proceeded to calculate the NDVI image using both Landsat bands calibrated (Infrared and Red) using the formula $NDVI = \frac{IR - R}{IR + R}$. Calculation of NDVI was performed in ARCGIS environment using the Raster Calculator tool. Then we created a shapefile layer containing polygons which will be used to extract the average value of the vegetation index NDVI on sampling stations. We drew each polygon on a size of 3600 m², which are exactly four pixels of Landsat image with a spatial resolution of 30 m. NDVI values were calculated as means for polygon rather than being calculated as values for plots. The use of polygons as a basis for extraction of NDVI instead of punctual points is justified by the fact that the coverage of seagrass is somewhat heterogeneous, in some mudflats and thus the polygon will get an average estimate of vegetation coverage and minimize error that could arise when using a single point. For this latter operation, we used the zonal statistical tool available in ArcGIS. Finally, to get the final file of NDVI values for each image, we used the Raster conversion tool to text values. This tool called Extract Values to Points is also available under the ArcGIS Data Management Tools menu.

The NDVI values of each sampling station were calculated for each calibrated image and assigned the date of acquisition of the same scene. The time-series allow obtaining the annual distribution of seagrass cover each year. Values of NDVI near zero represent surface conditions of barren rock or sand, with increasing values of NDVI representing more lushly vegetated surfaces.

Temporal dynamic of seagrass

We processed the time-series of analysis in R by testing for NDVI seasonality and/or a time-trend. The first objective is to study the annual cycle of NDVI by grouping all of the sampling points set for an overall idea about the inter-annual dynamics of seagrass meadows as well as seasonal one. As the density of seagrass varies with elevation, we have added the values of the elevation of the sampling points. These points are taken from a bathymetric map that we produced by using the iso- contours of the tide and corrected with measurement with Differential GPS RTK of centimeter accuracy. The sampling stations were also classified into three categories according to their elevation areas as well: High areas (>-0.1 m), medium areas (-0.4 to -0.1 m) and low areas (<-0.4 m). This classification allowed rolling out the effect of the elevation factor in the variation of seagrass density in the statistical analysis.

The harmonic analysis was performed for sampling sites depending on elevation classes in order to decrease variance in NDVI per month as a result of site/elevation effects. In addition, we accounted for a within-site effect and a time-effect by putting site and month (as a factorized continuous variable) as a random effect in the model. Because of data lacking in for most months in early years (<2000) we only used data from 2000 onwards.

We apply harmonic analyses and non-parametric trend tests to the GIMMS NDVI dataset (1981-2006). Using the complete dataset, greening and browning trends were analyzed using a linear model corrected for seasonality by subtracting the seasonal component, and a seasonal non-parametric model [14].

Climate parameters

The series have been based on the three-hourly daily wind records, archived in direction angle sectors of 20° and speed ranges of 7.2 km.h⁻¹. The metric performed is the number of occurrences aggregated per month and per year and that is according to each angle sector. The number of occurrences has been considered more relevant than average to reflect the chronic stress pressure on the natural system.

The oceanic winds aggregate the wind origin angles from 240° to 340°; speed range that is equal or over 28.8 km.h⁻¹, have been selected as effective to a severe swell over the Arguin Gulf. It is considered as a proxy parameter of the hydrodynamic. In the absence of characterization based on *in situ* measurements of sea states on the Mauritanian continental shelf, the threshold was set as \geq wind speed average at Nouadhibou over the 1980-2016 periods, i. e. \geq 28.8 km.h⁻¹; this threshold corresponds about Beaufort with the formation of breaking waves.

In parallel, wind occurrences with a speed less than 7.2 km.h⁻¹ whatever the angle direction have been quantified to illustrate some calm hydrological situation which can help the sediment material deposition. The data at Nouakchott station are considered for this parameter.

The representation of sediment load in water and on coastal barrier dunes is the easterlies that are wind origin angles from 20° to 80°; winter months has been considered from December to February which correspond to the maximum frequency. A threshold about 6 to 8 m.s⁻¹ is considered relevant for stirring up the sediment under the atmosphere's humidity conditions in the northeastern Mauritania [15]. Furthermore, the World Meteorological Organization (WMO) describes a dust uplift as a storm when the horizontal visibility is less than 1 km with a severe wind (speed >10.3 m.s⁻¹). The data used are archived by speed class of 7.2 km.h⁻¹ range; wind equal or over 21.6 km.h⁻¹ has been therefore selected to establish the data series from the Nouakchott station.

The monthly occurrence of sand storm has been also calculated from the Nouakchott station. This events can happen in winter with northeasterlies and also in summer when monsoon storms.

The drying conditions were defined by the number of days \geq 95 percentiles with a parameter above the period average for the months of August to October. This method was adopted during the seagrass study on Aouatif Bay that is an eastern small part of the area studied [8]. The parameters considered to define drying conditions are air temperature, dew point temperature, wind speed and humidity. The Nouakchott station data has been used. The period studied is extended from 1985 to 2017. All data were centered and reduced to work on anomalies for each of the parameters.

Statistical analysis

The relationship between intertidal seagrass area variations and climatic conditions was tested by the Pearson correlation test. The confidence level was calculated with the probability, p-value with a coefficient $\alpha=0.1$.

Results

Two-time scales were analysed: interannual variations and trends over the series.

Short-term

Strong oceanic wind occurrences have a negative effect on the extension of the meadows in the central area of the Arguin Gulf. Oceanic winds arise mainly in the fall and winter.

Northeasterly winds that occur mainly during spring and summer have also a negative effect on seagrass beds. In addition, the stress induced for one year can have an impact on the seagrass bed (that is measured at the beginning of the following year in our study) and to a lesser extent at the beginning of the second post-stress year.

On the contrary, the number of occurrences of calmness has a beneficial effect on the seagrass beds if it is not alternating with strong negative anomalies of the other climatic parameters; lack of calmness is harmful if not (Table 1).

Seagrass (NDVI)	n+1	n+2
Oceanic wind (Occurrence) >28.8 km.h ⁻¹	-0.862 ($p=0.338$)	-0.42 No confidence
Oceanic wind (speed)	-0.695 ($p=0.511$)	--
Easterlies >21.6 km.h ⁻¹	-0.765 ($p=0.446$)	-0.52 No confidence
Sand storm	-0.508 ($p=0.661$)	No confidence
Monsoon storm	-0.92 ($p=0.249$)	No confidence
Calm wind (speed <7.2 km.h ⁻¹)	0.668 ($p=0.534$)	--

Table 1: Correlation coefficient (and critical probability p) between NDVI indices and climate parameters for different winds. Correlations were calculated between the climatic conditions of year n and the January NDVI of years n+1 and n+2.

In 1998, 2009 and 2011, the drying conditions during the time of exposure show maximum values for the period 1998 to 2015 (Table 2).

By analyzing years on a case-by-case basis, different periods appear to have been controlled by specific stress (Figure 2).

The 1984 to 1990 period is controlled by winter sedimentary deposits related to northeast winds and sand storms. During 1984 and 1985, 1988 and 1989 then 1999 and 2000, the occurrence of northeast winds was abnormally high over two to three consecutive months between November and February. Other years have seen abnormally strong but less than a month-long occurrence.

Long term trend

The extension of grass cover since 1999 after lower values observed from 1985 to 1987 and 1990 is a medium-term trend consistent with the wind patterns over these periods. Indeed, the years 1984 to 2001 were characterized by a strong anomaly of northeasterly wind occurrences (over the average value); the number of sandstorms was also at maximum during the 1984 to 1994 decade. From 2001, this dominant northeasterly regime recorded a drop excepted the 2009 year (Figure 2). At the same decade, severe oceanic winds (speed>28.8 km.h⁻¹) recorded maximum occurrences; the decrease in average of wind intensity and a strong interannual variability characterize the following years with significant one-off events in 2007, 2011 and 2013. Occurrences of calms show a steady increase since 2004.

Variables	T avg (°C)	T-Td	Wind speed (m/s)	H
1997	2	0	5	49
1998	7	9	11	46
1999	1	0	8	76
2000	0	2	7	61
2001	2	4	13	65
2002	2	1	9	58
2003	3	2	1	62
2004	4	5	3	61
2005	5	1	0	61
2006	3	5	5	68
2007	3	2	0	61
2008	6	6	6	57
2009	10	11	3	71
2010	2	2	3	78
2011	5	11	6	57
2012	2	5	7	64
2013	7	3	4	30
2014	6	4	0	--
2015	4	2	2	--

Table 2: Number of days per year when parameters defining conditions that can induce desiccation of marine phanerogamous leaves occurred in the intertidal zone of the Gulf of Arguin (Method developed by de Fouw et al., 2016). The 95 percentile value was selected for each year and parameter.

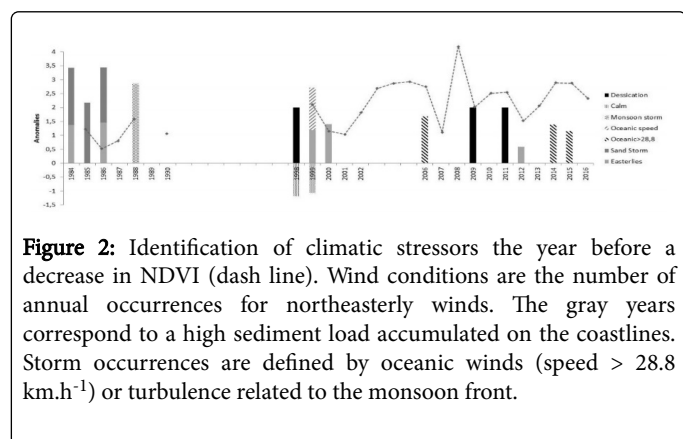


Figure 2: Identification of climatic stressors the year before a decrease in NDVI (dash line). Wind conditions are the number of annual occurrences for northeasterly winds. The gray years correspond to a high sediment load accumulated on the coastlines. Storm occurrences are defined by oceanic winds (speed > 28.8 km.h⁻¹) or turbulence related to the monsoon front.

Discussion

The period from 1983 to 2001 is characterized by very high sediment inputs towards and along the Gulf of Arguin coasts (Littaye et al. 2018). Alternating with the northeasterly winds which are the

driving force behind these inflows, northwesterly winds were also very frequent until 2004, peaking in 1999. This context can corroborate the hypothesis of patched sedimentary deposition on seagrass and mudflats. The *in situ* observations from 1985 to 1988 and 1990 were part of this context of strong hydrodynamics and sediment loading. Phanerogams are known to trap suspended sediments in the water; flow velocities would be slowed by the leaves depending on the seagrass architecture and density. Annual deposits have been estimated to be between 2 cm and 13 cm thick per year for the Banc d'Arguin [16]. This estimate is the result of accretions and redistribution, particularly by tidal currents. The configuration of mudflats in the study area, sheared from channels and with a gently slope, could be favourable to tidal currents sufficient for a sedimentary deposit to be remodelled in the following days. Modelling of storm effects on sediment deposition has shown that neap tides are conducive to accretion and spring tides induce erosion [17].

Cabaço et al. [9] advanced a one-week time limit for the mortality-free burial of *Cymodocea* (*Cymodocea nodosa*). For this species, the recovery would have resulted in adapting the growth of rhizomes and leaves for deposits greater than 16 cm in experimental conditions; for a sediment deposits less than 2 cm thick, the growth remains unchanged. The threshold value of 7 cm of burial is advanced as being capable of causing mortalities according duration. However, the growth pattern is different for each of the species present; vertical or horizontal growth of the rhizomes for *Cymodocea nodosa* and *Zostera noltii* respectively should determine a differentiated response to burial. One or the other species would therefore be more favoured than the other in recurrent situations of sediment input.

Experiments have shown that the impact of deposit thickness on resilience consequently determines the rate of post-stress recovery [18]. However, in the Arguin gulf, the favourable conditions for these deposits were almost permanent until 2004, which could explain the limited development of seagrass compared to their extension a decade later.

In 1997 and 1998, the number of occurrences of oceanic winds or southern storms was lower than in previous years, while northeast winds and coastal sediment loadings were high. Resuspension may have been lower that is consistent with a higher NDVI value in January 1999. Nevertheless, NDVI dropped in 2000. The year 1999 is the peak in the series of oceanic wind occurrences, which are conducive to the resuspension of coastal sediments and in consequence in burial conditions.

In 2001 and 2002, during experiments conducted by van der Laan et al. [4], sediment load conditions were expected to be significant in regards to ten years of accretion, but the sharp drop in easterlies and wind speed in average in any direction (2001 recorded the lowest value of the decade) were not conducive to mass transport from the coast to the mudflats of the study area. No new burial situation was observed nor seagrass recovery.

Stress conditions in 1999 of sedimentation or mechanical effect by hydrodynamics may have impacted the seagrass to a degree that results in a delay of NDVI recovery til year n+1 as in 2001 to 2002. On the contrary, in 2008, the NDVI shows a very strong value after the decrease in 2007. *In situ* experiments and observations have shown that recovery after a burial episode may take several months to two years if the plants survive [4,9].

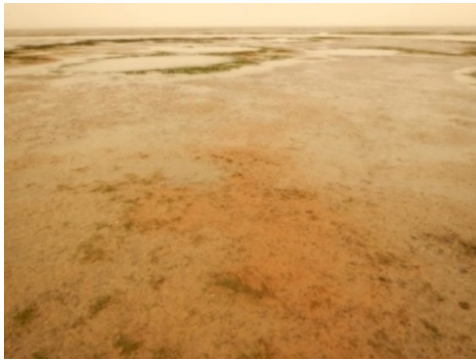


Figure 3: Image of February 7, 2016 shows the extent of the deposition zones; the northeast winds $>21.6 \text{ km.h}^{-1}$ blew from February 1 to 3 and on February 7; they remained from the same northeast sector from February 4 to 6 with a lower intensity. ©Laura Govers.

It should also be taken into consideration, the estimation of vegetation cover by satellite imagery certainly makes it difficult to account for recovery areas. Indeed, the declines in density or the emergence of new growth must be difficult to detect in the first few years, unlike the return of plant growth which were stressed but not dead. Maximum northeast wind events were recorded in winter. Several years 1985, 2000, 2009, 2012 have recorded anomalies of easterlies [more than 40% of days per month with wind speed $>21.6 \text{ km. h}^{-1}$ and nearly 100% of days per month with North-easterlies]. The effect of stress is not immediate on plants, but a bias may have occurred in the NDVI estimation due to remote sensing (Figure 3).

Conclusion

The design of time series allowed put the observations in a meaningful context in time and space of the seagrass bed extent. The various hypotheses on stress complement each other to explain the interannual variations and the long-term trend in the expansion of intertidal seabed. The 1990s climatic conditions were conducive to burial events. On contrary, in the last decade context of a low sediment load in coastal areas and low frequency of dust storms, major stresses appear to have been due to hydrodynamics during storms and air-drying extremes. However, current projections for the coming years suggest a persistence or even a strengthening of these latter conditions with the rise in air temperature and an increase in intensity and number of turbulence.

These seagrasses are formed by two species and if *Zostera noltii* is at its southern limit of geographical distribution, which may be a threat to its survival, *Cymodocea nodosa* has a wider temperature tolerance. The prevalence of oceanic air masses at the expense of northeasterly limits the nutrient input necessary for primary production but maintains a moisture content. Nevertheless, the seagrass beds in the Arguin Gulf seem to be resilient (fast recovery time after stress) and it is necessary to underline in this respect that this seagrass area is protected up to now, against many anthropogenic stresses.

The benefit of having continuous observation series was demonstrated in this study. In addition, in order to anticipate potential climate related changes, the discrimination between the two species

and better assessment of densities in seagrass could be explored using the latest advances in sensors from Earth observation satellites.

Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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