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Par **M. SOILAM BOUTOUMIT**

« Les écosystèmes benthiques des lagunes marocaines : Biodiversité et fonctionnement dans le cadre des changements globaux actuels »

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Rapporteurs avant soutenance :

Mme. Rhimou EL HAMOUMI — Professeure, Université Hassan II, Casablanca, Maroc
Mme. Céline ARZEL — Docent-HDR, Université de Turku, Finlande

Composition du Jury :

Président :	M. Abdelaziz BENHOUSSA	Professeur, Faculté des Sciences de Rabat, Maroc
Examinateurs :		
	Mme. Rhimou EL HAMOUMI	Professeure, Université Hassan II, Casablanca, Maroc
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	Mme. Oumnia HIMMI	Professeure, L'Institut Scientifique de Rabat, Maroc
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Co-directeur de thèse :	M. Hocein BAZAIRI	Professeur, Faculté des Sciences de Rabat, Maroc

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"Les espèces qui survivent ne sont pas les espèces les plus fortes, ni les plus intelligentes, mais celles qui s'adaptent le mieux aux changements."

Charles Darwin

Titre : Les écosystèmes benthiques des lagunes marocaines : biodiversité et fonctionnement dans le cadre des changements globaux actuels.

Mots clés : Systèmes côtiers semi-fermés, Macrofaune benthique, Checklist, Lagune de Moulay Bousselham, Variation temporelle, Maroc.

Résumé

Ce travail a, tout d'abord, examiné et synthétisé les données existantes sur la macrofaune benthique des systèmes côtiers semi-fermés marocains (SCSF). Puis il a proposé de manière préliminaire, en tant qu'ouverture mais également dans une logique de complémentarité, une approche fonctionnelle différente des invertébrés benthiques de la lagune de Moulay Bousselham au travers un échantillonnage exhaustif et un suivi saisonnier. Ce travail constitue une des premières études traitant le compartiment benthique en relation avec les paramètres environnementaux à une échelle spatiale aussi étendue couvrant toute la lagune. Il est également, à notre connaissance, une des premières à évaluer la variation saisonnière de ce compartiment prenant en considération les différents type d'habitats de l'écosystème.

Les résultats ont en premier lieu montré l'importance de la richesse spécifique des 12 écosystèmes étudiés (au total 496 espèces) et les facteurs contrôlant la variation totale observée dans la composition des assemblages benthiques : le type de SCSF (estuaires vs lagunes vs baie), l'écorégion marine (Atlantique vs Méditerranée), la surface du SCSF et les caractéristiques environnementales (température minimale, salinité minimale et maximale). D'un autre côté, nos résultats ont montré que la richesse en espèces et la diversité taxonomique n'avaient aucune relation avec la latitude. De telles différences dans la composition de la macrofaune benthique à grande échelle pourraient résulter du fait que chaque écosystème a ses propres caractéristiques spécifiques, ce qui implique une approche individualiste de l'écologie des écosystèmes. Cette étude a souligné également l'insuffisance des connaissances pour répondre aux lacunes perçues dans la connaissance de la biodiversité, de son importance pour la fonction des écosystèmes, et des menaces et conséquences des perturbations par les activités anthropiques.

En deuxième lieu, la présente étude propose une évaluation de la diversité et de la distribution spatiale des communautés de macrofaune benthique le long de la lagune de Moulay Bousselham et discute les facteurs environnementaux contribuant aux modèles observés. Ainsi, en automne 2018, 68 stations ont été échantillonnées avec trois réplicats par station dans les zones subtidales et intertidales. Les résultats des conditions environnementales ont montré que la gamme de température de l'eau était comprise entre 25,0°C et 12,3°C, la salinité varie entre 38,7 et 3,7,

tandis que la moyenne des valeurs de pH fluctue entre 7,3 et 8,0. Dans les habitats végétalisés, la biomasse de *Zostera noltei* Hornemann se situe entre 31,7 gDW/m² et 170,2 gDW/m² tandis que la biomasse de *Ruppia cirrhosa* (Petagna) Grande se situe entre 54,2 gDW/m² et 84,7 gDW/m². Les analyses des sédiments ont montré que la lagune est principalement composée de sédiments sableux et limoneux. De point de vu faunistique, nous avons identifié 37 165 individus de macrofaune répartis dans 63 taxons appartenant à 50 familles, avec une valeur d'abondance moyenne de 4582,8 ind/m² et une biomasse moyenne de 22,2 g PSLC/m². Nos résultats ont clairement révélé que le régime hydrographique (marin et terrestre d'eau douce), la distribution et les caractéristiques des sédiments et le type d'habitat (substrat végétalisé vs non végétalisé) sont les facteurs clés qui déterminent la composition des espèces et les modèles des assemblages de macrozoobenthos.

La dynamique saisonnière des structures communautaires dans la lagune de Moulay Bousselham menée à court terme, a permis de travailler sur des moyennes saisonnières des paramètres abiotiques et biotiques. Afin d'examiner les tendances de la biodiversité à travers une échelle de variation saisonnière les communautés benthiques ont été étudiées dans la lagune pendant l'hiver et l'été 2019. Les valeurs plus faibles de la température de l'eau ont été enregistrées en aval, reflétant l'influence des eaux océaniques froides à l'entrée de la lagune. Alors que la salinité montre un gradient décroissant de l'aval vers l'amont de la lagune. Les analyses de sédiments ont montré que la lagune est principalement composée de sédiments sableux et limoneux. Dans les stations avec les habitats végétalisés, la biomasse *Zostera noltei* varie entre 0,79 gDW et 46,69 gDW en hiver et entre 9,34 gDW et 47,67 gDW en été. Alors que la biomasse de l'herbier *Ruppia cirrhosa* se situe entre 5,53 gDW et 28,66 gDW en hiver et entre 14,48 gDW et 34,06 gDW en été. Hormis la température et la salinité de l'eau, les variables environnementales ne présentent aucune différence significative entre l'hiver et l'été (test Anova : $p > 0,05$).

Dans les 29 stations échantillonnées, 42 taxons ont été dénombrés en hiver et 32 taxons en été avec une valeur moyenne de biomasse de 25,10 g PSLC/m^2 (hiver) et 9,14 g PSLC/m^2 (été). En dehors de la biomasse, qui est soumise au rythme saisonnier, les paramètres de diversité ne présentent pas de différence significative entre les saisons (test Anova : $p > 0,05$). Les résultats de l'analyse DistLM ont révélé que la diversité et la distribution de la macrofaune dans la lagune sont contrôlées par une combinaison de facteurs : les caractéristiques des sédiments (teneur en vase, granulométrie, la matière organique totale, % carbone, % $CaCO_3$ et % $CaCO_2$), les caractéristiques de l'eau (température et salinité) et le type d'habitat (biomasse de *Z. noltei* et *R. cirrhosa*).

Title: Benthic ecosystems of Moroccan lagoons: Biodiversity and functioning in the light of current global changes.

Keywords: Semi enclosed coastal systems, Benthic macrofauna, Checklist, Moulay Bousselham lagoon, Temporal variation, Morocco.

Abstract

This work has first examined and synthesized the existing data on the benthic macrofauna of Moroccan semi-enclosed coastal systems (SECS). Then it proposed in a preliminary way, as an opening but also in a logic of complementarity, a different functional approach of the benthic invertebrates of the lagoon of Moulay Bousselham through an exhaustive sampling and a seasonal monitoring. This work constitutes one of the first studies treating the benthic compartment in relation to environmental parameters at such an extended spatial scale covering the whole lagoon. It is also, to our knowledge, one of the first to evaluate the seasonal variation of this compartment taking into consideration the different types of habitats of the ecosystem.

The results first showed the importance of the species richness of the 12 ecosystems studied (a total of 496 species) and the factors controlling the total variation observed in the composition of the benthic assemblages: the type of SECS (estuaries vs lagoons vs bay), the marine ecoregion (Atlantic vs Mediterranean), the surface of the SECS and the environmental characteristics (minimum temperature, minimum and maximum salinity). On the other hand, our results showed that species richness and taxonomic diversity had no relationship with latitude. Such differences in the composition of the benthic macrofauna on a large scale could result from the fact that each ecosystem has its own specific characteristics, which implies an individualistic approach to ecosystem ecology. This study also highlighted the lack of knowledge to address perceived gaps in knowledge of biodiversity, its importance for ecosystem function, and the threats and consequences of disturbance by anthropogenic activities.

Secondarily, this study proposes an assessment of the diversity and spatial distribution of benthic macrofauna communities along Moulay Bousselham Lagoon and discusses the environmental factors contributing to the observed patterns. Thus, in autumn 2018, 68 stations were sampled with three replicates per station in the subtidal and intertidal zones. The results of the environmental conditions showed that the water temperature range was between 25.0°C and 12.3°C, salinity ranged from 38.7 to 3.7, while the average pH values fluctuated between

7.3 and 8.0. In the vegetated habitats, the biomass of *Zostera noltei* Hornemann ranged from 31.7 gDW/m² to 170.2 gDW/m² while the biomass of *Ruppia cirrhosa* (Petagna) Grande ranged from 54.2 gDW/m² to 84.7 gDW/m². Sediment analyses showed that the lagoon is mainly composed of sandy and silty sediments. From a faunistic point of view, we identified 37,165 individuals of macrofauna distributed in 63 taxa belonging to 50 families, with a mean abundance value of 4582.8 ind/m² and a mean biomass of 22.2 g AFDW/m^2. Our results clearly revealed that hydrographic regime (marine and freshwater terrestrial), sediment distribution and characteristics, and habitat type (vegetated vs. non-vegetated substrate) are the key factors that determine species composition and patterns of macrozoobenthos assemblages.

Seasonal dynamics of community structures in Moulay Bousselham lagoon conducted in the short term, allowed working on seasonal averages of abiotic and biotic parameters. In order to examine trends in biodiversity through a scale of seasonal variation benthic communities were studied in the lagoon during winter and summer 2019. Lower water temperature values were recorded downstream, reflecting the influence of cold oceanic waters at the lagoon entrance. While salinity shows a decreasing gradient from downstream to upstream of the lagoon. Sediment analyses showed that the lagoon is mainly composed of sandy and silty sediments. At stations with vegetated habitats, *Zostera noltei* biomass ranged from 0.79 gDW to 46.69 gDW in winter and from 9.34 gDW to 47.67 gDW in summer. The biomass of the *Ruppia cirrhosa* meadow ranges from 5.53 gDW to 28.66 gDW in winter and from 14.48 gDW to 34.06 gDW in summer. Except for water temperature and salinity, the environmental variables showed no significant difference between winter and summer (Anova test: $p > 0.05$).

In the 29 stations sampled, 42 taxa were counted in winter and 32 taxa in summer with a mean biomass value of 25.10 g AFDW/m^2 (winter) and 9.14 g AFDW/m^2 (summer). Apart from biomass, which is subject to the seasonal rhythm, the diversity parameters do not show significant differences between seasons (Anova test: $p > 0.05$). The results of the DistLM analysis revealed that the diversity and distribution of macrofauna in the lagoon are controlled by a combination of factors: sediment characteristics (mud content, grain size, total organic matter, carbon %, $CaCO_3$ % and $CaCO_2$ %), water characteristics (temperature and salinity) and habitat type (biomass of *Z. noltei* and *R. cirrhosa*).

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Chapter 3

Table 1. SIMPER results showing the average similarity between benthic assemblages identified by Cluster analysis and the contribution of characteristic species of each benthic assemblage.

Table 2. Results of DistLM analyses showing relationships between environmental predictor variables and macrofauna community structure.

Chapter 4

Table 1. Results of ANOVA testing for environmental variables differences between seasons. **Df:** Degrees of freedom; **MS:** Mean square; ***p* (perm):** Level of significance. Significant effects are indicated in bold.

Table 2. Results of ANOVA testing for macrobenthic assemblages differences in S, N, H', J' and biomass. **Df:** Degrees of freedom; **MS:** Mean square; ***p* (perm):** Level of significance. Significant effects are indicated in bold.

Table 3. Results of SIMPER analysis showing the average similarity between stations of the benthic assemblages in the two seasons identified by the cluster analysis and the characteristic species of each benthic assemblage.

Table 4. Results of sequential test of the multivariate regression analysis (DistLM).

General introduction

Coastal ecosystems are among the most productive areas of the planet (Costanza et al., 1997). These ecosystems represent nearly 20% of primary production, 17% of CO_2 assimilation by the oceans, 90% of sediment remineralization of the oceans and 80% of the burial of organic matter (allowing for high secondary production) (Agardy et al., 2005, Cai 2011). Their high biological richness and their crucial role in the life cycle of many species (nursery, refuge, growth place and migration axis) thus give these areas a strong ecological stake (Chevillot, 2016). In addition, they provide numerous ecosystem services such as the supply of raw materials and food, the stabilization of sediments and the protection of coasts against erosion, the regulation of nutrient cycling and the bioremediation of pollutants (Liquete et al., 2013). In addition, coastal areas harbor diverse systems in terms of climate, geomorphology, hydrography or geochemistry (Spalding et al., 2007, Greenlaw et al., 2011). This diversity promotes high biodiversity on a global scale (Tittensor et al., 2010, Sanford & Kelly 2011).

Although these coastal environments represent only 9% of the marine environment in surface area, they contribute more than 70% of the economic value due to the importance of the ecosystem services provided (Costanza et al., 1997). From a socio-economic point of view, this interface situation gives coastal and estuarine areas a strategic position for the development of numerous anthropic activities: port and industrial activities, urban and tourist areas (Allain et al., 2006). They currently concentrate nearly 60% of the population and future estimates suggest that by 2025, 75% of this population will live near the coasts in response to increases in (1) population growth (2) the high rate of migration to these richer and more productive coastal areas (3) the growing development of tourism and (4) the intensification of anthropogenic activities (Bianchi, 2006, Chevillot, 2016).

The recent human population explosion is accompanied by the intensification and modification of anthropogenic activities that strongly affect coastal ecosystems (Maanan et al., 2013). The anthropogenic pressures affecting these ecosystems are multiple: habitat loss (caused by port activities, dredging and diking) and its fragmentation, eutrophication, pollution, hydrological imbalances and the introduction of alien species. In addition to these local pressures, there are the progressive effects of climate change, the global result of anthropogenic forcing from greenhouse gas emissions (Lee et al., 2006; IPCC, 2013). These pressures do not just lead to ecological disruption. They limit or remove the economic and ecological services provided by these ecosystems, initiating vicious cycles of disturbance (Beck et al., 2001). Disturbance of these ecosystems has socioeconomic impacts that generate multiple use conflicts. Therefore, these areas require management that integrates legal, socioeconomic and ecological aspects (Dauvin, 2002).

In order to detect the ecological impact of a disturbance, it is necessary to distinguish natural variability on different time scales from variations linked to the disturbance of the ecosystem (seasonal, interannual, etc.). In this sense, the benthic macrofauna is a good indicator of environmental variations (Dauvin, 1993). The benthos and the sedimentary substratum are two important elements for analyzing coastal marine ecosystems. The benthic macrofauna is the most considered biological component in ecological studies of benthic ecosystems since it provides information that is absolutely essential for understanding the functioning and changes that these ecosystems undergo (Zaabi-Sendi, 2013).

These benthic animals have the ability to integrate environmental disturbances and respond with changes in their structural parameters, such as abundance and number of species (Boero, 1994; Occhipinti-Ambrogi et al., 2005). Therefore, these organisms are often used as indicators of the quality and health of marine and coastal environments (Pearson & Rosenberg, 1978; Bilyard, 1987; Gibson et al., 2000). In general, these relatively sedentary organisms have long life cycles that allow them to integrate the effects of both accidental and chronic disturbances (Dauvin, 1993; Reiss & Kröncke, 2005) and have different degrees of tolerance to stress (Torres-Gavila, 2008). In addition, macrobenthic communities are key elements that play an important role in the food chain for many higher order consumers, particularly for fish and birds. Several studies have shown that the distribution of the bird community is strongly correlated with local variations in the benthic macrofaunal community and their accessibility (Degre 2006, Dwyer 2010, Van Dusen et al., 2012).

The Moroccan coastline is host to a large number of paralic ecosystems such as coastal lagoons, estuaries and bays. These areas, often of international importance, harbor a remarkably rich and diverse biodiversity and represent ecotones fulfilling various ecological functions, giving them important biological, hydrological and socio-economic values.

Given the scientific and socio-economic importance of these areas, a better knowledge of their ecosystem is necessary to improve and rationalize the management of their resources. The works related to the benthic macrofauna of the benthic ecosystems in Morocco are few and the knowledge acquired on this biological compartment is incomplete. It is in this context that this work has for objectives:

1. A synthesis of existing data on Moroccan benthic ecosystems:

The objectives are:

- To provide the first national and comprehensive checklist of the soft bottom macrozoobenthic species in semi-enclosed coastal systems of Morocco.
- To test for the presence of a latitudinal diversity gradient in soft bottom macrozoobenthic species of semi-enclosed coastal systems of Morocco.
- To understand their drivers by comparing the benthic assemblages between the different sites according to their ecoregion, their latitudinal position, the type of ecosystem (lagoon, estuary or bay), the site surface area, temperature and salinity.
- To identify the current knowledge and gaps and make recommendations on respective research in future years.

2. Multi-proxy study of the benthic structures of the Moulay Bousselham lagoon:

The aim of our thesis research is to update and deepen the knowledge on the benthic component of the Moulay Bousselham lagoon. It is based on a sampling strategy covering the entire lagoon in both intertidal and subtidal. Few studies of this type have been carried out in other Moroccan ecosystems, which justifies the lack of an appropriate database on which to compare and discuss the results obtained. This lack is probably due to the considerable effort, time and logistics required to carry out this type of study.

The objectives of this section are:

- To provide new insight into the biodiversity of the macrozoobenthos assemblages inhabiting the Moulay Bousselham lagoon, their composition, structure and spatial patterns.
- To highlight the environmental drivers that govern the spatial distribution of benthic communities.
- To investigate the seasonal variation in macrozoobenthic assemblages and the environmental factors driving their patterns in different areas within the Moulay Bousselham lagoon over two seasons (winter and summer).

This thesis has been presented as a set of articles. Each part is intended to be complete if separated from the thesis. Nevertheless, the topics addressed in each of the four chapters are closely related, as an attempt has been made through each part to address our main objective.

After a general introduction, the general context of the study area through a description of its geographical location, geology, climatology, hydrology, habitats, importance and threats were presented in the first part. As well as the steps of data acquisition and processing (sampling, laboratory processing, data analysis...). In the second part we attempted to synthesize existing data on the benthic macrofauna of the main benthic ecosystems in Morocco. We also tested the presence of a latitudinal gradient of diversity, identified gaps and made recommendations for future studies. The third part updates the composition of soft bottom macrofaunal assemblages in Moulay Bousselham lagoon. This chapter provide the most extensive and comprehensive research on the biodiversity of macrozoobenthos assemblages inhabiting this semi enclosed coastal system, their composition, structure, spatial patterns. In addition, it highlight the environmental drivers that govern their spatial distribution. The fourth part was devoted to the study of the seasonal variation of the benthic communities of this lagoon and the relationship between this macrofauna and the environmental factors.

Chapter 1

Material and methods

(©by S. Boutoumit)

« Vagabonder à la surface des océans est souvent source de sérénité et, parfois, permet de tutoyer ses rêves. S'y immerger, c'est s'ouvrir à son observation et à sa compréhension »

Nicolas Hulot

This thesis aimed fisrt at synthesing the existing published and unpublished data on Moroccan benthic ecosystems. Then, we focused on the Moulay Bousselham lagoon with a multi-proxy approach that aims to study the benthic structures of the lagoon in relation to environmental patterns and seasonal variation.

For this purpose, this chapter 'material and methods' will be treated in two parts:

- For the first part, which deals with benthic ecosystems, we will briefly present the studied sites (Figure 1), except the Moulay Bousselham lagoon that will be dealt sufficiently in the second part. All the data analysis and processing will be presented in chapter 2: **"Soft-bottom macrozoobenthos in semi-enclosed coastal systems of Morocco: A latitudinal and biogeographic analysis"**.
- For part 2, which deals with the multi-proxy approach of the Moulay Bousselham lagoon, we will present a detailed description of the site and the sampling strategies as well as the steps followed for the processing of samples and data analysis.

Part 1: Moroccan semi-enclosed coastal systems: Study sites

The Nador lagoon

The lagoon of Nador, also called Mar Chica or Sebkha Bou Areg, is the second largest Mediterranean lagoon of the southern shore, with an area of 115 km^2. It is located in the northeast of the Moroccan Mediterranean coast (Rif) between the Cape of Three Forks and Cape Water, between latitudes 34 ° 54'N and 35 ° 17'N and between longitudes 02 ° 10'W and 03 ° 05'W. It is separated from the sea by a dune cordon of 25 km length oriented NW-SE. Its communication with the Mediterranean is ensured by a pass locally called Bukhana.

The site was classified as a Site of Biological and Ecological Interest (SIBE) in 1996, and was included in the list of Ramsar sites of conservation and protection of wetlands since 2005 (El Agbani et al., 2011).

The Smir lagoon

The lagoon of Smir is located in the northwest of Morocco, 25 km south of the Strait of Gibraltar and a few kilometers north of the town of M'diq. Its geographical position (35°43'N and 5°20'W) makes it the most western lagoon of the Mediterranean basin. The Smir lagoon covers an area of about 3 km^2, its maximum depth is 2.5 m for an average depth of 1.5 m. This lagoon ecosystem communicates with the port of Kabila, then with the sea through a gully and is subject to regular tidal movements whose average amplitude can reach 1 m (Chaouti and Bayed, 2005).

The wetland complex of Smir was classified as a Site of Biological and Ecological Interest (SIBE) in 1996. The Smir wetland was one of the Moroccan sites included in the 'Mediterranean Intercontinental Biosphere Reserve' shared between northern Morocco and Andalusia (Spain), which was designated by UNESCO in October 2006. The site was included in the list of Ramsar sites of conservation and protection of wetlands in 2019.

The Sidi Moussa lagoon

The lagoon of Sidi Moussa is located approximately 37 km south of the city of El Jadida. It is characterized by an elongated shape that was imposed by the morphology of the interdunal depression between the consolidated continental and coastal dunes. The lagoon is part of a straight strip parallel to the coast of 5.5 km long and 0.5 km wide, the total area is estimated at 4.2 km². Three morphological units characterize the lagoon: the intertidal mudflats, the schorres and the primary and secondary channels (Maanan, 2008).

The Oualidia lagoon

The lagoon of Oualidia (32° 52' 0"N/ 8° 51' 05"W) is located 75 km south of the city of El Jadida and 65 km north of the city of Safi. It has an elongated shape more or less parallel to the coast with an axis of elongation oriented 27°N. Its length is 7 km, with a width of 0.5 km and a total area of 3.5 km² of which 53% are occupied by the intertidal zone while the rest (47%) is represented by the channels.

It forms with the Sidi Moussa lagoon the Sidi Moussa-Oualidia complex which was selected in the Master Plan of Protected Areas of Morocco as a Site of Biological and Ecological Interest (SIBE) and was declared a RAMSAR site in 2005 (Hilmi et al., 2005; Maanan et al., 2014).

The Khnifiss lagoon

Located 120 km south of Tan-Tan and 70 km north of Tarfaya, the Khnifiss lagoon (also called Naïla) is the largest Moroccan Atlantic lagoon. It has a length of 20 km and an area of 65 km². This lagoon opens onto the Atlantic coast through a narrow pass called "Foum Agouitir", about a hundred meters wide and extends to a salt pan known as "the Sebkha Tazra". The site has been listed since 1980 on the Ramsar Convention as a wetland of international importance (Lefrere, 2013).

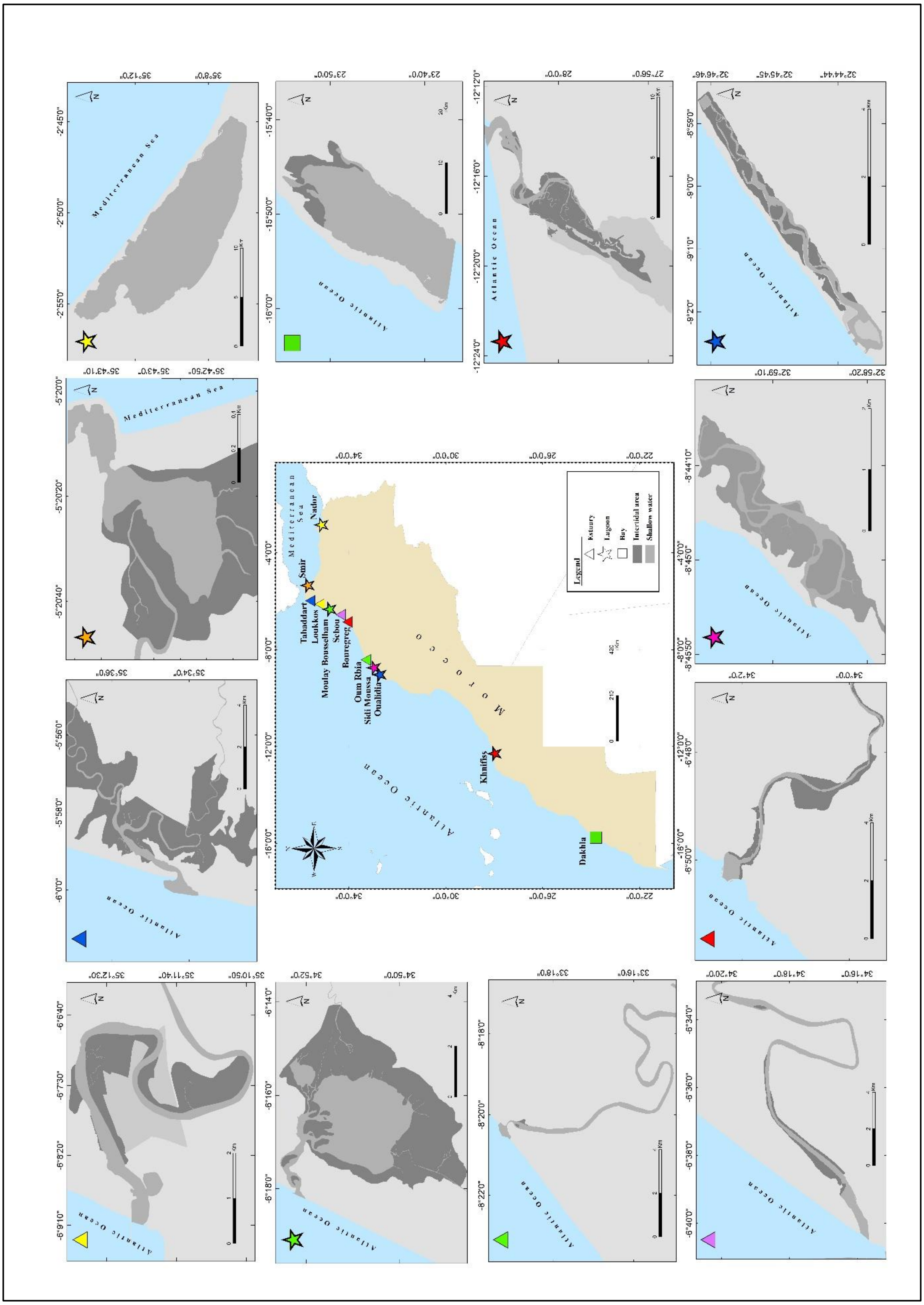

Figure 1. Maps showing the geographical position and the geomorphology of the study sites considered in the latitudinal analysis of benthic macrofauna (©by S. Boutoumit).

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The Dakhla bay

Dakhla Bay is a particular coastal environment. It is located in the South of Morocco, in the Dakhla-Oued Eddahab region. It is located between the points 23°35'N-16°00'W and 23°55'N-15°45'W. It is a relatively narrow bay, open to the South on the Atlantic Ocean, 37 km long and between 10 and 12 km wide.

Dakhla Bay has the shape of a finger of glove, parallel to the coast, oriented NE-SW and limited on the side of the Atlantic Ocean by the Oued Eddahab peninsula, formed by sandy dunes consolidated in unconformity on a Mesozoic bedrock (Beaubrun, 1990).

Dakhla Bay is known as a Site of Biological and Ecological Interest (SIBE) according to the national study on protected areas carried out between 1993 and 1995, an Important Bird Area (IBA) and finally a site retained by the RAMSAR convention. According to the RAMSAR criteria, Dakhla Bay is unique in North Africa; it is both a migration relay, wintering and nesting area for thousands of waterbirds (Qninba et al., 2003).

The Tahaddart estuary

The Tahaddart estuary is located in the northwest of Morocco and occupies the northern part of the Atlantic coastline of the Tangier peninsula, it is located about 30 km south of the city of Tangier and 15 km north of the city of Asilah. The estuary extends for about 3.5 km in a N30 direction from the junction in the NE of the Mharhar (north) and El Hachef (south) rivers to the Atlantic coast in the SW. With its wetland annexes, it has been classified as a Site of Biological and Ecological Interest (SIBE) and RAMSAR site (Dakki et al., 2003).

The Loukkos estuary

The Loukkos estuary is a river that winds between the ancient city of Lixus and the present city of Larache. This environment consists of two parts: the upstream part of the Loukkos river with a sinuous channel, characterized by free meanders in the alluvium of a muddy and marshy plain and the downstream part of the continental shelf. The Loukkos complex has been listed since 2005 in the RAMSAR convention (El Morhit, 2009).

The Sebou estuary

The Sebou estuary has the shape of an arm of the ocean that extends over a distance of 15 km oriented roughly N-W from upstream to downstream (Oveed and Bahraoui, 1970). It is characterized by a particular tidal dynamics that conditions the different parameters of the environment, especially its hydrology and generates sediment reworking (Lebunetel et al., 2014).

The Bouregreg estuary

The Bouregreg, one of the main estuaries of Morocco, is located between the cities of Rabat and Salé. It extends over a length of 23 km, limited by the dam of Sidi Mohammed Ben Abdellah and an average width of 150 m. The estuary is generally oriented southeast and northwest, except in the sector from the kilometer point 13.5, to the confluence of Oued Akrech where it is oriented southwest/northeast (Cherkaoui, 2006).

The Oum Er Rbia estuary

The estuary of Oum Er Rbia is located in the city of Azemmour, 17 km north of El Jadida. It has a length of 16 km, on the left bank of its mouth, 14 km from the sea, there is a dam "Sidi Daoui" which was built on the central course of the estuary since 1985, limiting its length and profoundly changing its hydrodynamic properties (Chaouti et al., 2016).

Part 2: Multi-proxy study of the benthic structures of the Moulay Bousselham lagoon

The Moulay Bousselham lagoon: a hotspot of international relevance

Location and general morphology

Moulay Bousselham (34º47’N and 6º13’W) is an Atlantic lagoon located in northern Morocco, at the northern limit of the Gharb plain, about 70 km north of the city of Kenitra and 35 km south of the city of Larache (Figure 2). The overall area of the biological reserve of the lagoon is 7,300 ha. The lagoon environment occupies the core of this reserve, has an elliptical shape with an area of about 3,000 ha, with a maximum length and width of 9 km and 5 km, respectively (Benhoussa, 2000). It is surrounded by low sandy dunes; one of them, in the form of a barrier beach, separates the lagoon from the ocean and is interrupted by a gully that ensures the circulation of water between these environments.

Two permanent channels flow into the lagoon: the artificial channel of Nador to the south and Oued Drader to the northeast of the lagoon. The tidal part of the latter course divides the lagoon into two parts of unequal size. The most important is the Merja Zerga located in the South, with an area of 2,700 ha and the Merja Kahla (or Merja Mellah) in the North, with an area of 300 ha.

At high tide, the entire lagoon slikke is completely submerged in water, however, at low tide, the two parts of the lagoon show vast intertidal mudflats surrounded by belts of emergent halophilic vegetation (schorres). Only the channels and the downstream parts of Oued Drader and Canal Nador remain submerged.

Habitats

The Moulay Bousselham Lagoon has a high diversity of habitats (Figure 3). This diversity results from the combined influence of hydrology, sedimentology and the richness of its vegetation (Dakki et al., 1998; Qninba, 1999; Benhoussa et al., 1999; Benhoussa, 2000). Among all the habitats identified in the site, the intertidal mudflats are the main component (Table 1), with about 1,300 ha, representing over 44% of the wetland. The habitat map of the lagoon shows the existence of three systems (estuarine, palustrine and flowing water):

The estuarine system: it represents more than 80% of the total area of the site with an area of about 2,500 ha. The Mediterranean Wetlands (MedWet) terminology allows four classes to be distinguished:

- **The surface water (180 ha):** corresponds to the subtidal channel network connecting the Ocean to the slikke.

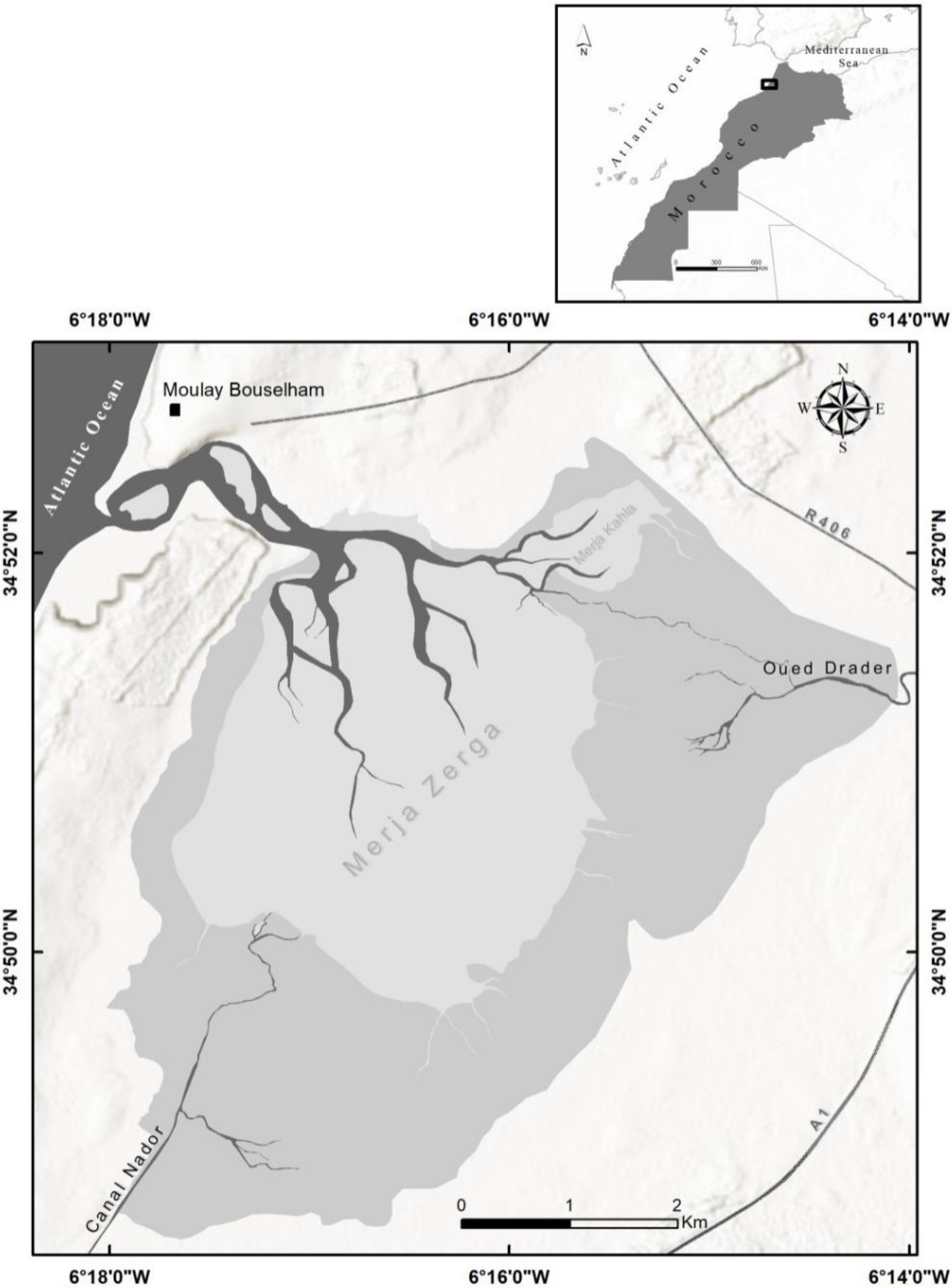

Figure 2. Map showing the geographical position of the Moulay Bousselham lagoon (©by S. Boutoumit).

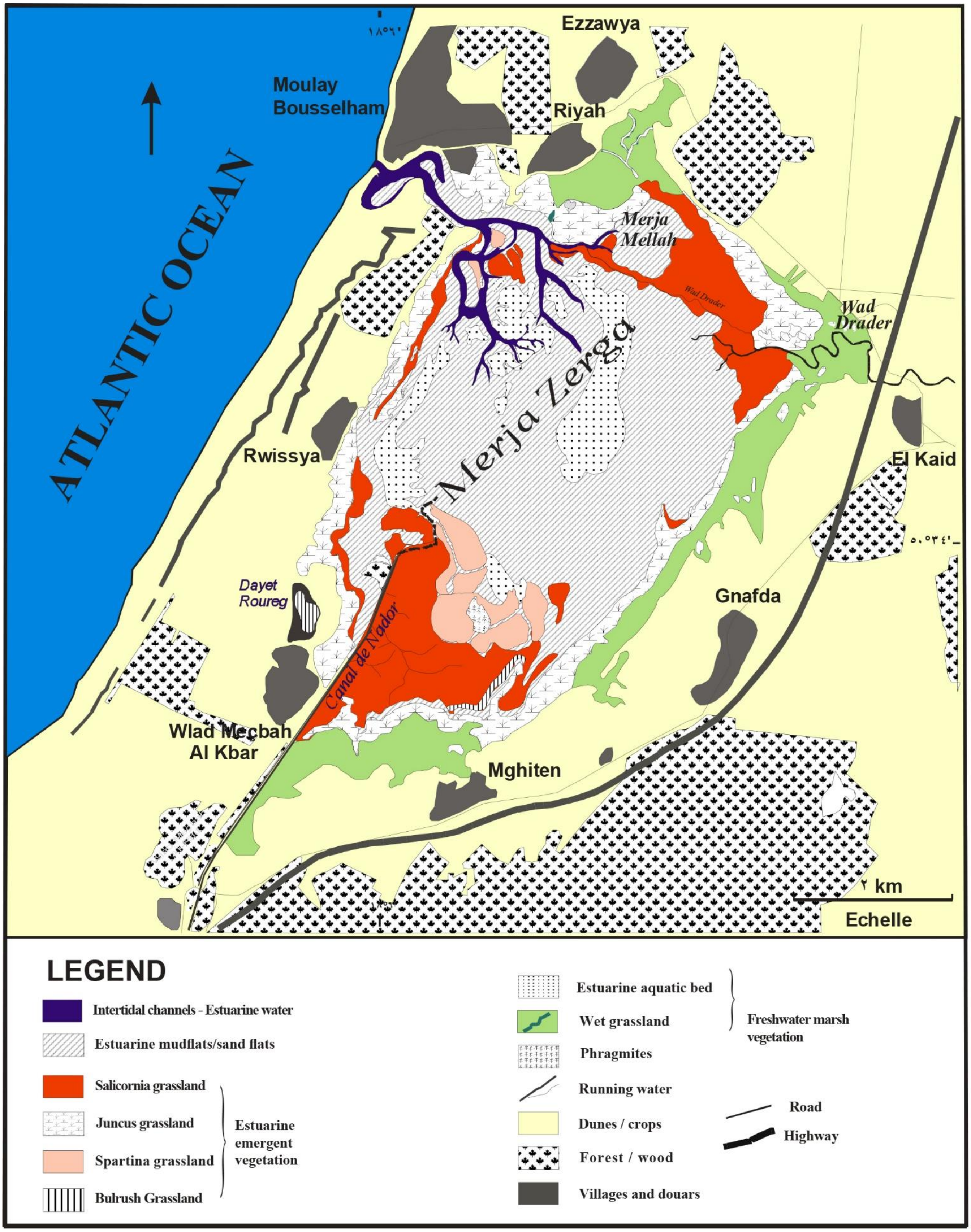

Figure 3. Habitat map of Moulay Bousselham lagoon (Qninba et al., 2006).

- **The aphytic substratum:** it consists of mudflats (1300 ha) and sandflats (20 ha).
- **The aquatic beds (140 ha):** it is the seaweed and seagrass beds, covering the mudflats and the sandflats.
- **The Emergents (halophilic meadows):** we differentiate from the interior of the lagoon to the exterior: the meadows with Spartina (130 ha), the meadows with Sarcocornia/Salicornia (440 ha) and the meadows with *Juncus rigidus* (340 ha).

The palustrine system (wet grasslands: 380 ha): forms the outermost habitat of the lagoon, providing a transition from estuarine to terrestrial habitats. The outer limits of this system mark the beginning of a dune formation invaded by crops and reforestation.

The system of flowing water: represented by the watercourses of Oued Drader and the artificial canal of Nador.

Table 1. Surface areas of the main habitats identified in Moulay Bousselham lagoon (Qninba et al., 2006).

Habitats	Surface area (ha)	Percentage
Water body (permanently flooded channels and slikke)	180	6.14
Sand flats (exondable at low neap tide)	20	0.68
Mudflats (exondable at low tide of neap tide)	1 300	44.37
Seagrass beds (algae and zostera)	140	4.78
Spartina halophilic grasslands	130	4.43
Sarcocornia/*Salicornia* grasslands	440	15.02
Grasslands with *Juncus rigidus*	340	11.60
Peripheral lawns	380	12.97
Total	2 930	100.00

Hydrodynamics and Hydrology

The hydrological regime of the Moulay Bousselham lagoon is mainly determined by the rhythm of the tides. At low tide of neap tide, only the channels and the downstream parts of the oued Drader and the Nador Canal are immersed; on the other hand, at high tide of spring tide, the whole slikke is submerged. This regime is subject to the dual oceanic and continental influence, resulting from the dynamics of three inputs (oceanic, continental surface and underground - Figure 4):

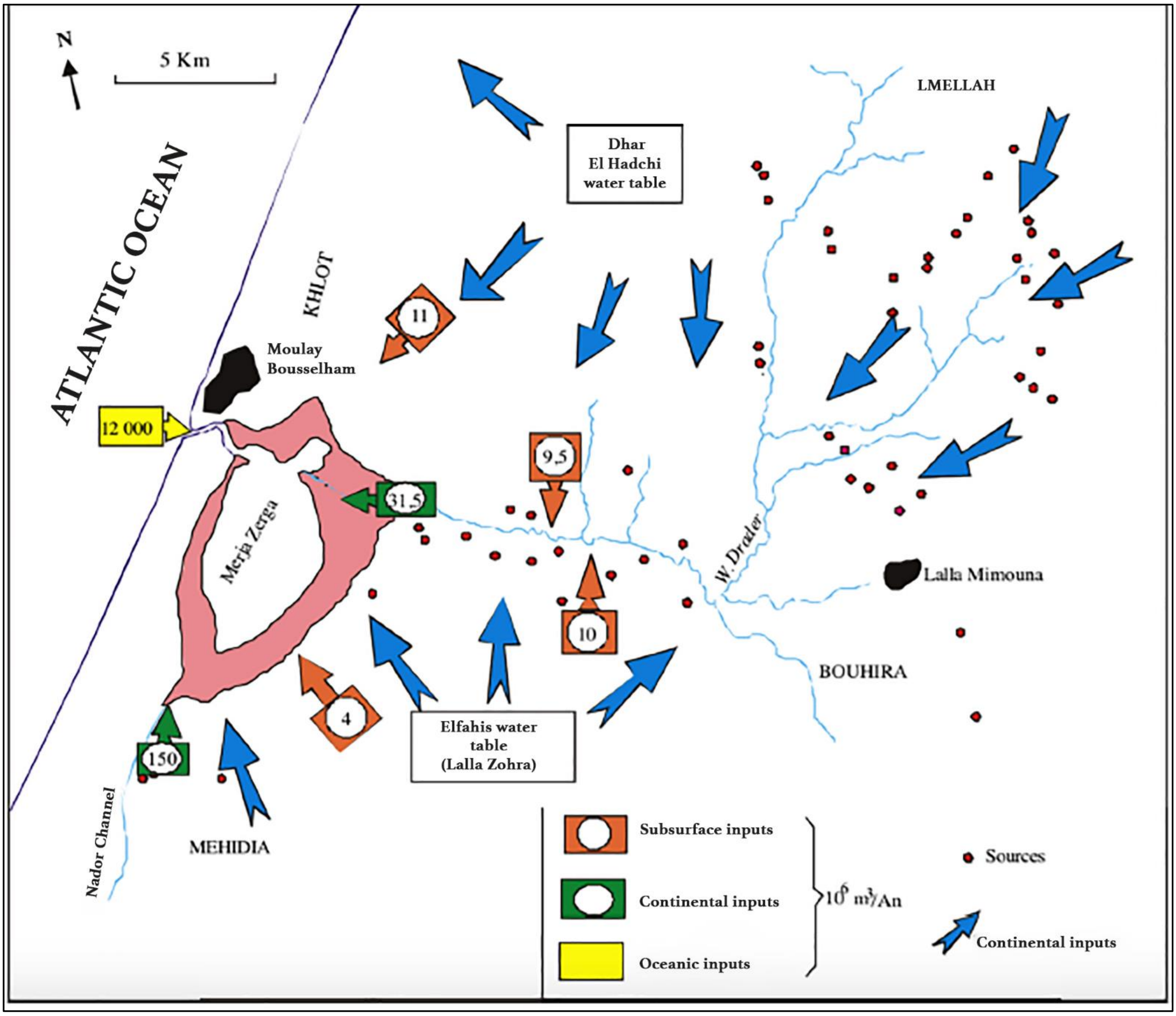

Figure 4. Hydrological assessment of the Moulay Bousselham watershed (Combe, 1968).

Oceanic inputs:

Oceanic waters that pass through the gully regularly feed the lagoon. This supply depends on two factors, the tidal rhythm and the morphological evolution of the gully (Benhoussa, 2000). These contributions of marine water are very important, with an average annual volume of about 12,000 106 m^3/year (98% of the overall amount of water that transits in the lagoon). The rhythm of the tides in Moulay Bousselham is semi-diurnal, with a tidal range oscillating between 0.15 and 1.5 m (Carruesco, 1989a, b).

Surface continental inputs:

Provided by:

Oued Drader: which drains a small catchment area of about 700 km^2 and which discharges into the northeastern part of the lagoon in two places forming a small delta very silted. The annual input of Oued Drader is estimated at 31.5 106 m^3/year (Combe, 1968).

Nador Canal: It was built in 1953, essentially to drain the Rharb marshy complex, the Oued M'da basin and part of the right side of Oued Sebou. The average annual inflow of the Nador Canal is estimated at about 150,106 m^3/year (Figure 4) (Benhoussa, 2000).

Underground water inputs:

The region is endowed with two important water tables that constitute a real water tower of the basin. The water table of Dhar El Hadechi, located northeast of Merja Zerga and the water table of El Fahis, located east of the lagoon (Figure 4). These two aquifers contribute with more than 34,106 m^3/year of the lagoon water (Combe, 1968).

The total continental and underground inputs do not exceed 2% of the waters of Merja Zerga (Benhoussa, 2000). These freshwater inputs can be more important during the winter (rainy) periods, following the swelling of the water table and the increase in the flow of the two permanent rivers that feed the lagoon. The continental edge of the lagoon, where the main wet meadows develop, has a hydrological regime that is mainly dependent on rainfall. These habitats are particularly swampy during the wet season and become dry in summer (Qninba et al., 2006).

The water temperature of the lagoon varies between 13 and 15ºC in winter and 27 and 28ºC in summer. The salinity varies according to the seasons and the tides. In summer, the salinity is almost equal to the oceanic salinity (35 psu) in the whole lagoon, except for the remote edges where it is less than 35 psu, while in winter and due to the freshwater inflow it decreases to 30 psu. At high tide, the salinity of the water varies from 27.9 to 31.5 psu. At low tide, it is much lower due to water dilution and reaches 3.4 psu at the mouth of the Nador canal and Oued Drader, and 27 psu at the gully (Labbardi et al., 2005).

Geology

The lagoon of Moulay Bouselham is located between the Rif and the Atlantic Meseta. It has a tectonic origin, occupies the northern part of the Rharb plain and appears as a satellite plain of that of Sebou (Bidet et al., 1980; Carruesco, 1989a). It is limited to the west by a cordon of consolidated dunes and to the northeast and south by anticlinal structures of villafranchian glacis to soltano-mellahian (Lacoste, 1984). The immediate watershed of the lagoon belongs to the Middle Villafranchian, covered by a thick series of marl from the Upper Miocene, which outcrops to the east of the lagoon (Lalla Zohra hills) and ends in clay formations of marine origin (Combe, 1968).

The basin also has Quaternary deposits of continental black clay and sandy formations attributed to the Rharbian. The soil in the immediate watershed is sandy in nature, with a variable structure. The western side of the merja is occupied by sandy soils, while the continental edges (North and East) have “tirs” type soils. In the interior of the site, the intermittently flooded areas have a bottom consisting of fine sand rich in organic matter, or even sandy mud or pure mud locally. Oued Drader and the Nador canal are bordered by alluvial soils.

Sedimentology

Two main granulometric sets characterize the lagoon (Bidet et al., 1977):

- A sandy set of essentially marine origin. It is linked to the action of the swell and the tidal currents and is deposited essentially during the flow in the zones with high energy level.
- A muddy set located in the calm zones of the lagoon. Its origin is continental by fine contributions of the oued Drader and the channel of Nador. During the strong winter floods, the leaching of the banks also contributes to the feeding of this set.

The predominance of one or the other of these two groups is related to the hydrodynamic and morphological conditions of the lagoon, on the one hand, and according to climatic variations, on the other hand (Bidet et al., 1980).

Climatic conditions

The Figure 5 presents the data related to weather parameters (temperatures, precipitation and wind strength) during the study period (2018-2019) which were obtained from the Larache meteorological station, located 35 kilometers from Moulay Bousselham lagoon (https://www.wofrance.fr/Maroc/Larache.htm).

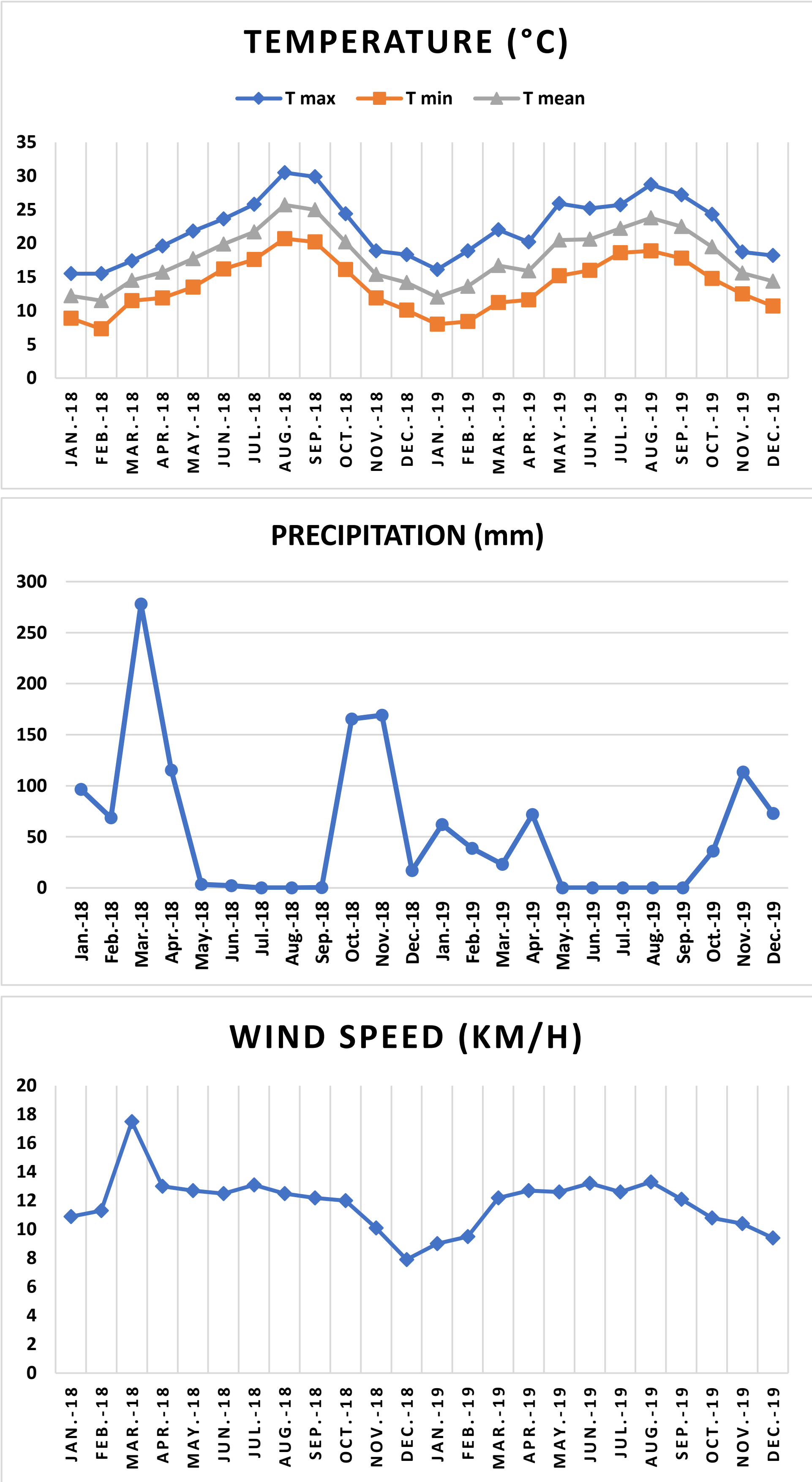

Figure 5. Monthly climatological data speed during the study period (2018-2019).

For temperatures, the years 2018 and 2019 recorded an average temperature of 17.8°C and 18.1°C respectively. The average minimum temperature was 13.82°C in 2018 and 13.64°C in 2019, while the average maximum temperature was 21.76°C in 2018 and 22.59°C in 2019.

These data show that these years have been dry. The year 2018 received an annual average rainfall of 76.35 mm, while the year 2019 was less rainy with an average of 34.83 mm. Several previous works (Rharbi, 1990; Qninba, 1999; Benhoussa, 2000) have reported this irregularity in the rainfall pattern of the region.

The wind regime in the region during the study period was characterized by a predominance of winds of western component and mainly from the northwest with a maximum speed of 17.5 km/h recorded in March 2018 and a minimum speed of 7.9 km/h recorded in December 2018.

The monthly variations in rainfall and temperature show a wet and cold period, which extends from October to April, and a dry and hot period, which begins in May and extends until September. In general, the climate of the region is considered Mediterranean with a dominance of oceanic influences. It is Mediterranean because of its long dry season and the irregularity of its rainfall. It is oceanic by the spread of its wet season, relatively fresh, and by the wind regime (Benhoussa, 2000).

Importance of Moulay Bousselham lagoon

Of worldwide interest for the avifauna, the lagoon of Moulay Bousselham is declared biological reserve since 1978 (Biological Reserve of Merja Zerga). It is also one of the 38 Moroccan sites retained by the RAMSAR convention for the conservation of wetlands of international importance. It is the most important Moroccan wetland as a stopover or wintering site for a large number of migratory waterbirds (El Agbani et al., 1998).

Biological diversity

The lagoon of Moulay Bousselham shelters a rich and characteristic biodiversity of flora and fauna, which has earned it a national and international recognition as an exceptional natural heritage to be preserved and valorized.

The flora

The flora inventoried at the level of this biological reserve has about 190 taxa, belonging to 55 families (Dakki et al., 1998). The dominant families are Asteraceae and Poaceae with 21 species each. Followed by Leguminosaea, Cyperaceae and Umbelliferaea with 12, 11 and 9 species respectively. While the other families are composed of 1 to 5 species each (Benhoussa, 2000).

This flora is characterized by the presence of 12 rare to very rare species (*Anagallis crassifolia*, *Calystegia sepium*, *Cotula coronopifolia*, *Ipomoea imperati*, *Mentha aquatica*, *Oenanthe peucedanifolia*, *Pulicaria sicula*, *Paspalum vaginatum*, *Rumex palustris*, *Spartina densiflora*, *Thymelae alythroides*, *Triglochin striata*). Two endemic Hispano-Moroccan species (*Lippiano diflora* and *Lotus chazaliei*) and two other endemic Mauritanian-Moroccan species (*Limonium ovalifolium* and *Sarcocornia perennis*) (Fennane and Ibn Tattou, 1998; Benhoussa et al., 2003).

Fauna

Aquatic avifauna

The lagoon of Moulay Bousselham is the first Moroccan site for the transit, the wintering and the reproduction of water birds (more than 50% of the total national numbers). The ornithological population of Moulay Bousselham counts about 110 species. It is dominated by shorebirds (36 species). Anseriformes and Larids occupy the second place with 19 species each. The Ciconiiformes contribute with 15 species, most of which are rare species while the order Gruiformes contains six species. Diurnal raptors have five rare and protected species. The Cape eagle-owl *Asio capensis* is the only species of Strigiformes that frequents the lagoon. The Colymbiformes, Pelecaniformes and Coraciiformes, are orders that are very little represented in Moulay Bousselham (Benhoussa, 2000).

Ichtyofauna

The lagoon of Moulay Bousselham is characterized by an important halieutic richness with species belonging essentially to the families of Anguillidae, Mugilidae and Moronidae. The close communication between the lagoon and the ocean allows an enrichment with fishes of marine origin of which the most common are Sparidae, Soledae, Mullidae and Torpedinidae.

Amphibians, reptiles and mammals

Sixteen species of amphibians and reptiles live within the perimeter of the Moulay Bousselham, including four Moroccan endemic species: *Acanthodactylus lineomaculatus*, *Chalcides mionecton*, *Chalcides pseudostriatus* and *Pelobates varaldii* (Benhoussa et al., 2003).

Socio-economic importance

The total population of the city is more than 26,000 inhabitants, the majority of which (73%) live in rural areas and (27%) in the urban center (HCP, 2014). The Moulay Bousselham lagoon plays a crucial socio-economic role for the survival of this local population. The nature of the system and the diversity of these habitats provides a large number of agricultural, fisheries and tourism potentialities.

Agricultural activities

The Moulay Bousselham lagoon is located in an agricultural region. The main agricultural exploitations are cereals, fodder crops and market gardening (red fruits, avocados, tomatoes, etc.). In recent years, there has been an increase in greenhouse agro-industrial crops, mainly strawberries and bananas. The breeding of sheep and cattle is also one of the main activities of the inhabitants of some Douars around the lagoon.

Fishing activities

The anglers belong to the villages located around the lagoon and the fishing practiced is artisanal. The main fish caught in the lagoon belong to the families of Mugilidae, Moronidae, Soleidae, Anguilliidae and Sparidae. The lagoon is also known by an important activity of harvesting mollusks on foot, which is practiced mainly by women and young girls. It concerns mainly the clam *Ruditapes decussatus*, the razor clam *Solen marginatus* and the cockle *Cerastoderma edule*.

Seaside and naturalist tourism

The landscape diversity of the site (lagoon, forest and ocean), offers very important tourist assets. The site receives thousands of tourists who stay there in summer and hundreds of Moroccan and foreign tourists in winter to practice ornithological observations and enjoy the scenic attractiveness of the site.

Anthropogenic actions and threats

Anthropic activities, increasingly increased, are becoming a source of considerable impact on the lagoon, in that many problems are currently posed. Therefore, the implementation of conservation and management measures to ensure the sustainability of these resources is becoming an ongoing necessity for this site. The consequences of these activities can be cited as follows:

Loss of habitat

The residents, who inhabit the area around the lagoon, exploiting all the living resources, are an essential source of impact on the balance of this ecosystem. There is currently a regression of the natural habitats of this wetland due to the cutting of rushes, overgrazing and the development of agricultural fields around the lagoon. In addition, the urban pressure of the population is oriented towards the construction of houses to the detriment of natural habitats. In fact, the current area occupies only about 3,000 ha of the 4,500 to 5,000 ha, representing their initial area when the site was listed as a Ramsar site in 1980, representing a loss of over 62% (Qninba, 1999).

Degradation of biodiversity

The degradation of the flora is caused mainly by the abusive harvesting of different plant species, leading to a degradation of natural habitats.

On the other hand, the manner of fishing practice constitutes a major problem whose impact on the biological components of the lagoon is becoming more and more alarming. Several species of mollusks and fish are exploited commercially (Bayed et al., 1998). The unavoidable reduction of resources that has been noticed in recent years has pushed anglers to reduce the mesh size of their fishing gears that are not regulatory. The use of such gears leads to the capture of young individuals, a significant amount of which have not yet reached the commercial size allowed and recommended by the law, thus depleting the stock and damaging the biological quality of the site. In addition, illegal fishing of birds does not respect the status of the species (rare, threatened...) nor their reproduction periods.

Uncontrolled tourist activity also has a negative impact on the lagoon, particularly through the disturbance of avifauna and the discharge of solid waste directly into the site (Benhoussa, 2000).

Pollution

Agricultural developments are a source of environmental impacts on the lagoon system. These activities have direct impacts on the hydro-sedimentary balance of the lagoon, on the one hand, and on the quality of the lagoon waters, through the contribution of nutrient residues (nitrogen and phosphorus products of fertilizers) and toxic substances (pesticides and fungicides), on the other hand. These impacts on the abiotic compartment of the lagoon would have inevitable repercussions on the different biological components of the ecosystem.

In addition, the sewage system of the highway discharges part of the runoff directly into the lagoon, which increases the concentrations of hydrocarbons and some heavy metals in the waters and sediments of the site (Benhoussa, 2000; Alaoui et al., 2010; Maanan et al., 2013). The extension of the seaside village of Moulay Bousselham affects the latter through wastewater and solid waste that are currently deposited in wild dumps scattered around the lagoon.

Valorization, management and conservation of the lagoon of Moulay Bousselham

The lagoon of Moulay Bousselham constitutes a site of immense bioecological importance on a national and international scale. Its conservation represents a priority for the maintenance of biodiversity, which is a national patrimony.

The lagoon is endowed with a very complex administrative and legal system. Indeed, the management of Moulay Bousselham involves several ministries and administrations (Benhoussa et al., 2003):

- The channels (surface waters) are part of the maritime domain.
- A part of the mud flats is under the control of the Ministry of Public Works.
- The components of the nature reserve (flora and fauna), as well as the regulation of hunting are under the control of the High Commission for Water and Forests and the Fight against Desertification.
- The majority of the agricultural lands with a collective status are under the supervision of the Ministry of the Interior.

In an exploited ecosystem such as the Moulay Bousselham lagoon, it is important to identify appropriate management measures to maintain the long-term integrity of the specific diversity, functionality and production linked to benthic ecosystems. Indeed, the disturbance or destruction of benthic habitats can, for example, lead to an increase in predation on the juveniles of exploited species or even reduce the recruitment of certain stocks.

It should also be noted that the national legislation remains devoid of clear legal texts, conferring a particular management and protection status to wetlands. Despite all the efforts made by all these actors in the conservation and management of Moulay Bousselham, the diversity of these stakeholders complicates the effective management of the site and the smooth implementation of solutions, insofar as their interventions in the wetland are varied and often difficult to unite around the same development objectives.

The main suggestions are:

Knowledge is a primary key to governance. The deepening of our knowledge on the site (physical environment, species, functions and interactions) constitutes, in fact, a necessary step to the implementation of effective measures of valorization, management and conservation.

A monitoring of benthic populations must be set up. Indeed, in order to understand the evolution of the benthic ecosystems of the Moulay Bousselham lagoon in the face of anthropic pressures and changes on a global scale, a monitoring of the evolution of the populations seems indispensable.

It would be advisable to target the habitats of the richest benthic populations as a priority in the development of management and conservation plans for Moulay Bousselham.

The communication of the lagoon with the ocean is a main asset of this ecosystem, hence the need to maintain tidal flows in order to preserve the usual hydrological functioning of the site and ensure the hydrological rebalancing and avoid a possible silting of the lagoon.

Conservation strategies must extend beyond the lagoon to the entire basin in order to control human activities, especially excessive agricultural development (phytosanitary products) that dangerously affects the ecosystem.

The socio-economic development of the local population is a necessity to reduce the pressure on the natural resources of the site. Hence the need to orient them towards other alternative income-generating activities such as ecotourism.

Strengthen the role of the media and civil society in order to raise the awareness of the local population on the interest of the site, the impact of human pressure on its environment and the need to adopt behaviors respectful of nature to ensure sustainability.

Currently, a clear political commitment to spatialized management measures for the protection of local features is emerging. The use of such protection measures, often called protected areas, is increasingly recognized as a necessary condition within an ecosystem approach for the protection of both species and habitat.

The consultation and cooperation of the various partners and users is an essential step in the definition and development of such management plans for exploited ecosystems. In particular, the inhabitants have a major role to play. Thus, their knowledge and opinions must be considered, evaluated and compared with those of the scientists in order to arrive at a clear basis for the identification of acceptable and therefore effective management measures.

The effectiveness of such areas relies on long-term scientific monitoring, with clearly defined monitoring parameters that allow the evaluation and success of the objectives set for the protected area.

Sampling, treatment and analysis of data

The objective of a sampling strategy is to achieve, through sampling, the most accurate estimate possible of the parameters studied and their variability. This sampling plan is a delicate compromise between the objectives of the research undertaken and various logistical constraints.

The main objective of this study is to understand the composition, structuring and functioning of the macrozoobenthic populations of the Moulay Bousselham lagoon. Two approaches are necessary and complementary, one spatial and another spatio-temporal. Moreover, due to its hydrodynamic regime, the lagoon shows two different zones: an intertidal zone and a subtidal zone. Spatial and temporal sampling of the lagoon's macrofauna has interested both the intertidal and subtidal zones in order to better understand the functioning of this ecosystem.

In addition, in order to highlight the relationships between macrofauna and environmental variables, this study requires the consideration of abiotic data: edaphic characteristics (granulometry and organic matter rate), water parameters (temperature, salinity, pH) and vegetation (*Zostera noltei* and *Ruppia cirrhosa*).

Sampling strategy

For the sampling of our stations, both in the intertidal and subtidal zones, we were limited to working during the low tides of neap tides. The difficulties of moving on the mudflats uncovered at low tide led us to work with a flat-bottomed boat. This type of boat seems to be the most suitable for this kind of environment, since it allows a displacement even on low drafts.

For the study of the spatial patterns of the macrozoobenthos communities, a grid sampling design encompasses the entire intertidal and subtidal areas of the Moulay Bousselham lagoon was used. Sixty-eight stations (Figure 6) were sampled in autumn 2018 with three replicas per station and with a combination of sample points taken at 500 m intervals.

While for the study of the trends of spatio-temporal variations, sampling was performed in winter and summer 2018 in 29 stations among the lagoon (Figure 7). The selection of these stations was based on previous works undertaken in this lagoon considering both benthic communities and environmental parameters (Touhami et al., 2017; Boutoumit et al., 2021).

The choice of these stations was based on a sampling strategy that took into consideration the heterogeneity of the environment. Thus, the choice of sampling stations was made according to four main criteria:

- Tidal level (subtidal or intertidal)
- Biosedimentary units
- Presence/absence of *Zostera noltii* or *Ruppia cirrhosa* meadows
- The influence of the main oceanic and internal water masses (freshwater inflow)

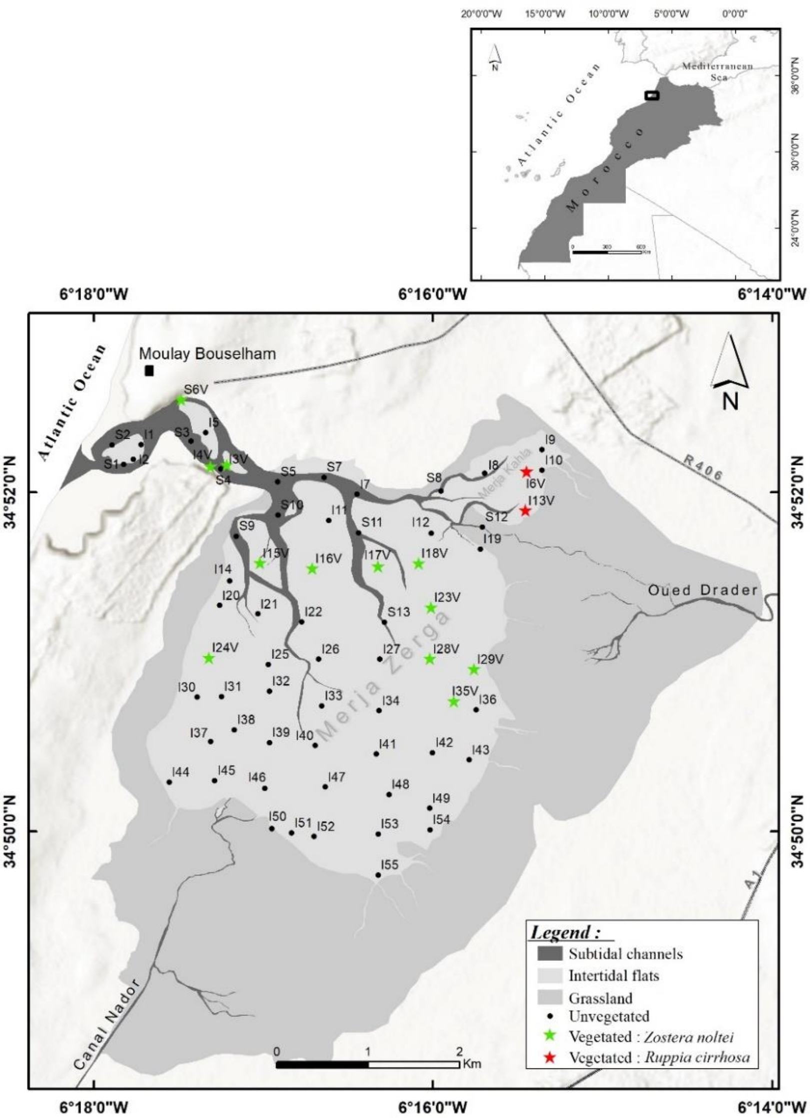

Figure 6. Map showing the sampling stations for the spatial patterns study (©by S. Boutoumit).

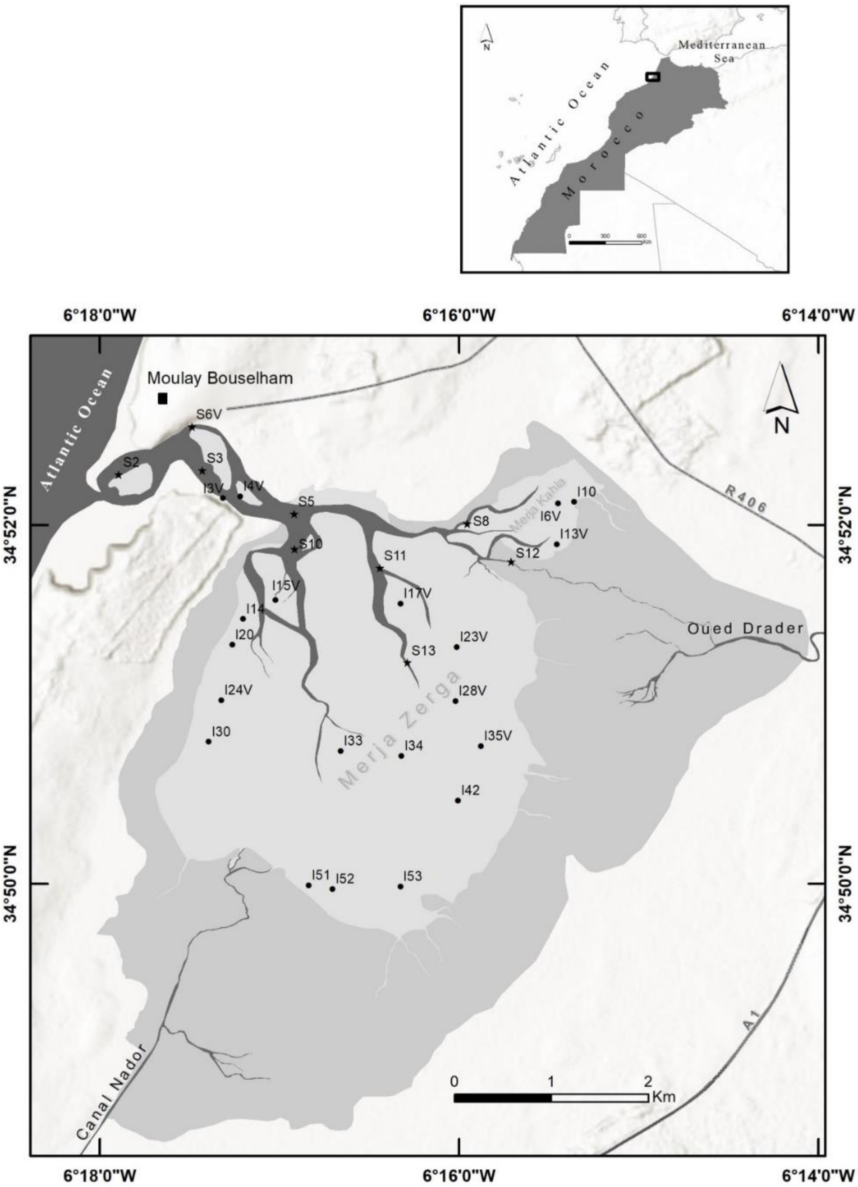

Figure 7. Map showing the sampling stations for the seasonal variation study (©by S. Boutoumit).

In intertidal area, the benthic macrofauna was sampled using a manual circular corer of 12.5 cm diameter, which allowed 0.012 m² of sampling. To account for spatial heterogeneity, at each station ten corers were made, allowing a total area of 0.12 m², considered as the minimum area for the macrofauna. While, in subtidal area the samples were collected using a Van Veen grab and each sample had a surface area of 0.1 m².

In the field, samples are immediately sieved on a 1 mm nylon mesh. The sieve rejects are fixed and preserved in 4% formulated lagoon water and stained with Rose Bengal to facilitate sorting in the laboratory (Figure 8).

Physicochemical parameters (water temperature, salinity and pH) were also measured in situ with a HANNA portable multiparameter. Each sample of the macrofauna was accompanied by an additional sediment sample to determine their precise granulometry, carbon content and total organic matter (TOM).

Figure 8. Illustrations of benthic macrofauna sampling steps in Moulay Bousselham lagoon.

Laboratory analysis

Sorting: In the laboratory, the sample is first washed with tap water on a 0.1 mm mesh sieve in order to eliminate all traces of formalin. Sorting consists of extracting the macro-benthic organisms and separating the different individuals according to the phylum or class to which they belong (molluscs, polychaetes, crustaceans...). The organisms were kept in pillboxes filled with 75 % alcohol until they were determined (Figure 9).

Identification: The identification of the specimens was done with a binocular magnifying glass (LEICA EZ 4HD). An optical microscope (LEICA DM 750) is often necessary for the small individuals and the observation of certain morphological details.

Such a determination is made possible thanks to numerous specialized determination keys, as well as to the existence of numerous articles on certain families or species in particular. After the identification, the species names were updated using the taxonomic repository "World Register of Marine Species" (WoRMS Editorial Board, 2020). A list of the species present, with their numbers, is then established for each station (Figure 9).

Biomass Estimation: In this study, we chose the Ash-Free Dry Weight (AFDW) method (Triplet, 2012). Its main advantage is the mitigation of the effects of variation between individuals of the same species due to stomach contents (van der Meer et al., 2005).

For mollusks, meat was extracted from the shells directly by forceps (for bivalves) or by decalcification (for gastropods) with Hydrochloric acid (HCL). Then, the individuals of each species were dried in an oven (Memmert) at 60°C for 48h, until the dry mass was stabilized. At the end of the drying, the first weighing was done with a precision balance of 0.1 mg (KERN ABS 220-4 Analytical Balance), in order to obtain the dry weight (DW). The samples were then passed through a calcination oven (MuffelFurnace NABERTHERM LE 2/11 R6) and burned at 450°C for 4 h. The second weighing following the cremation gives the weight of ash (AW). The difference between the two values (DW) and (AW) gives the ash free dry weight (AFDW). Biomass measurements were made for each combination of taxon, replica and station. From these data, the biomass of all benthic samples was estimated in g AFDW/m^2.

Sediment characterization

Sediment from each station was dried at 60°C in an oven for 48 h to perform particle size analyses and to estimate carbon and organic matter content. These analyses were performed in LETG (UMR-C 6554) laboratory at the University of Nantes.

Granulometry

Sediment grain size was determined by using a Malvern Master Sizer 2000 laser diffractometer after preparing the sediments in a Sodium Hexametaphosphate solution. This device uses the diffraction properties of a laser by a particle. The diffraction measured by the sensors of the device allows to measure the size of the particles and to count them. This semi-automated method allowed processing a large number of samples. The grain size distribution was then treated with the Gradistat© Excel package (Figure 10).

The following particle size classes, based on Buchanan's (1984) classification, were used: pelites (particle size <63 µm), very fine sands (particle size between 63 µm and 125 µm), fine sands (particle size between 125 µm and 250 µm), medium sands (particle size between 250 µm and 500 µm), and coarse sands (particle size greater than 500µm). The content of the sediment in each of these particle size classes was used to qualify the different sediments.

Figure 9. Illustration of some steps in the treatment of benthic samples in the laboratory (©by S. Boutoumit).

Carbon content

The samples undergo a first decarbonation step with Sulfuric Acid solution before treatment by the LECO analyzer. A crucible containing the sample to be analyzed is burned at 1400°C in a stream of oxygen (Figure 10).

The total organic matter

The organic matter (OM) content was evaluated by loss on ignition. Dry sediment samples are weighed before undergoing cremation at 500°C for 4 h to obtain the dry weight of mineral matter (Byers et al., 1978). The difference in mass between the dry weight and the dry weight of mineral matter gives an estimate of the dry weight of OM in the sediment, which is expressed as percent OM.

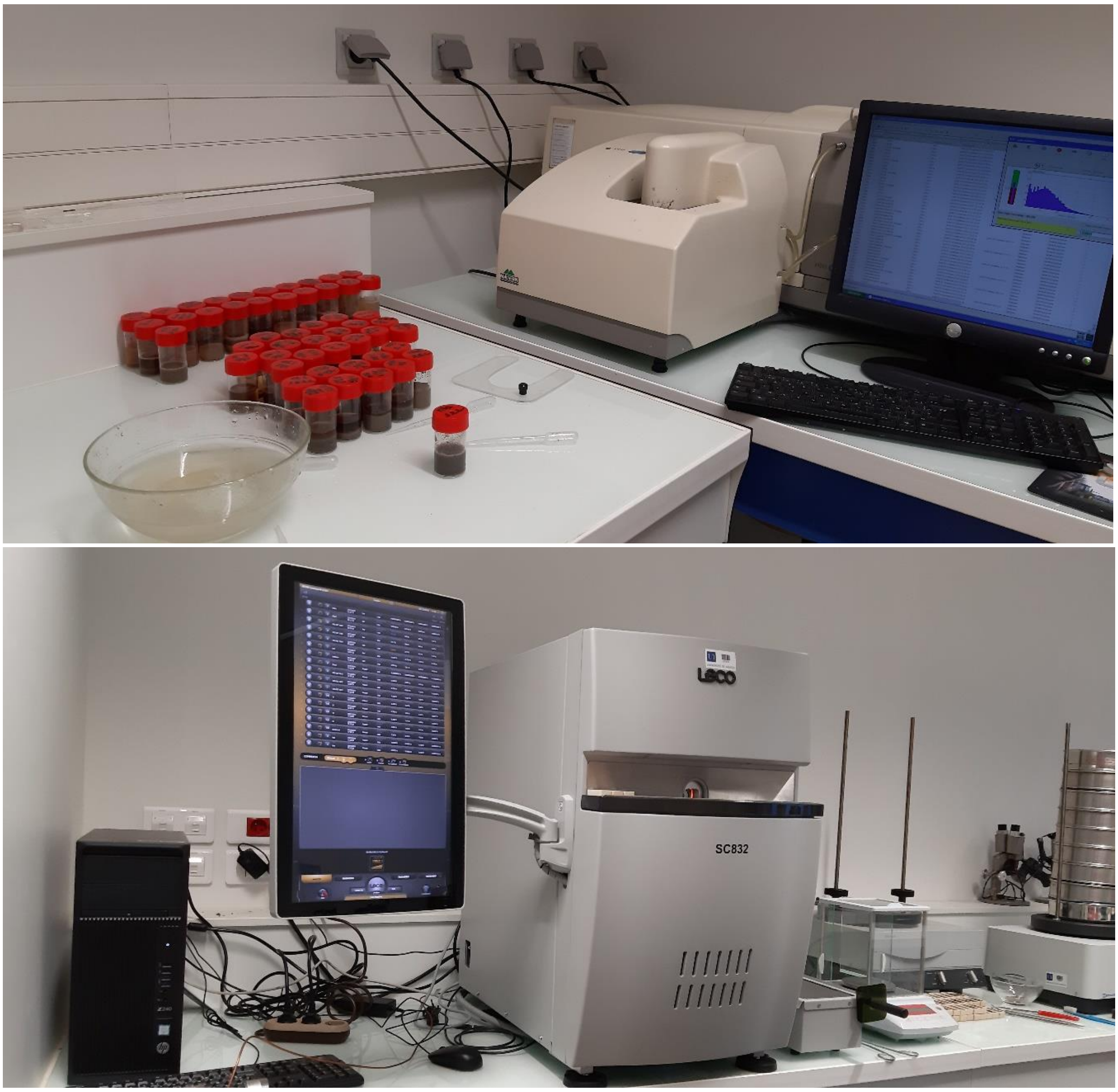

Figure 10. Malvern Master Sizer 2000 laser diffractometer and LECO analyser used in the treatment of the sediment (©by S. Boutoumit).

Data analysis

In ecology, the measurement of diversity is a constant preoccupation of ecologists and is therefore the objective of a considerable literature where numerous indices more or less used and/or more or less complex to calculate and/or interpret have been proposed (Piélou, 1975; Warwick & Clark, 1995; Heip et al., 1998; Gray, 2000, Ugland et al., 2003). In order to understand changes in benthic community structure over time and space, various uni-variate and multi-variate analyses are applied to the faunal results obtained.

These methods are usually used to highlight the general characteristics of the communities and measure their communities and measure their biodiversity such as species richness (S), abundance (A), diversity indices...

Parameters and characteristics of the communities

In order to determine the structure of benthic communities as well as their specific diversity, several uni-variate analyses were used, such as species richness (S), abundance (A) and diversity indices (H' and J'). These methods are usually used to show general community characteristics that are not a function of specific taxa. They are easier to use than multivariate methods but, like graphical and distributional methods, they are not as sensitive in detecting change (Warwick & Clarke, 1991).

Synthetic parameters of communities

Species richness (S): The species richness of a community is the simplest measure of diversity. It is represented by the total number of species observed (in absolute value or per unit area or volume). This method depends on the size of the samples and does not consider the relative abundance of the different species. Species richness is therefore simply the cumulative number of species in the n samples taken (Amanieu et al., 1980).

Abundance (A): Total abundance is the total number of individuals collected at a given station per unit area per unit area, usually per m^2.

Biomass: free dry weight of ash per unit area (g $AFDW/m^2$).

Diversity indices

Shannon & Weaver diversity index (H')

The introduction by ecologists of the notion of specific diversity was intended to account for the unequal distribution of individuals among species. Among the indices established for the estimation of this diversity, the index of Shannon & Weaver (H') (1954) remains the most used, it is endowed with an incontestable superiority on the others such that of Margalef (Daget, 1979).

The Shannon & Weaver index represents a whole quantity of information on the structure of the population of a given sample and on the manner of distribution of individuals between different species.

The H' index considers both abundance and species richness (Gray et al., 1990).

$$\boxed{H' = -\sum_{i=1}^{N} p_i . Log_2(p_i)}$$

With:

H’: Shannon index

Pi: Dominance of species “i”

N: Total number of species

H' is minimal (=0) if all individuals in the community belong to a single species; it is minimal if one species dominates the community; H' is also minimal if each species in a community is represented by a single individual. The index is maximal when all abundances are equally distributed among species (Frontier, 1983).

Pielou's equitability index (J')

The Shannon & Weaver index H' is often accompanied by Pielou's equitability index J' (Pielou, 1966) which represents the ratio of H' to the theoretical maximum index in the community (Hmax). It is also called regularity (Frontier, 1976) and equi-partition (Blondel, 1979).

The equitability J' of a sample is calculated with the formula:

$$J' = \frac{H'}{H'_{max}}$$

Where:

H': Shannon index

$H'_{max} = log_2S$: maximum value of H' in case of equidistribution of individuals

Equitability varies from 0 to 1: it tends towards 0 when almost all the numbers are concentrated on one or two species (one or two dominant species) and it is of the order of 1 when all species have the same abundance.

The Diversity Monitoring (DIMO) model

Qinhong (1995) proposed the Diversity Monitoring (DIMO) model as a tool for monitoring changes within stands. This model provides a single representation of taxonomic richness, Shannon index and equitability. In this model, each sample "i" is associated with a pair of coordinates (log_2S; H') and thus can be represented in the (x; y) plane. The tangent of the angle α formed between [O; x] and [O; i] then represents J' (tan (α) = H'/ log_2S = J'). The bisector of the [x; y] plane is such that log_2S = H' then represents H'_{max} since, by definition, $log_2S = H'_{max}$.

Univariate statistical analysis: ANOVA test

The one-factor Analysis of Variance (ANOVA) was used to compare the diversity indices of the different assemblages identified as well as the environmental parameters. Beforehand, the homogeneity of the variances was checked using Cochran's C test (Sokal & Rohlf, 1981). In case of non-homogeneity of variances, the data were transformed into log(x+1). In the case of non-homogeneity of variances, a non-parametric Kruskall-Wallis test of comparison for independent samples was used (Scherrer, 1984). Statistical processing was carried out using the STATISTICA ® software.

Multivariate analyses

Multivariate analyses of community structure are required in order to better study the complexity of benthic ecosystems in relation to environmental and population changes, (Underwood, 1996). Multivariate analyses were conducted to visualize the response of communities to different disturbances through changes in the relative abundance of species.

They are considerably more complex than other methods and require prior processing or data preparation, such as transformations. These analyses include Hierarchical Ascending Classification (HAC), Multidimensional Positioning (MDS) and were performed using PRIMER v.6 (**P**lymouth **R**outines **I**n **M**ultivariate **E**cological **R**esearch) (Clarke & Warwick, 2001; Clarke & Gorley, 2001).

Cluster analysis

There are several HAC methods and several methods for calculating the distance between two objects, two classes, or an object and a class (Benzecri, 1984). The most commonly used method in benthic studies is the clustering of means (Lance & Williams, 1967), which joins two groups of stations. This is a classification method designed to produce classes by successive aggregation of objects in pairs, providing a partition hierarchy of objects (Legendre & Legendre, 1984). The criterion of similarity between pairs of objects uses the Bray-Curtis index (Bray & Curtis, 1957) and the criterion of class aggregation, i.e. the average distance between all the objects taken in either of the two different classes. The results are displayed in a graph called a dendrogram.

Proximity Analysis MDS (Multidimensional Scaling)

It consists of modeling the proximities (similarity or dissimilarity) between "individuals" in such a way that they can be represented as closely as possible in a low-dimensional space (usually 2 dimensions) (Frontier, 1983). Dissimilarities are distances that describe the optimal representation of "individuals". The measure of the difference between the disparities and the measured distances (Bray-Curtis distance) on the representation obtained by the MDS is called the stress: the lower the stress, the better the representation of the "individuals". The stress is a normalized indicator varying between 0 and 1, the null value indicating a perfect fit. Thus, a stress value lower than 0.1 reflects an excellent representation, between 0.1 and 0.25 it gives a satisfactory image, between 0.25 and 0.5 the quality is poor and values higher than 0.5 reveal a random representation (Ehrhold et al., 2006).

SIMPER analysis

A more objective method for identifying discriminating features of benthic communities is the similarity percentage analysis (SIMPER), described by Clarke (1993) and available in PRIMER v6 software. The SIMPER analysis allows determining the typical species of each sample based on their contribution to the similarity between the samples of these collections, as well as the discriminating species between these samples, this time based on the dissimilarity between the groups of samples.

Relationship between environmental parameters and benthic macrofauna

The DistLM (Distance-based Linear Model) analysis was used to identify the environmental variables that could explain the observed variations in the spatial distribution of the benthic macrofauna. The DistLM analysis was performed on the Bray-Curtis similarity matrix of the faunal data (benthic species) and the previously standardized environmental variables. The results were presented as a sequence test. This test identifies the environmental variables that contribute significantly to the variation in the faunal data. The results of the DistLM test were visualized using the distance based redundancy analysis (dbRDA) plot.

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Chapter 2

Soft-bottom macrozoobenthos in semi-enclosed coastal systems of Morocco: A latitudinal and biogeographic analysis

Abstarct:

Although soft-bottoms are the largest ecosystem on Earth in terms of area, only a small percentage of their macrobenthos has been studied and most of its species are not yet described. Herein, the most up-to-dated comprehensive inventory and the broad-scale baseline of the soft-sediment macrozoobenthos in semi-enclosed coastal systems (SECS) of the Moroccan Atlantic and Mediterranean coasts (3500 km) is presented. In total, 496 species (7 phyla, 21 classes, 65 orders and 201 families) were recorded among which 95 species were exclusively Mediterranean, 99 species were Atlantic–Mediterranean and 302 species exclusively Atlantic.

The best multivariate model, explaining 33% of the total variation observed in benthic assemblages' composition, included the type of the SECS (estuaries vs lagoons vs bay), the marine ecoregion (Atlantic vs Mediterranean), the surface of the SECS and the environmental features (minimal temperature, minimal and maximal salinity) as predictors of benthic macrofauna composition in the Moroccan SECS. In contrast to the general latitudinal diversity gradient (LDG) pattern, our results showed that species richness and taxonomic diversity showed no relationship with latitude. Such differences in benthic macrofaunal composition across a large scale could result from the fact that each ecosystem has its own specific characteristics, which implies an individualistic approach to ecosystem ecology.

The sample of the 12 SECS considered in this study covers most of the range of variation along the coasts of Morocco. The current compilation is relevant in such poorly known area at the global scale and fulfills a knowledge gap on benthic macrofauna in SECS of the Southern part of the North-Eastern Atlantic and Mediterranean ecoregions. However, the knowledge gained here is insufficient to address perceived shortfalls in knowledge of biodiversity, its importance to ecosystem function, and the threats and consequences of disturbance by anthropogenic activities.

Keywords: Benthic macrofauna, Checklist, Latitudinal diversity gradient, North-East Atlantic, Mediterranean

Introduction

Ecologists have long been intrigued by global patterns in biodiversity (Piacenza et al., 2015) and the understanding of the distribution of life on earth is a main goal in ecology and biogeography (Gaston, 2000; Hillebrand, 2004). The latitudinal diversity gradient, hereafter LDG (Hawkins, 2001), with the highest numbers of species in the tropics and gradual decrease poleward, is the most famous large-scale biodiversity pattern (Hillebrand, 2004; Kinlock et al., 2018). Explanations for the LDG have been related to many potential mechanisms but no broad consensus on the causes of the LDG has emerged (Kinlock et al., 2018). The many explanations that have been proposed can be categorized broadly into ecological, evolutionary and historical processes (see Cruz- Motta et al., 2020 for recent summaries). Given the challenge of inferring process from pattern, disentangling these hypothesized drivers remains one of the great challenges in macroecology (Hurlbert and Stegen, 2014).

While the LDG is a well-recognized and long-established pattern in terrestrial ecology, the knowledge of global diversity patterns in marine ecosystems is limited to a small number of studies (Barboza and Defeo, 2015). For marine biota, the first suggestion of the latitudinal diversity cline was formulated in late 1950ies for hard bottom epifauna (Thorson, 1957) with pronounced decrease in the species richness of hard substratum epifauna towards arctic areas, whereas the number of soft-sediment infauna species was roughly the same in tropical, temperate and arctic areas. Latitudinal clines in benthic diversity of shallow waters have been also reported for gastropods (Roy et al., 1998), bivalve mollusks (Crame, 2000; Roy et al., 2000), in shallow and deep-seas benthos (Sanders, 1968; Poore and Wilson, 1993; Rex et al., 1993), and for pelagic taxa (Angel, 1997; Pierrot-Bults, 1997). Nevertheless, many studies have shown a deviation from the general LDG for the shallow-water marine fauna (Kendall and Aschan, 1993; Boucher and Lambshead, 1995). Furthermore, in the southern hemisphere, the evidence of a latitudinal gradient of decreasing richness from the tropics to Antarctica is less convincing than in the northern hemisphere (Clarke, 1992; Poore and Wilson, 1993; Crame, 2000). Recently, Kinlock et al. (2018) revisited the challenge of synthesizing individual LDGs and indicated that the phenomenon is not ubiquitous among habitats of the marine realm. More precisely, they indicated that the phenomenon is non-significant in the benthic habitat. However, Menegotto et al. (2019), in their comment on Kinlock et al. (2018), suggest that the marine habitat categories used by them (i.e., benthic, coral reefs, coastal, Open Ocean) are not independent and that reclassifying the studies significantly alters one of their main results. By assigning the studies into benthic and pelagic categories, and additionally into coastal or oceanic zones, they show that nonambiguous, evolutionarily meaningful marine habitats display a significant latitudinal decline in species richness. Thus, there is no convincing evidence of a latitudinal cline across all taxa in the sea comparable to that seen on land (Clarke, 1992; Clarke and Crame, 1997).

Meta-analysis represents a suitable technique to analyze latitudinal gradients across different biota and regions and thus to generalize or not findings on the latitudinal distribution of species richness (Hillebrand, 2004; Kinlock et al., 2019). Therefore, Open science and the accumulation of spatially explicit biodiversity data are crucial to document LDG patterns better and to evaluate hypotheses broadly or for particular groups of organisms (Kinlock et al., 2018, 2019).

Soft-bottom substrates cover most of the world's ocean bottom and maintain a substantial part of the world's biodiversity (Snelgrove, 1998; Labrune et al., 2008). Assessing their biodiversity and latitudinal patterns, even though it is complicated by the difficulty in sampling and sharply delineating habitats in these systems, is thus of special importance (Labrune et al., 2008). Macrobenthos constitute the dominant organism biomass of marine soft sediments (Snelgrove, 1998). All of the known nonsymbiont phyla but one are found in the marine environment, with most being represented in marine sediments (Grassle et al., 1991). Soft bottom macrobenthos is a key biological component of marine ecosystems where it plays an important role in ecological processes such as nutrient cycling, pollutant metabolism or secondary production (Snelgrove, 1998; Pratt et al., 2014). Although soft-bottoms are the largest ecosystem on Earth in terms of area, only a small percentage of their macrobenthos has been studied and most of its species are not yet described (Snelgrove, 1998). In this way, it is useful to improve our knowledge of its biodiversity (Ellingsen, 2002; Veiga et al., 2016).

Semi-enclosed coastal systems (SECS), such as lagoons and estuaries, are particular ecosystems of the coastal zone where the macrobenthos is a dominant biological component. The SECS are largely distributed worldwide under all the latitudes and are therefore ideal systems to study LDGs and their potential drivers because they (a) are easily accessible and (b) have very diverse, abundant, macrobenthic organisms belonging to various taxonomic groups.

The Moroccan coast stretches over 3500 km and 15◦ of latitude along both the Mediterranean Sea and the Atlantic Ocean. Moroccan low coasts offer an important succession of particular geomorphological forms (Chafik et al., 2001) among which several lagoons, estuaries and bays. Nador and Smir lagoons lie on the Mediterranean coast, whereas Moulay Bousselham, Sidi Moussa, Oualidia and Khnifiss are located in the Atlantic coast. The largest estuaries are located in the Atlantic coast: Tahaddart, Loukkos, Sebou, Bouregreg and Oum Rbia. Finally, Dakhla bay is the most important bay of the Atlantic coast of Morocco, it is unique in North Africa as a migration, wintering and nesting area for thousands of waterbirds (Qninba et al., 2003). Those ecosystems are heterogeneous, mainly due to their typology (bay, estuaries, lagoons), geomorphology, catchment geology and the spatio-latitudinal variation in different environmental factors along the Moroccan coasts.

Up-to-now, there is no synthesis of the benthic species of the Moroccan SECS, despite several studies conducted in the last decades (e.g. Elkaïm, 1974; Lacoste, 1984; Bekkali, 1987; Guelorget et al., 1987; Bayed et al., 1988; Cheggour, 1988; Zine, 1989; Chbicheb, 1996; Bazaïri, 1999; Mergaoui et al., 2003; Chaouti and Bayed, 2005; Zine, 2005; Azirar, 2006; Cherkaoui, 2006; Gauteur, 2006; Lefrere, 2012; Joulami, 2013; Cuvelier et al., 2014; Boutahar, 2014; El Asri et al., 2015, 2017; Touhami, 2018; El Asri, 2019). This was a stimulating fact to provide a first baseline meta-data on such ecosystems in such poorly known area at the global scale and to fulfill a knowledge gap on benthic macrofauna in SECS of the Southern North-East Atlantic and Mediterranean ecoregions.

The overall objectives of this study were (1) to provide the first national and comprehensive checklist of the soft bottom macrozoobenthic species in semi-enclosed coastal systems of Morocco, (2) to test for the presence of a latitudinal diversity gradient in soft bottom macrozoobenthic species of semi-enclosed coastal systems of Morocco and (3) to understand their drivers by comparing the benthic assemblages between the different sites according to their ecoregion, their latitudinal position, the type of ecosystem (lagoon, estuary or bay), the site surface area, temperature and salinity. Additionally, we identified the current knowledge and gaps and make recommendations on respective research in future years.

Materials and methods

Study sites

12 SECS were considered in this study based on data availability (Figure 1). There are distributed along a large latitudinal gradient and are situated both in the Mediterranean coast of Morocco (two lagoons) and the Atlantic coast of Morocco (four lagoons, five estuaries and one bay). These SECS differ in terms of configuration, surface area and environmental conditions (Table 1). These sites have a very important ecological interest; most of them have been listed to the RAMSAR Convention as wetlands of international importance. They represent the most important Moroccan wetlands for the migration and wintering of birds.

These SECS are contrasting in the climate: Mediterranean semi-arid to temperate variant at the level of Nador lagoon to a desert climate at Dakhla bay. On the other hand, anthropogenic activities differ from one site to another: traditional fishing (all sites), aquaculture (Oualidia and Dakhla), thermal power station (Tahaddart), intensive agriculture (Moulay Bousselham, Sidi

Moussa and Oualidia), port’s activities (Nador, Loukkos, Sebou, Bouregreg, and Dakhla), dredging activities (Sebou and Oum Rbia,), mining (Nador, Sidi Moussa, Oualidia and Khnifiss) and industrial effluents (Nador, Sidi Moussa and Dakhla).

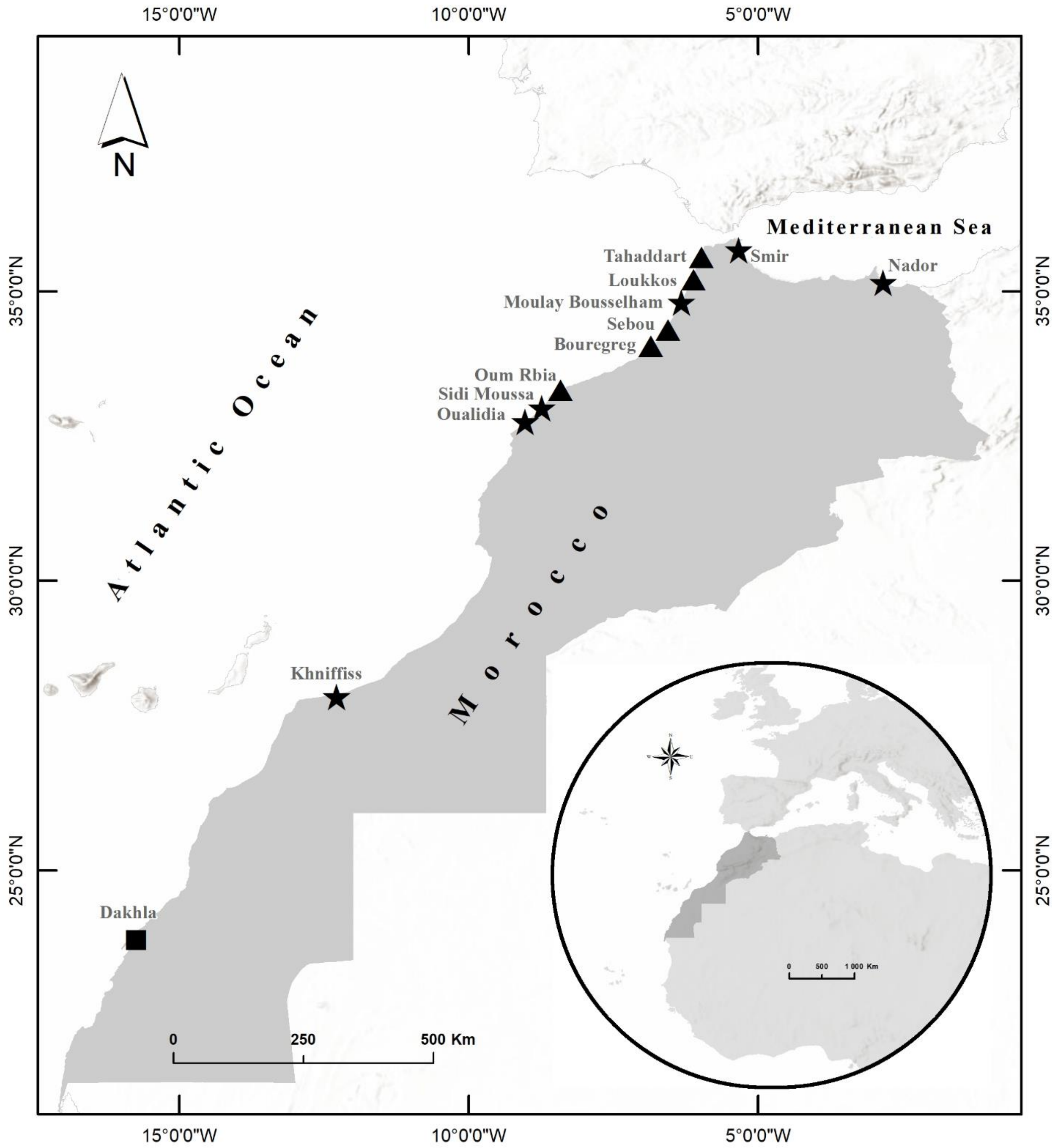

Figure 1. Map showing the geographical position of the semi-enclosed coastal systems of Morocco considered in this study. ⋆: lagoon; ▲: estuary; ■: bay (©by S. Boutoumit).

Table 1. Environment descriptors of the semi-enclosed coastal systems of Morocco in terms of aquatic system type (1 = lagoon; 2 = estuary; 3 = bay), latitude (LAT, N), longitude (LON, W), surface area (km^2), maximum annual water temperature (M Temp, °C), minimum annual water temperature (m Temp, °C), maximum annual water salinity (M Sal), minimum annual water salinity (m Sal). NA: Nador, SM: Smir, TA: Tahaddart, LO: Loukkos, MB: Moulay Bousselham, SE: Sebou, BR: Bouregreg, OR: Oum Rbia, SI: Sidi Moussa, OU: Oualidia, KH: Khnifiss, DA: Dakhla.

System	Type	LAT	LON	Surface Area	M Temp	m Temp	M Sal	m Sal	Reference
Nador (NA)	1	35°10'	02°51'	115	28	14	38	32	El Kamcha et al., 2020
Smir (SM)	1	35°42	05°20	0.3	32	12	41	7.8	Chaouti & Bayed 2005
Tahaddart (TA)	2	35°46'	05°42'	10	26	13	41	21	Achab 2011
Loukkos (LO)	2	35°07'	06°00'	72	27	15	34	22	Geawhari et al., 2014
Moulay Bousselham (MB)	1	34°51'	06°16'	27	28	11	35	27	Gam et al., 2010
Sebou (SE)	2	34°16'	06°39'	17.5	30	16	35	12	Haddout et al., 2015
Bouregreg (BR)	2	34°	06° 50 '	4000	45	14	30	10	Cherkaoui 2006; El Amraoui et al., 2015
Oum Rbia (OR)	2	33°28'	08°34'	1.5	25	15	35	30	Khalki & Moncef 2007
Sidi Moussa (SI)	1	32°54'	08°49'	4.2	27	15	33	22	Maanan et al., 2004
Oualidia (OU)	1	32°45'	08°30'	3.0	21	16	36	28	Hilmi et al., 2005
Khnifiss (KH)	1	28°03'	12°15'	65	22	16	38	34	Semlali et al., 2012
Dakhla (DA)	3	23°45'	15°50'	400	26	14	40	37	Zidane et al., 2018

Data sources

The checklist was based on published data from 1974 to 2020 as well as co-authors unpublished data (see Appendix 1 Table S1 and Table 4 for references' details). The list of benthic macrofauna species and total species richness were compiled for each SECS. Species names were checked and updated to current nomenclature according to World Register of Marine Species (http://www.marinespecies.org) (consulted January 14, 2020). Only a few species were not included in WORMS. Taxa identified at a higher taxonomic level than the species were removed from the checklist. Only the taxa sp. and cf. were retained if cited only once.

The heterogeneity and incompleteness of available information led to the selection of a subset of the SECS environment descriptors which fulfilled the criteria of data reliability (i.e. information coming from published sources), homogeneity (i.e. available for all the lagoons), and comparability (i.e. data which can be expressed with a shared measurement unit). Nine different SECS variables were included: type of aquatic system (1 = lagoon; 2 = estuary; 3 = bay), latitude (LAT), longitude (LON), surface area, maximum annual water temperature (M Temp, °C), minimum annual water temperature (m Temp, °C), maximum annual water salinity (M Sal), minimum annual water salinity (m Sal).

Biological data

Biotic parameters including the species richness (S), average taxonomic distinctness with presence/absence data ($\Delta+$), total taxonomic distinctness ($S\Delta+$), average phylogenetic diversity ($\Phi+$) and variation in taxonomic distinctness ($\Lambda+$), total phylogenetic diversity ($S\Phi+$) were calculated. Sampling effort leading to the compilation of the species lists was also measured by the total number of samples collected in each SECS (calculated as number of sampling sites x sampling frequency).

Data analysis

The relation between SECS characteristics (independent variables) on species richness and taxonomic diversity indices (dependent variables) was tested using multiple linear regressions after testing the collinearity between independent variables. The possible effect of sampling effort on biotic parameters was previously tested by univariate regression. Then, residuals of the univariate regression with sampling effort were considered instead of the original data in multiple regression analysis. Moreover, the effect of the types of SECS (lagoon vs estuary) was tested using univariate PERMANOVA (Anderson and Millar, 2004).

Differences in the structure of the taxonomic assemblages between Moroccan SECS were explored using a cluster analysis based on a Bray-Curtis coefficient. Similarities (Bray-Curtis coefficient) among Moroccan SECS were calculated based on the taxonomical composition (Bray-Curtis coefficient calculated on (0, 1) species presence-absence data corresponding to Sorensen coefficient (Clarke and Warwick, 2001). Affinity groups differences were visualized through Principal Coordinates Ordination analysis (PCO) (Clarke and Warwick, 2001). The abiotic variables that were correlated (Spearman ρ >0.5) to samples ordination were represented as superimposed vectors in the PCO graph.

The best subset of SECS characteristics explaining the observed variability in benthic macrofauna assemblages was selected by means of distance-based linear models (DistLM) (Anderson et al., 2008), using appropriate permutation (9999 permutations) and with Adjusted R^2 criterion and stepwise procedure for the model selection. Distances among aquatic systems were visualized through a dbRDA plot. Predictors variables were partitioned to four sets of predictor variables: environmental variables (surface area, maximum annual water temperature (minimum annual water temperature, maximum annual water salinity, minimum annual water salinity), type of SECS (lagoon, estuary, bay), province (Mediterranean and Atlantic) and geographical variables (latitude and longitude).

All multivariate analyses were conducted in the Primer 7 space (Clarke and Gorley, 2006), while correlation and regressions tests were carried out in Statistica 12.0 (Statsoft, 2017).

Results

Checklist

36 sets of both published and unpublished data were compiled to obtain the checklist of benthic macrofauna of SECS of Morocco (Table S1 Appendix 1). Most of them focused on a single SECS. There were 496 species recorded from the Moroccan SECS. They belong to 7 phyla, 21 classes, 65 orders and 201 families. Mollusks are the richest phylum with 179 species belonging to 5 classes, 31 orders and 71 families. Arthropods is the second richest phylum with 164 species belonging to 5 classes, 12 orders and 72 families. 120 species of Annelida were reported, with 2 classes, 7 orders and 33 families. Chordata presented 15 species, from 1 class, 5 orders and 9 families. The phylum of Echinodermata, Cnidaria, and Nemerteawere represented by 8, 6 and 4 species respectively.

Among the 496 species reported in this study, 95 species showed an exclusive Mediterranean distribution (M), 99 species have an Atlantic–Mediterranean distribution (AM) and 302 have an Atlantic distribution (A) (Figure 2).

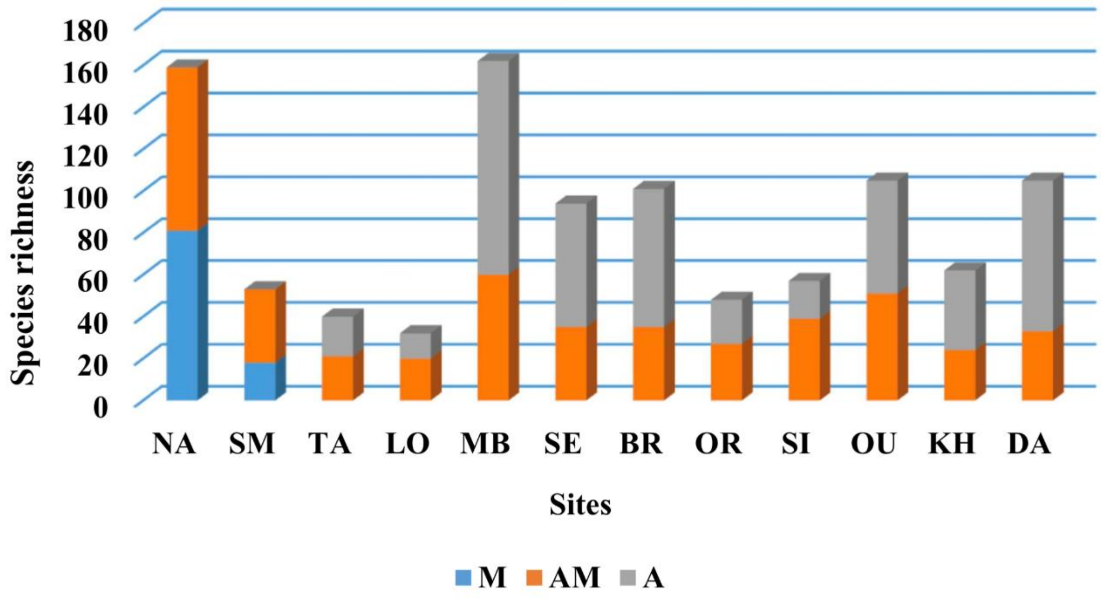

Figure 2. Species richness by biogeographical repartition in the semi-enclosed coastal systems of Morocco. A: Atlantic. AM: Atlantic–Mediterranean and M: Mediterranean. NA: Nador. SM: Smir. TA: Tahaddart. LO: Loukkos. MB: Moulay Bousselham. SE: Sebou. BR: Bouregreg. OR: Oum Rbia. SI: Sidi Moussa. OU: Oualidia. KH: Khnifiss. DA: Dakhla.

Species composition and taxonomic diversity

The number of taxa compiled by site fluctuated between 32 (Loukkos estuary) and the 161 (Moulay Bousselham lagoon) (Table 2). Values estimated for the different indices are summarized in Table 3. Sampling effort showed a wide variability among the studied sites, with the maximal value in Moulay Bousselham lagoon and the minimum in Loukkos estuary (Table 3). With the exception of average phylogenetic diversity ($\Phi+$) and variation in taxonomic distinctness ($\Lambda+$), all the other indices showed significant dependence with the sampling effort ($p<0.05$). Moreover, all the taxonomic indices were significantly ($p<0.05$) related to species richness except the average taxonomic distinctness ($\Delta+$). In the majority of the SECS, both average taxonomic distinctness ($\Delta+$) and variation in taxonomic distinctness ($\Lambda+$) were within the 95% confidence funnel ($p\geq0.05$). Only the Oum Rbia and the Sebou estuaries as well as the Khnifiss lagoon appeared out of the confidence funnels (Figure 3).

Multiple regression analysis ($p>0.05$) revealed that none of the SECS features considered here are structural abiotic features regarding the species richness and the taxonomic diversity indices. Moreover, permutational multivariate analysis of variance (PERMANOVA) showed no interactions between type of SECS ($p>0.05$) in terms of species richness (S) and all taxonomic diversity indices (Table 4).

Table 2. Species richness by phylum in the semi-enclosed coastal systems of Morocco. NA: Nador, SM: Smir, TA: Tahaddart, LO: Loukkos, MB: Moulay Bousselham, SE: Sebou, BR: Bouregreg, OR: Oum Rbia, SI: Sidi Moussa, OU: Oualidia, KH: Khnifiss, DA: Dakhla.

	NA	SM	TA	LO	MB	SE	BR	OR	SI	OU	KH	DA
Annelida	28	11	14	13	45	16	39	17	20	31	19	28
Arthropoda	58	21	14	10	55	20	34	12	17	27	23	24
Chordata	8	1	0	1	6	0	0	0	0	0	0	0
Cnidaria	1	0	0	0	3	1	2	0	1	1	1	2
Echinodermata	5	2	0	0	1	1	1	0	2	2	0	1
Mollusca	58	18	12	8	49	56	22	19	17	44	19	50
Nemertea	0	0	0	0	2	0	3	0	0	0	0	0
Total	158	53	40	32	161	94	101	48	57	105	62	105

Table 3. Species richness (S) and taxonomic distinctness indices values in the semi-enclosed coastal ecosystems of Morocco. Δ^+: taxonomic distinctness, $S\Delta^+$: total taxonomic distinctness, Φ^+: average phylogenetic diversity, Λ^+: variation in taxonomic distinctness, $S\Phi^+$: total phylogenetic diversity. NA: Nador, SM: Smir, TA: Tahaddart, LO: Loukkos, MB: Moulay Bousselham, SE: Sebou, BR: Bouregreg, OR: Oum Rbia, SI: Sidi Moussa, OU: Oualidia, KH: Khnifiss, DA: Dakhla.

Sites	Sampling effort	S	Δ^+	$S\Delta^+$	Λ^+	Φ^+	$S\Phi^+$
NA	366	158	90	14232	279.9	47.7	7533.3
SM	123	53	89.6	4748.1	293.3	56.3	2983.3
TA	99	40	88.7	3549.6	311.6	55.0	2200.0
LO	134	32	89.1	2852.7	300.5	60.4	1933.3
MB	599	161	90.5	14569.2	268.7	47.8	7700.0
SE	7	94	87.8	8162.0	275.5	52.9	4916.7
BR	120	101	89.9	9075.7	278.3	51.7	5216.7
OR	39	48	88.5	4247.5	328.8	51.4	2466.7
SI	117	57	90.2	5141.7	271.3	56.4	3216.7
OU	43	105	89.8	9428.2	268.2	48.6	5100.0
KH	29	62	88.6	5491.8	333.7	51.9	3216.7
DA	100	105	89.7	9414.4	255.7	50.6	5316.7

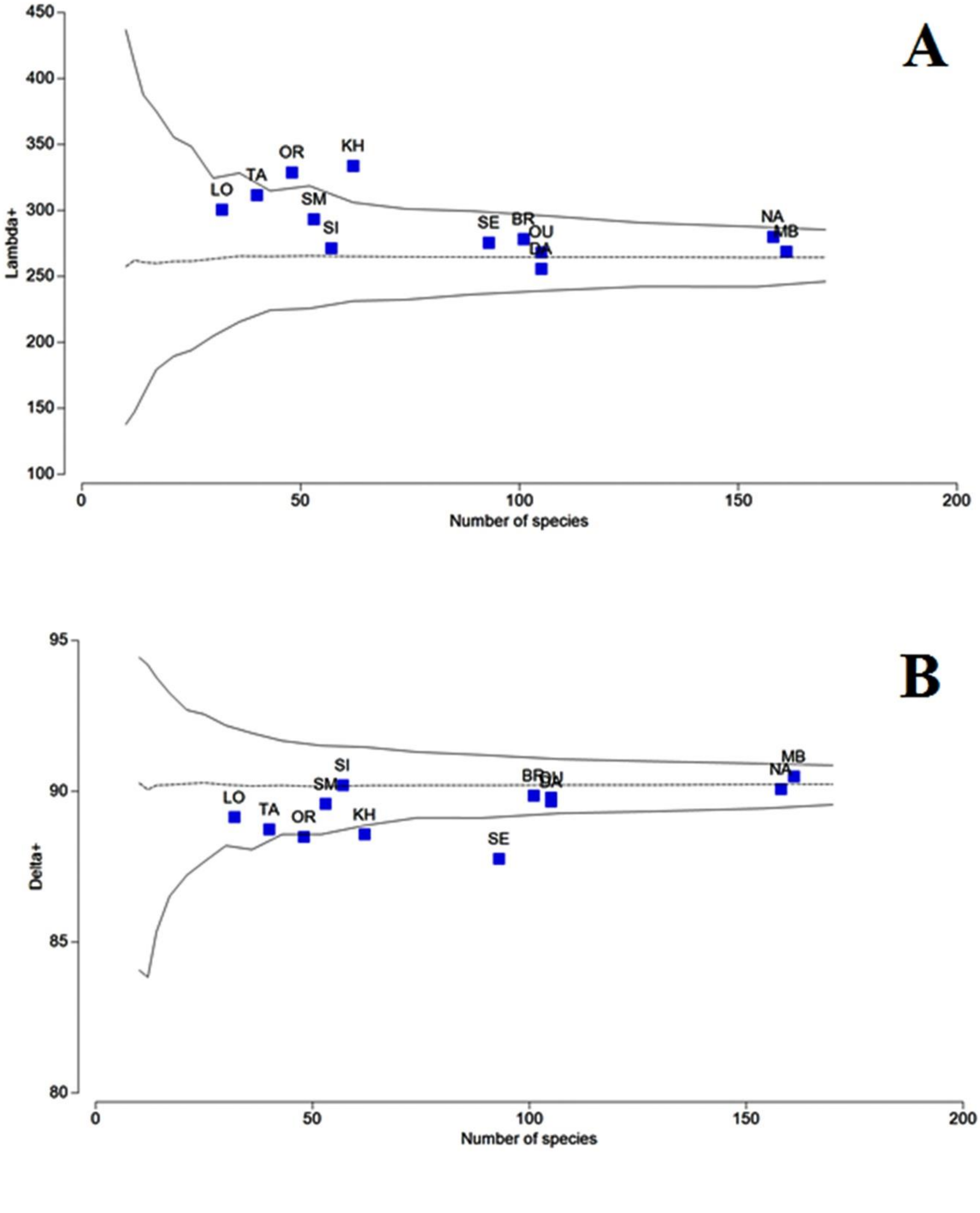

Figure 3. Confidence funnel (mean and 95% confidence interval) of the variation in taxonomic distinctness (A) and taxonomic distinctness (B) in the Moroccan semi-enclosed coastal systems. NA: Nador. SM: Smir. TA: Tahaddart. LO: Loukkos. MB: Moulay Bousselham. SE: Sebou. BR: Bouregreg. OR: Oum Rbia. SI: Sidi Moussa. OU: Oualidia. KH: Khnifiss. DA: Dakhla.

Table 4. Results of PERMANOVAs testing for each Species richness and taxonomic diversity indices at the scales of Type of the ecosystem (Lagoon - Estuary). Analyses based on a Bray Curtis similarity matrix of Square root transformed data. All tests used 9999 random permutations.

Source	*df*	MS	Pseudo-F	*P (perm)*	*df*	MS	Pseudo-F	*P (perm)*
	Species richness (S)				***Taxonomic distinctness (Δ+)***			
Type	1	312,26	1,9692	0,1845	1	0,20702	5,188	0,0528
Residual	9	158,57			9	3,99E-02		
Total	10				10			
	Total taxonomic distinctness (SΔ+)				***Variation in taxonomic distinctness (Λ^+)***			
Type	1	330,52	2,076	0,1825	1	3,5385	0,87669	0,3505
Residual	9	159,21			9	4,0363		
Total	10				10			
	Average phylogenetic diversity (Φ+)				***Total phylogenetic diversity($S\Phi^+$)***			
Type	1	5,0236	1,4911	0,2565	1	251,47	2,0287	0,1876
Residual	9	3,3689			9	123,95		
Total	10				10			

Macrobenthic assemblages' affinity

Cluster analysis, at a similarity distance of 40%, allowed to distinguish three affinity groups (Figure 4): G1 (40% of similarity) composed by Bouregreg estuary and Moulay Bousselham lagoon, G2 (50% of similarity) composed by Tahaddart, Loukkos and Oum Rbia estuaries and G3 (60% of similarity) composed by Oualidia and Sidi Moussa lagoons; the others SECS (Nador and Smir lagoons on the Mediterranean coast; Khnifiss lagoon and Dakhla bay on the Atlantic coast) remain individually separated from the previous groups with similarity fluctuating between 20% and 30%.

The obtained affinity groups as well as the other sites were represented on the PCO ordination graph (Figure 5). The first two ordination axes explained 36% (all sites considered) of the total variance in benthic macrofauna assemblages. The two-dimensional plots show a clear separation between lagoons and estuaries systems.

Through the DistLM analysis, only the SECS-type set of predictor variables had a significant relationship (type-estuary and type-lagoon) with species-derived multivariate cloud ($p<0.01$), explaining 27% of the total variation. However, the best model obtained through the DistLM procedure included height variables (Type-estuary, Type-lagoon, Type-bay, Province-Atlantic Surface, m-Temp, m-Sal and M-Sal) as predictors of benthic macrofauna composition, explaining 33% of the total variation (Adjusted $R^2 = 0.33$). When transposed to the dbRDA plot, the first two axes captured nearly 62% of the variability in the fitted model and 47% of the total variation in the data cloud (Figure 6). Axis 1 (representing 20% of total variation) was negatively correlated to Type-estuary ($r = -0.58$) and to M-Sal ($r = -0.52$). Axis 2 (representing

14% of total variation) was negatively correlated to Surface (r = −0.53). The axis 3 (representing 13% of total variation) was negatively correlated to Province-Atl (r = −0.52) and Type-bay (r = −0.55).

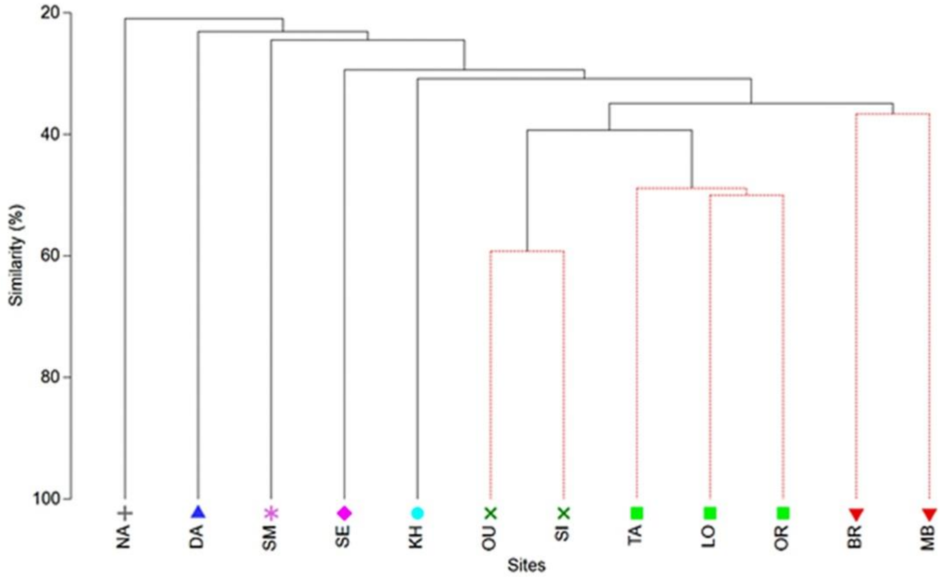

Figure 4. Dendrogram of cluster analysis using group-average linkage of Bray–Curtis similarities based on benthic macrofauna composition in the semi-enclosed coastal systems of Morocco. NA: Nador. SM: Smir. TA: Tahaddart. LO: Loukkos. MB: Moulay Bousselham. SE: Sebou. BR: Bouregreg. OR: Oum Rbia. SI: Sidi Moussa. OU: Oualidia. KH: Khnifiss. DA: Dakhla.

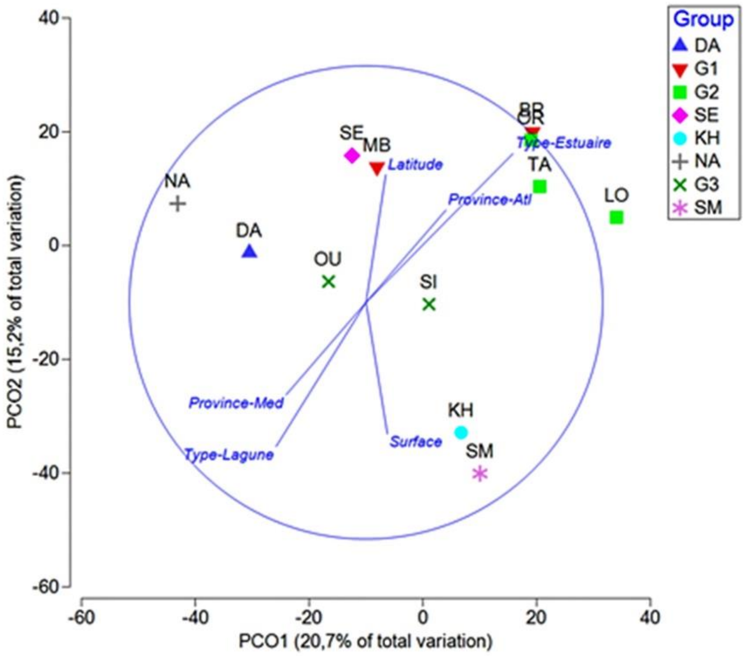

Figure 5. Ordination of the semi-enclosed coastal systems using the Principal coordinates ordination (PCO) with vectors (longer than 0.7) and clusters overlay. NA: Nador. SM: Smir. TA: Tahaddart. LO: Loukkos. MB: Moulay Bousselham. SE: Sebou. BR: Bouregreg. OR: Oum Rbia. SI: Sidi Moussa. OU: Oualidia. KH: Khnifiss. DA: Dakhla.

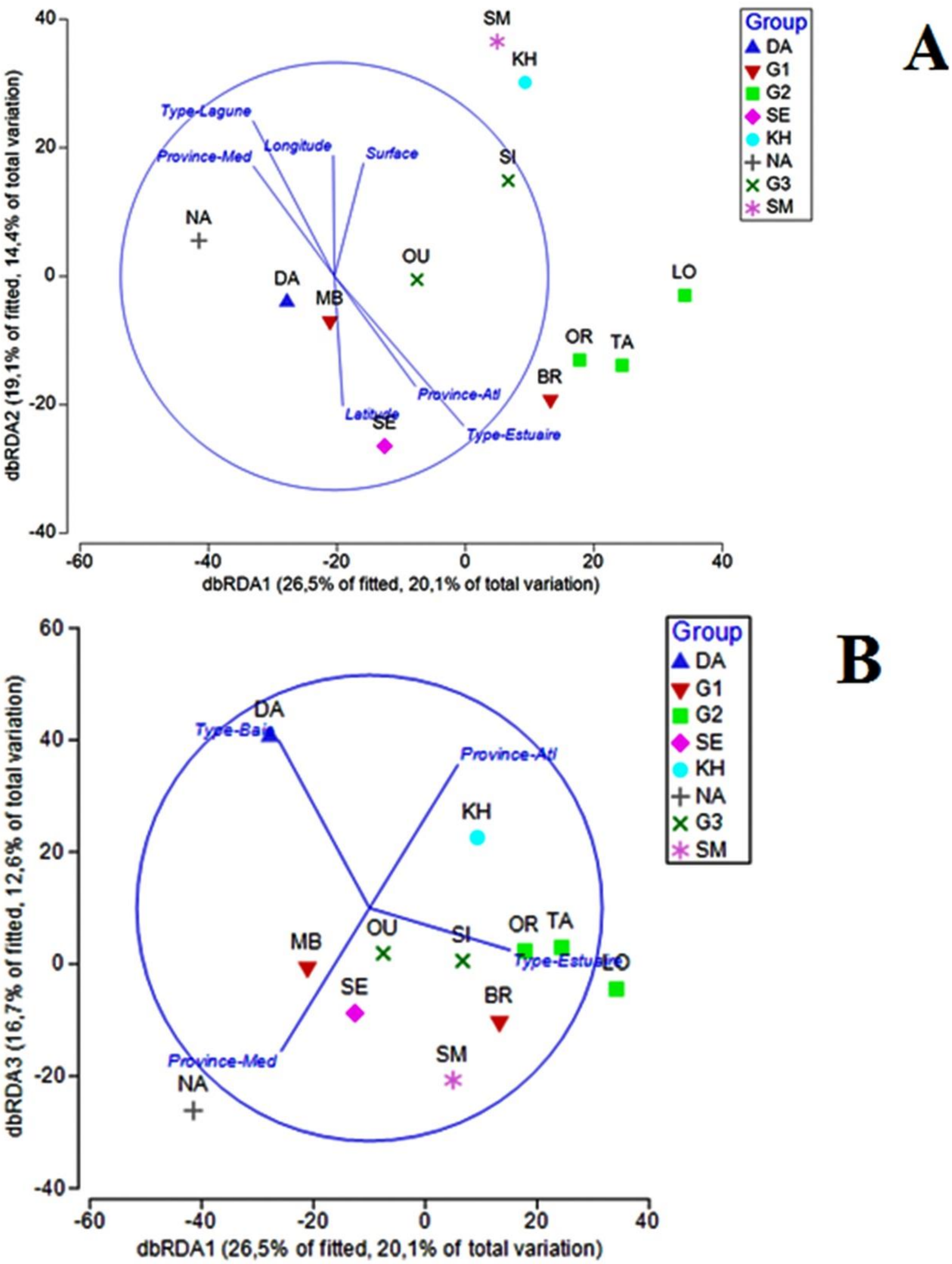

Figure 6. Distance-based redundancy analysis plot and the correlated variables that explained the semi-enclosed coastal systems distribution based on benthic macrofauna composition. NA: Nador. SM: Smir. TA: Tahaddart. LO: Loukkos. MB: Moulay Bousselham. SE: Sebou. BR: Bouregreg. OR: Oum Rbia. SI: Sidi Moussa. OU: Oualidia. KH: Khnifiss. DA: Dakhla.

Table 5. Gaps and knowledge gained from studies performed on soft-bottom zoomacrobenthos of the Moroccan SECS. NA: Nador. SM: Smir. TA: Tahaddart. LO: Loukkos. MB: Moulay Bousselham. SE: Sebou. BR: Bouregreg. OR: Oum Rbia. SI: Sidi Moussa. OU: Oualidia. KH: Khnifiss. DA: Dakhla. **I =** Intertidal **S=** Subtidal. **B** = Biomass. References (Numbers 1-36): **(1)** Elkaïm (1974); **(2)** Lacoste (1984); **(3)** Bekkali (1987); **(4)** Guelorget et al. (1987); **(5)** Bayed et al. (1988); **(6)** Cheggour (1988); **(7)** Zine (1989); **(8)** Chbicheb (1996); **(9)** Aksissou (1997); **(10)** Bazairi (1999); **(11)** Boussalwa et al. (2000); **(12)** Bazairi & Zourarah (2001); **(13)** Mergaoui et al. (2003); **(14)** Bazairi & Gam (2004); **(15)** Chaouti & Bayed (2005); **(16)** El Houssaini (2005); **(17)** Zine (2005); **(18)** Azirar (2006); **(19)** Bazairi & Bayed (2006); **(20)** Cherkaoui (2006); **(21)** Gauteur (2006); **(22)** Bazairi & Zourarah (2007); **(23)** Ait Mlik (2009); **(24)** Lefrere (2012); **(25)** Bououarour (2013); **(26)** Joulami (2013); **(27)** Boutahar (2014); **(28)** Cuvelier et al. (2014); **(29)** El Asri et al. (2015); **(30)** Bazairi et al. (2017); **(31)** El Asri et al. (2017); **(32)** Touhami (2018); **(33)** El Asri (2019); **(34)** Bououarour (unpublished data); **(35)** Boutoumit (unpublished data); **(36)** El Kamcha (unpublished data). Gray color indicates studies that can be considered as references for respective sites.

	Mediterranean		Atlantic									
	NA	**SM**	**TA**	**LO**	**MB**	**SE**	**BO**	**OR**	**SI**	**OU**	**KH**	**DA**
1974							1, IS					
1984					2, I							
1987	4, S, B	3, S										
1988							6, I				5, I	
1989	7, S											
1995												
1996										8, I		
1997		9, I										
1999					10, IS							
2000	11, S											
2001								12, IS, B				
2003						13, S						
2004				14, IS, B								
2005		15, I; 16, I				17, IS						
2006			19, IS				20, IS			21, IS		
2007								22, IS, B				
2009					23, IS							
2012											24, I	
2013					25, I				26, I, B			
2014	28, S									27, IS		
2015										29, IS		
2016												
2017								30, IS, B		31, IS		
2018					32, I, B							
2019										33, IS		33, IS
2020	36, S, B			34, I, B	34, I, B; 35, IS, B				34, I, B	34, I, B	34, I, B	34, I, B

Gaps and knowledge gained

Table 4 showed that there is a scarcity of studies and that there is no regular spatio-temporal monitoring. Sampling techniques, effort and objectives differ between sites and studies. Although all the existing studies are quantitative, most of them were single spot studies, had limited geographic scope (Mergaoui et al., 2003; Ait Mlik, 2009; Bououarour, 2013; Joulami, 2013), focused only on single taxonomic groups (e.g. Annelida: El Asri et al., 2017) Arthropoda: (Aksissou, 1997; Boussalwa et al., 2000), or on habitats (intertidal, subtidal, meadows). On the other hand, few studies have been carried out on benthos–predator interactions (Joulami, 2013; Touhami et al., 2019). Moreover, while few studies have considered biomass, there is no evaluation of secondary production and productivity in all the Moroccan SECS.

As a result, the studies that can be considered as references for soft sediments benthic assemblages are those of Guelorget et al. (1987), Zine (1989) and El Kamcha (unpublished data) for the lagoon of Nador, Bazairi and Gam (2004) for the Loukkos estuary, Bazaïri (1999) and Boutoumit (unpublished data) for the Moulay Bousselham lagoon, Elkaïm (1974) and Cherkaoui (2006) for the Bouregreg estuary, Gauteur (2006), Boutahar (2014) and El Asri (2019) for the Oualidia lagoon, Bazairi and Zourarah (2001, 2007) and Bazairi et al. (2017) for the Oum Rbia estuary and finally El Asri (2019) for Dakhla bay.

Discussion

Checklists of marine species at regional scale have multiple uses. In addition to offering comparative facts for biodiversity studies, they serve as a crucial device in spotting and delimiting regions in need of protection, inferring the capacity effect of anthropogenic interest, assessing the complexity of organic communities, and estimating the provision of dwelling resources (Hendrickx and Harvey, 1999).

The sample of SECS considered in this study covers most of the range of variation along the coasts of Morocco. Therefore, the current compilation represents the first comprehensive annotated checklist that gives an overall view on soft-bottom benthic macrofauna of the semi-enclosed coastal systems within the Atlantic and Mediterranean oceanographic regions of Moroccan waters, which is relevant in such poorly known area at the global scale. Moreover, it fulfilled a knowledge gap on benthic macrofauna in SECS of the Southern part of the Northeastern Atlantic and Mediterranean ecoregions. While all the existing inventories on Moroccan marine fauna focused on single taxonomic group and have large scope, our ecosystem-based checklist is more than a simple list of species inhabiting comparable ecosystems and constitutes a synthetic illustration of the relationships that species have with each other and with their environment. Furthermore, the resulting metadata, available in open access, will serve in comparing the soft-bottom macrobenthos assemblages at a large scale.

This study revealed a diverse benthic macrofauna for the Moroccan SECS with overall 496 species dominated by Mollusks, Arthropods and Annelids. It represents almost 46% of the known marine fauna of marine waters of Morocco (1068 taxa, all groups combined) (ONEM, 1998). However, comparison of diversity results between Moroccan SECS may be done with caution since the sampling methods, units and scales are often different, and moreover, the diversity of habitats in such ecosystems are high (Chardy and Clavier, 1988; Alongi, 1990).

Patterns in diversity are often related to latitude, a phenomenon known as the latitudinal diversity gradient (LDG), whereby a decrease with increasing latitude is found (Roy et al., 1998; Rex et al., 2000; Attrill et al., 2001; Willig et al., 2003; Hillebrand, 2004). Several hypotheses for the underlying causes for such pattern are suggested, yet none of them is solely sufficiently convincing (Willig et al., 2003; Hillebrand, 2004), although solar energy input (and for the marine territory, the sea surface temperature as its proxy) is most often mentioned as the main acting principle (Rohde, 1992; Roy et al., 1998). Species richness is the most elementary, easy to interpret and widely used measure of biodiversity (e.g. Dornelas et al., 2014). It has been shown to follow a - generally unimodal - large-scale (>45°) latitudinal gradient for marine benthic invertebrates with a peak in equatorial regions (Chaudhary et al., 2016). In contrast to the general LDG pattern, our results showed that speciesrichness and taxonomic diversity indices showed no relationship with latitude. Deviations from the general LDG pattern have also been reported before for European marine benthos by Renaud et al. (2009) who found no or weakly positive relationships. The explanation for this kind of diverting trend is that the impact of local variation in environmental factors is stronger than that of latitude related factors (Gaston, 2000; Renaud et al., 2009). Marine diversity might not follow a strict latitudinal gradient as the drivers of marine diversity themselves are not usually correlated with latitude (Piacenza et al., 2015).

In terms of assemblages composition, the best multivariate model, explaining 33% of the total variation observed in benthic assemblages, included the type of the SECS (estuaries vs lagoons vs bay), the marine ecoregion (Atlantic vs Mediterranean), the surface of the SECS and the environmental features (minimal temperature, minimal and maximal salinity) as predictors of benthic macrofauna composition in the Moroccan SECS. Such differences in benthic macrofaunal composition across a scale could result from the fact that each ecosystem has its own specific characteristics, which implies an individualistic approach to ecosystem ecology. Indeed, all ecosystems are subject to climatic and environmental forces and it is assumed that their variations induce a response from communities (Möllmann and Diekmann, 2012). The diversity and distribution of organisms can be influenced by the stochastic, ecological and evolutionary processes at local and regional scales (Hubbell, 2001), the limits of dispersion and recruitment of macroinvertebrate taxa (Hurtt and Pacala, 1995), the structural heterogeneity of the transitional waters (Basset and Abbiati, 2004) and the consequent selection of macroinvertebrate taxa according to their functional traits and niche needs (MacArthur, 1970). Variations in species richness and taxonomic composition of benthic macrofauna depends on local oceanographic processes (Aller et al., 2002; Coleman et al., 1997; McCallum et al., 2015), as well as on physiographic characteristics, such as surface area and outlet length (Basset et al., 2006). Variations might be related to ecosystem morphology, substrate type, organic residues (Galeron et al., 2001), salinity (Battaglia, 1959), degree of confinement (Guelorget and Perthuisot, 1983; Guelorget et al., 1983), changes in nutrient concentrations and changes in primary productivity (Galeron et al., 2001).

According to Spalding et al. (2007), the vast marine region of Morocco can be subdivided into two provinces, the Mediterranean Sea (Alboran Sea Ecoregion) and the Lusitanian (Saharan Upwelling Ecoregion). In corroboration to this subdivision, the type of province (Atlantic vs Mediterranean) was shown to be a significant predictor factor of the composition of the soft-bottom benthic fauna of the Moroccan SECS. Therefore, the currently described marine biogeographic boundaries in Morocco seem to apply to soft-bottom macrofauna of SECS and which environmental drivers were most associated with species differences among these two provinces. Significant differences have been found on the structure of the communities between the marine ecoregions, a fact which may be correlated with the specificities of the ecoregion's physiographical characteristics, as shown by Kong et al. (2013), which emphasizes that the distribution of the macroinvertebrate is correlated with ecoregional characteristics. Moreover, these marine ecoregions are affected by environmental factors (Lara-Lara et al., 2008).

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Chapter 3

Spatial Patterns of Macrozoobenthos Assemblages in a Sentinel Coastal Lagoon: Biodiversity and Environmental Drivers

Abstract:

This study presents an assessment of the diversity and spatial distribution of benthic macrofauna communities along the Moulay Bousselham lagoon and discusses the environmental factors contributing to observed patterns. In the autumn of 2018, 68 stations were sampled with three replicates per station in subtidal and intertidal areas. Environmental conditions showed that the range of water temperature was from 25.0°C to 12.3°C, the salinity varied between 38.7 and 3.7, while the average of pH values fluctuated between 7.3 and 8.0. In vegetated habitats, biomass values of the seagrass *Zostera noltei* Hornemann ranged between 31.7 gDW/m² and 170.2 gDW/m² while the biomass of the seagrass *Ruppia cirrhosa* (Petagna) Grande between 54.2 gDW/m² and 84.7 gDW/m². Sediment analyses showed that the lagoon is mainly composed of sandy and silty sediments. We recorded 37,165 individuals of macrofauna distributed in 63 taxa belonging to 50 families, with a mean abundance value of 4582.8 ind/m² and biomass average of 22.2 g AFDW/m^2. Distance-based linear modeling analysis (DistLM) identified sediment characteristics, water parameters and habitat type (biomass of *Z. noltei*) as the major environmental drivers influencing macrozoobenthos patterns. Our results clearly revealed that the hydrographic regime (marine and terrestrial freshwater), sediment distribution and characteristics and the type of habitat (vegetated vs unvegetated substrate) are the key factors determining the species composition and patterns of macrozoobenthos assemblages.

Keywords: Moulay Bousselham lagoon; benthic macrofauna; Semi Enclosed Coastal System; Atlantic Morocco

Introduction

Coastal lagoons are among the marine habitats with the highest biological productivity (Alongi, 1998) and perform an important ecological function by providing forty-one varieties of goods and services (Newton et al., 2018). However, coastal lagoons are semi-enclosed coastal systems (SECS) where environmental conditions are highly changeable due to their confined nature and their shallowness. SECS are especially vulnerable to the impacts of human activities resulting from mining, industry, tourism and urban development (Courrat et al., 2009; Ruiz- Fernández et al., 2014). The geomorphology of these SECS renders them particularly vulnerable to global changes, such as sea-level rises, increased temperatures, storminess, droughts, floods and changes in sediment dynamics. They are "hotspots" of global change and vulnerability to environmental, economic and social pressures (Newton et al., 2012).

Coastal lagoons are sentinel systems that are highly vulnerable to the impacts of climate change (Eisenreich, 2005). They have natural conditions that play a key role in regulating water movement and nutrient accumulation between land, rivers and the ocean (Brito et al., 2010). Sea level, temperature, precipitation and storms are expected to change significantly with global climate change and have a direct impact on coastal lagoons. These changes could modify the composition and diversity of natural communities, such as changes in community composition and diversity, sensitivity to eutrophication, loss of native species and their capacity to provide goods and services (Cossarini et al., 2008; Melaku Canu et al., 2011). The conservation of coastal lagoons is therefore relevant for their ecological importance, as well as for the valuable ecosystem services (ES) they provide for human welfare.

Macrozoobenthos is a key component of the coastal ecosystems process, which substantially modifies the physical structure of the abiotic or biotic materials forming the habitat and thus directly or indirectly changes the availability of resources to other species (Lu, 2005). They are important as food sources for organisms of the upper trophic levels (Dauer, 1993). Moreover, benthic macrofauna improves and preserves water quality through mineralization, and recycling of organic matters structures and oxygenates the bottom by reworking sediments, recycles nutrients, decomposes organic matter and linking primary production with higher trophic levels (Sarker et al., 2016). Hence, it is used as an indicator for the detection of types and levels of stress in environmental impact studies (Warwick, 1993) and in environmental quality assessment of coastal systems (Ponti and Abbiati, 2004).

The Moulay Bousselham lagoon is one of the most important coastal wetlands on the Moroccan Atlantic coast. It represents the most important Moroccan site for the migration and wintering of birds (exceeding 56% of the total number of wintering waders in Morocco); it relays migration between the European and African continents for many species of western Palearctic birds (Qninba, 1999; Benhoussa, 2000; Thévenot et al., 2003). The importance of this Ramsar site is primarily due to the remarkable diversity of its habitats (Qninba, 1999) and their associated flora and fauna. The lagoon of Moulay Bousselham is one of the Moroccan sites that has benefited the most from national and international conservation status: Ramsar Site, Biological Reserve, Game Reserve, Site of Biological and Ecological Interest (SIBE) and Area of Importance for the Conservation of Birds (ZICO).

Nevertheless, the close dependence of the local residents on the natural resources of the site calls into question its balance and threatens the sustainability of the availability of these resources. The intense development of human activities (urban pressure, overgrazing and overexploitation of water and plant resources) has reduced the surface area of the site's natural habitats and consequently its biological diversity (Touhami, 2018). In fact, the area of the latter currently occupies only about 3000 ha out of the 4500 to 5000 ha, representing their initial area when the site was listed as a Ramsar site in 1980 (Qninba, 1999). On the other hand, the misuse of fertilizers and phytosanitary products in adjacent agricultural areas and the discharge of sewage from the highway into the lagoon contribute to eutrophication and contamination of water and sediments (hydrocarbons, heavy metals) (Alaoui et al., 2010; Maanan et al., 2013).

The Moulay Bousselham lagoon is the most studied system on the Atlantic coast of Morocco for birds (Bazairi, 1999) and therefore is a good sentinel site to survey the global change effect, including climate change, on the African Atlantic and allows for comparison with other similar SECS on the European Atlantic coasts. Up until now, there is no extensive study of the benthic macrofauna and their spatial patterns in the Moulay Bousselham lagoon. Studies carried out by (Lacoste, 1984; Bazairi, 1999; Ait Mlik, 2009; Bououarour, 2013; Touhami, 2018), are all limited to a part of the ecosystem. Here, we attempt to contribute to filling this gap in our current knowledge with a basic study of the intertidal and subtidal macrofauna of this coastal lagoon. Our study, based on an extensive sampling, is the first to cover the whole area of the lagoon.

The aim of this study is to provide new insight into the biodiversity of the macrozoobenthos assemblages inhabiting the Moulay Bousselham lagoon, their composition, structure and spatial patterns. This study also aims to highlight the environmental drivers that govern the spatial distribution of benthic communities.

Materials and Methods

Study Area

The Moulay Bousselham lagoon is the northernmost lagoon on the Moroccan Atlantic coast (Figure 1). The lagoon is located 125 km north of Rabat; it has an elliptical shape, with a maximum length of 9 km, a maximum width of 5 km and an area of 35 km². The communication of the lagoon with the Atlantic Ocean is done through a narrow, sinuous and relatively deep gully (up to 6 m), which branches out in the direction of the lagoon by shallow subtidal channels, ensuring the circulation of water during the flood and ebb. The freshwater supply is provided by two rivers: Canal Nador in the south and Oued Drader in the northeast of the lagoon. The tidal part of the latter course divides the lagoon into two body-waters locally known as 'Merja': (i) The Merja Kahla, which is extended on 3 km on the north part of the lagoon, is very shallow, and its bottom is covered with a very dark mud; and (ii) the Merja Zerga, which represents the major part of the lagoon as it is extended over 27 km² and appears blue due to its high depth at high tides (Bazairi, 1999). The depth of the lagoon varies between 0 and 2 m depending on the tidal cycle and rainfall. During the annual cycle, the average salinity of the lagoon water fluctuates from 24.0 to 36.3 at high tide and from 8.0 to 32.5 at low tide (Labbardi et al., 2005).

Sample Collection and Environmental Analyses

Grid sampling design encompasses the entire intertidal and subtidal areas of the Moulay Bousselham lagoon, with a combination of sample points taken at 500 m intervals. Sixty-eight stations (Figure 1) were sampled in the autumn of 2018 with three replicas per station. In subtidal areas, the samples were collected using a Van Veen grab, and each sample had a surface area of 0.1 m². While in intertidal zone, samples were taken using a PVC corer with a diameter of 12.5 cm, and each replica was a fusion of 10 cores, covering a total area of approximately 0.12 m².

The samples were sieved *in situ* through a 1 mm mesh. The material retained on the mesh was fixed and preserved in seawater with formalin (4%) and colored with Rose Bengal. In the laboratory, macroinvertebrates were sorted, identified and counted. Biomasses were obtained after calcination in the oven at 450°C for 4 hours.

Physicochemical parameters (water temperature, salinity and pH) were also measured *in situ* with a HANNA portable multiparameter. Each sample of the macrofauna was accompanied by an additional sediment sample to determine their precise granulometry, carbon content and total organic matter (TOM).

Grain size was measured using a laser particle size analyzer (Malvern Mastersizer 2000©) after preparing the sediments in a sodium hexametaphosphate solution (Gee and Or, 2002). The grain size distribution was then treated with the Gradistat© Excel package (Blott and Pye, 2001). Mean, sorting, skewness, kurtosis, decile statistics (including the median used to characterize the sediment type: d50) and clay/silt/sand composition were calculated to precise the textural group of each sample (Pouzet et al., 2019; Pouzet and Maanan, 2020a). A LECO© carbon analyzer estimated the carbon, CO_2 and $CaCO_3$ percentages after 1400°C dioxygen burning and mineral decarbonizing with sulfuric acid solution (Andrews et al., 2008), while the organic matter content was determined by estimating the total organic matter (TOM). The samples were oven dried (at 60°C for 48 hours) and ignited in an oven for 4 hours at 500°C. The percentage weight loss during the ignition step is reported as TOM (Heiri et al., 2001). When present, the biomasses of the seagrasses *Zostera noltei* Hornemann and *Ruppia cirrhosa* (Petagna) Grande were measured using a dry weight (gDW/m²). The seagrasses were isolated and rinsed with water and then dried in an oven at 60°C for 48 hours.

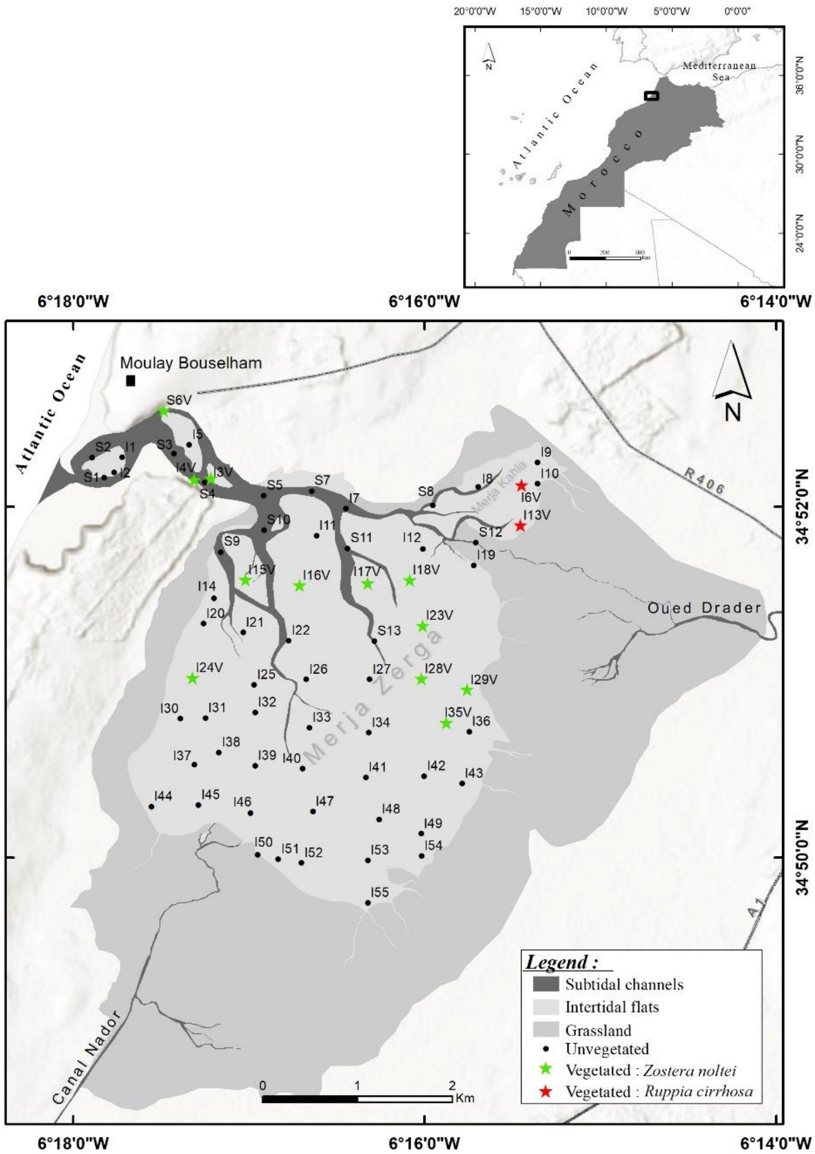

Figure 1. Map showing the location of the Moulay Bousselham lagoon and sampling stations. S: subtidal; I: intertidal; V: vegetated (©by S. Boutoumit).

Data Analysis

The data matrix with macrofaunal abundance per station was transformed into square root, and then the Bray-Curtis similarity was calculated between stations. The similarity matrix was analyzed using agglomerative hierarchical clustering (AHC) to identify macrofaunal affinities. The environmental variables were transformed to log (X+1). Percentage similarity analysis (SIMPER) was used to identify the taxa that contributed most to disparities between each identified assemblage and to the dissimilarity among them.

DistLM analysis (Distance-based linear modeling) was used to assess the contribution of environmental variables to the variability observed in the macrofaunal assemblages (McArdle and Anderson, 2001). Results were visualized using the graphical representation of the ordination method of redundancy analysis (RDA). RDA is a constrained ordinate used to identify the linear combinations of predictor variables that explain the greatest variation in the species/abundance matrix, i.e., it shows the pattern of species/abundance (response) data as constrained by the predictor variables (Legendre and Anderson, 1999).

Spatial distribution and biodiversity were described by univariate analyses based on the following parameters: abundance (N, the number of individuals per m²), species richness (S), Shannon- Weaver diversity index (H') (Shannon and Weaver, 1949) and Pielou's evenness index (J') (Pielou, 1969). All these analyses were performed with PRIMER v6.0 software (Clarke and Warwick, 2001; Clarke and Gorley, 2006).

The (S) ($\log_2$ S) and (H') indices of the assemblages were plotted together on a two-dimensional graphical representation in the Diversity Model (DIMO) considered as a synthetic tool (Qinghong, 1995).

Results

Environmental Variables

The spatial variation of environmental conditions is shown in Figure 2. The range of water temperature was from 12.3°C at station I50 to 25.0°C at station S1. The salinity varied among stations, with the maximum recorded at station S2 (38.7) and the minimum at the station I50 (3.7). The pH values fluctuated between 7.3 (station I9) and 8.0 (station I22). In stations with vegetated habitats (Figure 1), biomass values of *Zostera noltei* seagrass ranged between 31.7 gDW/m² in station I29V and 170.2 gDW/m² in station I23V, while the biomass of *Ruppia cirrhosa* seagrass ranged between 54.2 gDW/m² in I6V and 84.7 gDW/m² in I13V.

Grain size parameters also vary depending on the location of each station (Figure 2). Stations S10, S3 and S4 are dominated by sands (> 94%), with a median grain size (d50) higher than 350 µm and consequently low mud values (around 3-5%). S11, I1, S1, S12, S6V, I2, S5, S2, I46, S13 and S9 have more important silt proportion (around 10 to 20%). As their d50 reaches high values (> 300 µm), their main sediment type is characterized as “muddy sands” to “sands”, depending on their sand content. Fourteen other samples are more heterogeneous: S7, I41, I34, I5, I9, I11, S8, I22, I17V, I42, I30, I19, I28V and I3V (around 50% and reaching 75% of dominating silts and sands); depending on their dominance, they are characterized as “silty sands” or “sandy silts”. Their mud content reaches values from 25 to 75% in the order of the previous station list. The “sandy silts” textural category also includes a list of thirty stations studied: I40, I18V, I15V, I4V, I7, I32, I25, I20, I6V, I26, I48, I33 and I54 as silt variates between 70 and 80%, and the d50 is inferior to 25µm (“medium” or “coarse silt” category). The clay percentage reaches 4.8% for the most clayey-rich station (I27), integrated into the lower grain-sized sediment samples where the 27 other stations are integrated. These stations have the lowest granulometry, with a median grain size of 7.3 µm and the highest mud proportion (from 85 to 99%).

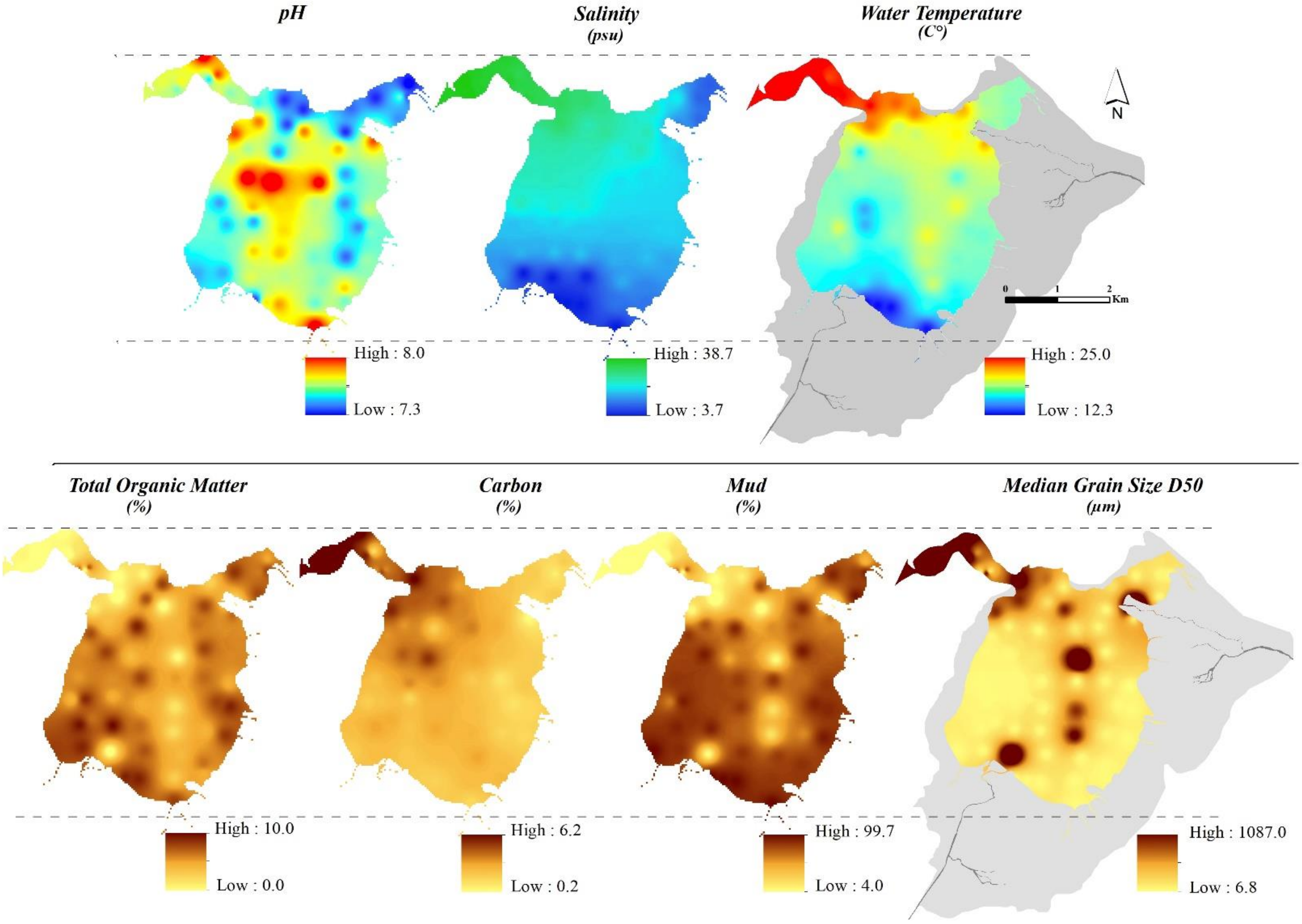

Figure 2. Maps showing the spatial distribution of environmental variables in the Moulay Bousselham lagoon.

Carbon content (carbon, CO_2 and $CaCO_3$ percentages) is higher in the “sand” and “silty sand” textural categories. These refer to the stations I2 (with the highest value of 6.2%), S2, S1, I1, S6V, S5, S3, S9, I22, S4, I11, S10 and I21, located nearest to the channels and the inlet (Figure 2). These high values refer to the shells that remain observed in marine sands. In opposition, carbon values are lower (< 1.5%) in the muddy dominated samples (in most of the "mud” and “sandy mud” textural categories): I24V, I39, I31, I29, I27, I46, I50, I44, I8, I13V, I9, I16V, I30, I51, I52, I42, I43, I36, I32, I10, I55, I5, S12, I35V, I28V, I6V and I19 (with the lowest 0.2% value), where most of these sediments sampled are located far from the channels (Figure 2).

The total organic matter (TOM) ranged from 0.3% (S10) to 9.6% (I39). Higher values of TOM are detected far from the inlet and the channels because the decrease of water currents allows for the deposition of fine sediments together with particulate organic matter and detritus in muddy sediments (Figure 2). Consequently, stations I39, I37, I52, I16V, I51, I36, I45, I31, I8, I43, I44, I55, I7, I21, I35V and I26 shows higher TOM proportions (> 8%). In opposition, marine sands have low values of TOM (values < 2% for the S2, S7, I2, S12, S13, S1, S5, S6V, I1, S11, S3, S4, I46 and S10 stations).

Benthic Macrofauna

Overall, 37165 individuals of benthic macrofauna were collected and are distributed on 63 taxa including 50 families. Mollusca was the predominant phylum with 24 species belonging to 18 families. For Arthropoda, 20 species were counted with 19 families. The phylum Annelida was the third dominant group with 18 species belonging to 12 families. One family represented the phylum Nemertea.

The species richness (S) ranges between 3 and 35, respectively, at stations I2 and I7, while the abundance fluctuates between 66.7 ind/m² (station I2) and 25625.0 ind/m² (station I23V). The values of the diversity index (H’) vary between 0.4 (station I1) and 2.5 (station I39). For the vast majority of stations, equitability index (J’) values are high, indicating the equity of species dominance. The lowest biomass value was recorded at station I2 (0.2 g AFDW/m^2), while the highest value was recorded at station I17V (92.5 g AFDW/m^2) (Figure 3).

Peringia ulvae (Pennant, 1777), *Capitella capitata* (Fabricius, 1780), *Lekanesphaera rugicauda* (Leach, 1814), *Heteromastus filiformis* (Claparède, 1864), *Scrobicularia plana* (da Costa, 1778), *Chironomidae*, *Melita palmata* (Montagu, 1804), *Pseudopolydora antennata* (Claparède, 1869), *Cyathura carinata* (Krøyer, 1847) and *Haminoea navicula* (da Costa, 1778) were the most abundant and/or common species with an average abundance respectively of:

1251.0 ind/m², 381.5 ind/m², 187.9 ind/m², 177.2 ind/m², 158.9 ind/m², 142.8 ind/m², 115.5 ind/m², 102.2 ind/m², 99.8 ind/m² and 90.6 ind/m².

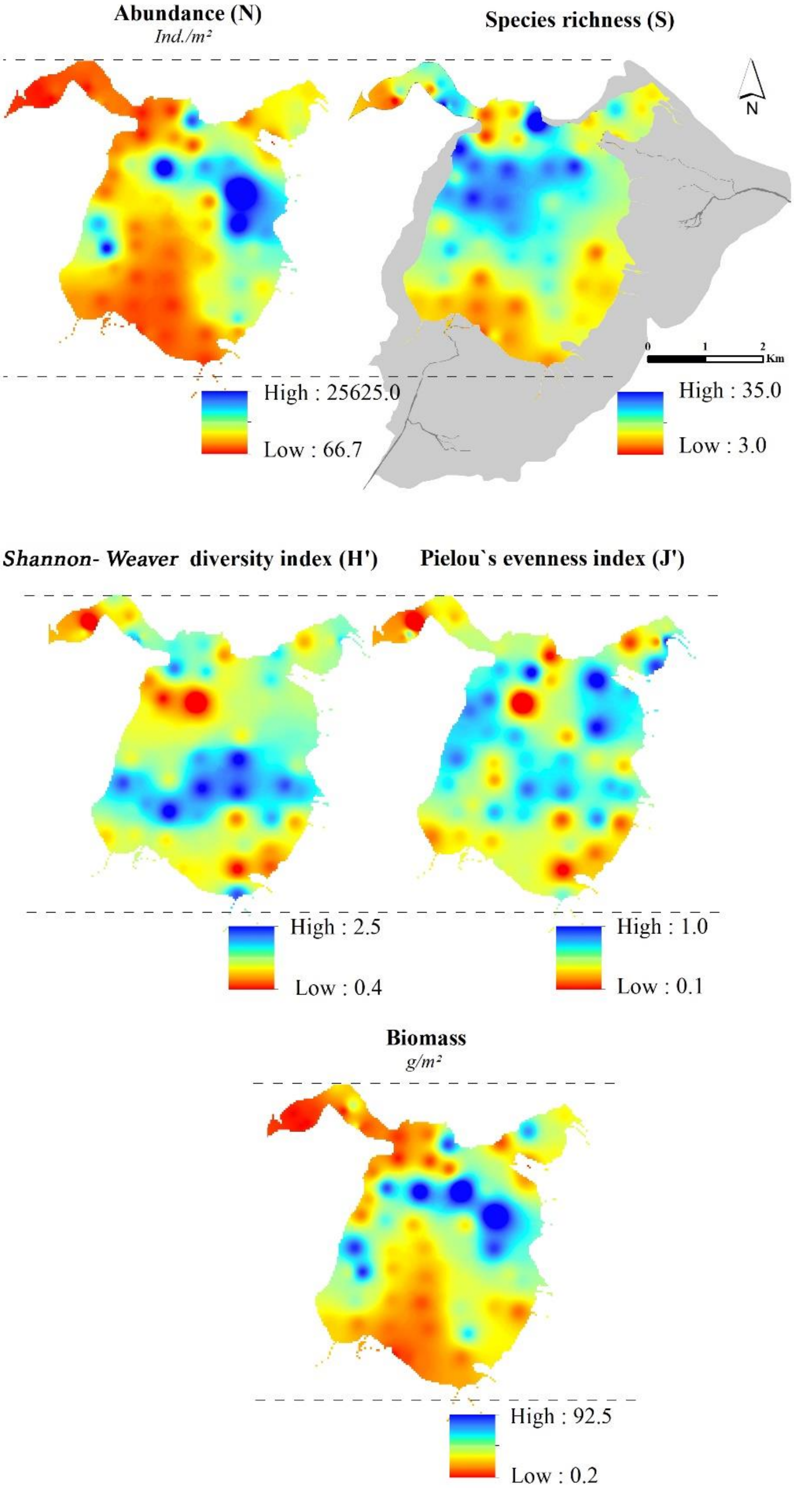

Figure 3. Interpolation of the spatial distribution of species richness (S), abundance (N), diversity index (H'), equitability index (J') and the biomass in the Moulay Bousselham lagoon.

Cluster analysis, based on the abundance matrix of the 68 stations, indicates a high degree of spatial heterogeneity (Figure 4 and 5). The dendrogram showed a stratification of fourteen clusters: 8 multi-stations, 1 doubleton and 4 singletons.

The characteristic species of each benthic assemblage have been identified by the SIMPER analysis (Table 1). Taxons that have largely contributed to the similarity of group G1 (67.36%) were *Peringia ulvae* (22.80%), *Capitella capitata* (14.89%) and *Chironomidae* (12.58%). The group G2 (63.59%) is dominated by *Peringia ulvae* (16.73%), *Capitella capitata* (12.09%), *Scrobicularia plana* (8.66%), *Lekanesphaera rugicauda* (6.97%) and *Cyathura carinata* (6.27%). Dominant species in the group G3 (67.94%) were *Scrobicularia plana* (10.34%), *Cyathura carinata* (9.87%), *Peringia ulvae* (8.51%), *Streblospio shrubsolii* (Buchanan, 1890) (7.70%), *Haminoea navicula* (7.64%) and *Heteromastus filiformis* (7.56%). In the group G4 (54.97%), the dominated taxa were *Cyathura carinata* (24.04%), *Peringia ulvae* (21.85%) and *Scrobicularia plana* (16.83%). Group G5 (66.32% of similarity) is characterized by the dominance of *Peringia ulvae* (17.83%), *Scrobicularia plana* (13.40%), *Cyathura carinata* (12.33%) and *Hediste diversicolor* (O.F. Müller, 1776) (11.29%). The characteristic species of the group G6 (67.73% of similarity) were *Heteromastus filiformis* (9.41%), *Cyathura carinata* (6.71%), *Capitella capitata* (5.85%), *Scrobicularia plana* (5.85%), *Streblospio shrubsolii* (5.30%), *Haminoea navicula* (5.06%), *Peringia ulvae* (4.61%), *Glycera tridactyla* (Schmarda, 1861) (4.60%) and *Cerastoderma edule* (Linnaeus, 1758) (4.49%). Contributing species for the group G7 (35.16%) were *Peringia ulvae* (40.33%) and *Lekanesphaera rugicauda* (26.68%). Regarding the group G8 (53.85%), the dominated taxa were *Heteromastus filiformis* (13.76%), *Abra tenuis* (Montagu, 1803) (12.65%), *Abra alba* (W. Wood, 1802) (10.94%), *Peringia ulvae* (10.70%) and *Nephtys hombergii* (Savigny in Lamarck, 1818) (7.86%). While *Peringia ulvae* (16.56%), *Glycera tridactyla* (9.39%), *Spio filicornis* (Müller, 1776) (8.49%) *Tritia pfeifferi* (Philippi, 1844) (8.49%) and *Cerastoderma edule* (7.14%) were the dominant taxon for G9 (56.08%). Stations S10, S4, S8, I12, and S13 were isolated to defined groups with a single station.

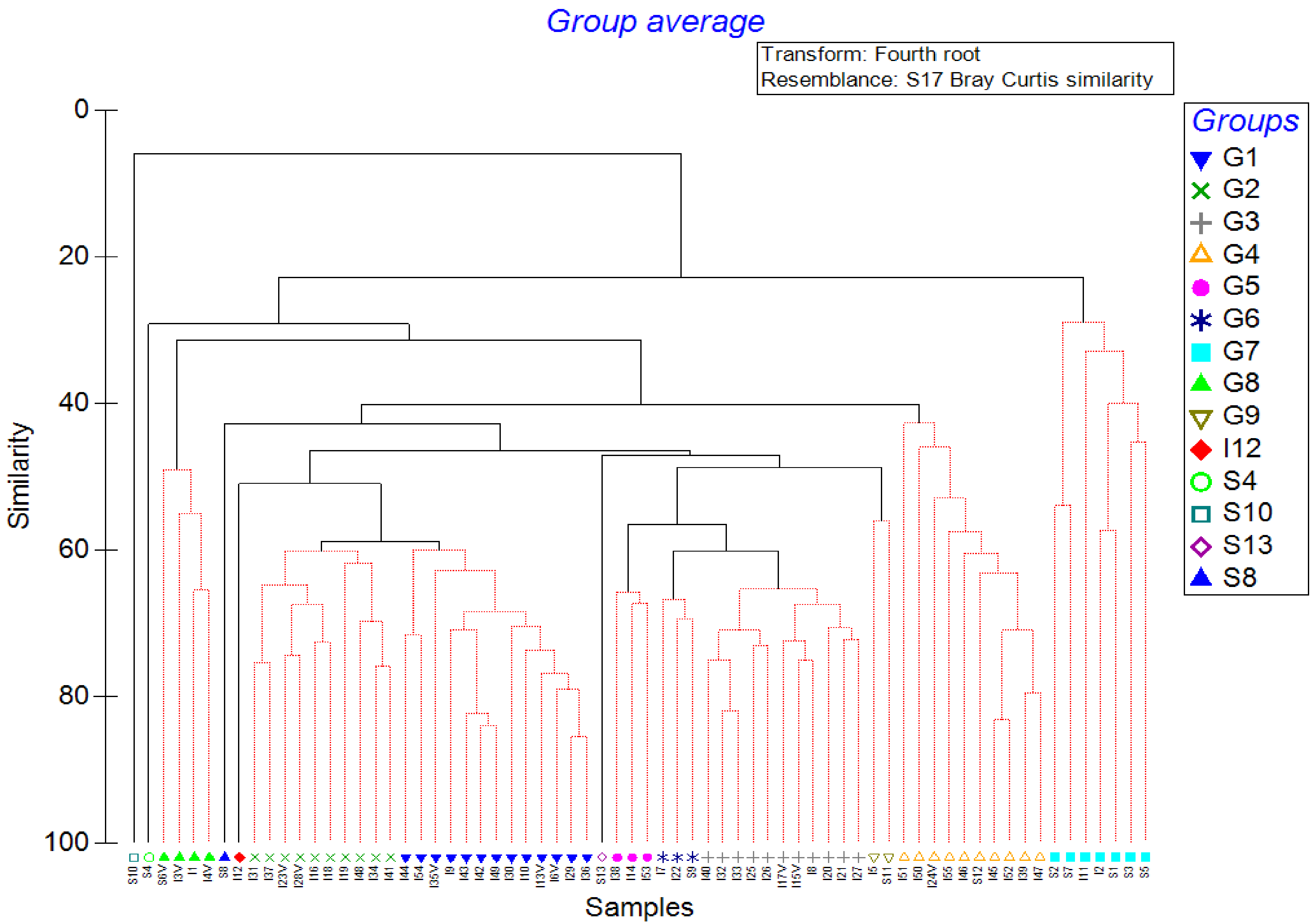

Figure 4. Cluster obtained from the ascending hierarchical classification (AHC) based on the similarity matrix of macrofauna.

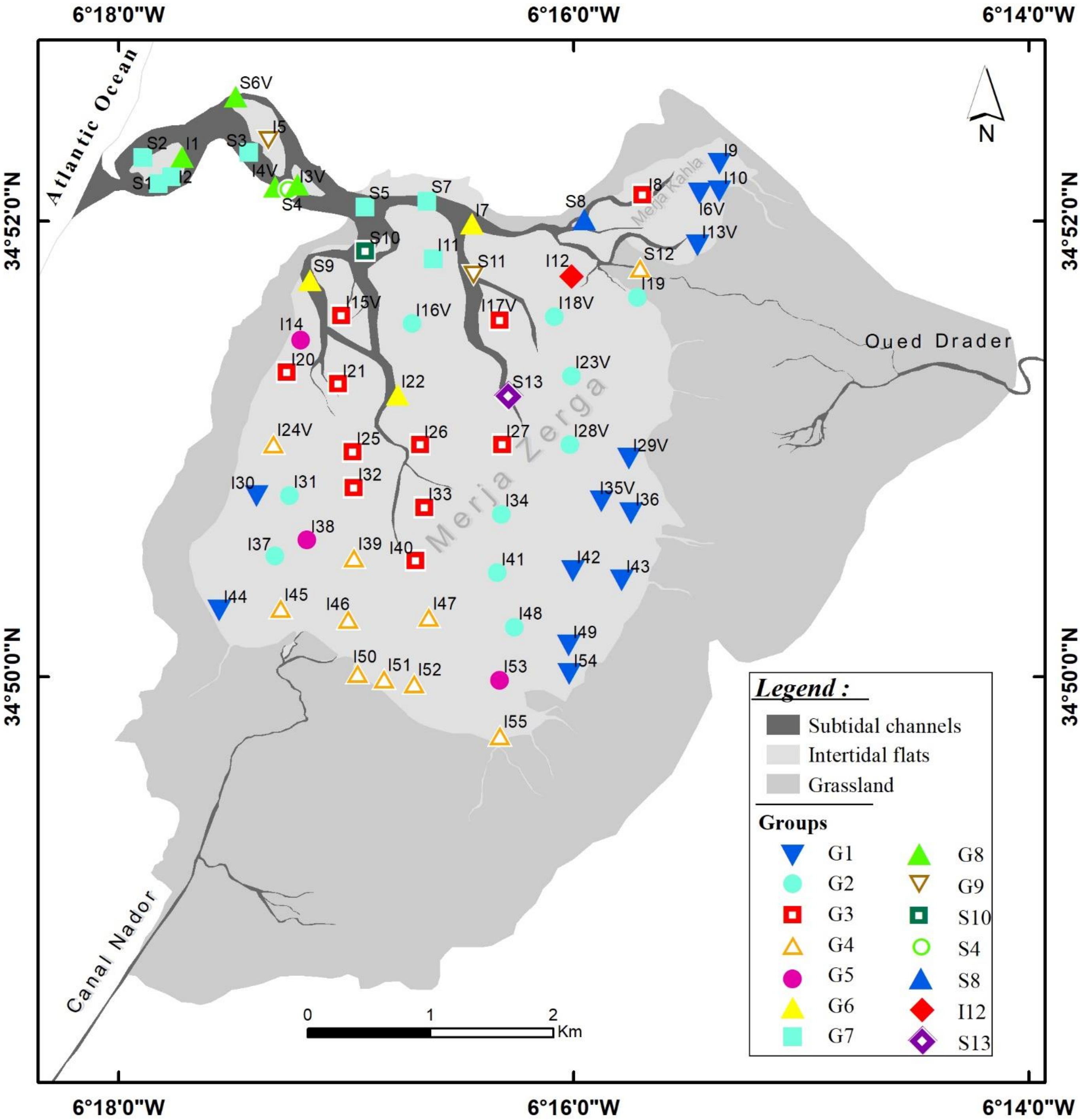

Figure 5. Map showing the spatial distribution of the groups of stations identified by cluster analysis based on the similarity matrix of macrofauna.

Table 1. SIMPER results showing the average similarity between benthic assemblages identified by Cluster analysis and the contribution of characteristic species of each benthic assemblage.

	G1	G2	G3	G4	G5	G6	G7	G8	G9
	67.36%	63.59%	67.94%	54.97%	66.32%	67.73%	35.16%	53.85%	56.08%
Species Contribution %									
Abra alba								10.94	
Abra tenuis								12.65	
Capitella capitata	14.89	12.09				5.85			
Cerastoderma edule						4.49			7.14
Chironomidae larvae	12.58								
Cyathura carinata		6.27	9.87	24.04	12.33	6.71			
Glycera tridactyla						4.60			9.39
Haminoea navicula			7.64			5.06			
Hediste diversicolor					11.29				
Heteromastus filiformis			7.56			9.41		13.76	
Lekanesphaera rugicauda		6.97					26.68		
Nephtys hombergii								7.86	
Peringia ulvae	22.80	16.73	8.51	21.85	17.83	4.61	40.33	10.70	16.56
Scrobicularia plana		8.66	10.34	16.83	13.40	5.85			
Spio filicornis									8.49
Streblospio shrubsolii			7.70			5.30			
Tritia pfeifferi									8.49

The DIMO model distinctly separated the community groups and displayed a type 4 dynamic (non-constant type), where all three parameters (S, H' and J') changed (Figure 6). According to the DIMO model, the stations located in the muddiest areas (near the Nador Canal); some stations in the subtidal zone and others near the sea are the least diversified and structured, while vegetated habitats and surrounding areas are the most diversified and the well-structured.

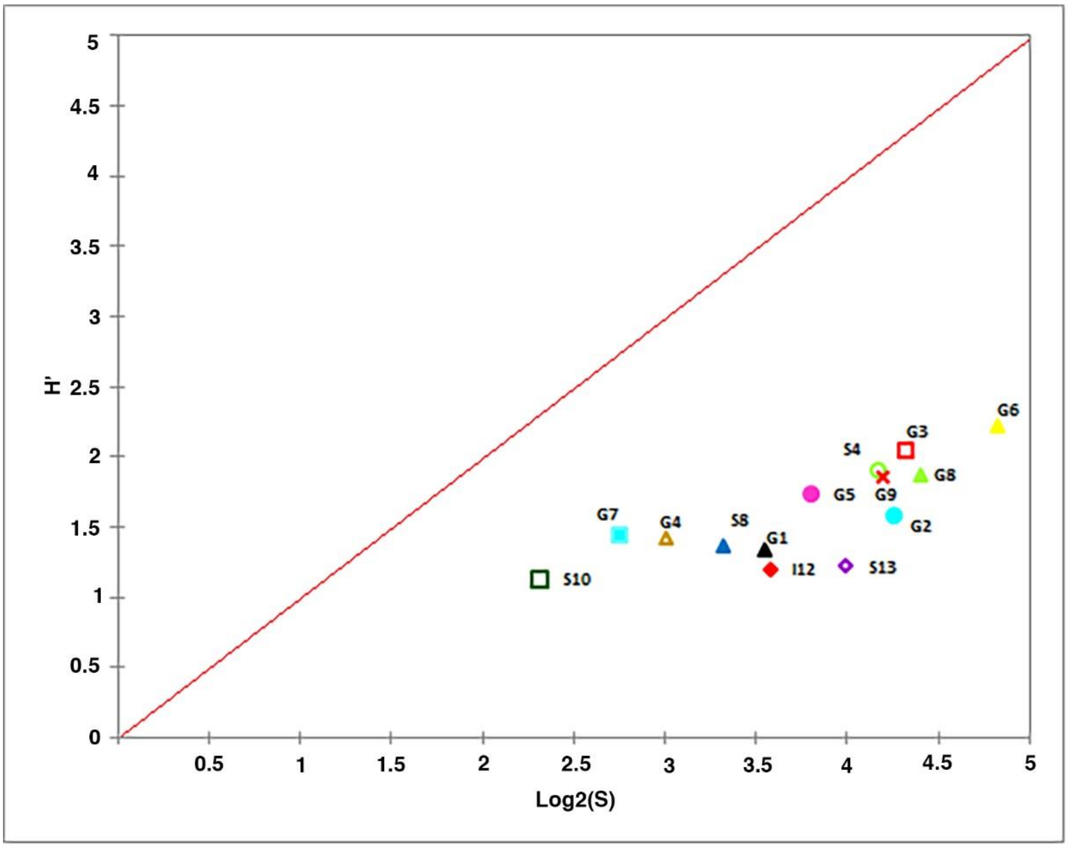

Figure 6. Simultaneous representation of species richness $Log_2(S)$, Shannon- Weaver index (H') of macrobenthos assemblages in the Moulay Bousselham lagoon using the DIMO model.

Relationships between Macrobenthos and Environmental Conditions

Results of the non-parametric multiple regression analysis (DistLM) between community composition and environmental variables showed significant correlations with nine variables (Adjusted R^2 = 0.41; $p < 0.01$). These corresponded to the sediment characteristics (mud content, median grain-size, TOM (%), carbon%, $CaCO_3$%, and CO_2%), water characteristics (T°, pH, salinity) and habitat type (biomass of *Zostera noltei*) (Table 2).

Figure 7 shows the RDA ordination obtained using DistLM. The pattern indicates that there are at least two trends in the macrofaunal community structure that can be modeled by these environmental drivers. The first clusters, which include stations located near/or in subtidal zones (G6, G7, G8, S4, and S10), are driven by salinity, pH, median grain size and carbon content in the sediment (percentage of: carbon, CO_2 and $CaCO_3$). The second trend highlights the variability between sites in the central and peripheral areas of the lagoon. These variations are related to differences in the percentage of TOM and mud in the sediment, water temperature, salinity and the presence of *Z. noltei*. The first axis explained 39.8% out of the fitted and 16.3% out of the total variation, while the second accounts for 26.2% of the fitted and 10.7% of the total variation. In total, the first two RDA axes explain 66% of the adjusted change, and this accounts for about 27% of the total change in the multivariate community data. The full RDA axis explains 100% of the adjusted variation and 41.02% of the total variation.

Table 2. Results of DistLM analyses showing relationships between environmental predictor variables and macrofauna community structure.

Variable	**Pseudo-F**	***p-Value***	**Proportion**	**Cumulative Proportion**
Carbon (%)	10.1160	0.0001	0.1329	0.1329
Mud (%)	4.1626	0.0001	0.0521	0.1850
Water Temperature (°C)	3.9751	0.0002	0.0476	0.2327
Z. noltei Biomass (gDW/m^2)	3.1734	0.0007	0.0369	0.2695
pH	2.8565	0.0016	0.0321	0.3017
Salinity (PSU)	2.5107	0.0080	0.0276	0.3293
CO_2 (%)	1.9516	0.0435	0.0211	0.3504
$CaCO_3$ (%)	3.0121	0.0004	0.0315	0.3819
Median Grain-size (μm)	1.6806	0.0693	0.0174	0.3994
Total Organic Matter (%)	1.0395	0.4134	0.0107	0.4101

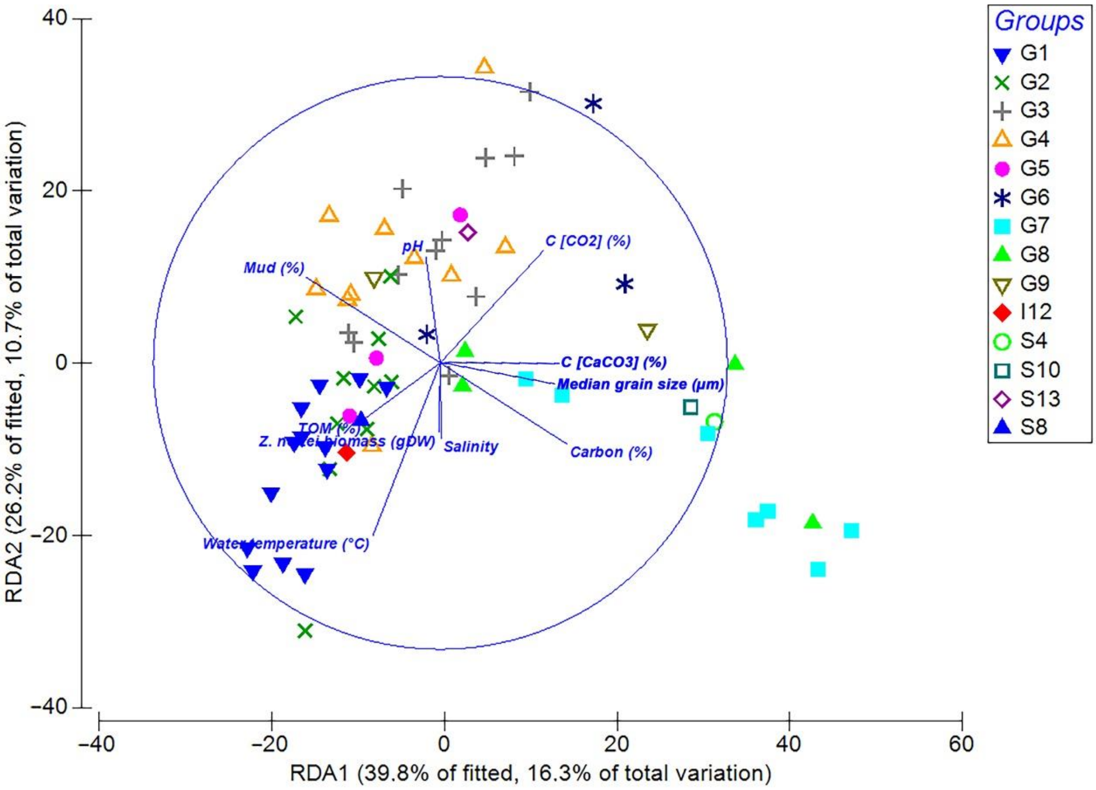

Figure 7. Two-dimensional redundancy analysis (RDA) ordination representing the model of spatial variation in macrozoobenthos community structure related to the predictor variables selected through the best linear models based on distance (DistLM).

Discussion

Large spatial scale studies are crucial to better manage habitats and resources, particularly for the development of the relatively new ecosystem approach (Desroy et al., 2002; Ysebaert and Herman, 2002; Ellis et al., 2006; Fraschetti et al., 2011). The relationships between macrobenthos and natural environmental drivers can thus be used to describe habitats, defined as the physical and chemical environment in which a species or community lives, and to provide a baseline for the detection of spatial and temporal changes (Van Hoey et al., 2004; Bolam et al., 2008; Shumchenia and King, 2010). In this context, our study, which covers the entire lagoon, gives an overview on the spatial patterns of the benthic macrofauna of the Moulay Bousselham lagoon in relation to environmental drivers.

Environmental Variables

In this study, not all water parameters varied as gradients between upstream and downstream areas. Only salinity and temperature clearly decreased with gradients upstream in conformity with the findings of (Bazairi, 1999; Touhami et al., 2017). Both salinity and temperature gradients resulted from the ocean-continent gradient related to the position of stations across the lagoon and the sampling time.

The salinity of coastal lagoons can vary from freshwater to hypersaline according to local climatic conditions and the degree of hydrological connectivity (Kjerfve, 1986). However, within a single lagoon system, there may be three salinity zones whose spatial extent varies depending on seasonal conditions. These are relatively fresh water near the mouths of influent rivers, brackish water in the central part of a lagoon, and marine salinities at the entrance channel (s).

The Moulay Bousselham lagoon is mainly composed of sandy and silty sediments, and no gravel has been detected in each sample measured. The median grain size shows high variations, from fine silts to coarse sands. The main part of the lagoon is composed of poorly sorted sediments according to the Folk and Ward classification, with a mean sorting index of 3.9 estimated from the 68 samples. The sandy dominated stations revealed refer to sediments sampled downstream or in the channels, where higher grain-sized sediments are transported (Pouzet et al., 2019), while the lower grain-sized sediments with high mud content identified refer to sediments present in the upstream sections of the lagoon far. They are stations located away from the channels and where morphogenic conditions decrease (Pouzet and Maanan, 2020b). Hydrodynamic energy affects sedimentation and resuspension of sediment particles (Rhoads and Boyer, 1982; Snelgrove and Butman, 1994), as well as organic enrichment of sediments (Kröncke, 2006; Kröncke and Bergfeld, 2003). Thus, higher currents and turbulence inhibit the deposition of organic matter and produce the deposition of coarse sediments (Rhoads and Boyer, 1982; Pearson and Rosenberg, 1978), whereas muddy sediments occur in calmer hydrodynamic conditions.

In opposition to the grain size parameters, carbon content presents lower variation, and only low carbon percentages have been recorded by LECO© for the 68 stations studied. Higher carbon values in stations located nearest channels can be linked to the marine influence providing shell remains in the sands content, whereas the low values (in central and peripheral areas) can be influenced by the continental inputs coming from the watershed and bringing organic matter remains from vegetated areas (Pouzet and Maanan, 2020a). The high level of TOM in the center and periphery of the lagoon can be attributed to the presence of fine particles entrapped by the structure of seagrass leaves and the abundance of fragments of dead seagrass encrusted in the sediment (Chaouti et al., 2019). With higher water currents, TOM values are lower near the channels.

Benthic Macrofauna

In the 68 sampled stations, 63 taxa belonging to 50 families were identified. The soft-bottom macrofauna of the Moulay Bousselham lagoon was mainly characterized by the dominance of Mollusca (38.09%), followed by Arthropoda (31.75%), Annelida (28.57%) and Nemertea (1.59%). These results contrast both with previous studies carried out on the lagoon (Lacoste, 1984; Touhami et al., 2017; Kersten et al., 1983; Rharbi, 1990), which noted the dominance of mollusks, polychaetes and crustaceans, and with the conclusions of (Bazairi, 1999), who noted the predominance of crustaceans, followed by polychaetes and mollusks. These results may be related to differences in sampling methods and designs.

Compared with previous studies, the number of species was higher than observed by (Lacoste, 1984): 45, (Ait Mlik, 2009): 54, (Touhami et al., 2017): 46 and lower than that obtained by (Bazairi, 1999):173 taxa. In comparison with other lagoon systems, the species richness shows higher values than the lagoons of Sidi Moussa (Kersten et al., 1983; Joulami, 2008 and 2013), Oualidia (Chbicheb, 1996; Lefrere, 2012; El Asri et al., 2020), Khnifiss (Lefrere, 2012; Bayed et al., 1988), Ghar El-Melh (Afli et al., 2009), Mellah (Magni et al., 2015), Cabras (Como and Magni, 2009; Magni et al., 2004), Celestun (Morelos-Villegas et al., 2018), Epe (Uwadiae, 2010) and Lesina (Marzano et al., 2003). However, the species number was still lower than that Oualidia (Chaouti et al., 2019), Nador (Menioui and Zine, 1995), Ria Formosa (Gamito, 2006), Venice (Sfriso et al., 2001), Lagos (Brown, 2000), Bay of Muggia (Solis-Weiss et al., 2004), Marano and Grado lagoon (Bettoso et al., 2010) and similar to those observed in Sacca di Goro lagoon (Marchini et al., 2004).

On the other hand, the macrobenthic faunal densities observed in this study (4582.8 ind/m²) were higher than those reported by (Bazairi et al., 2005) (3106.0 ind/m²) and lower to those observed by (Touhami et al., 2017) (5763.0 ind/m²). The maximum biomass value reported in our study (92.5 g AFDW/m^2) is higher than that reported by (Touhami et al., 2017). The highest values were recorded in the vegetated habitats, while the mean value of the biomass (22.2 g AFDW/m^2) is similar to that reported by (Piersma, 1981) (22.0 g AFDW/m^2) and very close to the results of Touhami et al. (2017) (20.0 g AFDW/m^2). Comparisons with these previous studies reveal that the benthic assemblages of the Moulay Bousselham lagoon are relatively stable, indicating a certain durability. Abundance and biomass were clearly lower compared with several other coastal systems: Venice lagoon (Sfriso et al., 2001), Prévost lagoon (Bachelet et al., 2000), Arcachon bay (Blanchet et al., 2004) and the Somme bay (Sueur et al., 2003), but they were higher than those recorded in Boughrara lagoon (Khedhri et al., 2016) and Celestun lagoon (Morelos-Villegas et al., 2018).

Spatial Patterns and Environmental Drivers

The spatial pattern of the benthic communities in the lagoon follows a downstream- upstream gradient, essentially due to environmental factors including sediment characteristics, water parameters and the type of habitat (seagrass beds). The particular combination of those factors generates a macrofaunal structure characterized by 14 assemblages can be clearly seen in the cluster analysis. Assemblages are identified from downstream to upstream and from the center to the peripheral areas. According to cluster analysis, these assemblages showed a clear distinction between the part close to the sea communication (similarity not exceeding 30%) and the parts inside the lagoon (similarity around 60%). Our results also showed the association of stations located in the subtidal with others in the intertidal areas in the identified clusters (G6, G7 and G8). In contrast to the results obtained in the Moulay Bousselham lagoon by (Touhami et al., 2017) and in the Oualidia lagoon by (El Asri et al., 2020), our assemblages do not show a clear dominance of one or two species.

Most of the benthic species inventoried in the Moulay Bousselham lagoon had a wide spatial pattern and were not limited to a single habitat. Such a pattern corresponds better to the concept of a continuum of communities across an environmental gradient (Mills, 1969) than to the concept of discrete communities as distinct assemblages of species defined by (Thorson, 1957). The biological continuum and the absence of ecotonal zones seem to be characteristic of estuaries in particular and semi-enclosed coastal ecosystems (Bazairi et al., 2003). Indeed, this pattern has been found in different estuaries in Morocco (Elkaim, 1977; Cherkaoui et al., 2003; Chaouti et al., 2016), France (Le Bris, 1996), Portugal (Carvalho et al., 2001; Sousa et al., 2008) and Spain (De Paz et al., 2008; Sánchez-Moyano et al., 2010). The explanation for this finding is probably the high tolerance of the macrozoobenthos species inhabiting such ecosystems. These patterns could also be related to the fact that environmental gradients are not so strong in the Moulay Bousselham lagoon, with the exception of salinity, and that the lagoon lacks large hydrodynamic variations, which commonly have a significant impact on the spatial distribution of benthic communities (Herman et al., 1999; Cozzoli et al., 2017). Analysis of macrobenthic assemblages indicates that the spatial distributions of the 63 taxa found along the subtidal and the intertidal stations of the Moulay Bousselham lagoon showed a relatively high correlation with environmental drivers and can be best explained by a combination of ten natural abiotic variables. DistLM highlights sediment characteristics (mud content, median grain-size, TOM%, carbon%, $CaCO_3$%, and CO_2%), water parameters (salinity, T°, pH) and habitat type (biomass of *Zostera noltei*). There is a gradient from west to east, and the most important stations in terms of specific richness and/or density are those located in the central and peripheral mudflat areas, which are characterized by the presence of a seagrass bed, or located near vegetated areas (*Zostera noltei, Ruppia cirrosa,* Algae). Past works have shown that the spatial pattern of the benthic communities at Moulay Bousselham lagoon follows an upstream-downstream gradient and demonstrated the primordial role of environmental drivers (sediment grain-size, organic matter, hydrodynamics parameters and the presence of seagrass) on this distribution (Bazairi, 1999; Touhami et al., 2017).

For macrobenthic invertebrates, such patterns are eventually the result of a complex interaction of a number of processes occurring in both the water column and the sedimentary compartment. Coastal lagoons are complex systems with a high degree of physical and biological variability. The biodiversity of these ecosystems is commonly thought to be spatially distributed along the vertical and horizontal gradients of salinity, temperature, sediment characteristics (particle size, mud and/or organic matter enrichment) (Quintino and Rodrigues, 1989; Teske and Wooldridge, 2003; Ysebaert et al., 2003). This spatial structure results from the environmental tolerances of organisms to stresses within these variable systems (water mass dynamics, physiological stress and biotic interactions) (Elliott and Quintino, 2007; MacKay et al., 2010).

The presence of vegetation creates conditions for the formation of stable and complex habitats, thus promoting the installation of dense and diversified benthic communities (Fredriksen et al., 2010; Ganthy et al., 2013). The composition of the fauna is also driven by sediment, which is known to be a determinant of macrobenthic composition and plays an important role at different stages of the life cycle (settlement, tube building, burying and feeding) of soft-bottomed benthic organisms (Self and Jumars, 1988; Pinedo et al., 2000). Our analyses have also highlighted salinity as a key factor, a parameter that has usually been considered essential to explain gradients in lagoon density, biomass, richness or diversity (Por, 1980; Mariani, 2001) and as one of the main drivers of similarities and differences in lagoon assemblages (Petit, 1953; Aguesse, 1957; D'Ancona, 1959; McLusky, 1999).

Lagoons, however, are characterized by large seasonal, often unpredictable, variation in physical and chemical variables (Magni et al., 2006; Padedda et al., 2012). This may act as a driving force regulating the macrozoobenthic assemblages from season to season. At Moulay Bousselham lagoon, previous studies showed that benthic population density and species richness revealed seasonal variation with maxima in the autumn (Bazairi, 1999). In the present study, the spatial patterns and associated key environmental drivers were evidenced from sampling performed during autumn where benthic macrofauna are the most diverse. Nevertheless, future studies should consider sampling over different seasons to better trace the physical and biotic factors regulating spatial and seasonal changes in the benthic assemblages of this temperate lagoon.

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Chapter 4

Seasonal trends in benthic macrofauna communities and their relationship with environmental factors in an Atlantic lagoonal system

Abstract:

We studied benthic communities with different types of habitats in the Moulay Bousselham lagoon during the winter and summer of 2019. We aimed to investigate biodiversity trends across a scale of seasonal variation. The lowest water temperatures were recorded downstream. This reflects the influence of cold oceanic waters at the lagoon entrance while the salinity shows a decreasing gradient from downstream to upstream. Sediment analyses showed that the lagoon is mainly composed of sandy and silty sediments. In stations with vegetated habitats, the biomass of *Zostera noltei* seagrass ranged from 0.79 gDW to 46.69 gDW in winter and from 9.34 gDW to 47.67 gDW in summer, while the biomass of *Ruppia cirrhosa* seagrass ranged from 5.53 gDW to 28.66 gDW in winter and from 14.48 gDW to 34.06 gDW in summer. Apart from water temperature and salinity, environmental variables are not significantly different in winter and summer (Anova test: $p > 0.05$).

In the 29 sampling stations we used, we found 42 taxa in winter and 32 taxa in summer with a mean biomass value of 25.10 g AFDW/m^2 (winter) and 9.14 g AFDW/m^2 (summer). Apart from biomass, which is subject to seasonal variations, diversity parameters are not significantly different from one season to the next (Anova test: $p > 0.05$). Results from DistLM analysis revealed that the diversity and distribution of benthic macrofauna in the Moulay Bousselham lagoon were controlled by a combination of factors: sediment characteristics (mud content, median grain size, TOM %, carbon %, $CaCO_3$ % and $CaCO_2$ %), water characteristics (temperature and salinity) and habitat type (biomass of *Z. noltei* and *R. cirrhosa*).

Keywords: Benthic macrofauna, temporal variation, Moulay Bousselham lagoon, Morocco

Introduction

Coastal ecosystems account for only 8% of the surface of the hydrosphere (Wollast, 1991) and 0.5% of the ocean volume (Alongi, 1998). However, they are among the most productive systems on the globe (Mann, 1982). These ecosystems are subject to various influences: terrestrial, atmospheric, estuarine and marine. Primary production is vital, and this mainly in temperate coastal ecosystems because they are among the marine environments that are the most intensely fertilized by nutrients (Nixon and Buckley, 2002) due to their proximity to the continent and the recycling of matter by pelagic and benthic microheterotrophs (Nixon et al., 1986). One third of annual marine organic carbon production comes from these areas (Wollast, 1991).

Coastal lagoons are shallow aquatic environments separated from the open sea by sand or shingle bars, to which they remain connected at least intermittently through one or more restricted inlets (Bird, 1994). They are known for their marked spatial and temporal (daily and seasonal) fluctuations in environmental conditions, due to their confinement to the open sea and shallowness (Nicolaidou et al., 2005; Orfanidis et al., 2005). They are typically characterized by large, often unpredictable seasonal variations in physical and chemical parameters (Magni et al., 2006; Padedda et al., 2012). This can greatly vary the importance of processes that regulate macrozoobenthic assemblages from season to season. In coastal lagoons, numerous studies have reported that macrozoobenthic assemblages undergo marked temporal fluctuations (Como et al., 2007; Kanaya et al., 2011).

In coastal ecosystems, it is mandatory to assess and conserve biodiversity so as to maintain productivity. Invertebrates have attracted attention in terms of conservation in addition to monitoring (Brendan et al., 2007). Evaluation of changes in coastal ecosystems can be effectively monitored using benthic fauna, as they play an integral role in the transfer of materials from primary production through the detrital pool to higher trophic levels (Ingole et al., 2006).

In the Moulay Bousselham lagoon, most studies did not consider the variation of macrobenthic assemblages at temporal scales. Furthermore, when they did, it was limited to a specific environment; even though habitat heterogeneity and varying environmental conditions strongly shape lagoonal benthic communities (Como et al., 2012; Zettler et al., 2013). For these reasons, we strongly need in-depth studies to improve our understanding of ecological responses of macrozoobenthos assemblages to seasonal variations.

To fill these gaps, we investigated the seasonal variation in macrozoobenthic assemblages and the environmental factors driving their patterns in different areas within the Moulay Bousselham lagoon over two seasons (winter and summer). These areas are representative of the all-main habitats characterizing this sentinel lagoon (Boutoumit et al., 2021).

Materials and methods

Study area

The Moulay Bousselham lagoon is on the Moroccan Atlantic coast in the northwestern part of the Gharb plain between 34°48' and 34°53' north latitude and 6°19' and 6°16' west longitude (Figure 1). It has an elliptical shape, with a maximum length of 9 km, a maximum width of 5 km and a surface area of 35 km². The lagoon is divided into two Merjas: Merja Kahla, which is 3 km², very shallow and covered by a very dark mud at the bottom, and Merja Zerga, which is 27 km², always covered by the flood at high tide and which appears blue at low tide because of its greater depth. The gully and the pass occupy the rest of the lagoon's surface.

Two freshwater sources flow into the lagoon. To the north, the Wadi Drader, which drains a watershed of 1,150 km ², leads into the lagoon at two points, the first at the end of the main channel while the second ends in a delta in the northeastern part of Merja Zerga. To the south, the Nador canal, built in 1953, drains the 700km^2 Mda watershed (intermittent stream) as well as the right shore area of the Sebou (Lamrini et al., 2007).

The lagoon is filled and emptied through a network of permanent channels (main, secondary and tertiary) that allow communication between the lagoon and the ocean through a narrow gully (50 m). The tidal regime is semi-diurnal with an average of 0.15 to 1.5 m of tidal range (Carruesco, 1989).

Sample collection and environmental analyses

We selected 29 stations to sample in winter and summer 2019 in the Moulay Bousselham lagoon (Figure 1). These stations were selected based on previous works undertaken in this lagoon considering both benthic communities and environmental parameters (Touhami et al., 2017; Boutoumit et al., 2021). Those studies pointed at the existence of different biologically and environmentally distinct areas in the lagoon according to tidal zones, water parameters, sediment characteristics and the presence of seagrasses. In the intertidal zone, samples were taken using a PVC corer with a diameter of 12.5 cm, and each replica was a fusion of 10 cores, covering a total area of approximately 0.12 m². In subtidal areas, the samples were collected using a Van Veen grab and each sample had a surface area of 0.1 m².

Macrofaunal samples were washed through a 1 mm square mesh sieve, and the retained material was preserved in 4% buffered formalin stained with Rose Bengal. In the laboratory, animals were hand sorted into major taxonomic groups, identified to the lowest practical taxonomic level and counted. Biomass, obtained after calcination in the oven at 450 °C for 4 hours, was determined per taxon, station and sampling period.

We also measured the hydrological parameters (water temperature and salinity) *in situ* using a HANNA portable multi-parameter. We associated each sample of the macrofauna with a sample of sediment collected to determine the carbon content and granulometry.

Grain size was measured with a laser granulometer (Malvern Mastersizer 2000). The overall distribution was then calculated with the Gradistat© Excel package (Blott and Pye, 2001; Pouzet and Maanan, 2020). A LECO© carbon analyzer was used to estimate the carbon, CO_2 and $CaCO_3$ percentages after mineral decarbonizing with a sulfuric acid solution and dioxygen burning at 1400 °C (Andrews et al., 2008). We determined the organic matter content by estimating the total organic matter. It was assessed by the loss on ignition method. Three 4 g replicates taken from each previously oven-dried sediment sample were ignited in an oven at 500°C for 4 h to obtain the dry weight of mineral matter (Byers et al., 1978). The difference in mass between the dry weight and the dry weight of mineral matter gives an estimate of the dry weight of organic matter in the sediment. The results were then expressed as a percentage. In vegetated stations, the biomasses of the seagrasses *Zostera noltei* Hornemann and *Ruppia cirrhosa* (Petagna) Grande were measured using a dry weight (gDW). The seagrasses were isolated and rinsed with water and then dried in an oven at 60 °C for 48 hours.

Data analysis

We used the DIVERSE routine to calculate the species number (S), Abundance (N: ind/m^2), Shannon-Weaver diversity index (H') and Pielou's evenness index (J) of the macrobenthic communities.

After the fourth root transformation to downplay the importance of high-abundance species, a Hierarchical Ascending Classification (HAC) based on Bray-Curtis distance and non-metric multidimensional scaling (nMDS) were used to determine the similarity of the sampling stations based on the density matrix. At the same time, the contribution of each macrobenthic species to similarity in the different stations was analyzed by the similarity percentages (SIMPER) method and the species with the highest contribution in each station were defined as the main characteristic species (Clarke and Gorley, 2006). Environmental variables were transformed to log(X+1). We performed a DistLM analysis to study the optimal combination of environmental factors affecting the community structure. Difference between seasons was tested using

One-way ANOVA. All the above procedures were carried out with the PRIMER 6 + PERMANOVA© software (Clarke and Warwick, 2001; Anderson, 2008), while the one-way ANOVA of benthic community structure indexes was carried out in STATISTICA software package (StatSoft Inc., 2011, version 10).

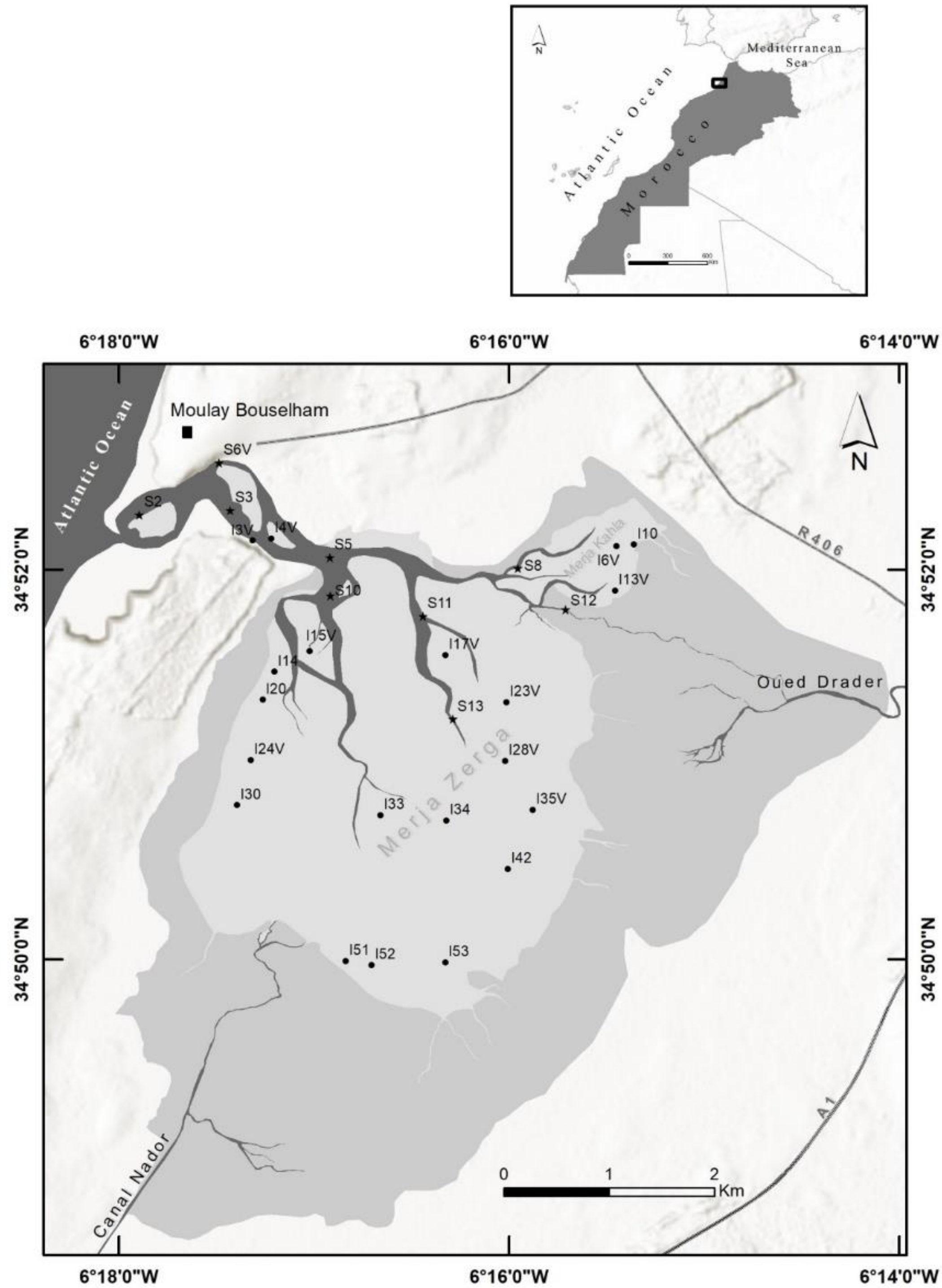


Figure 1. Map showing the location of the Moulay Bousselham lagoon and sampling stations (©by S. Boutoumit).

Results

Environmental Data

The spatial distribution of the water temperature in the Moulay Bousselham lagoon is presented in Figure 2. In winter, this temperature varies from 17.23°C to 25.31°C with a mean value of 22.32°C and shows an increasing gradient from downstream to upstream. The lower values recorded downstream reflect the influence of cold oceanic waters at the entrance to the lagoon and the higher values observed upstream reflect the shallow depth at this level favoring the rapid warming of the waters. In summer, the temperature values are generally higher and vary from 22.84°C to 29.34°C with a mean value of 26.61°C. They show about the same variation trend as in winter but with a more marked gradient.

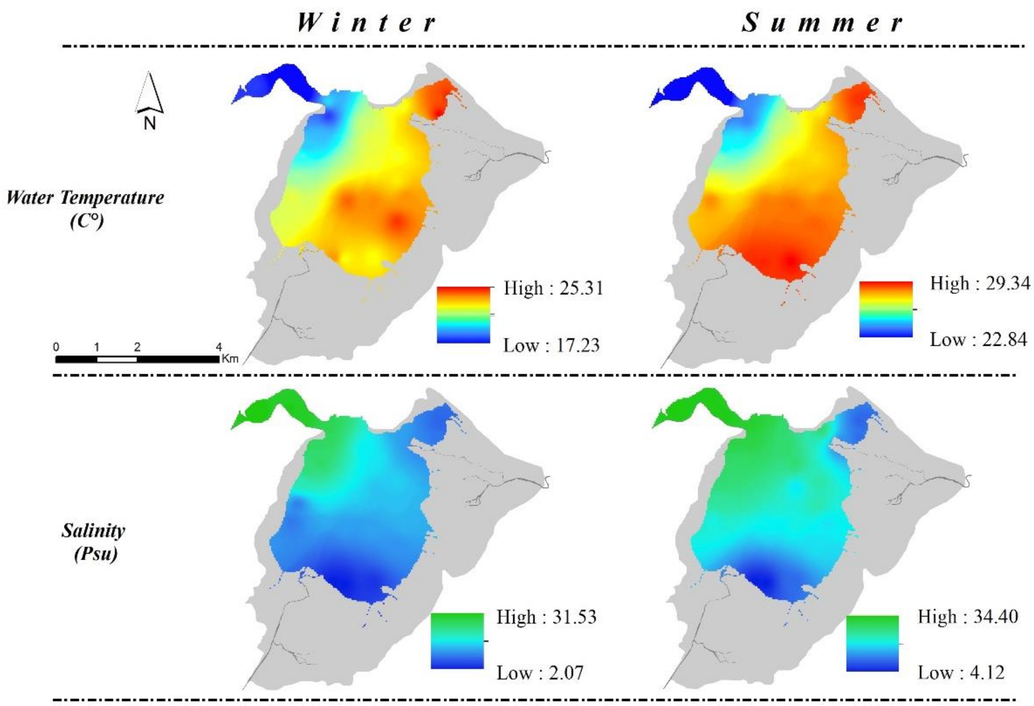


Figure 2. Maps showing the spatial distribution of water parameters in the Moulay Bousselham lagoon.

In winter, the salinity varies from 2.07 to 31.53 (mean value of 15.83) and shows a decreasing gradient from downstream to upstream. The highest salinities are mainly observed at the stations located downstream of the lagoon, which are directly subjected to marine influences. The lower values observed upstream can be explained by the distance from marine influences and the dilution by freshwater inputs. These inputs are caused by the presence of numerous freshwater sources of continental origin and submarine freshwater resurgences within the lagoon. In summer, the spatial variation of salinity shows about the same trend as in winter but with a more marked upstream-downstream decreasing gradient. Its values vary between 4.12 and 34.4 with a mean of 22.37.

The spatial distribution of the grain size parameters is presented in Figure 3. During the winter, the d50 values and mud percentage respectively vary from 7.3 to 599µm (mean value of 85.6µm) and from 4.5% to 99.7% (mean value of 74.2%). These results show two distinct trends: a first d50 decreasing gradient- and a second mud percentage increasing gradient- from downstream to upstream of the lagoon. The highest d50 grain sizes are observed mainly at the stations located downstream, directly subjected to marine influences and consequently presenting higher sand percentages and lower muds. The lower grain-size values (d50) and higher mud content observed upstream are explained by the distance from marine influences, producing lower morphogenic conditions in the two lagoonal Merjas. In summer, the spatial variation of these two parameters shows about the same trend as in winter, the muddy upstream-downstream decreasing gradient and d50 downstream-upstream decreasing trend are slightly more marked. The d50 values vary from 5.2 to 708.7µm (mean of 129µm) and the mud content from 0% to 98% (mean of 61%) during the winter. Consequently, no significant seasonal variation is observed for the d50 values and mud percentages.

Carbon, CO_2, $CaCO_3$ and TOM percentages follow the same trends during these two seasons (Figure 3). Carbon, CO_2 and $CaCO_3$ are higher in the downstream stations which are under the influence of marine conditions that bring shell remains in the sandy sediments. In opposition, the TOM content is more important far from the marine influence in the upstream stations where the muddy sediments are dominant. Reflecting these results, the $CaCO_3$ and TOM percentages respectively vary from 3.3% to 53% (mean of 20.4%) and from 0.4% to 9% (mean of 6.6%) during the winter. During the summer, the $CaCO_3$ and TOM percentages respectively vary from 2.1% to 39.9% (mean of 16.9%) and from 0% to 9.6% (mean of 5.6%). Consequently, there is also no significant seasonal variation for $CaCO_3$ (and also carbon and CO_2 that are correlated to $CaCO_3$) and TOM environmental variables.

In stations with vegetated habitats (Figure 1), biomass values of *Zostera noltei* seagrass ranged from 0.79 gDW in station I28V to 46.69 gDW in station I3V in winter and from 9.34 gDW (I17V) to 47.67 gDW (I4V) in summer. While the biomass of *Ruppia cirrhosa* seagrass ranged from 5.53 gDW in I13V to 28.66 gDW in I6V in winter and from 14.48 gDW (I13V) to 34.06 gDW (I6V) in summer. Apart from water temperature and salinity, which are subject to the seasonal rhythm ($p<0.05$), we can see no significant differences in the environmental variables between winter and summer (Anova test: $p >0.05$) (Table 1).

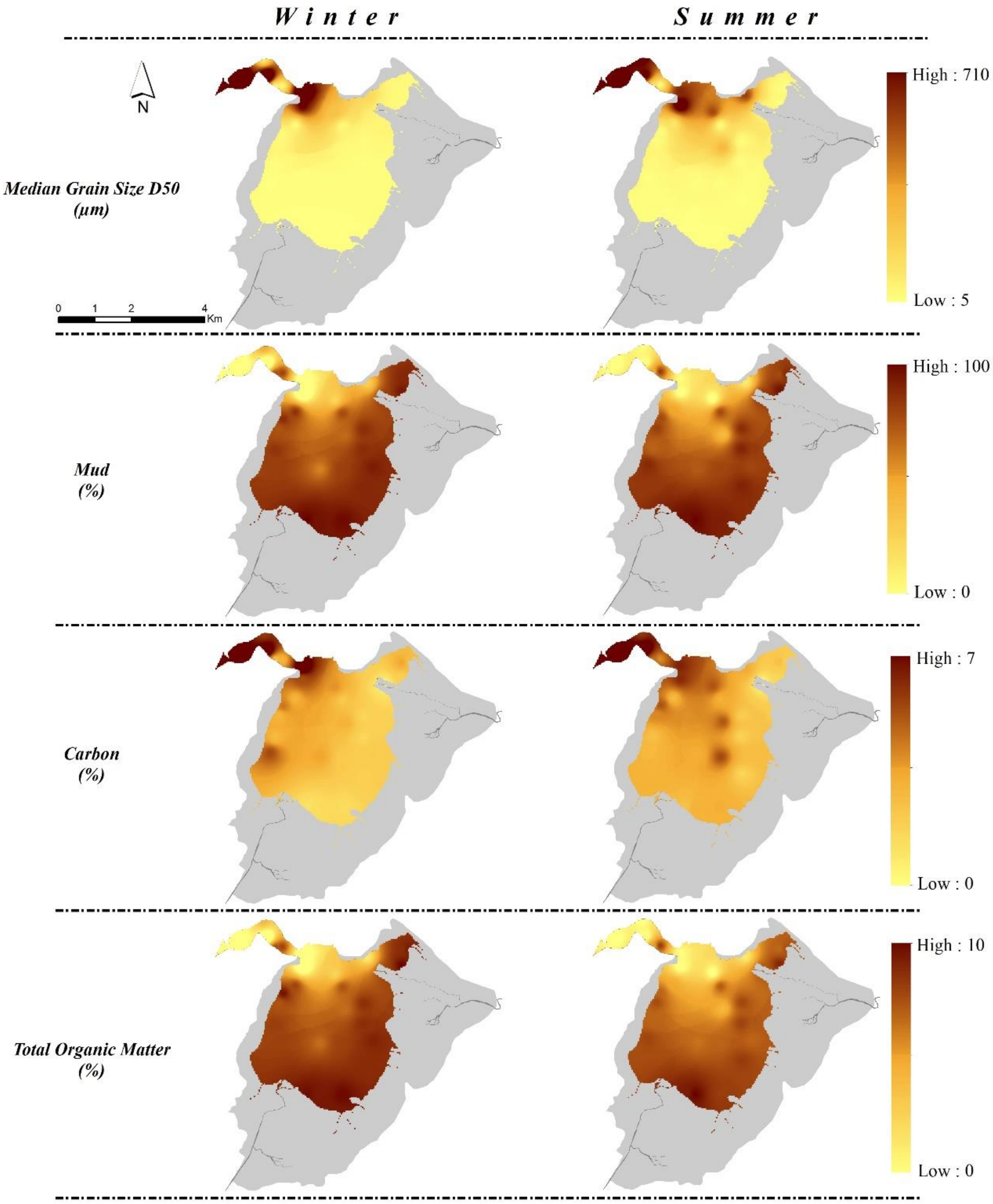


Figure 3. Maps showing the spatial distribution of the sedimentary structure in the Moulay Bousselham lagoon.

Table 1. Results of ANOVA testing for environmental variables differences between seasons. **Df:** Degrees of freedom; **MS:** Mean square; ***p* (perm):** Level of significance. Significant effects are indicated in bold.

	Water temperature			**Salinity**		
Df	**MS**	**F**	***p***	**MS**	**F**	***p***
1	267.33	47.07	**0.00**	621.10	6.97	**0.01**
56	5.67			89.04		
	Median Grain Size			**Mud%**		
Df	**MS**	**F**	***p***	**MS**	**F**	***p***
1	27342.65	0.75	0.38	2483.32	2.29	0.13
56	36047.56			1081.03		
	TOM%			**Carbon (%)**		
Df	**MS**	**F**	***p***	**MS**	**F**	***p***
1	13.01	1.44	0.23	2.55	1.49	0.22
56	9.03			1.70		
	C [CO2] (%)			**C [CaCO3] (%)**		
Df	**MS**	**F**	***p***	**MS**	**F**	***p***
1	34.14	1.49	0.22	177.31	1.49	0.22
56	22.89			118.31		
	***Z.noltei* biomass (gDw)**			***R. cirrhosa* biomass (gDw)**		
Df	**MS**	**F**	***p***	**MS**	**F**	***p***
1	97.91	0.56	0.45	0.93	0.03	0.86
56	172.77			30.25		

Species composition and diversity

Out of the 29 samples taken in the Moulay Bousselham lagoon in winter, we counted 42 taxa which comprised 22,371 individuals. The phylum Mollusca is the most abundant taxonomic group (38.1%), followed by Arthropoda (35.71), Annelida (19.5%), Nemertea (2.38%), Platyhelminthes (2.38%) and Chordata (2.38%).

Species richness ranged from 3 (station S2 and I51) to 17 (station I17V). The maximum abundance value was recorded in station I23V (336.61 ind/m^2) while the lowest was recorded in station S2 (33.78 ind/m^2). Biomass was the highest in vegetated samples with a value of 112.28 g AFDW/m^2 (station I23V), while the lowest biomass value was noted for station S2

(0.07 g AFDW/m^2) and the mean value was 25.10 g AFDW/m^2. Shannon diversity (H') varied from 1.58 (station S2 and I51) to 3.86 bits (station I17V) while evenness values (J') are high for the majority of the stations indicating the equity of species dominance (Figure 4).

In summer, among the 12,961 individuals counted, we identified 32 macrobenthic taxa which belonged mainly to six taxonomic groups. Mollusca and Arthropoda are the most diverse groups with 11 taxa each (34.37%), followed by Annelida (7 taxa - 21.87%). Nemertea, Platyhelminthes and Chordata are represented by only one taxon each (3.13%).

The values of species richness oscillate between 1 and 19 taxa (S12 and I17V respectively) while the density varies from 10 ind/m^2 (S12) to 315.23 ind/m^2 (I15V). In terms of biomass, station S6V shows the highest value (38.93 g AFDW/m^2) and station S12 reveals a minimum value of 0.04 g AFDW/m^2 with a mean value of 9.14 g AFDW/m^2. The Shannon-Weaver index varies from 0 (S12) to 4.04 (I17V) and the values of the Pielou's evenness index are close to 1 which indicates equitability in species abundance (Figure 4).

Apart from biomass, which is subject to the seasonal rhythm (p<0.05), there is no significant difference in the diversity parameters between winter and summer (Anova test: p >0.05) (Table 2).

Assemblages Structure

In winter, the Hierarchical Ascending Classification and MDS analysis allowed us to individualize five benthic assemblages (multi-stations) according to their specific composition (Figure 5, 7). The SIMPER procedure identified the species of greatest importance by creating patterns of similarity between different groups of samples (Table 3).

The species contributing most to average similarity within group G1W (48.76% of similarity) were *Clibanarius erythropus* (Latreille, 1818) (11.07%), *Hediste diversicolor* (O.F. Müller, 1776) (11.47%), *Heteromastus filiformis* (Claparède, 1864) (25.82%) and *Idotea chelipes* (Pallas, 1766) (10.68%). Group G2W (76.64%) was characterized by the presence of *H. diversicolor* (8.50%), *I. chelipes* (10.28), *Peringia ulvae* (Pennant, 1777) (22.97%) and *Scrobicularia plana* (da Costa, 1778) (11.32%). Group G3W (69.13%) was dominated by *Cyathura carinata* (Krøyer, 1847) (9.72%), *Lekanesphaera rugicauda* (Leach, 1814) (11.75%), *P. ulvae* (23.56%) and *S. plana* (9.32%). The most dominant species in group G4W (58.85%) were *C. carinata* (25.99%) and *H. diversicolor* (28.58%). However, *Nephtys hombergii* (Savigny in Lamarck, 1818) (28.86%) and *Spio filicornis* (Müller, 1776) (28.17%) were the dominant species for group G5W (27.07).

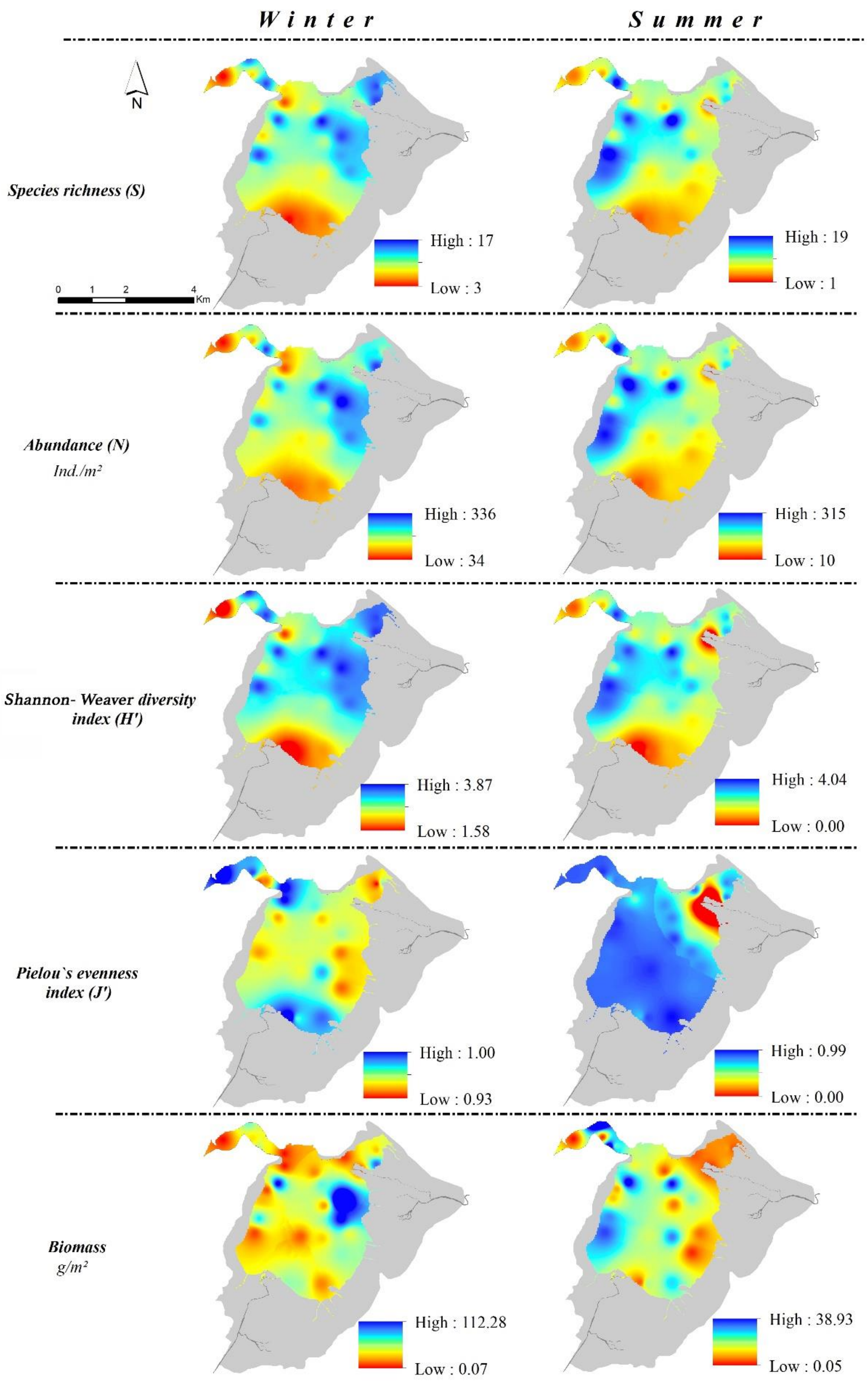


Figure 4. Interpolation of the spatial distribution of diversity parameters (S, N, H', J' and the biomass).

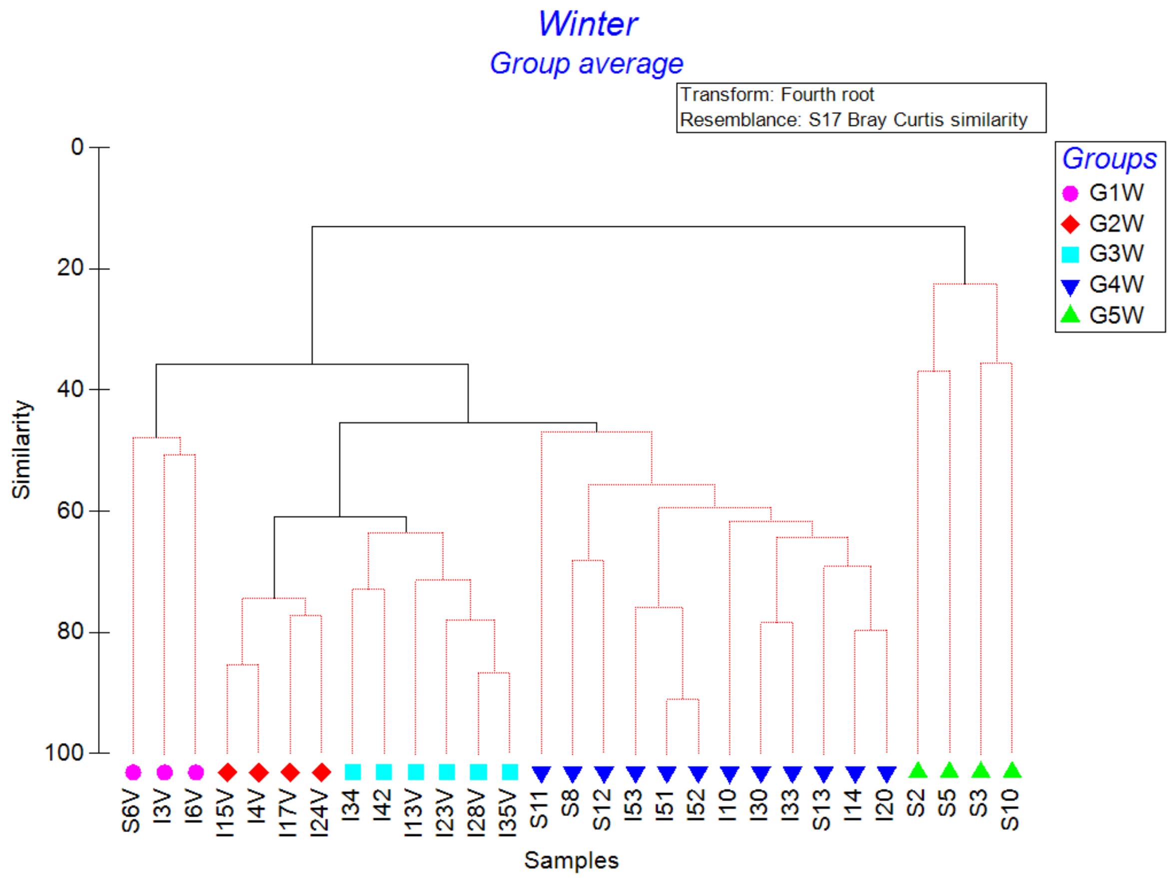
Table 2. Results of ANOVA testing for macrobenthic assemblage's differences in S, N, H', J' and biomass. **Df:** Degrees of freedom; **MS:** Mean square; ***p* (perm):** Level of significance. Significant effects are indicated in bold.

	Species richness (S)			**Abundance (N) ind/m²**			**H'(log₂)**			**J'**			**Biomass gAFDW/m²**		
Df	**MS**	**F**	***p***	**MS**	**F**	***p***	**MS**	**F**	***p***	**MS**	**F**	***p***	**MS**	**F**	***p***
1	43,10	1,88	0,175	19595	2,73	0,103	1,96	2,82	0,0986	0,022	1,405	0,240	3694,17	10,18120	**0,002**
56	22,88			7163			0,69			0,016			362,84		

In summer, a cluster analysis highlighted a spatial structure with five groups (4 multi-stations and 1 singleton) within the macrobenthic communities of the Moulay Bousselham lagoon (Figure 6, 7). The species responsible for groupings are shown in Table 3 (SIMPER analysis). The taxa which had a major influence on similarity in group G1S (58.62%) were *H. diversicolor* (42.81%) and *S. plana* (38.78%). In group G2S (61.30%), the dominant taxa responsible for the similarities between stations were *P. ulvae* (39.31%) and *S. plana* (15.49). Dominant species in the G3S group (56.52%) were *C. carinata* (12.58%), *H. diversicolor* (10.03%), *P. ulvae* (17.78%) and *S. plana* (13.68%). Group G4S (66.32%) was characterized by the dominance of *Bittium reticulatum* (da Costa, 1778) (51.20%). Station S12 was isolated from the four defined groups and characterized by the lowest species abundance.

Table 3. Results of SIMPER analysis showing the average similarity between stations of the benthic assemblages in the two seasons identified by the cluster analysis and the characteristic species of each benthic assemblage.

	Average similarity (%)								
	Winter					**Summer**			
	G1W	**G2W**	**G3W**	**G4W**	**G5W**	**G1S**	**G2S**	**G3S**	**G4S**
	48.76	**76.64**	**69.13**	**58.85**	**27.07**	**58.62**	**61.30**	**56.52**	**41.00**
Species contribution (%)									
Bittium reticulatum									51.20
Clibanarius erythropus	11.07								
Cyathura carinata			9.72	25.99				12.58	
Hediste diversicolor	11.47	8.50		28.58		42.81		10.03	
Heteromastus filiformis	25.82								
Idotea chelipes	10.68	10.28							
Lekanesphaera rugicauda			11.75						
Nephtys hombergii					28.86				
Peringia ulvae		22.97	23.56				39.31	17.78	
Scrobicularia plana		11.32	9.32			38.78	15.49	13.68	
Spio filicornis					28.17				



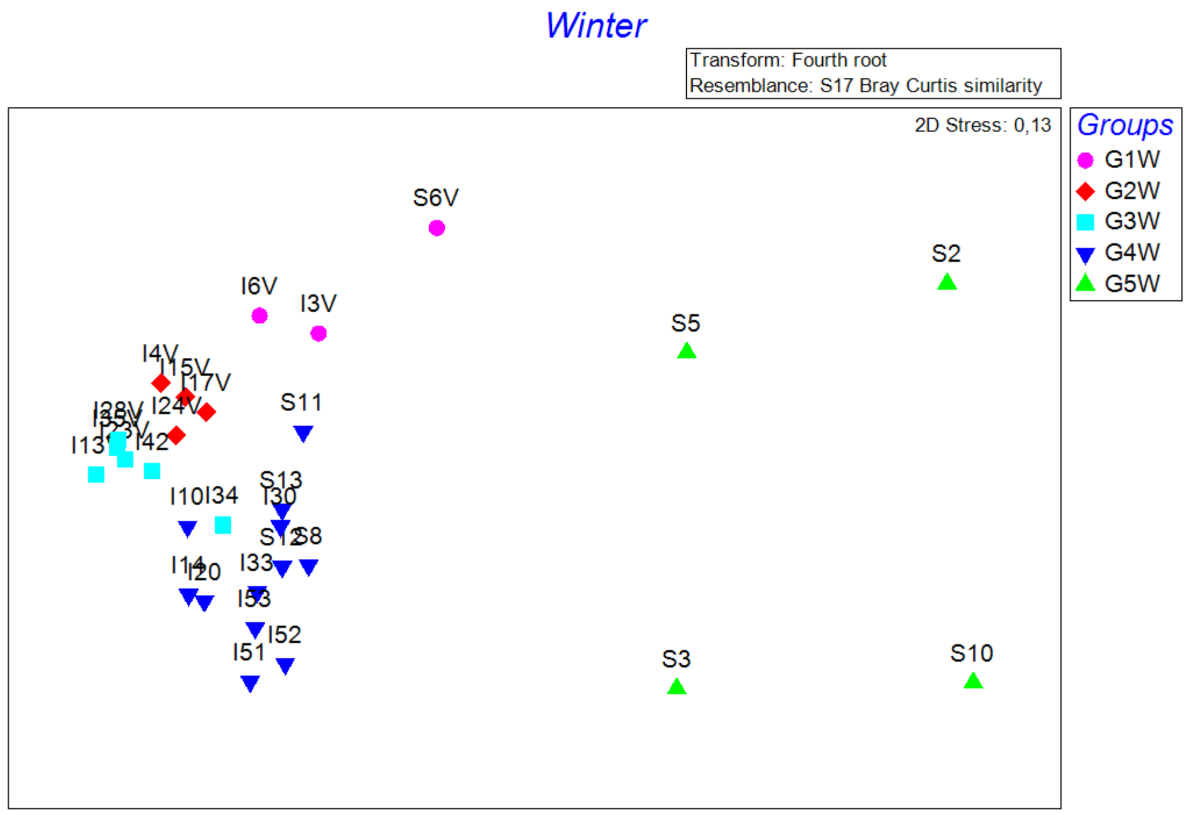


Figure 5. Structure of the macrofaunal assemblages based on abundance: Dendogram obtained from HAC and MDS plot showing the groups inferred from HAC in winter.

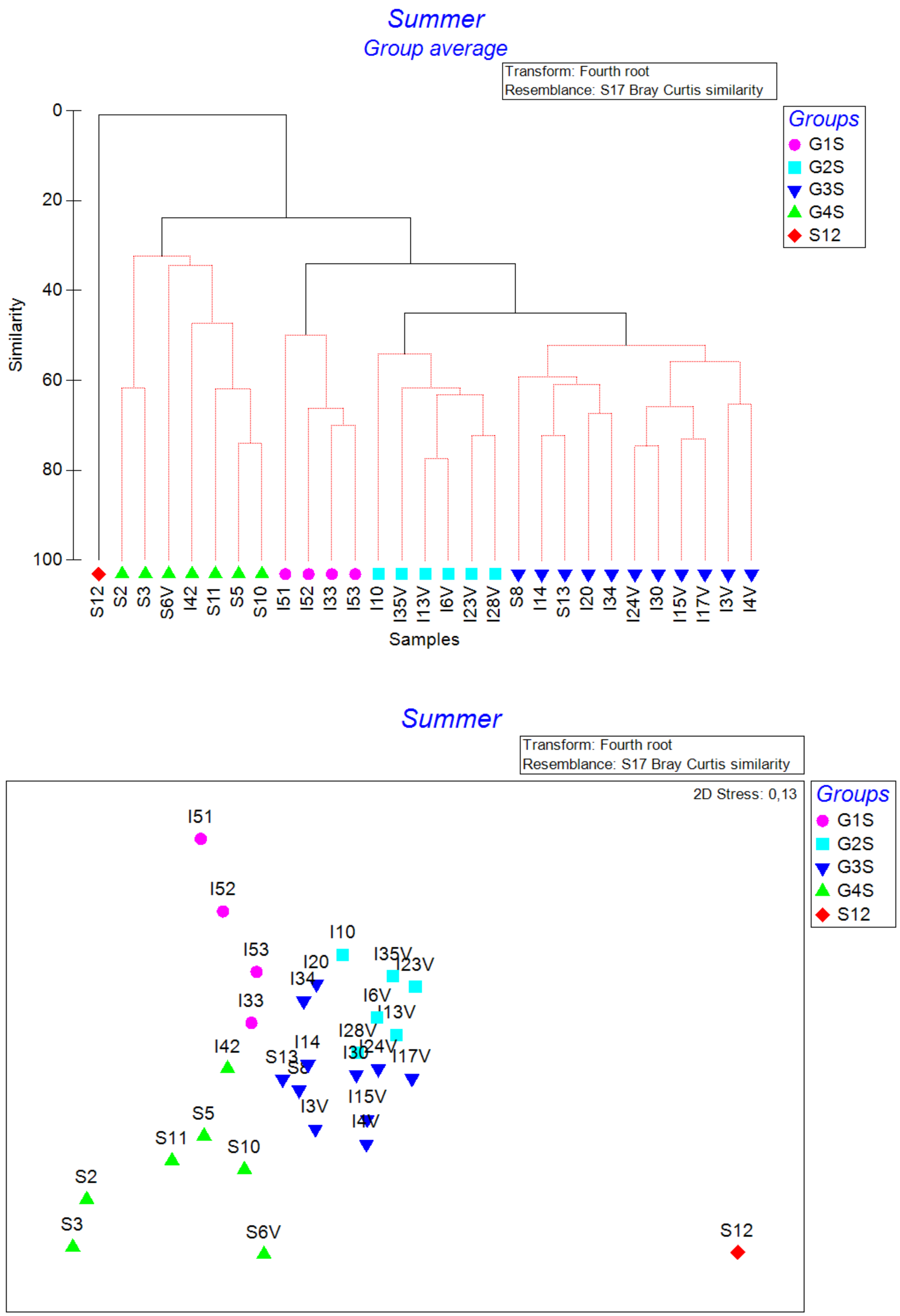


Figure 6. Structure of the macrofaunal assemblages based on abundance: Dendogram obtained from HAC and MDS plot showing the groups inferred from HAC in summer.

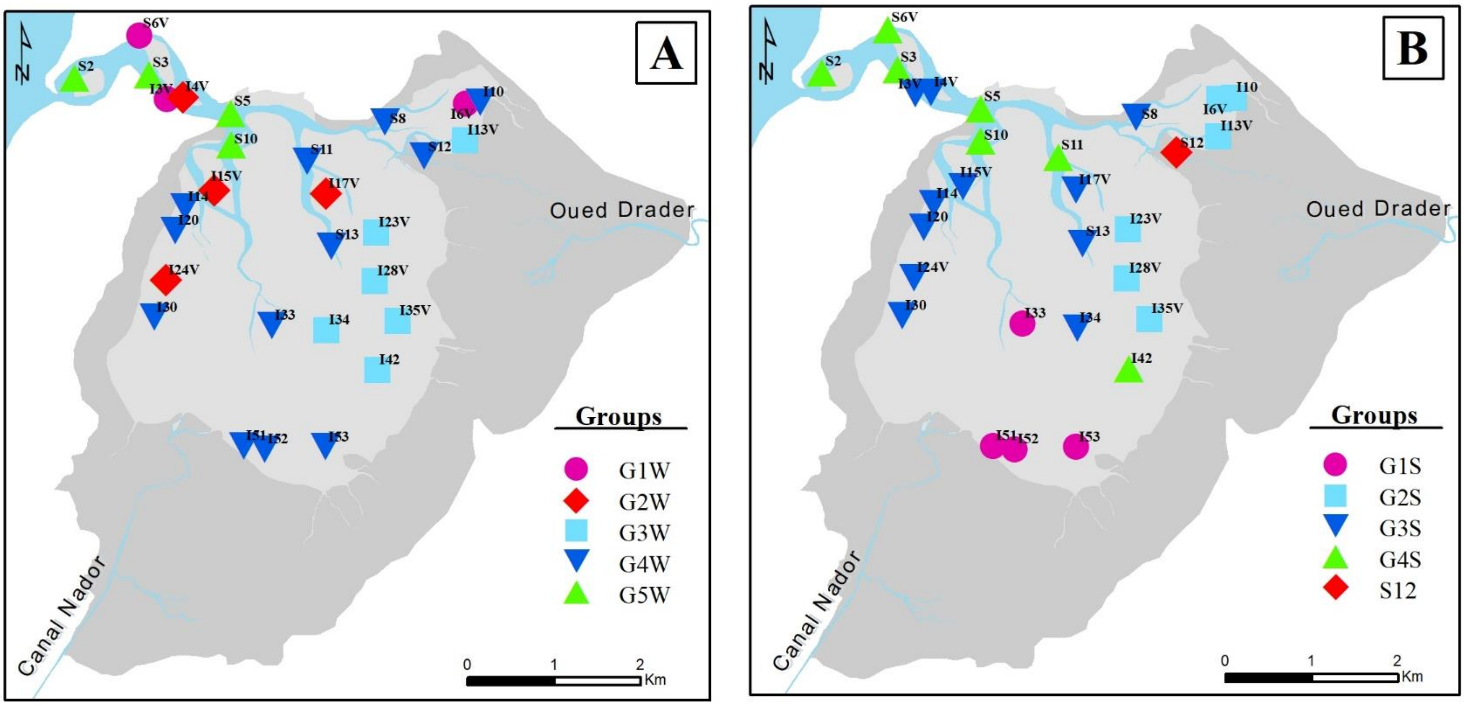


Figure 7. Maps showing the spatial distribution of the groups of stations identified by cluster analysis based on the similarity matrix of macrofauna with: **A:** Winter and **B:** Summer.

Relationships between Biotic and Environmental Patterns

The effect of environmental variables on the spatial distribution of benthic macrofauna was evaluated by the DistLM (Distance-based Linear Model) analysis (Table 4).

In winter, the results of this analysis's test sequence show that ten variables have an impact on the spatial variation of the macrofauna (Adjusted R^2=0.50). These variables are the sediment characteristics (mud content, median grain size, TOM %, carbon %, $CaCO_3$ % and $CaCO_2$ %), water characteristics (temperature and salinity) and habitat type (biomass of *Z. noltei* and *R. cirrhosa*). In summer, except for the median grain size added, DistLM showed the same factors as "best combination" of abiotic parameters playing a relevant role in shaping the macrobenthic assemblages (Adjusted R^2=0.56).

The results of the test sequence are visualized graphically by redundancy analysis (dbRDA), which ranks and orders the relationships between environmental variables and faunal composition (Figure 8).

For the winter data, the first two dbRDA axes captured 65% of the variability in the fitted model and 44.5% of the total variation in the data cloud. The full RDA axis explains 100% of the adjusted variation and 68.42% of the total variation. For stations located in the channels, the dbRDA shows that salinity, carbon content (percentage of carbon, $CaCO_3$ and $CaCO_2$) and median grain size are the most contributing parameters. On the other hand, the stations in the center and periphery are correlated with water temperature, Mud %, TOM % and habitat type (biomass of *Z. noltei* and *R. cirrhosa*).

For the summer data, the first dbRDA axis alone explained 38.6% of the fitted and 26.8% of the total variation while the second axis explained 21.7% of the fitted and 15% of the total variation. Jointly, the first two axes explained 60.3% of the adjusted change, and this accounts for about 41.8% of the total change in the multivariate community data. The RDA plot showed the same trends as in winter except for the absence of median grain size as a driver.

Table 4. Results of sequential test of the multivariate regression analysis (DistLM).

Environmental variables	Adjusted R^2	Pseudo-F	*p* value	Cumulative proportion
Winter				
Mud (%)	0.2377	9.7324	**0.0001**	0.2649
Z.noltei biomass (gDw)	0.3101	3.8349	**0.0005**	0.3594
Water temperature (°C)	0.3556	2.8371	**0.0069**	0.4247
Median Grain-size d50 (µm)	0.3940	2.5842	**0.0057**	0.4806
R. cirrhosa biomass (gDw)	0.4305	2.5347	**0.0090**	0.5322
Salinity	0.4700	2.7151	**0.0045**	0.5835
Carbon (%)	0.4807	1.4545	0.1727	0.6105
C [$CaCO_3$] (%)	0.4927	1.4973	0.1690	0.6376
TOM (%)	0.5071	1.5832	0.1330	0.6655
C [CO_2] (%)	0.5087	1.0639	0.3991	0.6842
Summer				
Mud (%)	0.2076	8.3378	**0.0001**	0.2359
Salinity	0.2879	4.0442	**0.0002**	0.3387
C [$CaCO_3$] (%)	0.3695	4.3667	**0.0003**	0.4371
C [CO_2] (%)	0.4349	3.8911	**0.0005**	0.5156
Carbon (%)	0.4793	3.0457	**0.0010**	0.5722
Water temperature (°C)	0.5185	2.8746	**0.0023**	0.6217
R. cirrhosa biomass (gDw)	0.5534	2.7192	**0.0057**	0.6650
Z.noltei biomass (gDw)	0.5647	1.5450	0.1480	0.6890
TOM (%)	0.5666	1.0883	0.3932	0.7059

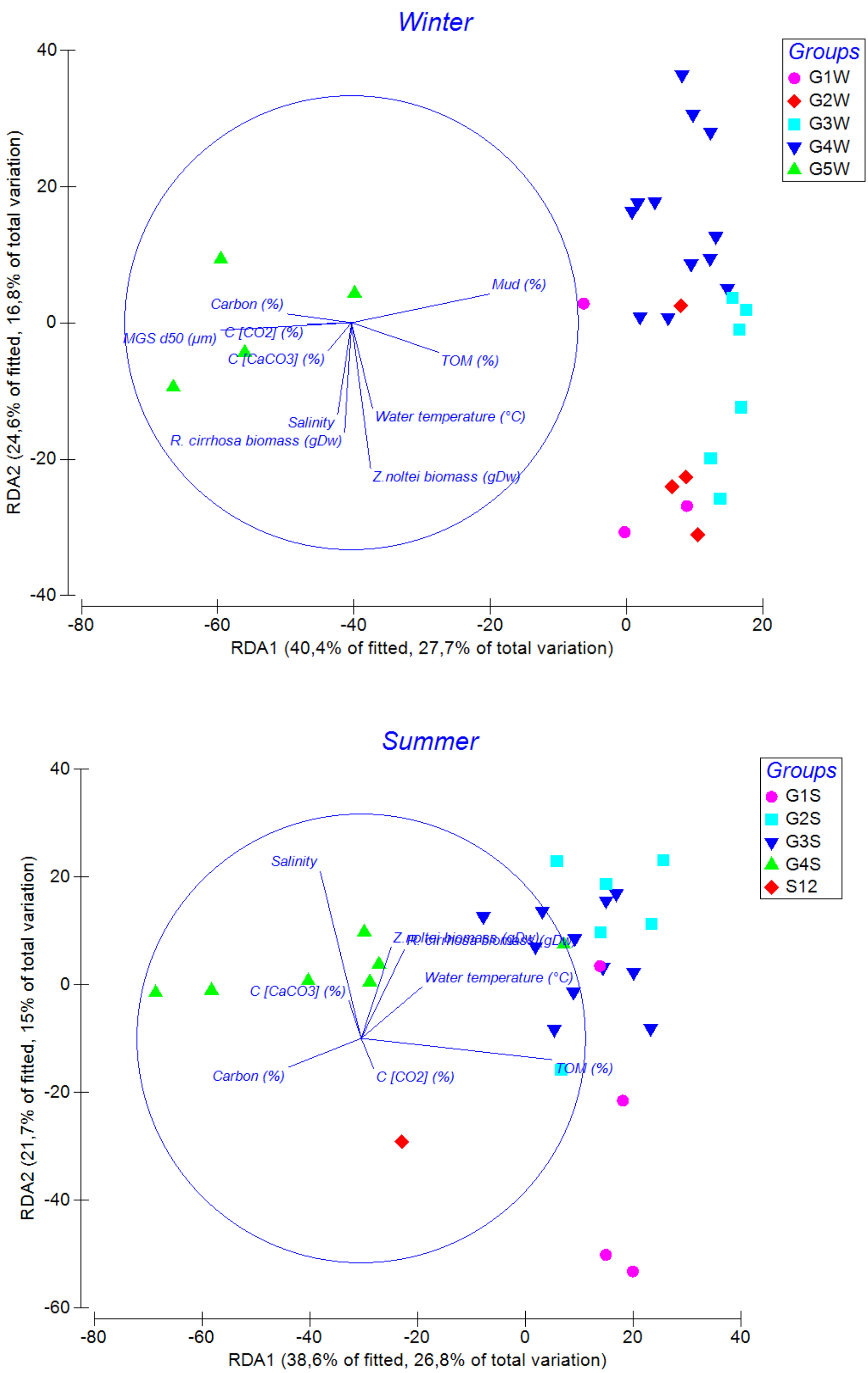


Figure 8. Two-dimensional distance-based redundancy analysis (dbRDA) ordination representing the model of spatial variation in macrofaunal community structure related to the predictor variables selected through the best linear models based on distance (DistLM).

Discussion

In our previous study, spatial distribution of macrozoobenthos was assessed in 68 stations along the Moulay Bousselham lagoon. We found out that water parameters, sediment characteristics and the presence of seagrasses were the most significant structuring factors (Boutoumit et al., 2021). The present research constitutes the first study encompassing the seasonal variations in biodiversity across macrozoobenthic communities and their responses to environmental factors in the Moulay Bousselham lagoon. In the present study, seasonal monitoring was conducted on the macrozoobenthic community structure in winter and summer at 29 locations in the lagoon. Sediment variables (e.g. median grain size, carbon content, mud and TOM), water parameters (temperature, salinity) and biomasses of seagrasses were monitored to determine how the spatiotemporal environmental changes affect the macrozoobenthic assemblages in the habitats.

Environmental variables

The water temperature of the Moulay Bousselham lagoon is mainly depends on solar radiation, exchanges with the atmosphere, and exchanges with the seawater at high tide. Regarding the exchanges by mixing with the underlying water, the shallow waters of the lagoon, the winds and the important currents cause a sufficient mixing to distribute the solar energy in an almost homogeneous way.

The water temperature follows a seasonal rhythm with minimum values in winter and maximum in summer. This temperature increases from downstream to upstream, reflecting both the influence of cold oceanic waters at the entrance of the lagoon and reflecting the decrease in depth upstream, which favors a rapid warming of the water.

Salinity shows extensive variability (2.07-4.12 to 31.53-34.40). The spatial distribution of salinity within the Moulay Bousselham lagoon follows a decreasing gradient from downstream to upstream. Indeed, the salinity in the downstream stations is equivalent to the oceanic water that feeds the lagoon through the passes and it gradually decreases to the upstream. This decrease is explained by the discharge of freshwater inputs along the lagoon.

Maximum salinity values were reported in summer and minimum in winter. The haline characteristics of the Moulay Bousselham lagoon are strongly influenced by climatic conditions. In winter, a desalination induced by precipitation occurs, while a sunshine-induced oversalination, which leads to the evaporation of water, occurs in the summer.

The sedimentary structure of the Moulay Bousselham lagoon presents a spatial variation (Boutoumit et al., 2021). The d50, carbon, CO_2, and $CaCO_3$ values follow an upstream-downstream decreasing gradient. On the contrary, the mud and TOM percentages are higher upstream and their values decrease when going downstream. Theses six variables depend on the morphogenic conditions influencing the different parts of the lagoon. The marine conditions upstream bring sandy sediments composed of shell remains, inducing an increase of d50 and Carbon, CO_2 and $CaCO_3$ values. The lower morphogenic conditions observed far from the lagoon pass and the channels lead to the deposit of finer sediments with less sands and higher mud proportions, also inducing a higher TOM content. However, despite detecting this important spatial variation, these results show that no significant seasonal variations can be discussed for these six environmental variables.

Benthic macrofauna

From a faunistic point of view, the macrobenthic community of the Moulay Bousselham lagoon has a classic faunal composition which is characteristic of lagoonal environments with the dominance of three zoological groups: mollusks, arthropods and annelids. This result is similar to those obtained for other lagoons in Morocco (Chbicheb, 1996; Bazaïri et al., 2003; Chaouti and Bayed, 2005; Touhami et al., 2017; El Asri et al., 2020; Bououarour et al., 2021).

The specific richness inventoried (42 in winter and 32 in summer) is lower than the one reported by Bazairi (1999), Touhami et al. (2017) and Boutoumit et al. (2021) in the same lagoon. In comparison with other semi-enclosed coastal systems, the macrobenthic fauna of Moulay Bousselham lagoon is more diverse than Margherita lagoon’s (Sigala et al., 2012), Monolimni lagoon’s (Kevrekidis, 2004), Idoura lagoon’s (Kanaya et al., 2011), Spiaxho lagoon’s (Nonnis Marzano et al., 2010), the Laguna Estuarine System’s (Meurer and Netto, 2007), the BEN estuary’s, the PAE estuary’s and the VIB estuary’s (Bissoli and Bernardino, 2018).

However, it remains less rich than Oualidia lagoon (El Asri et al., 2020), Mellah lagoon (Draredja, 2005), Gialova lagoon (Koutsoubas et al., 2000), Tunis lagoon (Tlig-Zouari and Maamouri-Mokhtar, 2008), Karavasta lagoon, Godulla lagoon (Nonnis Marzano et al., 2010), Lesina lagoon (Nonnis Marzano et al., 2003), Lagarou Lagoon (Sigala et al., 2012), Schelde estuary (Ysebaert and Herman, 2002). This difference could be related to the characteristics of each ecosystem (e.g. the surface area of each system provides a multitude of habitats for a diverse fauna), but could also be related to the number of samples and the techniques used.

The average biomass of the Moulay Bousselham lagoon varies with time with a maximum of about 25.10 g AFDW/m² recorded in winter. This biomass is similar to the average biomass (25 g AFDW/m²) available for shorebirds in intertidal habitats (Piersma et al., 1993).

This biomass value is higher than the value noted in the Banc d'Arguin in Mauritania (17 g AFDW/m²) (Wolf et al., 1993). However, it is lower than those reported in the Bay of Cadiz in

Spain (53 g AFDW/m²) (Masero et al., 1999) and in the lagoon of Ria Formosa in Portugal (68.5 g AFDW/m²) (Masero et al., 2000, Piersma et al., 1993).

Temporal variations appear to have less effect on community structure in Moulay Bousselham lagoon with seasonal changes in water temperature and salinity. Temporal changes in species richness and community structure are often insignificant in coastal lagoons. This lack of seasonality has been assigned primarily to the continuous reproduction of some abundant species and to species interactions (Nicolaidou, 2007).

The distribution of benthic assemblages and environmental factors follows a downstream-upstream gradient. This distribution is a well-known pattern in most semi-enclosed coastal systems. This spatial distribution pattern is consistent with results obtained by previous works in the same site (Bazairi et al., 2003, Touhami et al., 2017; Boutoumit et al., 2021) and in other similar ecosystems (Giménez et al., 2005; Joulami, 2013; Lefrere et al., 2015; Philippe et al., 2016).

DistLM analysis highlights that the spatial distribution of the benthic communities of Moulay Bousselham follows a clear downstream-upstream gradient, mainly due to environmental parameters including water temperature, salinity, characteristics of the substrate (median grain size, carbon content, mud, TOM) and the parameter related to the presence, absence or proximity of seagrass beds (*Z.noltei* and *R. cirrhosa*).

It is generally acknowledged that the spatial distribution of the macrozoobenthos is related either to abiotic factors (e.g. water parameters, sediment characteristics, vegetation type) (Cognetti and Maltagliati, 2000; Arocena, 2007; Reizopoulou and Nicolaidou, 2004) or to biotic factors (e.g. competition and predation or interactions among them) (Como and Magni, 2009). The lagoon surface area and hydrology also influence species richness and diversity in lagoonal systems (Barbone and Basset, 2010).

Salinity has long been considered as the primary ecological factor capable of discriminating the composition and distribution of aquatic fauna inhabiting coastal ecosystems. Salinity acts as a constraining factor in the distribution of living organisms, and its variability caused by dilution and evaporation affects the most likely fauna in the intertidal zone (Gibson, 1982).

Bottom water temperature also plays a pivotal role in the structure of macrobenthic communities (Day et al., 1989). Living organisms have an optimal temperature range for growth, at which species numbers quickly reach a maximum value. The relationship between temperature and species distribution has been examined in various research studies. Some studies have shown that temperature affects the metabolism and survival of benthic organisms (Vaquer-Sunyer and Duarte, 2011; Mfilinge and Tsuchiya, 2008).

The nature of the sediments is one of the main environmental factors affecting the benthic macrofauna (Jayaraj et al., 2007). Some authors have reported that the post-larval dispersal of benthic organisms can be closely linked to the physico-chemical type of sediments and that different sediment classes can attract specific taxa (Hughes et al., 1999). Macrobenthic communities may be strongly related to sedimentological features such as median grain size and organic matter content (Wilhelmsson and Malm, 2008). Indeed, fine grains could also draw more organic matter; thus, more food would be available for macrobenthos (Cheng et al., 2004). On the other hand, it is well documented that benthic diversity and abundance are typically higher in vegetated than in unvegetated bottoms (e.g. Mistri et al., 2000; Carvalho et al., 2006). Vegetation provided environmental stability, a food source, and stabilized invertebrate habitat, making it a key driver of the observed high abundance and biomass (Yuan and Lu, 2002).

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Conclusion and Perspectives

The work carried out during this thesis constitutes a primordial attempt to valorize the Moroccan benthic ecosystems. Our objectives were to elaborate a reference of existing data on the macrofauna of coastal ecosystems on a national scale.

On the other hand, we tried to understand the functioning of an ecosystem of international interest: the Moulay Bousselham lagoon. A study of the benthic macrofauna based on a coverage of 68 stations, sampled once, and 29 stations surveyed once during the winter and summer. Its aim is to provide elements for the knowledge of the current state of biodiversity of this coastal ecosystem and to establish a reference state for the macrobenthic fauna of the lagoon. It also proposes to study the evolution of benthic populations both in space (spatial variability) and in time (short-term spatio-temporal variability). This approach allows us to highlight the links between the benthic macrofauna and the environmental context, which allows us to understand the functioning of the benthic ecosystem of the lagoon.

The first result of this work was therefore to synthesize the data on semi-enclosed coastal systems. Our results provide the first broad-scale baseline of composition and diversity patterns of soft-bottom macrozoobenthos in SECS of Morocco and elucidate the main environmental factors that shape their latitudinal and biogeographic patterns. To our knowledge, the presently reviewed meta-data would be considered as most up-to-dated checklist of the soft-sediment macrozoobenthos in Moroccan SECS. This checklist is relevant in such poorly known area and fulfills a knowledge gap on SECS in the Northeastern Atlantic and Mediterranean ecoregions. However, the knowledge gained here is insufficient to address perceived shortfalls in knowledge of biodiversity, its importance to ecosystem function, and the threats and consequences of disturbance by anthropogenic activities.

The study of the Moulay Bousselham lagoon has shown that the benthic assemblages are distributed according to a downstream-upstream gradient. This downstream-upstream gradient is a known pattern in semi enclosed coastal ecosystems. This distribution is essentially due to environmental parameters; our results clearly revealed that the hydrographic regime (marine and terrestrial freshwater), the sediment distribution and characteristics, and the type of habitat (vegetated area) are the key factors determining the species composition and patterns of macrozoobenthos assemblages.

The lagoon of Moulay Bousselham receives both water inflows of oceanic origin via the tide and freshwater inflows from Oued Drader and Canal Nador. The fluctuation of these inputs affects the hydrological parameters and sedimentological characteristics. Indeed, in the oceanic part of the system, where hydrodynamics is strong, the substrate is dominated by the sandy fraction. Moving away from the gully, the hydrodynamics diminish and the fine continental inputs become more important, favoring a fine organic sedimentation towards the innermost part of the lagoon (muddy habitats).

The influence of hydrological parameters is altered by the presence of seagrass beds. Indeed, the vegetated habitats create stable and complex conditions that favor the installation of dense and diversified benthic communities. It should be noted that the highest abundances were identified in the central muddy habitats, covered with seagrass or located near the vegetated areas.

On the other hand, the seasonal monitoring conducted on the macrozoobenthic community structure in winter and summer shows that temporal variations appear to have less effect on community structure in Moulay Bousselham lagoon with seasonal changes in water temperature and salinity.

The present work has made it possible to synthesize data on Moroccan benthic ecosystems and to update the information available on the distribution and abundance of macrozoobenthos at the Moulay Bousselham site. Above all, it has made it possible to characterize the spatial distribution patterns of these communities. This approach responds to two issues:

- Scientific issue: the knowledge of these communities is an essential element before any decision of conservation and management measures
- Protection issue: the acquired results will allow deciding on the orientations in terms of management of the fauna and its habitats and the safeguard of the coastal wetland ecosystems.

Despite the relevance of the results obtained in this study, certain gaps remain. Filling these gaps would provide more elements for a better understanding of the functioning of the lagoon and other ecosystems.

This study provides a detailed description of the spatial distribution of benthic communities and short-term seasonal variation. While a good knowledge of the functioning of an ecosystem requires monitoring of the populations on a monthly, seasonal and interannual scale. This type of monitoring should also concern other particularly important components of the benthos such as the meiofauna and the biofilm. Other gaps in the macrozoobenthos appear necessary to be filled, in particular: the dynamics and production of benthic populations and the composition of their feeding regime and trophic functioning. Important questions remain concerning the interactions between species (interspecific and intraspecific) as well as between species and their biotopes.

The use of other ecosystem components (plankton, fish, physico-chemical variables, heavy metals, effects of plastic waste, etc.), as well as the establishment of lagoon-specific reference conditions, is strongly recommended to ensure a more robust assessment of the ecological status of the lagoon.

Studies on the trophic relationships between shorebirds and their prey are essential. These studies should include detailed analysis of the diets of key shorebird species, including either stable isotope analyses or environmental barcoding.

On the other hand, the realization of a reference state of the benthic populations of the Moroccan ecosystems is essential. As well as the elaboration of an inventory of the seagrass beds and the mapping of their habitats at the scale of Morocco and the study of the state of health of these beds.

The above proposals present some suggestions for future research, and illustrate the enormous amount of work that remains to be completed to deepen our understanding of the processes that govern the structuring and functioning of coastal ecosystems. Continued efforts through rigorous scientific research are needed to make informed and effective decisions for the management, enhancement and conservation of these internationally important ecosystems.

Appendix

Appendix 1

Table S1. Checklist of benthic macrofauna species reported in the semi-enclosed coastal systems of Morocco. References (numbers) are listed in chronological order and given in the list. Species are listed by taxonomical group and alphabetical order inside each group as well as biogeographical repartition along the Moroccan coasts (A: Atlantic, AM: Atlanto-Mediterranean, and M: Mediterranean). References (Numbers 1-36): **(1)** Elkaïm (1974); **(2)** Lacoste (1984); **(3)** Bekkali (1987); **(4)** Guelorget et al. (1987); **(5)** Bayed et al. (1988); **(6)** Cheggour (1988); **(7)** Zine (1989); **(8)** Chbicheb (1996); **(9)** Aksissou (1997); **(10)** Bazairi (1999); **(11)** Boussalwa et al. (2000); **(12)** Bazairi & Zourarah (2001); **(13)** Mergaoui et al. (2003); **(14)** Bazairi & Gam (2004); **(15)** Chaouti & Bayed (2005); **(16)** El Houssaini (2005); **(17)** Zine (2005); **(18)** Azirar (2006); **(19)** Bazairi & Bayed (2006); **(20)** Cherkaoui (2006); **(21)** Gauteur (2006); **(22)** Bazairi & Zourarah (2007); **(23**) Ait Mlik (2009); **(24)** Lefrere (2012); **(25)** Bououarour (2013); **(26)** Joulami (2013); **(27)** Boutahar (2014); **(28)** Cuvelier et al. (2014); **(29)** El Asri et al. (2015); **(30)** Bazairi et al. (2017); **(31)** El Asri et al. (2017); **(32)** Touhami (2018); **(33)** El Asri (2019); **(34)** Bououarour (unpublished data); **(35)** Boutoumit (unpublished data); **(36)** El Kamcha (unpublished data).

Phylum Cnidaria
  Class Anthozoa
    Order Actiniaria
      Family Actiniidae
        Actinia equina (Linnaeus, 1758) 10, 13, 17, 21, 23, 26, 34, 36; **AM**
        Anemonia sulcata (Pennant, 1777) 33; **A**
      Family Diadumenidae
        Diadumene cincta (Stephenson, 1925) 1; **A**
      Family Edwardsiidae
        Edwardsia sp (Quatrefages, 1842) 10; **A**
      Family Hormathiidae
        Calliactis parasitica (Couch, 1842) 1; **A**
      Family Sagartiidae
        Cereus sp (Ilmoni, 1830) 10; **A**
Phylum Nemertea
  Class Hoplonemertea
    Order Monostilifera
      Family Tetrastemmatidae
        Tetrastemma coronatum (Quatrefages, 1846) 2; **A**

Class Palaeonemertea;

Order (Not assigned)

Family Tubulanidae

Tubulanus polymorphus (Renier, 1804) 1; **A**

Class Pilidiophora

Order Heteronemertea

Family Lineidae

Cerebratulus marginatus (Renier, 1804) 1, 2; **A**

Lineus sanguineus (Rathke, 1799) 1; **A**

Phylum Annelida

Class Clitellata

Order Haplotaxida

Family Naididae

Monopylephorus irroratus (Verrill, 1873) 1; **A**

Tectidrilus gabriellae (Marcus, 1950) 1; **A**

Class Polychaeta

Order Echiuroidea

Family Thalassematidae

Thalassema thalassema (Pallas, 1774) 13, 17; **A**

Order Eunicida

Family Dorvilleidae

Schistomeringos neglecta (Fauvel, 1923) 33; **A**

Family Eunicidae

Eunice pennata (Müller, 1776) 4; **M**

Eunice vittata (Delle Chiaje, 1828) 21, 28, 33; **AM**

Lysidice unicornis (Grube, 1840) 33; **A**

Marphysa sanguinea (Montagu, 1813) 5, 19, 24, 34; **A**

Paucibranchia bellii (Audouin & Milne Edwards, 1833) 21, 27, 28; **AM**

Family Lumbrineridae

Lumbrineris coccinea (Renier, 1804) 31; **A**

Lumbrineris latreilli (Audouin & Milne Edwards, 1833) 7, 21, 26,27, 28, 34; **AM**

Scoletoma impatiens (Claparède, 1868) 1, 2, 4, 6, 7, 13, 17, 20; **AM**

Scoletoma tetraura (Schmarda, 1861); 10, 32, 35; **A**

Family Oenonidae

Arabella iricolor (Montagu, 1804) 33; **A**

Family Onuphidae

Diopatra marocensis (Paxton, Fadlaoui & Lechapt, 1995) 31; **A**

Diopatra neapolitana (Delle Chiaje, 1841) 1, 2, 5, 6, 7, 10, 12, 13, 14, 17, 18, 19, 20, 21, 25, 26, 27, 30, 35; **AM**

Onuphis eremita (Audouin & Milne Edwards, 1833) 10; **A**

Order Phyllodocida

Family Glyceridae

Glycera alba (O.F. Müller, 1776) 1, 6, 20, 28, 31, 33; **AM**

Glycera tridactyla (Schmarda, 1861) 1, 2, 4, 6, 7, 10, 12, 13, 14, 17, 18, 19, 20, 21, 22, 23, 25, 26, 27, 28, 30, 31, 32, 33, 34, 35; **AM**

Glycera unicornis (Lamarck, 1818) 23; **A**

Family Goniadidae

Glycinde nordmanni (Malmgren, 1866) 33; **A**

Family Hesionidae

Gyptis propinqua (Marion & Bobretzky, 1875) 12, 18; **A**

Family Nephtyidae

Nephtys caeca (Fabricius, 1780) 8; **A**

Nephtys cirrosa (Ehlers, 1868) 1, 6, 10, 14, 19, 20, 21, 22, 26, 27, 28, 30; **AM**

Nephtys hombergii (Savigny in Lamarck, 1818) 1, 2, 4, 5, 6, 8, 10, 12, 13, 14, 15, 17, 18, 19, 20, 21, 22, 23, 25, 30, 31, 32, 34, 35; **AM**

Nephtys kersivalensis (McIntosh, 1908) 31; **A**

Family Nereididae

Hediste diversicolor (O.F. Müller, 1776) 1, 3, 4, 5, 6, 8, 9, 10, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 30, 31, 32, 35, 34; **AM**

Neanthes acuminata (Ehlers, 1868) 4, 7; **M**

Nereis zonata (Malmgren, 1867) 6; **A**

Perinereis cultrifera (Grube, 1840) 6, 17; **A**

Platynereis dumerilii (Audouin & Milne Edwards, 1833) 10, 19, 33, 35; **A**

Websterinereis glauca (Claparède, 1870) 15; **M**

Family Pholoidae

Pholoe inornata (Johnston, 1839) 10; **A**

Family Phyllodocidae

Eteone barbata (Malmgren, 1865) 33; **A**

Eteone longa (Fabricius, 1780) 1, 12, 18, 30, **A**

Eulalia viridis (Linnaeus, 1767) 6, 10; **A**

Eumida sanguinea (Örsted, 1843) 33; **A**

Mysta picta (Quatrefages, 1866) 6, 20; **A**

Phyllodoce maculata (Linnaeus, 1767) 17; **A**

Family Polynoidae

Harmothoe extenuata (Grube, 1840) 10; **A**

Harmothoe spinifera (Ehlers, 1864) 4; **M**

Lepidasthenia maculata (Potts, 1910) 20; **A**

Lepidonotus clava (Montagu, 1808) 13, 17; **A**

Family Sigalionidae

Sigalion mathildae (Audouin & Milne Edwards in Cuvier, 1830) 1, 6, 22; **A**

Sthenelais boa (Johnston, 1833) 10, 13, 17, 21, 26, 33; **A**

Family Syllidae

Syllis gracilis (Grube, 1840) 6; **A**

Syllis prolifera (Krohn, 1852) 10; **A**

Order Sabellida

Family Oweniidae

Owenia fusiformis (Delle Chiaje, 1844) 1, 6, 8, 10, 20, 21, 23, 27, 28, 34; **AM**

Family Sabellidae

Branchiomma bombyx (Dalyell, 1853) 12, 18, 20; **A**

Chone duneri (Malmgren, 1867) 21, 26, 27, 28, 34; **AM**

Dialychone collaris (Langerhans, 1881) 10; **A**

Laonome kroyeri (Malmgren, 1866) 5; **A**

Panousea africana (Rullier & Amoureux, 1969) 31, 33; **A**

Sabella pavonina (Savigny, 1822) 2; **A**

Family Serpulidae

Ficopomatus enigmaticus (Fauvel, 1923) 3, 6, 9, 26; **AM**

Serpula concharum (Langerhans, 1880) 10; **A**

Serpula vermicularis (Linnaeus, 1767) 6, 20; **A**

Spirobranchus lamarcki (Quatrefages, 1866) 10; **A**

Spirobranchus triqueter (Linnaeus, 1758) 6, 17; **A**

Spirorbis (Spirorbis) spirorbis (Linnaeus, 1758) 6; **A**

Order Spionida

Family Poecilochaetidae

Poecilochaetus serpens (Allen, 1904) 2; **A**

Family Spionidae

Aonides oxycephala (Sars, 1862) 10, 19, 21, 22, 23, 26, 27, 28, 34; **AM**
Dipolydora giardi (Mesnil, 1893) 15; **M**
Malacoceros fuliginosus (Claparède, 1868) 10, 12, 14, 18, 21, 22, 23, 26; **A**
Malacoceros tetracerus (Schmarda, 1861) 1, 4; **AM**
Paraprionospio pinnata (Ehlers, 1901) 33; **A**
Polydora ciliata (Johnston, 1838) 1, 2, 10, 12, 18, 20, 23, 30, 35; **A**
Polydora hoplura (Claparède, 1868) 1; **A**
Prionospio cf. cirrifera (Wirén, 1883) 14; **A**
Prionospio fallax (Söderström, 1920) 10, 32, 35; **A**
Prionospio malmgreni (Claparède, 1869) 21, 23, 26; **A**
Pseudopolydora antennata (Claparède, 1869) 1, 10, 32, 35; **A**
Scolelepis (Scolelepis) foliosa (Audouin & Milne Edwards, 1833) 4; **M**
Scolelepis (Scolelepis) squamata (O.F. Muller, 1806) 1, 6, 10, 20; **A**
Scolelepis cantabra (Rioja, 1918) 17; **A**
Spio filicornis (Müller, 1776) 10, 35; **A**
Streblospio shrubsolii (Buchanan, 1890) 1, 10, 14, 16, 20, 25, 32, 35; **AM**

Order Terebellida

Family Ampharetidae

Alkmaria romijni (Horst, 1919) 1, 10, 14, 15, 16, 20, 21, 23, 31; **AM**
Amage adspersa (Grube, 1863) 28; **M**
Amage gallasii (Marion, 1875) 24; **A**
Ampharete grubei (Malmgren, 1865) 10; **A**
Melinna palmata (Grube, 1870) 5, 24; **A**

Family Cirratulidae

Aphelochaeta sp (Blake, 1991) 34; **A**
Cirratulus cirratus (O. F. Müller, 1776) 20; **A**
Cirriformia tentaculata (Montagu, 1808) 1, 5, 7, 10, 13, 17, 21, 22, 26, 27, 28, 30, 33, 34; **AM**

Family Pectinariidae;

Lagis koreni (Malmgren, 1866) 2, 4, 6, 10, 14, 20, 21, 22, 23, 26, 27, 28, 30, 31, 32, 34, 35; **AM**
Petta pusilla (Malmgren, 1866) 13, 17; **A**

Family Terebellidae

Amaeana trilobata (Sars, 1863) 33; **A**
Amphitritides gracilis (Grube, 1860) 15; **M**
Lanice conchilega (Pallas, 1766) 1, 2, 10; **A**
Neoamphitrite edwardsi (Quatrefages, 1865) 5, 16; **AM**
Pista maculata (Dalyell, 1853) 5; **A**
Pistella lornensis (Pearson, 1969) 33; **A**
Terebella lapidaria (Linnaeus, 1767) 24, 34; **A**

Order (Not assigned)

Family Arenicolidae

Arenicola sp (Lamarck, 1801) 22; **A**

Family Capitellidae

Capitella capitata (Fabricius, 1780) 1, 4, 8, 10, 12, 14, 18, 19, 20, 21, 23, 25, 26, 27, 28, 30, 32, 34, 35; **AM**
Heteromastus filiformis (Claparède, 1864) 6, 7, 10, 12, 14, 15, 17, 18, 19, 20, 21, 22, 23, 25, 26, 27, 30, 32, 34, 35; **AM**
Mediomastus fragilis (Rasmussen, 1973) 10, 32, 35; **A**

Notomastus latericeus (Sars, 1851) 10, 15, 21, 26, 27, 34; **AM**
Notomastus lineatus (Claparède, 1869) 28; **M**
Family Magelonidae
Magelona filiformis (Wilson, 1959) 28; **M**
Magelona mirabilis (Johnston, 1865) 10; **A**
Magelona papillicornis (F. Müller, 1858) 1, 14, 19; **A**
Family Maldanidae
Axiothella constricta (Claparède, 1868) 33; **A**
Euclymene oerstedii (Claparède, 1863) 5; **A**
Euclymene palermitana (Grube, 1840) 21, 26, 27, 28, 34; **AM**
Leiochone leiopygos (Grube, 1860) 2, 21; **A**
Maldane sarsi (Malmgren, 1865) 33; **A**
Nicomache (Loxochona) trispinata (Arwidsson, 1906) 34; **A**
Petaloproctus terricolus (Quatrefages, 1866) 21; **A**
Family Opheliidae
Ophelia bicornis (Savigny, 1822) 10; **A**
Ophelia radiata (Delle Chiaje, 1828) 19; **A**
Ophelia rathkei (McIntosh, 1908) 33; **A**
Polyophthalmus pictus (Dujardin, 1839) 10, 35; **A**
Family Orbiniidae
Naineris laevigata (Grube, 1855) 28, 33, 34; **AM**
Orbinia latreillii (Audouin & H Milne Edwards, 1833) 20; **A**
Phylo foetida (Claparède, 1868) 19, 21, 28; **AM**
Scoloplos armiger (Müller, 1776) 5, 10, 19, 27, 32, 34; **A**
Family Sabellariidae
Sabellaria alveolata (Linnaeus, 1767) 6, 17; **A**
Sabellaria spinulosa (Leuckart, 1849) 10; **A**

Phylum Mollusca
Class Bivalvia
Order Adapedonta
Family Solenidae
Solen marginatus (Pulteney, 1799) 1, 2, 5, 6, 7, 10, 12, 13, 17, 18, 19, 20, 21, 22, 24, 26, 27, 29, 30, 34, 35; **AM**
Order Arcida
Family Glycymerididae
Glycymeris pilosa (Linnaeus, 1767) 24; **A**

Family Noetiidae
Striarca lactea (Linnaeus, 1758) 19; **A**
Order Cardiida
Family Cardiidae
Acanthocardia echinata (Linnaeus, 1758) 3, 7, 9, 36; **M**
Acanthocardia tuberculata (Linnaeus, 1758) 36; **M**
Cerastoderma edule (Linnaeus, 1758) 1, 2, 5, 6, 8, 10, 12, 13, 14, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 29, 30, 32, 33, 34, 35; **A**
Cerastoderma glaucum (Bruguière, 1789) 4, 8, 15, 16, 27, 36; **AM**
Laevicardium oblongum (Gmelin, 1791) 8; **A**
Papillicardium papillosum (Poli, 1791) 33; **A**
Family Donacidae
Donax trunculus (Linnaeus, 1758); 1, 6, 11, 13, 15, 18, 19, 22, 28, 35; **AM**

Donax vittatus (da Costa, 1778) 1, 12, 13, 17, 18; **A**
Family Psammobiidae
Asaphis sp (Modeer, 1793) 13; **A**
Family Semelidae
Abra alba (W. Wood, 1802) 4, 7, 8, 10, 13, 17, 19, 21, 22, 23, 26, 27, 28, 29, 32, 33, 34, 35, 36; **AM**
Abra nitida (O. F. Müller, 1776) 36; **M**
Abra segmentum (Récluz, 1843) 10, 36; **AM**
Abra tenuis (Montagu, 1803) 5, 21, 23, 26, 27, 32, 34, 35; **A**
Scrobicularia plana (da Costa, 1778) 1, 2, 6, 8, 10, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 30, 32, 34, 35; **AM**
Family Solecurtidae
Azorinus chamasolen (da Costa, 1778) 36; **M**
Family Tellinidae
Gastrana fragilis (Linnaeus, 1758) 4, 7, 28, 34, 36; **AM**
Macomangulus tenuis (da Costa, 1778) 1, 2, 3, 9, 10, 14, 19, 23, 27; **AM**
Moerella distorta (Poli, 1791) 4, 28, 36; **M**
Moerella pulchella (Lamarck, 1818) 33; **A**
Oudardia compressa (Brocchi, 1814) 21, 27; **A**
Peronidia albicans (Gmelin, 1791) 36; **M**
Order Carditida
Family Carditidae
Cardita calyculata (Linnaeus, 1758) 33; **A**
Order Galeommatida
Family Lasaeidae
Kellia suborbicularis (Montagu, 1803) 10, 23; **A**
Kurtiella bidentata (Montagu, 1803) 10; **A**
Order Limida
Family Limidae
Limaria tuberculata (Olivi, 1792) 17, 36; **AM**
Order Lucinida
Family Lucinidae
Loripes orbiculatus (Poli, 1795) 4, 7, 15, 16, 17, 21, 24, 26, 27, 28, 29, 33, 34, 36; **AM**
Loripinus fragilis (Philippi, 1836) 7, 36; **M**
Lucina adansoni (d'Orbigny, 1840) 33; **A**
Order Myida
Family Corbulidae
Corbula gibba (Olivi, 1792) 1, 4, 7, 10, 12, 13, 14, 17, 18, 22, 23, 28, 30, 33, 34; **AM**
Corbula laticostata (Lamy, 1941) 33; **A**
Family Pholadidae
Barnea candida (Linnaeus, 1758) 2, 10; **A**
Pholas dactylus (Linnaeus, 1758) 2, 7; **AM**
Order Mytilida
Family Mytilidae
Gregariella petagnae (Scacchi, 1832) 10; **A**
Lithophaga lithophaga (Linnaeus, 1758) 34; **A**
Modiola opifex (Say, 1825) 7; **M**
Modiolula phaseolina (Philippi, 1844) 3, 7, 9; **M**
Modiolus sp (Lamarck, 1799) 4; **M**
Musculus costulatus (Risso, 1826) 4, 10, 23, 30; **AM**
Musculus subpictus (Cantraine, 1835) 10, 13, 17, 33, 35; **A**

Mytilaster lineatus (Gmelin, 1791) 28, 36; **M**
Mytilaster minimus (Poli, 1795) 10, 35; **A**
Mytilus edulis (Linnaeus, 1758) 6, 12, 13, 17, 18; **A**
Mytilus galloprovincialis (Lamarck, 1819) 2, 7, 29, 33, 36; **AM**
Order Nuculanida
Family Nuculanidae
Lembulus pella (Linnaeus, 1758) 33; **A**
Order Nuculida
Family Nuculidae
Nucula nucleus (Linnaeus, 1758) 33, 36; **AM**
Nucula sulcata (Bronn, 1831) 7; **M**
Order Ostreida
Family Ostreidae
Crassostrea sp (Sacco, 1897) 17; **A**
Magallana angulata (Lamarck, 1819) 2; **A**
Magallana gigas (Thunberg, 1793) 15; **M**
Ostrea edulis (Linnaeus, 1758) 4, 17, 13; **AM**
Family Pinnidae
Pinna nobilis (Linnaeus, 1758) 28; **M**
Order Pectinida
Family Anomiidae
Anomia ephippium (Linnaeus, 1758) 10, 13, 17, 20, 23, 35; **A**
Family Pectinidae
Aequipecten opercularis (Linnaeus, 1758) 13, 17; **A**
Mimachlamys varia (Linnaeus, 1758) 2, 17; **A**
Order Solemyida
Family Solemyidae
Solemya togata (Poli, 1791) 33; **A**
Order Venerida
Family Mactridae
Eastonia rugosa (Helbling, 1779) 17; **A**
Lutraria lutraria (Linnaeus, 1758) 17; **A**
Mactra glauca (Born, 1778) 10; **A**
Mactra stultorum (Linnaeus, 1758) 4, 7, 17; **AM**
Spisula subtruncata (da Costa, 1778) 2, 10, 17, 19, 23, 27, 29, 30, 34; **A**
Family Neoleptonidae
Neolepton sulcatulum (Jeffreys, 1859) 33; **A**
Family Ungulinidae
Diplodonta rotundata (Montagu, 1803) 5; **A**
Family Veneridae
Chamelea gallina (Linnaeus, 1758) 10, 14, 28; **AM**
Clausinella fasciata (da Costa, 1778) 17, 33; **A**
Dosinia exoleta (Linnaeus, 1758) 17; **A**
Dosinia lupinus (Linnaeus, 1758) 20; **A**
Irus irus (Linnaeus, 1758) 17, 30; **A**
Petricola lithophaga (Retzius, 1788) 2, 17, 13; **A**
Polititapes aureus (Gmelin, 1791) 2, 4, 7, 13, 17, 19, 27, 28, 30, 33, 34, 36; **AM**
Polititapes rhomboides (Pennant, 1777) 17, 22, 34; **A**
Ruditapes decussatus (Linnaeus, 1758) 2, 4, 6, 7, 8, 10, 12, 13, 15, 17, 18, 20, 21, 23, 25, 26, 27, 28, 29, 32, 34, 35; **AM**

Timoclea ovata (Pennant, 1777) 33; **A**
Venerupis corrugata (Gmelin, 1791) 7, 8, 11, 13, 17, 19, 32, 34, 35; **AM**
Venerupis geographica (Gmelin, 1791) 36; **M**
Venus casina (Linnaeus, 1758) 36; **M**
Venus verrucosa (Linnaeus, 1758) 8, 33; **A**
Order (Not assigned)
Family Thraciidae
Thracia phaseolina (Lamarck, 1818) 33*;* **A**
Class Cephalopoda
Order Octopoda
Family Octopodidae
Octopus vulgaris (Cuvier, 1797) 13, 17, 29; **A**
Order Sepiida
Family Sepiidae
Sepia officinalis (Linnaeus, 1758) 13, 17; **A**
Sepia orbignyana (Férussac [in d'Orbigny], 1826) 7; **M**
Class Gastropoda
Order Caenogastropoda
Family Cerithiidae
Bittium latreillii (Payraudeau, 1826) 34; **A**
Bittium reticulatum (da Costa, 1778) 3, 4, 9, 16, 17, 23, 25, 27, 28, 32, 33, 34, 35; **AM**
Cerithium vulgatum (Bruguière, 1792) 4, 8, 23, 26, 28, 36; **AM**
Family Epitoniidae
Epitonium clathratulum (Kanmacher, 1798) 17; **A**
Epitonium clathrus (Linnaeus, 1758) 29, 33; **A**
Epitonium pulchellum (Bivona, 1832) 17; **A**
Gyroscala commutata (Lamarck, 1822) 17; **A**
Family Turritellidae
Mesalia mesal (Deshayes, 1843) 24, 33; **A**
Turritellinella tricarinata (Brocchi, 1814) 24; **A**
Order Aplysiida
Family Akeridae
Akera bullata (O. F. Müller, 1776) 27; **A**
Family Aplysiidae
Aplysia depilans (Gmelin, 1791) 6, 15; **AM**
Aplysia fasciata (Poiret, 1789) 10; **A**
Aplysia parvula (Mörch, 1863) 10; **A**
Aplysia punctata (Cuvier, 1803) 10, 13, 17 29, 33; **A**
Bursatella leachii (Blainville, 1817) 28; **M**
Order Cephalaspidea
Family Bullidae
Bulla striata (Bruguière, 1792) 28, 33, 34, 35, 36; **AM**
Family Haminoeidae
Haloa japonica (Pilsbry, 1895) 29; **A**
Haminoea hydatis (Linnaeus, 1758) 17, 36; **AM**
Haminoea navicula (da Costa, 1778) 2, 10, 15, 16, 20, 21, 23, 26, 28, 32, 34, 35; **AM**
Haminoea orbignyana (Férussac, 1822) 1, 5; **A**
Family Retusidae
Retusa truncatula (Bruguière, 1792) 33; **A**

Order Cycloneritida
Family Neritidae
Smaragdia viridis (Linnaeus, 1758) 36; **M**
Order Ellobiida
Family Ellobiidae
Leucophytia bidentata (Montagu, 1808) 13, 17; **A**
Myosotella myosotis (Draparnaud, 1801) 29; **A**
Order Lepetellida
Family Fissurellidae
Fissurella nubecula (Linnaeus, 1758) 17; **A**
Order Littorinimorpha
Family Barleeiidae
Barleeia unifasciata (Montagu, 1803) 13, 17; **A**
Family Calyptraeidae
Calyptraea chinensis (Linnaeus, 1758) 33; **A**
Crepidula porcellana (Lamarck, 1801) 24, 33, 34; **A**
Family Cymatiidae
Linatella caudata (Gmelin, 1791) 17; **A**
Family Hydrobiidae
Hydrobia acuta (Draparnaud, 1805) 21, 27, 32, 34; **A**
Peringia ulvae (Pennant, 1777) 1, 2, 3, 9, 10, 12, 13, 15, 16, 17, 18, 20, 21, 22, 23, 24, 25, 26, 27, 30, 32, 33, 34, 35; **AM**
Family Littorinidae
Echinolittorina punctata (Gmelin, 1791) 13, 17, 33; **A**
Littorina littorea (Linnaeus, 1758) 6; **A**
Littorina saxatilis (Olivi, 1792) 24; **A**
Melarhaphe neritoides (Linnaeus, 1758) 6; **A**
Family Naticidae
Cochlis vittata (Gmelin, 1791) 10, 17, 19, 20, 21, 23, 24, 32, 34, 35; **A**
Euspira catena (da Costa, 1778) 17; **A**
Euspira macilenta (Philippi, 1844) 33; **A**
Euspira nitida (Donovan, 1804) 2; **A**
Naticarius hebraeus (Martyn, 1786) 13, 17; **A**
Family Rissoidae
Alvania cimex (Linnaeus, 1758) 36; **M**
Pusillina lineolata (Michaud, 1830) 13, 17; **A**
Pusillina philippi (Aradas & Maggiore, 1844) 3, 9; **M**
Rissoa guerinii (Récluz, 1843) 7; **M**
*Rissoa membranacea (*J. Adams, 1800) 7, 1; **AM**
Rissoa parva (da Costa, 1778) 15, 16, 17, 23, 25, 35; **AM**
Family Skeneopsidae
Skeneopsis planorbis (O. Fabricius, 1780) 3, 9; **M**
Order Neogastropoda
Family Buccinidae
Buccinum sp (Linnaeus, 1758) 24; **A**
Family Cancellariidae
Bivetiella cancellata (Linnaeus, 1767) 17; **A**
Family Conidae
Conus pulcher (Lightfoot, 1786) 33; **A**
*Conus ventricosus (*Gmelin, 1791) 33; **A**

Family Cystiscidae
Gibberula chudeaui (Bavay in Dautzenberg, 1910) 24; **A**
Gibberula miliaria (Linnaeus, 1758) 33, 34; **A**
Persicula cingulata (Dillwyn, 1817) 34; **A**
Family Marginellidae
Marginella glabella (Linnaeus, 1758) 33; **A**
Prunum amygdalum (Kiener, 1841) 34; **A**
Prunum cf. martini (Petit de la Saussaye, 1853) 33; **A**
Family Melongenidae
Pugilina morio (Linnaeus, 1758) 7; **M**
Family Muricidae
Bolinus brandaris (Linnaeus, 1758) 4, 36; **M**
Hexaplex trunculus (Linnaeus, 1758) 4, 7, 28, 29, 36; **AM**
Family Nassariidae
Tritia cuvierii (Payraudeau, 1826) 7; **M**
Tritia grana (Lamarck, 1822) 19, 21, 22, 23, 26; **A**
Tritia incrassata (Strøm, 1768) 10, 13, 17, 22, 33, 36; **AM**
Tritia mutabilis (Linnaeus, 1758) 8, 36; **AM**
Tritia pfeifferi (Philippi, 1844) 29, 32, 33, 34, 35; **A**
Tritia pygmaea (Lamarck, 1822) 2, 22; **A**
Tritia reticulata (Linnaeus, 1758) 6, 8, 10, 12, 13, 17, 18, 19, 20, 21, 22, 23, 26, 27, 29, 30, 33, 34, 35, 36; **AM**
Order Nudibranchia
Family Dendrodorididae
Dendrodoris sp (Ehrenberg, 1831) 29; **A**
Family Discodorididae
Jorunna tomentosa (Cuvier, 1804) 29; **A**
Order Runcinida
Family Runcinidae
Runcina coronata (Quatrefages, 1844) 29; **A**
Order Systellommatophora
Family Onchidiidae
Onchidella celtica (Audouin & Milne-Edwards, 1832) 29; **A**
Order Trochida
Family Phasianellidae
Tricolia pullus (Linnaeus, 1758) 10; **A**
Tricolia tenuis (Michaud, 1829) 36; **M**
Family Trochidae
Clanculus jussieui (Payraudeau, 1826) 36; **M**
Gibbula magus (Linnaeus, 1758) 33; **A**
Gibbula tingitana (Pallary, 1902) 7; **M**
Phorcus lineatus (da Costa, 1778) 29; **A**
Phorcus mutabilis (Philippi, 1851) 8; **A**
Phorcus sauciatus (Koch, 1845) 29, 33; **A**
Steromphala divaricata (Linnaeus, 1758) 8; **A**
Steromphala pennanti (Philippi, 1846) 10, 17, 23, 24, 26, 32, 35; **A**
Steromphala umbilicalis (da Costa, 1778) 6, 8, 17, 27, 29; **A**
Steromphala umbilicaris (Linnaeus, 1758) 7, 36; **M**

Order (Not assigned)
Family Acteonidae
Acteon tornatilis (Linnaeus, 1758) 3, 9, 13, 17; **AM**
Family Limapontiidae
Limapontia capitata (O. F. Müller, 1774) 1; **A**
Family Patellidae
Cymbula safiana (Lamarck, 1819) 29, 33; **A**
Patella cf caerulea (Linnaeus, 1758) 17; **A**
Patella depressa (Pennant, 1777) 29, 33; **A**
Patella rustica (Linnaeus, 1758) 29; **A**
Family Physidae
Physa fontinalis (Linnaeus, 1758) 9; **M**
Physella acuta (Draparnaud, 1805) 9; **M**
Family Plakobranchidae
Elysia cf translucens (Pruvot-Fol, 1957) 10; **A**
Class Polyplacophora
Order Chitonida
Family Chitonidae
Rhyssoplax olivacea (Spengler, 1797) 36 **M**
Family Lepidochitonidae
Lepidochitona cinerea (Linnaeus, 1767) 10, 29, 36; **AM**
Class Scaphopoda
Order Dentaliida
Family Dentaliidae
Antalis vulgaris (da Costa, 1778) 33; **A**
Dentalium sp (Linnaeus, 1758) 28; **M**
Phylum Arthropoda
Class Branchiopoda
Order Anostraca
Family Artemiidae
Artemia salina (Linnaeus, 1758) 2; **A**
Class Hexanauplia
Order Scalpelliformes
Family Pollicipedidae
Pollicipes pollicipes (Gmelin, 1790) 6; **A**
Order Sessilia
Family Balanidae
Amphibalanus amphitrite (Darwin, 1854) 6; **A**
Perforatus perforatus (Bruguière, 1789) 2, 6, 13, 17, 33; **A**
Family Chthamalidae
Chthamalus montagui (Southward, 1976) 11; **M**
Class Insecta
Order Diptera
Family Chironomidae
Chironomus salinarius (Kieffer, 1915) 1; **A**
Class Malacostraca
Order Amphipoda
Family Ampeliscidae
Ampelisca anophthalma (Bellan-Santini & Kaim-Malka, 1977) 36; **M**

Ampelisca brevicornis (Costa, 1853) 5; **A**
Ampelisca diadema (Costa, 1853) 5; **A**
Ampelisca gibba (Sars, 1883) 34; **A**
Ampelisca spinimana (Chevreux, 1900) 24; **A**
Ampelisca spinipes (Boeck, 1861) 5; **A**
Family Ampithoidae
Ampithoe ferox (Chevreux, 1901) 21, 26, 27, 34; **A**
Ampithoe ramondi (Audouin, 1826) 5, 10, 15, 33, 34; **AM**
Pleonexes helleri (Karaman, 1975) 7; **M**
Family Aoridae
Lembos websteri (Spence Bate, 1857) 21, 27, 33; **A**
Microdeutopus algicola (Della Valle, 1893) 10; **A**
Microdeutopus anomalus (Rathke, 1843) 27; **A**
Microdeutopus chelifer (Spence Bate, 1862) 10, 26, 34, 35; **A**
Microdeutopus gryllotalpa (Costa, 1853) 4; **M**
Microdeutopus versiculatus (Spence Bate, 1857) 27; **A**
Family Atylidae
Nototropis swammerdamei (H. Milne Edwards, 1830) 1; **A**
Family Bathyporeiidae
Bathyporeia cf nana (Toulmond, 1966) 19; **A**
Bathyporeia pilosa (Lindström, 1855) 1, 12, 18, 22; **A**
Family Calliopiidae
Apherusa jurinei (H. Milne Edwards, 1830) 10; **A**
Family Caprellidae
Caprella acanthifera (Leach, 1814) 33, 34, 36; **AM**
Caprella grandimana (Mayer, 1882) 34; **A**
Caprella scaura (Templeton, 1836) 36; **M**
Caprella takeuchii (Guerra-García, Sánchez-Moyano & García-Gómez, 2001) 34; **A**
Phtisica marina (Slabber, 1769) 36; **M**
Pseudolirius kroyeri (Haller, 1879) 36; **M**
Pseudoprotella phasma (Montagu, 1804) 28; **M**
Family Colomastigidae
Colomastix pusilla (Grube, 1861) 11; **M**
Family Corophiidae
Apocorophium acutum (Chevreux, 1908) 5, 7, 10; **AM**
Corophium orientale (Schellenberg, 1928) 3, 9, 10, 20; **AM**
Corophium volutator (Pallas, 1766) 1, 6, 17, 20, 26; **A**
Leptocheirus hirsutimanus (Spence Bate, 1862) 34; **A**
Leptocheirus pilosus (Zaddach, 1844) 3, 9, 19; **AM**
Monocorophium acherusicum (Costa, 1853) 1, 10, 15, 16, 18, 32, 35; **AM**
Monocorophium insidiosum (Crawford, 1937) 1, 4, 11, 21, 27; **AM**
Monocorophium sextonae (Crawford, 1937) 10; **A**
Family Dexaminidae
Dexamine spiniventris (Costa, 1853) 11; **M**
Dexamine spinosa (Montagu, 1813) 10, 11, 21, 28, 36; **AM**
Family Gammaridae
Gammarus aequicauda (Martynov, 1931) 11; **M**
Gammarus chevreuxi (Sexton, 1913) 3, 9; **M**
Gammarus insensibilis (Stock, 1966) 7, 10, 11, 32, 36; **AM**

Gammarus locusta (Linnaeus, 1758) 2, 28; **AM**
Gammarus pulex (Linnaeus, 1758) 9; **M**
Gammarus subtypicus (Stock, 1966) 10, 11; **AM**
Chaetogammarus sp (Martynov, 1924) 28; **M**

Family Haustoriidae

Haustorius algeriensis (Mulot, 1968) 28; **M**
Haustorius arenarius (Slabber, 1769) 1, 5, 6, 10, 12, 18, 20, 22; **A**

Family Hyalidae

Hyale sp (Rathke, 1837) 13; **A**
Protohyale (Protohyale) schmidtii (Heller, 1866) 11; **M**

Family Ischyroceridae

Centraloecetes dellavallei (Stebbing, 1899) 28; **M**
Ericthonius brasiliensis (Dana, 1853) 10, 36; **AM**
Ericthonius punctatus (Spence Bate, 1857) 7, 11, 34; **AM**
Ericthonius rubricornis (Stimpson, 1853) 36; **M**
Jassa ocia (Spence Bate, 1862) 10; **A**

Family Leucothoidae

Leucothoe incisa (Robertson, 1892) 5; **A**
Leucothoe richiardii (Lesson, 1865) 5, 34; **A**

Family Lysianassidae

Lysianassa caesarea (Ruffo, 1987) 33; **A**
Lysianassa ceratina (Walker, 1889) 5, 26, 27, 34; **A**

Family Maeridae

Elasmopus rapax (Costa, 1853) 11, 28, 34, 36; **AM**
Maera grossimana (Montagu, 1808) 11, 36; **M**

Family Melitidae

Melita palmata (Montagu, 1804) 7, 10, 12, 14, 15, 16, 18, 19, 20, 21, 23, 26, 27, 30, 32, 33, 34, 35; **AM**

Family Nuuanuidae

Gammarella fucicola (Leach, 1814) 26, 34, 36; **AM**

Family Oedicerotidae

Kroyera carinata (Spence Bate, 1857) 36; **M**
Pontocrates altamarinus (Spence Bate & Westwood, 1862) 5; **A**
Pontocrates arenarius (Spence Bate, 1858) 1, 10; **A**

Family Phliantidae

Pereionotus testudo (Montagu, 1808) 27; **A**

Family Photidae

Photis (Krøyer, 1842) 5; **A**

Family Phoxocephalidae

Metaphoxus simplex (Spence Bate, 1857) 33, 34; **A**

Family Pontogeneiidae

Eusiroides dellavallei (Chevreux, 1899) 28; **M**

Family Stenothoidae

Stenothoe monoculoides (Montagu, 1813) 11; **M**

Family Talitridae

Deshayesorchestia deshayesii (Audouin, 1826) 3, 9; **M**
Orchestia gammarellus (Pallas, 1766) 9, 15; **M**
Talitrus saltator (Montagu, 1808) 3, 6, 9, 15; **AM**

Family Urothoidae

Urothoe atlantica (Bellan-Santini & Menioui, 2004) 33 **A**

Urothoe elegans (Spence Bate, 1857) 34; **A**
Urothoe grimaldii (Chevreux, 1895) 1, 10, 12, 14, 18, 19, 22, 35; **A**
Urothoe poseidonis (Reibish, 1905) 19; **A**
Urothoe pulchella (Costa, 1853) 16, 36; **M**

Order Cumacea

Family Bodotriidae

Cumopsis fagei (Băcescu, 1956) 1; **A**
Cumopsis goodsir (Van Beneden, 1861) 1; **A**
Iphinoe serrata (Norman, 1867) 21, 26, 34, 36; **AM**
Iphinoe trispinosa (Goodsir, 1843) 21, 34; **A**

Order Decapoda

Family Alpheidae

Alpheus glaber (Olivi, 1792) 36; **M**
Athanas nitescens (Leach, 1813) 27, 30, 34, 36; **AM**

Family Atelecyclidae

Atelecyclus rotundatus (Olivi, 1792) 15, 17; **A**

Family Callianassidae

Gilvossius tyrrhenus (Petagna, 1792) 1; **A**

Family Carcinidae

Carcinus maenas (Linnaeus, 1758) 1, 2, 6, 8, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 28, 30, 32, 33, 34, 35, 36; **AM**
Sirpus zariquieyi (Gordon, 1953) 10, 13, 17, 19, 36; **AM**

Family Crangonidae

Crangon crangon (Linnaeus, 1758) 1, 11, 15, 19, 23, 33; **A**

Family Diogenidae

Clibanarius erythropus (Latreille, 1818) 10, 32, 34, 35; **A**
Diogenes pugilator (Roux, 1829) 1; **A**

Family Epialtidae

Pisa sp (Leach, 1814) 10; **A**

Family Eriphiidae

Eriphia verrucosa (Forskål, 1775) 17; **A**

Family Galatheidae

Galathea sp (Fabricius, 1793) 36; **M**

Family Grapsidae

Pachygrapsus marmoratus (Fabricius, 1787) 2, 4, 6, 7, 11, 13, 17; **AM**
Pachygrapsus transversus (Gibbes, 1850) 17; **A**

Family Hippolytidae

Hippolyte leptocerus (Heller, 1863) 10; **A**

Family Inachidae

Achaeus cranchii (Leach, 1817) 10; **A**
Macropodia rostrata (Linnaeus, 1761) 10, 13, 17, 36; **AM**

Family Lysmatidae

Lysmata unicornis (Holthuis & Maurin, 1952) 2; **A**

Family Ocypodidae

Afruca tangeri (Eydoux, 1835) 1, 2, 6, 10, 17, 19, 20, 35; **A**

Family Paguridae

Pagurus bernhardus (Linnaeus, 1758) 2, 8; **A**

Family Palaemonidae

Palaemon cf adspersus (Rathke, 1837) 21; **A**
Palaemon elegans (Rathke, 1837) 4, 7, 17, 8, 12, 13, 15, 16, 17, 25, 32, 34, 35; **AM**

Palaemon longirostris (H. Milne Edwards, 1837) 10; **A**
Palaemon serratus (Pennant, 1777) 2, 10, 25, 32; **A**
Palaemon varians (Leach, 1813); 3, 9, 10, 23; **AM**
Family Panopeidae
Panopeus africanus (A. Milne-Edwards, 1867) 1; **A**
Family Penaeidae
Penaeus kerathurus (Forskål, 1775) 10, 36; **AM**
Family Pinnotheridae
Pinnotheres pisum (Linnaeus, 1767) 10, 17, 32; **A**
Family Polybiidae
Liocarcinus depurator (Linnaeus, 1758) 10; **A**
Liocarcinus navigator (Herbst, 1794) 36; **M**
Liocarcinus pusillus (Leach, 1816) 28; **A**
Family Porcellanidae
Porcellana platycheles (Pennant, 1777) 14, 17; **A**
Family Processidae
Processa canaliculata (Leach, 1815) 14, 17; **A**
Family Upogebiidae
Upogebia pusilla (Petagna, 1792) 1, 2, 10, 13, 14, 17, 19, 20, 25, 26, 32, 34, 35; **A**
Family Varunidae
Brachynotus foresti (Zariquiey Álvarez, 1968) 36; **M**
Brachynotus sexdentatus (Risso, 1827 in [Risso, 1826-1827]) 14, 17; **A**
Family Xanthidae
Lophozozymus incisus (H. Milne Edwards, 1834) 27; **A**
Xantho poressa (Olivi, 1792) 36; **M**
Order Isopoda
Family Anthuridae
Cyathura carinata (Krøyer, 1847) 1, 2, 3, 9, 10, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22 ,23, 24, 25, 26, 27, 30, 32, 33, 34, 35; **AM**
Family Arcturidae
Astacilla longicornis (Sowerby, 1806) 21; **A**
Family Chaetiliidae
Parachiridotea panousei (Daguerre de Hureaux & Elkaïm, 1972) 1, 10, 12, 14, 18, 35; **A**
Family Cirolanidae
Cirolana cf cranchii (Leach, 1818) 34; **A**
Eurydice dollfusi (Monod, 1930) 1; **A**
Eurydice pulchra (Leach, 1815) 1, 5, 10, 12, 14, 18, 19, 20, 22, 24, 27; **A**
Eurydice spinigera (Hansen, 1890) 20; **A**
Family Cylisticidae
Cylisticus convexus (De Geer, 1778) 15; **M**
Family Gnathiidae
Paragnathia formica (Hesse, 1864) 23; **A**
Family Idoteidae
Idotea balthica (Pallas, 1772) 11, 17, 36; **AM**
Idotea chelipes (Pallas, 1766) 2, 6, 10, 19, 21, 23, 25, 26, 27, 32, 34, 35; **A**
Idotea emarginata (Fabricius, 1793) 10; **A**
Idotea pelagica (Leach, 1816) 33; **A**
Synischia hectica (Pallas, 1772) 7; **M**
Family Sphaeromatidae
Cymodoce emarginata (Leach, 1818) 11; **M**

Cymodoce spinosa (Risso, 1816) 11; **M**
Cymodoce truncata (Leach, 1814) 11, 36; **M**
Dynamene bidentata (Adams, 1800) 15, 24; **AM**
Dynamene edwardsi (Lucas, 1849) 11, 34; **AM**
Lekanesphaera bocqueti (Daguerre de Hureaux, Hoestlandt & Lejuez, 1961) 10; **A**
Lekanesphaera hoestlandti (Daguerre de Hureaux, Elkaim & Lejuez, 1965) 1; **A**
Lekanesphaera hookeri (Leach, 1814) 2, 3, 9, 10, 15, 16; **AM**
Lekanesphaera levii (Argano & Ponticelli, 1981) 21, 26, 34; **A**
Lekanesphaera rugicauda (Leach, 1814) 10, 30, 32, 34, 35; **A**
Lekanesphaera weilli (Elkaïm, 1967) 1; **A**
Paracerceis sculpta (Holmes, 1904) 36; **M**
Sphaeroma serratum (J. C. Fabricius, 1787) 11, 32; **AM**
Order Leptostraca
Family Nebaliidae
Nebalia bipes (Fabricius, 1780) 15, 26, 36; **AM**
Order Mysida
Family Mysidae
Gastrosaccus sanctus (Van Beneden, 1861) 19; **A**
Gastrosaccus spinifer (Goës, 1864) 1, 10, 14, 20; **A**
Mesopodopsis slabberi (Van Beneden, 1861) 10; **A**
Mysis sp (Latreille, 1802) 15; **M**
Paramysis sp (Czerniavsky, 1882) 10; **A**
Order Tanaidacea
Family Apseudidae
Apseudes talpa (Montagu, 1808) 21; **A**
Apseudopsis latreillii (Milne Edwards, 1828) 34, 36; **AM**
Family Leptocheliidae
Chondrochelia savignyi (Kroyer, 1842) 11, 33, 34, 36; **AM**
Family Tanaididae
Parasinelobus chevreuxi (Dollfus, 1898) 11; **M**
Tanais dulongii (Audouin, 1826) 3, 9, 10, 11, 26, 27, 34, 35; **AM**
Class Pycnogonida
Order Pantopoda
Family Phoxichilidiidae
Anoplodactylus cf. pygmaeus (Hodge, 1864) 10; **A**
Phylum Echinodermata
Class Asteroidea
Order Valvatida
Family Asterinidae
Asterina gibbosa (Pennant, 1777) 28, 36; **M**
Class Echinoidea
Order Camarodonta
Family Parechinidae
Paracentrotus lividus (Lamarck, 1816) 4, 8, 10, 13, 15, 17, 23, 26, 34, 36; **AM**
Order Clypeasteroida
Family Rotulidae
Heliophora orbiculus (Linnaeus, 1758) 33; **A**

Order Spatangoida

Family Loveniidae

Echinocardium cordatum (Pennant, 1777) 1; **A**

Class Holothuroidea

Order Dendrochirotida

Family Cucumariidae

Ocnus planci (Brandt, 1835) 4; **M**

Order Holothuriida

Family Holothuriidae

Holothuria (Roweothuria) poli (Delle Chiaje, 1824) 4, 8; **AM**

Class Ophiuroidea

Order Amphilepidida

Family Amphiuridae

Amphipholis squamata (Delle Chiaje, 1828) 15, 26; **AM**

Family Ophiotrichidae

Ophiothrix fragilis (Abildgaard in O.F. Müller, 1789) 7; **M**

Phylum Chordata

Class Actinopterygii

Order Anguilliformes

Family Anguillidae

Anguilla anguilla (Linnaeus, 1758) 10, 32; **A**

Order Lophiiformes

Family Lophiidae

Lophius budegassa (Spinola, 1807) 11; **A**

Order Perciformes

Family Blenniidae

Lipophrys pholis (Linnaeus, 1758) 7; **M**

Family Gobiidae

Gobius niger (Linnaeus, 1758) 7; **M**

Gobius paganellus (Linnaeus, 1758) 7; **M**

Lesueurigobius sanzi (de Buen, 1918) 7; **M**

Pomatoschistus microps (Krøyer, 1838) 10, 14, 32; **A**

Family Mullidae

Mullus surmuletus (Linnaeus, 1758) 7; **M**

Family Sparidae

Lithognathus mormyrus (Linnaeus, 1758) 7; **M**

Family Trachinidae

Echiichthys vipera (Cuvier, 1829) 10; **A**

Order Pleuronectiformes

Family Soleidae

Solea senegalensis (Kaup, 1858) 10; **A**

Solea solea (Linnaeus, 1758) 7; **M**

Order Syngnathiformes

Family Syngnathidae

Hippocampus hippocampus (Linnaeus, 1758) 10; **A**

Syngnathus acus (Linnaeus, 1758) 15; **M**

Syngnathus phlegon (Risso, 1827) 7; **M**

DOCTORAT BRETAGNE LOIRE / SCIENCES DE LA MER ET DU LITTORAL

UNIVERSITÉ DE NANTES

Titre : **Les écosystèmes benthiques des lagunes marocaines : biodiversité et fonctionnement dans le cadre des changements globaux actuels.**

Mots clés : Systèmes côtiers semi-fermés, Macrofaune benthique, Checklist, Lagune de Moulay Bousselham, Variation temporelle, Maroc.

Résumé : La macrofaune benthique constitue une composante fondamentale des écosystèmes côtiers et marins. Ce travail avait pour objectif premier de synthétiser les connaissances sur cette composante biologique dans les systèmes côtiers semi-fermés (SCSF : lagunes, estuaires et baies) du Maroc et ensuite de se focaliser sur la lagune de Moulay Bousselham, à travers un échantillonnage spatial et saisonnier sur toute l'étendue de la lagune, pour une meilleure compréhension de son fonctionnement.

Au total 496 taxons y ont été recensés dans les 12 SCSF (6 lagunes, 5 estuaires et 1 baie) analysés aussi bien sur la côte méditerranéenne et atlantique du Maroc. La richesse spécifique et la diversité taxonomique ne montrent pas de gradients latitudinaux et les assemblages benthiques semblent être contrôlés par le type de SCSF (estuaires vs lagunes vs baie), l'écorégion marine (Atlantique vs Méditerranée), la surface du SCSF et ses caractéristiques environnementales (température minimale, salinité minimale et maximale).

Dans la lagune de Moulay Bousselham, les assemblages benthiques sont relativement bien diversifiés et abondants. Les paramètres hydrologiques, sédimentaires ainsi que la présence ou l'absence d'herbiers sont les facteurs qui régissent la structure et la répartition spatiale de la macrofaune benthique. D'un autre côté, l'analyse de la dynamique saisonnière a révélé, qu'à part la température, la salinité de l'eau et la biomasse des espèces, les autres variables environnementales et les paramètres de diversité et de structure de peuplements ne présentent aucune variation saisonnière entre l'hiver et l'été.

En définitif, nos résultats ont permis d'établir des états de référence pour les SCSF des côtes marocaines et en particulier pour la lagune de Moulay Bousselham. Ils serviront de base pour toute étude future visant l'appréciation de l'évolution et de la trajectoire de réponse de ces écosystèmes face aux changements globaux y compris le changement climatique.

Title: **Benthic ecosystems of Moroccan lagoons: Biodiversity and functioning in the light of current global changes.**

Keywords: Semi enclosed coastal systems, Benthic macrofauna, Checklist, Moulay Bousselham lagoon, Temporal variation, Morocco.

Abstract: The benthic macrofauna is a fundamental component of coastal and marine ecosystems. The first objective of this work was to synthesize the knowledge on this biological component in the semi-enclosed coastal systems (SECS: lagoons, estuaries and bays) of Morocco and then to focus on the Moulay Bousselham lagoon, through a spatial and seasonal sampling over the entire lagoon, for a better understanding of its functioning.

A total of 496 taxa were recorded in the 12 SECS (6 lagoons, 5 estuaries and 1 bay) analyzed on both the Mediterranean and Atlantic coasts of Morocco. Species richness and taxonomic diversity do not show latitudinal gradients and benthic assemblages seem to be controlled by the type of SECS (estuaries vs. lagoons vs. bay), the marine ecoregion (Atlantic vs. Mediterranean), the surface of the SECS and its environmental characteristics (minimum temperature, minimum and maximum salinity).

In the Moulay Bousselham lagoon, the benthic assemblages are relatively well diversified and abundant. Hydrological and sedimentary parameters, as well as the presence or absence of seagrass beds, are the factors that drive the structure and spatial distribution of the benthic macrofauna. On the other hand, the analysis of seasonal dynamics revealed that, apart from temperature, water salinity and species biomass, the other environmental variables and the parameters of diversity and structure of the populations do not present any seasonal variation between winter and summer.

Finally, our results have allowed us to establish reference conditions for the SECSs of the Moroccan coasts and in particular for the Moulay Bousselham lagoon. They will serve as a basis for any future study aimed at assessing the evolution and response trajectory of these ecosystems in the face of global changes, including climate change.