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Ali Badreddine

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THÈSE DE DOCTORAT

Les écosystèmes côtiers du littoral libanais:
état écologique, conservation, évolution

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Laboratoire : ECOMERS

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Les écosystèmes côtiers du littoral libanais: état écologique, conservation, évolution

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Titre : Les écosystèmes côtiers du littoral libanais: état écologique, conservation, évolution

Résumé

Dans le monde entier, les écosystèmes côtiers marins souffrent l'effet des impacts humains, déjà bien établis et en voie d'augmentation. Les écosystèmes côtiers du bassin Levantin (sud-est de la Méditerranée) sont soumis à une transformation côtière dramatique due à une interaction complexe entre les impacts locaux et globaux. Le but de la recherche présentée dans cette thèse est de mieux connaître les effets des activités anthropiques sur l'état de conservation des habitats côtiers importants (forêts de *Cystoseira* et trottoirs à Vermets) dans une région relativement peu connue de la Méditerranée: la côte Libanaise. Plusieurs approches ont été appliquées pour la première fois le long de la côte Levantine, comme l'indice CARLIT (cartographie des communautés benthiques du littoral rocheux), un outil conçu pour évaluer l'Etat Ecologique (EE) dans le cadre de la Directive des Eaux (DCE 2000/60/UE). La corrélation entre l'état de conservation des écosystèmes côtiers avec la pression humaine a également été réalisée. Une description générale du littoral Libanais, résumant les principales caractéristiques environnementales et les activités anthropiques influençant les communautés benthiques, a souligné que le Liban a été (et est actuellement) soumis à plusieurs pressions de plusieurs origines. La prise en conscience que ces pressions ne cessent d'augmenter et la nécessité d'intégrer des programmes de gestion des zones côtières dans les projets futurs, est généralement reconnue par les spécialistes marins Libanais. L'application de l'indice CARLIT, basé sur les communautés de macroalgues et conçu dans le contexte de la DCE (2000/60/UE), a fourni des idées importantes sur l'EE actuel de la côte rocheuse Libanaise en relation avec les impacts humains. En outre, elle a permis d'établir une cartographie détaillée de la répartition et de l'abondance des communautés côtières, et en particulier des grandes forêts d'algues brunes (par exemple les forêts de *Cystoseira* et de *Sargassum*). Cette cartographie détaillée représente la première évaluation de leur distribution, fournissant un outil important pour la conservation de ces habitats biotiques importants des côtes rocheuses. L'étude de certains trottoirs à Vermets Libanais a permis de fournir des informations précises sur leur état actuel (à savoir leur présence ou leur érosion) en fonction des différentes pressions humaines. Cette étude a mis en évidence que les trottoirs à Vermets Libanais sont hautement affectés par les impacts humains et que peu d'entre eux sont encore vivants, comme cela a déjà été observé dans d'autres zones du bassin Levantin. Dans une perspective futur en relation avec la découverte de pétrole et du gaz dans les eaux Libanaises, les écosystèmes marins Libanais seront soumis à plusieurs menaces; les données fournies dans les recherches effectuées dans cette thèse présentent une base de référence de la distribution et de l'état de conservation des habitats côtiers importants présents sur les côtes Libanaises et ceci permettant de suivre leur évolution et présentant un outil de gestion (connaissance de leur répartition) en cas de la fuite de pétrole accidentelle et catastrophique. Une surveillance continue et à long terme devrait être mis en place pour leur conservation; l'indice CARLIT appliqué dans cette thèse s'est avéré être un outil intéressant et efficace, conforme aux directives européennes (à savoir la DCE 2000/60/UE), pour réaliser un tel suivi sur l'ensemble du bassin Levantin.

Mots clés : Etat Ecologique, Directive des Eaux, Macroalgues, *Cystoseira*, trottoirs à Vermets, CARLIT, bassin Levantin, côte Libanaise.

Title : Coastal ecosystems of the Lebanese coast: ecological status, conservation, evolution

Abstract

Marine coastal ecosystems worldwide are suffering from well established and growing pressures by human activities. Coastal ecosystems of the Levantine basin (south-eastern Mediterranean Sea) are experiencing a dramatic coastal transformation due to a complex interaction of local and global impacts.

The aim of the research presented in this thesis was to provide further knowledge of the effects of anthropogenic disturbance on the conservation status of important shallow habitats (vermetid reefs, *Cystoseira* forests) in a relatively poorly known region of the Mediterranean Sea: the Lebanese coast. Multiple approaches were applied for the first time along the Levantine Sea, such as the CARLIT (CARtography of rocky-shore LITtoral communities) index, a tool conceived to quantify the Ecological Status (ES) in the framework of the Water Framework Directive (WFD 2000/60/EU). The correlation of the conservation status of shallow ecosystems with human pressure was also performed. A general description of the Lebanese coastline, summarizing the major environmental features and anthropogenic activities influencing benthic communities, highlighted that Lebanon has been (and is at present) subject to multiple stressors. The awareness of this phenomenon is increasing and the need of integrating coastal zone management program in future actions is generally recognized in Lebanese marine stakeholders. The application of the CARLIT index, based on macroalgal assemblages and conceived in the context of WFD (2000/60/EU), gives important insights on the ES of Lebanese ecosystems in relation to human impacts. Furthermore it provides a detailed cartography on the distribution and abundance of shallow communities, and in particular large brown seaweeds forests (e.g. *Cystoseira* and *Sargassum* forests). Such detailed cartography represents the first assessment of their distribution, providing an important tool for the conservation of these key biotic habitats in shallow rocky coasts. The survey of some Lebanese vermetid reefs allowed the collection of accurate information on their current status (i.e. presence of bioconstruction or erosion) according to different human pressures. This study highlighted that Lebanese vermetid reefs are highly affected by human impacts and only few of them are still alive, as already observed in other areas in the Levantine basin. In a view of the upcoming oil and gas discovery offshore Lebanon, Lebanese marine ecosystems are under multiple and massive threats; the data provided in the research performed provide a baseline of the distribution and conservation status of key habitats along Lebanese coasts, in order to follow their evolution and to have a management tool (knowledge of their distribution) in case of catastrophic oil spills. A continuous long-term monitoring should be implemented for their conservation; the CARLIT index applied in this thesis proved to be an interesting and efficient tool, compliant with European Directives (i.e. WFD 2000/60/EU), to perform such a monitoring on the entire Levantine Sea.

Keywords : Ecological Status, Water Framework Directive, Macroalgae, *Cystoseira*, vermetid reefs, CARLIT, Levantine Sea, Lebanese coast.

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Chapter 1 – General introduction

1.1 - Overview

Marine coastal ecosystems worldwide are suffering severe impacts due to a complex of human and natural pressures and recent estimations suggest the possibility of a further dramatic increase for the next decades (Barange et al., 2010; Gattuso et al., 2015; Halpern et al., 2015). Habitat destruction, pollution, eutrophication, biological invasions and overfishing, generally acting at the local/regional scale, often act synergistically also interacting with climate change (Boudouresque et al., 2017; Lejeune et al., 2010; Mannino et al., 2017). They affect species, ecosystems, their functions and ability to provide services (Betti et al., 2017; Halpern et al., 2008; Worm et al., 2006). The Mediterranean Sea is a biodiversity hotspot, hosting up to 18% of the global total of macroscopic species (in less than 1% of the global ocean surface), with 25% to 30% of them considered endemic (Coll et al., 2010). However, the Mediterranean Sea is highly affected by historical impacts: several Mediterranean resources are considered exploited since the fifth century BC (Coll et al., 2012). As a result of interacting and historically rooted impacts, important Mediterranean ecosystems such as *Lithophyllum byssoides* rims (Blanfuné et al., 2016b), shallow vermetid reefs (Milazzo et al., 2017), *Posidonia oceanica* seagrass meadow (Astruch et al., 2017), *Cystoseira* forests (Airoldi et al., 2014; Thibaut et al., 2005) and coralligenous assemblages (Ferrigno et al., 2017; Piazzini et al., 2017) are heavily affected, and their local loss has been described along many areas. The Levantine Sea, the easternmost region of the Mediterranean, hosts a variety of ecosystems such as vermetid reefs and *Cystoseira* forests. However, Lebanese marine ecosystems, as the entire Levantine Sea, are experiencing a dramatic and fast coastal transformation, due to the high impact of anthropogenic activities such as coastal development (MOE/UNDP/ECODIT, 2011), fishery (Lteif, 2015), pollution (Abboud-Abi Saab et al., 2008b) and ocean warming (Abboud-Abi Saab et al., 2004; 2013; Sternberg et al., 2015), often associated with a continuous income of invasive species from the Suez Canal (Bitar et al., 2017; Crocetta et al., 2013; Harmelin et al., 2016; Ramos-Esplá et al., 2014; Rilov and Galil, 2009a). The urgency to find indicators and set up efficient indices to assess ecological quality and prevent further deterioration is now recognized by scientists, decision maker and managers. However, a detailed knowledge of communities response to anthropogenic impacts is

still largely lacking, even if it is essential for the conception of such tools. The object of this PhD is therefore to better understand the processes affected by human impacts and their direct or indirect consequences on the conservation status of important habitats (vermetid reefs, *Cystoseira* forests) and to implement Ecological Status (ES) indexes to better manage and preserve Lebanese ecosystems.

1.2 - Management tools for coastal ecosystems protection and conservation

The distribution of habitats along rocky sea shores has been extensively studied (Birk et al., 2012; Díez et al., 2012) and, even if it far from being exhaustive and resolution is often progress, it represents one of the tools that nowadays political, scientific and managing stakeholders can apply for ecosystem management. As regards, the need of conservation and reasoned management of the ecosystems has led to the implementation of several laws worldwide (Hering et al., 2010; Katsanevakis et al., 2011). Some examples are the Directive for the management of bathing water quality (2006/7/EC), the Habitat Directive, Water Framework Directive (WFD, 2000/60/EU) and Marine Strategy Framework Directive (MSFD) in Europe the Clean Water Act (CWA) and the Oceans Acts in US, Australia and Canada; or the National Water Act in South Africa, as an example. In particular, in Europe, the WFD (2000/60/EC) and the MSFD (2008/56/EC) defined a roadmap that aims to the achievement and maintaining of a Good Environmental Status (GENS) of the European seas by 2020. Both these regulations recognize that biomonitoring by means of marine communities is the preferred way to evaluate the ES and therefore detect human impacts effects (Borja et al., 2012; Duarte et al., 2016; Martínez-Crego et al., 2010; Pedel and Fabri, 2012; Van Hoey et al., 2010). In the Mediterranean Sea, several indices based on the four Biological Quality Elements selected (BQEs: phytoplankton (Ninčević-Gladan et al., 2015), macroalgae (Ballesteros et al., 2007; Cecchi et al., 2014; Neto et al., 2012; Orfanidis et al., 2001), seagrasses (Montefalcone, 2009; Personnic et al., 2014) and macroinvertebrates (Cánovas-Molina et al., 2016; Piazzini et al., 2017)) have been developed for the evaluation of the ES of marine coastal waters. However, European Directives being mandatory only in European Union (EU) member states, they are rarely applied in non-EU countries. To test the applicability of existing indexes along non-EU countries coastlines, large scale assessments of marine assemblages should be performed, in order to assess the ES and provide baselines for future management (reaching and maintaining a good ES).

1.2.1 - Searching for suitable indicators

Several methods or indexes based on macroalgae assemblages have already been developed to assess the ES of rocky shores (Gall et al., 2016; Gaspar et al., 2012). Macroalgal communities responses to human impacts consists in the loss of species, generally associated to the decrease in diversity and structure of the communities, due to the loss of large perennial species that are replaced by opportunistic ones (Airoldi et al., 2014; Arévalo et al., 2007; Balata et al., 2011; Mangialajo et al., 2008; Orlando-Bonaca and Rotter, 2018; Pinedo et al., 2013; Strain et al., 2014). There are several quality indices using macroalgae communities (Ballesteros et al., 2007; Neto et al., 2012; Orlando-Bonaca et al., 2008; see chapter 3 for more details), that have been intercalibrated by the Geographical Intercalibration groups set up for every basin in the framework of the implementation of the WFD (2000/60/EU). Most of these indexes are basin specific, due to different environmental characteristics and communities composition. Every new index, or the application of an existing index in a new basin, exige an adaptation and the intercalibration of other indexes of the same BQE. Therefore, beyond a detailed knowledge of the community, it is essential to test cost-effective indicators that allow an efficient management of the coastal areas. Consequently, it is necessary to study in detail these communities in order to find common responses, which are essential to establish adequate environmental risk management. The fact that the Lebanese coastline is mostly characterized by rocky shores is making the indexes based on macroalgal communities very adequate for the assessment of the ES. Moreover, their role as ecological indicators is widely accepted due to their long lives, easy sampling, and to the existence of extensive literature on their distribution in specific environments and on their response to different environmental stresses.

1.2.1.a - Marine forests of large brown seaweeds as one of the most relevant “ecosystem-engineers” in the Mediterranean Sea

Along rocky shores of temperate and subtropical areas, large canopy-forming brown algae, in particular kelps (Laminariales, Phaeophyceae, Ochrophyta) and fucoids (Fucales, Phaeophyceae, Ochrophyta), are the dominant species in pristine environments (Schiel and Foster, 2015). These large perennial macroalgae are considered as “engineer species” (Jones et al., 1994), because their three-dimensional structure dramatically alters the physical, chemical and biological environment. These forests provide shelter, food, habitat and nurseries for a multiplicity of species (Ballesteros, 1989; Bologna and Steneck, 1993; Cheminée et al., 2013; Mangialajo et al.,

2012), as much as ecosystem functions and services (Bustamante et al., 1995; Mann, 1973; Salomidi et al., 2012). The decline of kelps (Connell and Russell, 2010; Franco et al., 2015; Raybaud et al., 2013; Smale et al., 2013; Vergés et al., 2016; Wernberg et al., 2011) and fucoids (Airoldi et al., 2014; Thibaut et al., 2005) is a global phenomenon due, directly or indirectly, to human-mediated activities. Such patterns are less clear for kelps (Krumhansl et al., 2016) but evident concerning fucoids, in particular in the Mediterranean Sea, where the two genera *Cystoseira* (30 species mostly endemic of the Mediterranean Sea) and *Sargassum* are the principal groups forming large brown algae forest (Aouissi et al., 2018; Cheminée et al., 2013; Draisma et al., 2010; Gianni et al., 2013; Robvieux, 2013; Sales and Ballesteros, 2011; Thibaut et al., 2016). Some kelp (*Laminaria*) species are also present, thriving in deep habitats (Schiel and Foster, 2015; Steneck et al., 2002; Teagle et al., 2017). In the Mediterranean Sea, regional and local extinctions have been recorded (Bouma et al., 2014; Krumhansl et al., 2016). The loss of these well-structured and diverse ecosystems is a well-known regime shift (Assis et al., 2017; Blamey et al., 2010; Gatti et al., 2017; Ling et al., 2015; Orlando-Bonaca and Rotter, 2018; Thibaut et al., 2017; Vergés and al., 2014) where resulting assemblages are less complex, being mostly dominated by articulated coralline and/or filamentous algal turfs, ephemeral seaweed assemblages and barren grounds dominated by encrusting algae and sea urchins (Asnaghi et al., 2013; Gianni, 2016; Mangialajo et al., 2008; Thibaut et al., 2017). The genus *Cystoseira* C. Agardh (Fucales, Phaeophyta) is distributed in temperate and subtropical coasts around the world. Species belonging to the *Cystoseira* genus are the main habitat-forming macroalgae in the Mediterranean Sea, with 80% of the species that are endemic of this basin, and thrive from the littoral to the lower limit of the euphotic zone (Gianni et al., 2013). Losses of *Cystoseira* forests have been reported all around the Mediterranean Sea and attributed to habitat destruction (Airoldi et al., 2014), urbanization (Mancuso et al., 2017; Mangialajo et al., 2008), eutrophication (Iveša et al., 2016) and overgrazing by herbivores (Guidetti et al., 2003; Vergés et al., 2009). Due to their high sensitivity to human impacts, several species of *Cystoseira* are considered indicator of high quality waters and this characteristic allowed the conception of an index widely applied within the implementation of the EU (WFD, 2000/06/EC). From a conservation point of view, all the Mediterranean species of the genus *Cystoseira*, except *C. compressa*, have been protected under the Annex II of the Barcelona Convention (2010). Five species, *C. amentacea*, *C. mediterranea*, *C. sedoides*, *C. spinosa* and *C. zosteroids*, are protected

under the Berne Convention (Annex I, 1979). Unluckily, when compiling the annexes of the Habitat Directive, marine habitats have been largely neglected and no *Cystoseira* forests are included. Nevertheless, all Mediterranean *Cystoseira* species are under the surveillance of international organizations, such as IUCN, RAC/SPA and MedPan. Most of *Cystoseira*, for their “habitat-forming” role are therefore considered EU habitats of interest (Micheli et al., 2013). Large brown algae forest (mostly *Cystoseira* species) also thrive in the Levantine Sea, including the Lebanese coast. Interestingly, one of the 41 *Cystoseira* species (and varieties), *C. rayssiae* is endemic to the Levantine Sea (Ramon, 2000). *Cystoseira* forests of the Levantine sea, as most *Cystoseira* forests of the Mediterranean Sea are under multiple and massive human pressures, but little is known about their distribution, ecology, health status and evolution (Bellan-Santini et al., 2015; Bianchi et al., 2014; Guy Haim, 2017; Rilov et al., 2017b). Therefore, more effort should be put in research, to increase the knowledge on algal forests in the Levantine Sea with the aim of conceiving new rules and tools that may be applied to reduce the loss and enhance the resilience of these systems, eventually considering ecological restoration, taking into account that conservation (and monitoring) of existing *Cystoseira* forests should always be the priority (Gianni et al., 2013).

1.2.1.b - Vermetid reefs of the Mediterranean Sea: a neglected marine ecosystems and an indicator of coastal change

Vermetid reefs are bioconstructions created by the gastropod mollusks belonging to *Dendropoma* (and related genera) in association with another vermetid, *Vermetus triquetrus* (Bivona-Bernardi, 1832) and the crustose coralline algae *Neogoniolithon brassica-florida* Harvey (Setchell & L.R.Mason 1943; Chemello and Silenzi, 2011; Milazzo et al., 2017). They are typically found in subtropical warm marine waters (e.g. Hawaii (Hadfield et al., 1972), Red Sea (Kappner et al., 2000), Northern Chile (Pacheco and Laudien, 2008) and Southern Caribbean (Miloslavich et al., 2010). In the Mediterranean basin, vermetid reefs are commonly distributed along the warm-water coasts of the southern part and their largest bioconstructions can be found along the Levantine Sea (Milazzo et al., 2017), including the Lebanese coast (see chapter 4 for more details). Vermetid reefs are bioconstructions due to gregarious habit and massive settlement on the rocky shore. They are structurally comparable with tropical coral reefs and Mediterranean coralligenous habitats, creating a three-dimensional zone in the area between the

midlittoral and the infralittoral (Colombo et al., 2013; Milazzo et al., 2017; Paoli et al., 2017). Vermetid reefs are one of the most important coastal ecosystems of the Mediterranean Sea for their distribution and guarantee many ecological services (e.g. productivity and biodiversity, refuges, nursery areas) (Milazzo et al., 2017). They are also used as paleobathymetric markers (Antonioli et al., 1999; Vescogni et al., 2008) and as potential bioindicators of global changes (Fevret and Sanlaville, 1966; Sisma-Ventura et al., 2009), particularly of rising sea-level (Fevret and Sanlaville, 1966; Laborel, 1987; Sanlaville et al., 1997; Schiaparelli et al., 2006) and of surface seawater temperature changes (Silenzi et al., 2004). From a conservation point of view, despite their ecological importance, vermetid reefs are not explicitly taken into account in international environmental laws (Abdulla et al., 2009), although they can be included in the European Habitat Directive (92/43/EEC) protects the biogenic reefs (code 1170). Due to several global and local human impacts, the environmental conditions may not anymore adequate for the development of *Dendropoma* spp., with a consequence death of the reef that is rapidly eroded. The death and erosion of vermetid reefs are presently observed in several area of the Mediterranean Sea, and in particular along the Levantine coast (Milazzo et al., 2017; Rilov, 2016). In this context, a thorough survey of vermetid reefs along the entire Mediterranean, and specifically the Levantine Sea, should be a priority in research programs, for a better understanding of the causes of loss, and in management programs, in order to better preserve such threatened habitats.

1.3 - Objectives of the study

The coast of Lebanon has been progressively exploited and regulations are often not respected, resulting in important cumulated human impacts along the coast. The research performed in this PhD has several objectives concerning two threatened shallow habitats in the Eastern basin of the Mediterranean Sea, and in particular along the Lebanese coast (shallow large brown algae forests and vermetid reefs):

- fulfilling the scarcity of data on the distribution and assess a baseline for future monitoring of their evolution;
- assess their ecological quality, applying an index conceived for the WFD (2000/60/EU) and never applied in the Levant basin of the Mediterranean Sea;

- deduce their conservation state in relation to human impacts and their past evolution (whenever possible in relation to historical data);

In a global perspective, the research performed in this PhD aims also at giving tools for promoting the conservation of such important biogenic habitats, suggesting zones where a better management of the shoreline should be a priority (i.e. in the framework of risk associated to oil spills or the increasing human pressures).

Following the present general introduction, constituting **Chapter I**, the thesis is divided as follows:

Chapter II is dedicated to a general description of the studied area, the Lebanese coast. It summarizes important characteristics of the Lebanese coast, such as environmental features, marine biodiversity and main threats it is facing along with their causes and consequences. **The** assessment of the ES by the application of the CARLIT index, based on macroalgal assemblages and conceived in the context of the WFD (2000/60/EU), is presented **Chapter III**. This research, already published on the international journal *Ecological Indicators*, represents the first application of this index in the Eastern Mediterranean Sea, providing a detailed cartography of shallow large brown seaweeds forests (most of them are reported in the major conservation agreements and conventions of the Mediterranean Sea) in a relatively poorly known region of the Mediterranean, and gives important insights on the ES of coastal waters in relation to human impacts.

Chapter IV presents a study focused on the Lebanese vermetid reefs, and represent one of the few investigations on such important biogenic habitats largely found in the Southern Mediterranean and that reach their maximum development in the Levantine Sea. The principal aim was to assess the current status of vermetid reefs according to different human impacts along five sites distributed from the south to the north of the Lebanese coastline and deduce their past evolution where past data were present.

Finally, the general discussion, conclusion, and perspectives of this work are presented in the last chapter (**Chapter V**).

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Chapitre 1 – Introduction générale

1.1 - Vue générale

Dans le monde entier, les écosystèmes marins et côtiers souffrent les effets des impacts humains et naturels et des estimations récentes suggèrent une dégradation dramatique dans les prochaines années (Barange et al., 2010; Gattuso et al., 2015; Halpern et al., 2015). La destruction des habitats, la pollution, l'eutrophication, l'invasion biologique et la surpêche, agissent généralement à l'échelle locale/régionale, et/ou en synergie interagissant avec le changement climatique (Boudouresque et al., 2017; Lejeune et al., 2010; Mannino et al., 2017). Ils affectent les espèces marines, les fonctions des écosystèmes et leur habilité à fournir des services (Betti et al., 2017; Halpern et al., 2008; Worm et al., 2006).

La mer Méditerranée est un point chaud de la biodiversité marine, abritant plus de 18% de la totalité des espèces macroscopiques (dans moins de 1% de la surface de l'océan globale), dont 25% à 30% sont considérées comme espèces endémiques (Coll et al., 2010).

Cependant, la mer Méditerranée est hautement affectée par les impacts historiques: plusieurs ressources Méditerranéennes sont considérées comme exploitées depuis le V^{ème} siècle av. J.-C. (Coll et al., 2012). Comme résultats de l'interaction entre les impacts historiques, importants écosystèmes Méditerranéens tels que les encorbellements à *Lithophyllum byssoides* (Blanfuné et al., 2016), les trottoirs à Vermets (Milazzo et al., 2017), les herbiers de *Posidonia oceanica* (Astruch et al., 2017), les forêts de *Cystoseires* (Airoldi et al., 2014, Thibaut et al., 2005) et les assemblages à coralligènes (Ferrigno et al., 2017; Piazzzi et al., 2017) sont fortement menacés, et leur régression locale a été décrite dans plusieurs zones. La Mer Levantine, la région la plus orientale de la Méditerranée, regroupe une variété d'écosystèmes tels que les trottoirs à Vermets et les forêts de *Cystoseires*.

Cependant, les écosystèmes marins Libanais, comme ceux de la mer Levantine, connaissent une transformation côtière inquiétante et rapide, en raison de l'effet de l'impact des activités anthropiques telles que le développement côtier (MOE/UNDP/ECODIT, 2011), la pêche (Lteif, 2015), la pollution (Abboud-Abi Saab et al., 2008b), le réchauffement des océans (Abboud-Abi Saab et al., 2004; 2013; Sternberg et al., 2015), souvent associés avec l'introduction continue des espèces invasives via le canal de Suez (Bitar et al., 2017; Crocetta et al., 2013; Harmelin et al.,

2016; Ramos-Esplá et al., 2014; Rilov and Galil, 2009a). L'urgence de chercher des indicateurs et établir des indices efficaces permettant l'évaluation de la qualité écologique et de prévenir un danger futur est aujourd'hui reconnu par les scientifiques, les preneurs de décision et les gestionnaires. Cependant, la connaissance détaillée concernant la réponse des communautés face aux activités anthropiques est encore largement manquante, malgré qu'elle est essentielle pour le concept de ces outils. L'objectif de ce doctorat est donc de mieux comprendre les processus affectés par les impacts humains et leurs conséquences directes ou indirectes sur l'état de conservation des habitats importants (trottoir à Vermets, forêts de *Cystoseires*) et de mettre en place et appliquer des indices de l'Etat Ecologique (EE) afin de mieux évaluer et préserver les écosystèmes Libanais.

1.2 - Outils de gestion pour la protection et la conservation des écosystèmes côtiers

La répartition des habitats marins le long des côtes rocheuses a fait l'objet d'études approfondies (Birk et al., 2012; Díez et al., 2012), et, même s'il est loin d'être exhaustive et parfois résolue, elle représente un des outils actuels qui peut-être utilisé par les politiciens, scientifiques et gestionnaires pour la gestion des écosystèmes.

Dans ce contexte, le besoin de conservation et de gestion efficace des écosystèmes à contribuer à la mise en place de plusieurs lois dans le monde entier (Hering et al., 2010; Katsanevakis et al., 2011). Citons entre autres, la Directive pour la gestion de la qualité des eaux de baignade (2006/7/EC), la Directives des Habitats, la Directive des Cadres des Eaux (DCE, 2000/60/EU) et la Directive des Cadres des Stratégies Marines (DCSM) en Europe, l'Eau Propre (CWA) et les Actes sur l'Océan en USA, Australie et au Canada; et/ou l'Acte Nationale sur les Eaux en Afrique du Sud. En particulier, en Europe, la DCE (2000/60/EC) et la DCSM (2008/56/EC) ont défini un chemin qui a pour but l'achèvement et la maintenance d'un Bon Etat de l'Environnement (GEnS) des eaux Européennes jusqu'à 2020. Ces deux stratégies reconnaissent que la biosurveillance en utilisant les communautés marines est le chemin le plus efficace pour l'évaluation de l'EE et donc la détection de l'effet des impacts humains (Borja et al., 2012; Duarte et al., 2016; Martínez-Crego et al., 2010; Pedel and Fabri, 2012; Van Hoey et al., 2010). En Méditerranée, plusieurs indices basés sur les quatre Eléments Biologiques indicateurs de la Qualité (BQEs: phytoplanctons (Ninčević-Gladan et al., 2015), macroalgues (Ballesteros et al.,

2007; Cecchi et al., 2014; Neto et al., 2012; Orfanidis et al., 2001), herbiers (Montefalcone, 2009; Personnic et al., 2014) and macroinvertébrés (Cánovas-Molina et al., 2016; Piazzini et al., 2017)) ont été développés pour l'évaluation de l'EE des eaux marine côtières. Cependant, les Directives Européennes étant obligatoire que pour les membres de l'Union Européenne (UE), sont rarement appliquées dans les pays non-Européens. Afin de tester l'applicabilité et l'efficacité des indices existants le long des côtes des pays non-UE, des évaluations à grande échelle des communautés marines devraient être effectuées, afin d'évaluer les EE et fournir des bases de référence pour la gestion au futur (atteindre et maintenir un bon EE).

1.2.1 - A la recherche d'indicateurs appropriés

Plusieurs méthodes et indices basés sur les communautés de macroalgues ont été déjà développés afin d'évaluer l'EE des côtes rocheuses (Gall et al., 2016; Gaspar et al., 2012). La réponse des communautés de macroalgues aux impacts humains consistent en la perte des espèces, généralement associées à la diminution de la diversité et de la structure des communautés, due à la perte de grandes espèces pérennes qui sont remplacées par des espèces opportunistes (Airoldi et al., 2014; al., 2007, Balata et al., 2011, Mangialajo et al., 2008, Orlando-Bonaca et Rotter, 2018, Pinedo et al., 2013, Strain et al., 2014). Plusieurs indices de l'EE utilisent les communautés de macroalgues (Ballesteros et al., 2007; Neto et al., 2012; Orlando-Bonaca et al., 2008; see chapter 3 for more details), qui ont été intercalibrés par les groupes de la Géographie d'Intercalibration mis en place pour chaque bassin dans le cadre de la mise en œuvre de la WFD (2000/60/EU). La plupart de ces indices sont spécifiques à chaque bassin, en raison des différences au niveau des caractéristiques environnementales et de la composition des communautés. Chaque nouvel indice, ou l'application d'un indice déjà présent dans un nouveau bassin, nécessite une adaptation et une interaction avec d'autres indices du même BQE. Par conséquent, au-delà d'une connaissance détaillée des communautés, il est essentiel de tester l'efficacité des indicateurs pour la bonne gestion des zones côtières. Par conséquent, il est nécessaire d'étudier en détail ces communautés afin de trouver des réponses communes, qui sont essentielles pour établir une gestion adéquate des risques environnementaux. Le fait que la côte Libanaise soit principalement rocheuse rend les indices basés sur les communautés de macroalgues très adéquats pour l'évaluation des EE. De plus, leur rôle en tant qu'indicateurs écologiques est largement accepté en raison de leur persistance, de la facilité de leur collection et

de l'existence d'une abondante littérature sur leur distribution dans des environnements spécifiques et leur réponse aux différents stress environnementaux.

1.2.1.a - Les forêts marines de grandes algues brunes comme l'un des «ingénieurs de l'écosystème» les plus productifs de la mer Méditerranée

Les forêts marines des algues brunes, en particulier les kelp (Laminariales, Phaeophyceae, Ochrophyta) et les fucoïdes (Fucales, Phaeophyceae, Ochrophyta), sont les espèces dominantes des environnements propres (Schiel et Foster, 2015) des côtes rocheuses des zones tempérées et subtropicales. Ces grandes macroalgues pérennes sont considérées comme des «espèces ingénieurs» (Jones et al., 1994), car leur structure tridimensionnelle modifie de façon dramatique l'environnement physique, chimique et biologique. Ces forêts fournissent un refuge, un habitat et des nurseries pour une multitude d'espèces (Ballesteros, 1989, Bologne et Steneck, 1993, Cheminée et al., 2013, Mangialajo et al., 2012), ainsi que des fonctions et services pour l'écosystème (Bustamante et al., 1995, Mann, 1973, Salomidi et al., 2012). Le déclin des kelp (Connell et Russell, 2010, Franco et al., 2015, Raybaud et al., 2013, Smale et al., 2013, Vergés et al., 2016, Wernberg et al., 2011) et des fucoïdes (Airoldi et al., 2014; Thibaut et al., 2005) est un phénomène global dû, directement ou indirectement, à des activités à des activités humaines. Ces tendances sont moins claires pour les kelp (Krumhansl et al., 2016) mais évidentes pour les fucoïdes, en particulier en Méditerranée, où les deux genres *Cystoseira* (30 espèces essentiellement endémiques de la Méditerranée) et *Sargassum*, sont les principaux groupes formant des forêts marine d'algues brunes (Aouissi et al., 2018, Cheminée et al., 2013, Draisma et al., 2010, Gianni et al., 2013, Robvieux, 2013, Sales et Ballesteros, 2011, Thibaut et al., 2016). Ainsi que, certaines espèces de laminaires (*Laminaria*) sont également présentes, prospérant dans les habitats profonds (Schiel et Foster, 2015, Steneck et al., 2002, Teagle et al., 2017). En Méditerranée, des extinctions régionales et locales ont été enregistrées (Bouma et al., 2014, Krumhansl et al., 2016). La perte de ces écosystèmes diversifiés et structurés est bien connu en tant qu'un changement du régime (Assis et al., 2017; Blamey et al., 2010; Gatti et al., 2017; Ling et al., 2015; Orlando-Bonaca and Rotter, 2018; Thibaut et al., 2017; Vergés and al., 2014) dont les assemblages résultants sont moins complexes, dominés principalement par les corallinacés et/ou les algues filamenteuses, les assemblages d'algues éphémères et de vastes fonds désertiques

dominés par des algues encroûtantes et les oursins (Asnaghi et al., 2013, Gianni, 2016, Mangialajo et al., 2008, Thibaut et al., 2017).

Le genre *Cystoseira* C. Agardh (Fucales, Phaeophyta) est réparti sur les côtes tempérées et subtropicales du monde entier. Les espèces appartenant au genre *Cystoseira* sont les principales macroalgues formant des habitats en Méditerranée, avec 80% des espèces étant endémiques de ce bassin, et sont présentes en allant du littoral à la limite inférieure de la zone euphotique (Gianni et al., 2013). Des pertes de forêts de *Cystoseira* ont été signalées dans plusieurs zones de la Méditerranée et ont été attribuées à la destruction des habitats (Airoldi et al., 2014), l'urbanisation (Mancuso et al., 2017, Mangialajo et al., 2008), l'eutrophisation (Iveša et al. 2016) et le surpâturage par les herbivores (Guidetti et al., 2003, Vergés et al., 2009). En raison de leur forte sensibilité aux impacts humains, plusieurs espèces de *Cystoseira* sont considérées comme des indicateurs de la qualité des eaux et cette caractéristique a permis la conception d'un indice largement appliqué dans la mise en œuvre de l'UE (WFD, 2000/06/EC). D'un point de vue conservatoire, toutes les espèces Méditerranéennes du genre *Cystoseira*, à l'exception de *C. compressa*, ont été signalées en tant qu'espèces à protéger dans l'Annexe II de la Convention de Barcelone (2010). Cinq espèces, *C. amentacea*, *C. mediterranea*, *C. sedoides*, *C. spinosa* et *C. zosteroids*, sont protégées d'après la Convention de Berne (Annexe I, 1979). Malheureusement, lors de la compilation des annexes de la Directive Habitats, les habitats marins ont été largement négligés et les forêts de *Cystoseires* n'ont pas été inclus. Néanmoins, toutes les espèces Méditerranéennes de *Cystoseira* sont sous la surveillance d'organisations internationales telles que l'UICN, le CAR/ASP et MedPan. La plupart des espèces de *Cystoseira* et pour leur rôle en tant que «ingénieurs d'habitat», sont donc considérés comme des habitats d'intérêt Européen (Micheli et al., 2013). Les grandes forêts d'algues brunes (principalement des espèces de *Cystoseira*) sont également présentes dans la mer Levantine, y compris la côte Libanaise. Et, l'une des 41 espèces (et variétés) de *Cystoseira*, *C. rayssiae* est endémique de la mer Levantine (Ramon, 2000). Les forêts de *Cystoseires* de la mer Levantine, comme ceux de la Méditerranée sont soumises à des pressions humaines multiples et massives et leur répartition, leur écologie, leur état écologique et leur évolution sont peu connus (Bellan-Santini et al., 2015; .., 2014, Guy Haim, 2017, Rilov et al., 2017). Par conséquent, beaucoup d'efforts devraient être consacrés à la recherche, afin d'accroître les connaissances sur les forêts d'algues brunes de la mer Levantine dans le but de concevoir de nouvelles règles et outils afin de réduire la perte de ces écosystèmes

et améliorer leur résilience, éventuellement envisager la restauration écologique, en tenant compte du fait que la conservation (et la surveillance) des forêts de *Cystoseira* déjà présentes devrait toujours être la priorité (Gianni et al., 2013).

1.2.1.b - Les trottoirs à Vermets de la Méditerranée: un écosystème marin négligé et un indicateur des changements côtiers

Les trottoirs à Vermets sont des bioconstructions formées par les mollusques gastéropodes appartenant à *Dendropoma* (et genres apparentés) en association avec d'autres vermetidés, *Vermetus triquetrus* (Bivona-Bernardi, 1832) et l'algue encroutante *Neogoniolithon brassica-florida* Harvey (Setchell & LR Mason 1943; et Silenzi, 2011, Milazzo et al., 2017). On les trouve généralement dans les eaux marines chaudes subtropicales (Hawaii (Hadfield et al., 1972), la Mer Rouge (Kappner et al., 2000), le Nord de la Chili (Pacheco et Laudien, 2008) et les Caraïbes du Sud (Miloslavich et al. 2010). Dans le bassin Méditerranéen, les trottoirs à Vermets sont généralement répartis le long des côtes d'eau chaude de la partie sud et les plus grandes bioconstructions se trouvent le long de la mer Levantine (Milazzo et al., 2017), y compris la côte libanaise. Les trottoirs à Vermets sont des bioconstructions dues à l'habitude grégaire et au peuplement massif sur le rivage rocheux, structurellement comparables aux récifs coralliens tropicaux et aux habitats coralligènes méditerranéens, créant une zone tridimensionnelle dans la zone comprise entre le milieu littoral et l'infra-littoral. (Colombo et al., 2013, Milazzo et al., 2017, Paoli et al., 2017)

Les trottoirs à Vermets sont l'un des écosystèmes côtiers les plus importants de la mer Méditerranée pour leur distribution et leur garanti de nombreuses fonctions pour l'écosystème (ex. productivité et biodiversité, refuges, nurseries) (Milazzo et al., 2017). Ils sont également utilisés comme marqueurs paléobathymétriques (Antonioli et al., 1999, Vescogni et al., 2008) et comme bioindicateurs potentiels des changements globaux (Fevret et Sanlaville, 1966, Sisma-Ventura et al., 2009), en particulier (Fevret et Sanlaville, 1966, Laborel, 1987, Sanlaville et al., 1997, Schiaparelli et al., 2006) des changements de température de l'eau de surface (Silenzi et al., 2004). D'un point de vue conservatoire, malgré leur importance écologique, les trottoirs à Vermets ne sont pas pris en compte dans les lois environnementales et internationales (Abdulla et al., 2009), bien qu'ils puissent être inclus dans le cadre de la directive des habitats Européens (92/43 / CEE) protégeant les récifs biogéniques (code 1170). En raison de plusieurs impacts

humains globaux et locaux, les conditions environnementales peuvent ne plus être adéquates pour le développement de *Dendropoma* spp., qui a comme conséquence la mort du trottoir qui s'érode rapidement. La perte et l'érosion des trottoirs à Vermets sont actuellement observées dans plusieurs zones de la Méditerranée, en particulier le long de la côte Levantine (Milazzo et al., 2017; Rilov, 2016). Dans ce contexte, une étude approfondie des trottoirs à Vermets de toute la Méditerranée, et plus particulièrement de la mer Levantine, devrait être une priorité dans les programmes de rec, pour une meilleure compréhension des causes de pertes et dans les programmes de gestion. habitats menacés.

1.3 - Objectifs de l'étude

La côte Libanaise a été progressivement exploitée et les réglementations ne sont souvent pas respectées, ce qui entraîne l'accumulation d'importants impacts humains le long de la côte. Les recherches effectuées dans cette thèse ont plusieurs objectifs concernant deux habitats naturels et menacés au niveau du bassin Levantin de la Méditerranée, et en particulier le long de la côte Libanaise (les forêts des grandes algues brunes et les trottoirs à Vermets):

- répondre à la rareté des données sur leur distribution et évaluer une base de référence pour le suivi futur de leur évolution;
- évaluer leur qualité écologique, en appliquant un indice conçu pour la DCE (2000/60/UE) et jamais appliqué dans le bassin Levantin de la Méditerranée;
- déduire leur état de conservation par rapport aux impacts humains et leur évolution passée (dans la mesure du possible par rapport aux données historiques).

Dans une perspective globale, la recherche effectuée dans cette thèse vise également à donner des outils pour promouvoir la conservation de tels habitats biogéniques importants, suggérant des zones où une meilleure gestion du littoral devrait être une priorité (i.e. dans le cadre des risques associés aux déversements pétroliers et/ou les pressions humaines croissantes).

Suite à la présente introduction générale, constituant le **chapitre I**, la thèse est divisée comme suit:

Le **chapitre II** est consacré à une description générale de la zone étudiée, la côte Libanaise. Il résume les caractéristiques importantes de la côte Libanaise, telles que les caractéristiques environnementales, la biodiversité marine et les principales menaces auxquelles elle est confrontée ainsi que leurs causes et leurs conséquences. L'évaluation de l'EE par l'application de

l'indice CARLIT, basée sur les assemblages de macroalgues et conçue dans le cadre de la DCE (2000/60/UE), est présentée au **chapitre III**. Cette recherche, déjà publiée dans la revue internationale *Ecological Indicators*, représente la première application de cet indice en Méditerranée orientale, fournissant une cartographie détaillée des forêts de grandes algues brunes (la plupart d'entre elles sont rapportées dans les principaux accords de conservation et conventions Méditerranéennes) dans une région relativement peu connue de la Méditerranée et donne des indications importantes sur les EE des eaux côtières en relation avec les impacts humains.

Le **chapitre IV** présente une étude centrée sur les trottoirs à Vermets Libanais et représente l'une des rares études sur des habitats biogéniques aussi importants largement trouvés dans le sud de la Méditerranée et qui atteignent leur maximum de développement au niveau des côtes du bassin Levantin. L'objectif principal était d'évaluer l'état actuel des trottoirs à Vermets en fonction des différents impacts humains le long de cinq sites répartis du sud au nord du littoral Libanais et en déduire leur évolution passée là où ces données étaient présentes.

Enfin, la discussion générale, la conclusion et les perspectives de ce travail sont présentées dans le dernier chapitre (**Chapitre V**).

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Chapter 2 - The Lebanese coast: features, conservation and threats to marine life

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The archeological rock of Raoucheh represents an impressive limestone rocky massif (about 50 m high) with very interesting littoral caves and tunnels. Photo: Badreddine A.

This chapter is dedicated to the description of the studied area, the Lebanese coast. It summarizes important characteristics of the Lebanese coast, such as environmental features, marine biodiversity and main threats it is facing along with their causes and consequences.

Summary

Despite the relatively small surface, because of the geographic location at the far Eastern end of the Mediterranean Sea and the proximity to the northern entrance of the Suez Canal, i.e. the gateway for massive exotic biota introduction into the Mediterranean Sea, the Lebanese coastal zone is an interesting area for investigating the effects of global change on Mediterranean biodiversity. However, the biotic composition along the Lebanese coast has experienced important ecological and bio-geographic changes in the last three centuries resulting from extreme natural conditions (e.g. sea warming and sea-level rise) and human impacts. Concerning human impacts, the opening of the Suez Canal, the damming of the Nile River and the fast urbanization along the Mediterranean coast of Lebanon, can be considered as the paramount sources of change. Major terrestrial-based impacts involved the heedless development along the coast, including industrial and domestic sewage outflow and industrial installations. Intensive fishing is another major culprit for the changes in species diversity and abundance. Recently, deep-water drilling for oil and gas has been started, having a potential impact on the deep water biota. For the coming years it is envisaged that the effects of human impacts on the Lebanese Mediterranean marine ecosystems may intensify. For this reason, a continuous long-term monitoring should be a priority for a better understanding of the effects of human impacts and for the assessment of the evolution of marine ecosystems. Only in this way it will be possible to identify causes and implement, when necessary preventive and mitigation measures. This chapter aim is to assess and synthesize the major environmental features and anthropogenic activities influencing benthic communities and their biodiversity along the Lebanese coast.

2.1 - General description of the Lebanese coast: environmental features

Lebanon is a small and largely mountainous country located at the Eastern shores of the Mediterranean Sea. It is geographically limited by north latitudes of $33^{\circ}05'45.6''$ and $34^{\circ}38'45.6''$ and east longitudes $35^{\circ}06'10.8''$ and $35^{\circ}58'37.2''$ (Fig. 1). It is bordered by Syria at the northern and Eastern limits and occupied Palestine at the southern (Fig. 1). The country surfaces over $10\,452\text{ km}^2$ with an average length of 220 km and an average width of 48 km. The Lebanese territory is dominated by two mountain ranges that run parallel to the sea (Fig. 1). The western range (Mount Lebanon) overlooks the narrow coastal plain and is separated from the Eastern chain (the Anti Lebanon) by the Beqaa Plain (also called The Beqaa Valley). This structure presents a variety of contrasting features, thus individualizing five major geomorphologic regions with different ranges of altitude, slope and width:

- The coastal zone including the shoreline and continental shelf, the coastal plains and the foothills Mount Lebanon with a shoreline length of about 220 km;
- The Mount Lebanon middle and high elevation zones above 250 meters;
- The Beqaa Plain separated the Mount Lebanon and Anti-Lebanon, it comprises an 8 – 12 km wide fertile corridor and is about 120 km from north to the south;
- The Anti Lebanon extends across the Lebanese – Syrian borders and peaks at 2600 meters;
- The South Lebanon, an elevated plateau that extends a short distance inland from the western shores of South Lebanon to the Mount Hermon foothills in the east.



Fig. 1: Map of Lebanon, showing the two mountain chains, the location of the major cities, the 4 commercial and 15 fishing harbors, the main rivers, the 4 bays.

2.1.1 - The coast of Lebanon: an interesting area for studying the evolution of biodiversity in the framework of global change

The Lebanese coastline is about 220 km long from Arida in the north to Ras El-Nakoura to the south. The Lebanese coastal and marine ecosystems are considered a global biodiversity hotspot in the Mediterranean since they support a diverse and abundant marine life (Abboud-Abi Saab et al., 2003; Bitar, 2014; Crocetta et al., 2013; Harmelin et al., 2016; Ramos-Esplá et al., 2014). It hosts a wide variety of ecosystems (Bellan-Santini et al., 2015; Kouyoumjian and Hamzé, 2012). These ecosystems range from shallower features such as vermetid reefs (Fig. 2A), coralligenous habitat (Fig. 2B), seagrass meadows (Fig. 2C) and seagrass beds (Fig. 2D) to deep-sea ones such as underwater canyons. The coast is characterised by a narrow continental shelf, which is perpendicularly crossed by various canyon systems that connect coastal zones to deep-sea habitats. Pebble beaches and rocky coasts are dominant along the coast, sandy beaches concerning only 20 percent of the coast (MOE/UNDP/ECODIT, 2011). These geographic features are 'keystone structures' due to their role in supporting important communities acting as nursery and shelter habitats, benefiting fisheries, enhancing carbon sequestration and providing goods and services to human society (Badreddine et al., 2018; Bellan-Santini et al., 2015). Several benthic habitats (e.g. coralligenous/maërl, vermetid reefs) and flag species (e.g. the coral *Desmophyllum dianthus*), are considered as threatened (Gubbay et al., 2016). New species for science, such as a sponge belonging to the genus *Axinella*, and a sea star belonging to the genus *Luidia*, have been recorded during a deep-sea fieldwork conducted along the Lebanese coastline in 2017 by the organization of OCEANA in cooperation with RAC-SPA, the Lebanese Ministry of Environment and the National Center for Marine Sciences. Additionally, the geographic location of Lebanon expose its coasts to the direct influence of the Suez canal. A high number of non-indigenous species can cross the canal or be transported in ballast waters, increasing invasion likeliness.

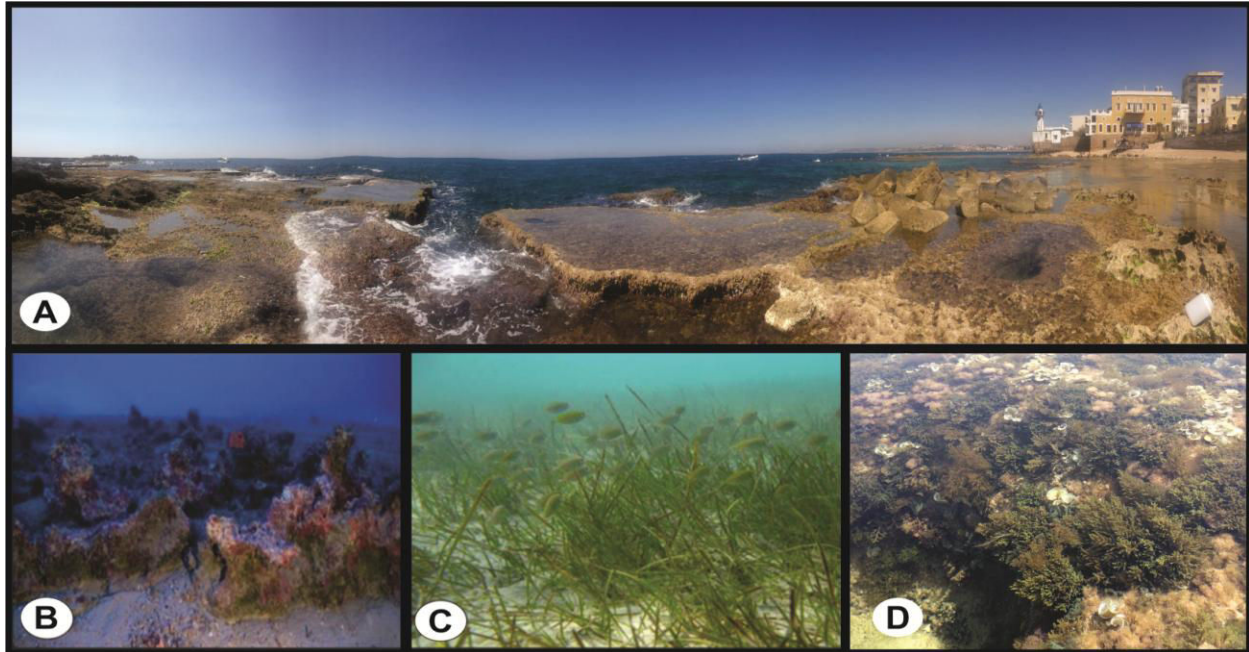


Fig. 2: Characteristic ecosystems of the Lebanese coastline. A- Vermetid reef in Tyr (south of Lebanon); B- Coralligenous habitat in Barbara (north of Lebanon); C- *Cymodocea nodosa* in the marine protected area of Tripoli (north of Lebanon) and D- Fucales (*Cystoseira* sp. and *Sargassum vulgare*) on the vermetid reef of Nakoura (south of Lebanon).

2.2 - Environmental features of Lebanon (climate, currents, bathymetry and salinity)

2.2.1 - Lebanon's climate.

Lebanese climate is a typical Mediterranean climate distinguished by 4 seasons: winter that is characterized by low temperatures and high rate of humidity and summer that is longer than winter, characterized by high temperatures and a low rate of humidity, are the two extreme seasons. Spring and autumn present intermediate and variable temperatures and humidity. Along the coast, winters are relatively mild and rainy and the annual temperature is relatively low, around 13 to 15°C (Abboud Abi Saab et al., 2012). In some cases, this temperature can reach exceptional extreme values of 30°C or 4°C especially in December and January. During summer, temperatures are relatively high and can reach 30°C to 35°C (maximal values can reach 38°C) in July and August and a minimum value of 9°C in January (Abboud Abi Saab et al., 2012; Compendium Statistique National, 2006; United Nations Development Program, 1970).

According to Abboud Abi Saab et al. (2013) the mean monthly variation of sea surface temperature between 2000 and 2012 varied from a minimum of 17.82°C in March and a

maximum of 27.7°C in August. The mean monthly variation of air temperature varied from a minimum of 12.4°C in January and a maximum of 27.59°C in August (Fig. 3). The diurnal range remains close to 7°C throughout the year (Abboud Abi Saab, 1985).

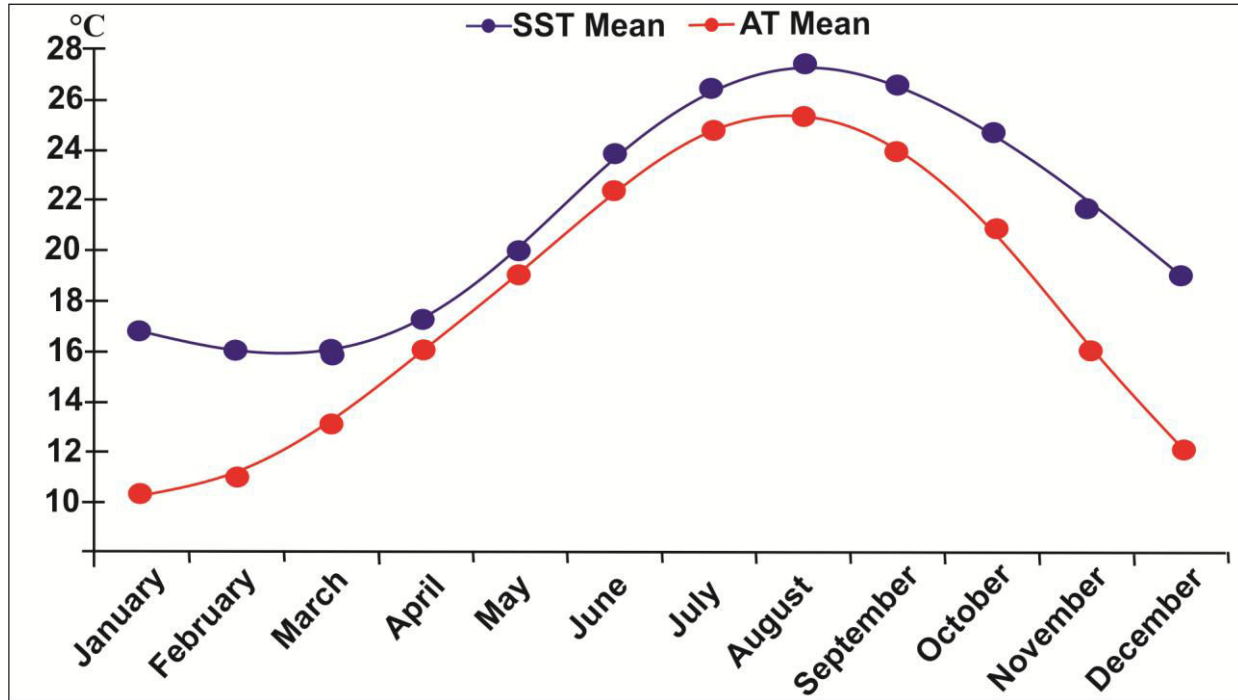


Fig. 3: Mean monthly variations of Sea Surface Temperature (SST) and Air Temperature (AT) in Lebanese marine waters between 2000-2012 (Abboud Abi Saab et al., 2013).

2.2.2 - Currents.

The water flow in the Mediterranean is counter-clockwise (Fig. 1). A general surface current from the Atlantic Ocean passes through the Strait of Gibraltar into the Mediterranean moving eastwards parallel to the North African coast and progressively losing speed through the cap of Tunisia, the Libyan and the Egyptian coasts. Afterward it turns end along the Palestinian, Lebanese and Syrian coasts. The water mass is characterized by a high degree of salinity and suspended sediments from the Egyptian and Palestinian coasts. The intensity of the current as much as the volume of the water mass is function of it's the flow through the Strait of Gibraltar (Taupier-Letage, 2008). Therefore, most of the year, the dominant circulation along Lebanon is northwards following the counter-clockwise current gyre of the Eastern Mediterranean (Fig. 1). This current is locally modified by the configuration of the coastline and the topography of the narrow continental shelf. A series of clockwise directed eddies and small gyres can be associated

to bays, headlands and submarine canyons (Goedicke, 1972). Water movements along the coast are also strongly related to surface currents and seasonal meteorological factors.

2.2.3 - Bathymetry.

An accurate bathymetric map is necessary for habitat mapping in marine environments: depth and bottom configuration play a critical role in the distribution of aquatic organisms. The bathymetry of the Lebanese coast is barely investigated. Ultrasound probe bathymetry has been performed by Pfannenstiel (1960) and Emery et al. (1966). Their studies characterized the very narrow continental shelf (3-4 km) up to 200 m isobath, situated at 8 to 10 km from the coast in the south of Lebanon and up to 20 km in the north. The mean depth of the continental shelf is 20 to 40 m (Goedicke, 1972), and the slope is parallel to the coast, reaching the abyssal plain 1100 to 1400 m depth and at a distance of 25 to 30 km from the coast. A recent update of bathymetry was performed in 2003 by the Shalimar marine survey. This survey was carried out as part of a French-Lebanese collaborative program to study recent deformation of the Levantine basin. The main objectives were to study the deformation of recent sedimentary layers, map potentially active faults on the seafloor, and identify possible seismic ruptures. A Simrad EM-300 multibeam echo sounder was used to produce high-resolution bathymetric and backscatter data at depths below 200 m, using a vessel speed of 7.5 to 10 knots over an area of 11,000 km² (Carton et al., 2009).

2.2.4 - Salinity

The Eastern Mediterranean has the higher salinity of the Mediterranean Sea (Mannino et al., 2017; Tanhua et al., 2013; Taupier-Letage, 2008). Indeed, the Levantine Sea waters have become saltier since the construction of the Aswan Dam, the regularization of the Nile waters and the opening of the Suez Canal (Berman et al., 1984; Gruvel, 1931; Moraitou-Apostolopolou, 1983). Specific studies on the variation of water salinity are scarce in Lebanon. A four month study of the salinity variation along four sites of the Lebanese coast (Abboud-Abi Saab et al., 2005) showing a significant increase of 0.70‰ in the level of salinity. It is worth noting that the variation in salinity expose the Lebanese coastal benthic communities specially those living in tidal pools of the vermetid reefs to an increasing salt level (Fig. 4). As consequence, the rise in the salinity level along the Levantine waters (Kress et al., 2014) in general and the Lebanese coast in particular (Abboud-Abi Saab et al., 2005; Abboud Abi Saab et al., 2012) enhance the

migration of species with some ecological tolerance from the Red to the Mediterranean Sea (Moraitou-Apostolopolou, 1983).



Fig. 4: Crystallisation of salt in a tide pool of the vermetid reef of Tyr (south of Lebanon).

2.3 - Biodiversity on the Lebanese coast: the origin and the status

The Mediterranean is a relatively enclosed sea, which is the cause for the development of a number of endemic species (Coll et al., 2010; 2012). Some claim that as many as 25% of the species in the Mediterranean are endemic. Apparently, the dynamic process of coastal evolution continues even to this day, creating future endemic species (Bianchi and Morri, 2000; Lejeusne et al., 2010; Mannino et al., 2017). Lebanon (Eastern Mediterranean Sea) is an area of particular biogeographic significance for studying the structure of Eastern Mediterranean marine biodiversity and its recent changes. The array of marine habitats in Lebanese waters, supports a diversity of marine life, represented by Atlanto–Mediterranean species. Furthermore, the main coastal features and the respective communities along the Lebanese coastline are similar to those

observed along all the Mediterranean shores (Bitar et al., 2007), several major engineering species are lacking, such as the seagrass *Posidonia oceanica* (Linnaeus) Delile, and the sea fans *Paramuricea clavata* (Risso, 1826) and *Eunicella* spp. (Harmelin et al., 2009). The total species richness, counted until now along the Lebanese coastline is estimated in the thousands. The list of species not exhaustive until now and being continuously updated, is represented by 972 species of macroinvertebrates (Abboud-Abi Saab et al., 2003; Bitar, 2014; Crocetta et al., 2013; Harmelin et al., 2016; Ramos-Esplá et al., 2014), 50 species of meiofauna (Mouawad, 2005), 425 species of fish (Harmelin-Vivien et al., 2007; Harmelin et al., 2009; Mouneimné, 2002) and 243 species of macroalgae (Basson et al., 1976; Kanaan et al., 2015). Recently, new species continue to be discovered as the endemic species to the Levantine Sea: *Cystoseira rayssiae* (Ramon, 2000), recorded for the first time along the Lebanese coastline (Badreddine et al., 2018). Among the species known to occur in the region are various iconic species that are considered at risk of extinction. For example, cetaceans such as sperm whales, fin whales, and striped dolphins are found in Lebanese waters, and monk seal has been irregularly spotted. Four species of threatened sea turtles (i.e., *Caretta caretta*, *Chelonia mydas*, *Dermochelys coriacea*, and *Trionix triunguis*) have been reported to occur, with the first two being relatively common (PNUE-PAM-CAR/ASP, 2010). Various threatened sharks and rays are also reported from the area (Lteif, 2015), including Critically Endangered species such as shortfin mako (*Isurus oxyrinchus*) and common guitarfish (*Rhinobatos rhinobatos*). Recently, major species represented by fucoids (*Cystoseira* spp. and *Sargassum* spp.) forests (Badreddine et al., 2018) and sessile marine Gastropod *Dendropoma anguliferum*, as endemic species for the Levant Sea were confirmed still present in some areas of the Lebanese coastline (see chapter 4 for more details). Those species were considered as ecosystems engineers and highly threatened and currently disappearing or in regression in many coastal areas in the Mediterranean Sea due to a complex mix of local and global impacts locally threatened.

2.4 - Threats to Lebanese marine life: human pressures, climate change (e.g. the rise of the sea level, eutrophication and ocean warming) and alien species.

2.4.1 - The Lebanese coastline under multiple and massive pressures

The Lebanese coastal zone suffers severe anthropogenic pressures (Box 1), as it hosts 55% of the total Lebanese population, concentrated in coastal urban areas (MOE/UNDP/ECODIT, 2011). Furthermore, due to the recent Syrian war, Lebanon's population has increased in an unprecedented manner, as the number of Syrian refugees reached 1,144,706 in 2014 (Lebanese Ministry of Environment). As a result, many commercial interests influence this area and compete for space. Thus, the status of the Lebanese coast has been described as declining due to over-exploitation and pollution from different origins (Box 1), making the current uses of coastal areas unsustainable (Abboud-Abi Saab et al., 2012a; Abboud-Abi Saab et al., 2008b; Badreddine et al., 2018; Bitar and Bitar-Kouli, 1995b; Bitar et al., 2017; Lteif, 2015). Major economic and social activities are concentrated along the coast, which represents 8% of the territorial area of the country (Abou-Dagher et al., 2012; El Asmar and Taki, 2014; Kouyoumjian and Hamzé, 2012).

Box 1 Major human source of pollution along the Lebanese coastline

Industrial waste (liquid and solid) caused by the lack of political will, the weak enforcement of legislative texts and the lack of waste management.

Domestic waste due to the absence of waste water treatment.

Potential spills due to the geographical reasons, for instance the intentional major oil spill during the Israel war on Lebanon 2006 and the absence of an oil and gas contingency plan.

Shipping and the discharge of ballast water which contain pollutants that occur due to the absence of maritime regulation.

Agriculture waste disposal (pesticide etc.) contaminate marine waters. Other root causes include the lack of law enforcement, awareness and social behavior (open dumping of solid waste and wastewater, overgrazing, overfishing etc.)

Air pollution (acidification) due to the transportation and industrial activities.



In total, Lebanon has (Fig. 1) four commercial ports, 15 fishing ports, 12 oil pipelines and three power stations run on fuel (Badreddine et al., 2018). Coastal development, including the construction of resorts and industrial development has progressed in coastal areas in a chaotic and unregulated manner, particularly during the period of the Lebanese Civil War. This development has affected landscapes and threatened biodiversity (Box 2), while structures like marinas have disrupted regular water flux, increasing sand deposition (MOE/UNDP/ECODIT, 2011). Most solid waste along the Lebanese coast is discarded, including non-biodegradable plastic (i.e., plastic bags, other plastic debris, lost fishing gear), with deleterious effects on marine fauna. Untreated domestic sewage and industrial effluents represent the main sources of chemical pollution, while episodic pollution events have also resulted in significant impacts to marine life (Fakhri et al., 2008). For example, airstrikes on a Jiyeh oil storage depot during the 2006 conflict with Israel resulted in a major oil spill, which constituted the largest oil-release accident in the Eastern Mediterranean (Khalaf et al., 2006). A large portion of the coastline was severely damaged, including a nature reserve in the north of Lebanon.

Box 2 Major consequences of anthropogenic activities on marine and ecosystem of the Lebanese coast

Increased erosion

Loss of nurseries ground such as *Cystoseira* forests

Loss of cultural value such as vermetid reefs

Species extinction/ increased risk of species extinction

Enhancement of toxic algae development of via the phenomena of eutrophication

Decrease of accessibility to the maritime public domain

Alteration of the food chains

Increased in invasive species



Effect of human pressures on Lebanese vermetid reefs from the south (A) to the north (B,C)



Lebanese rocky coast colonized by lessepsian species A) *Cerithium scabridum*, B) *Rhopilema nomadica* and C) *Brachidontes pharaonis*

2.4.2 - The Lebanese coastline under the effect of the climate change

Climate change poses a major threat to earth's biodiversity and ecosystem functions (Assis et al., 2017; Gatti et al., 2017; Lejeune et al., 2010; Parravicini et al., 2015b). Climate change is expressed in overall warming (Parravicini et al., 2010), increase in the frequency of extreme weather events (for example heat waves or intensifying storms), and in the oceans also sea level rise and acidification (Touratier and Goyet, 2011). The Levant Basin, the south Eastern limit of distribution of most Mediterranean and Atlanto-Mediterranean species, is potentially one of the marine regions more exposed to climate change effects (Abboud-Abi Saab et al., 2004; Coll et al., 2010; Sternberg et al., 2015). Eastern coastal water conditions are naturally extreme, with higher temperature and salinity values and showing the lowest primary productivity in the Mediterranean (Abboud-Abi Saab et al., 2013; Berman et al., 1984; Tanhua et al., 2013; Taupier-Letage, 2008). A "tropicalization" of Levantine waters has been observed during the last four decades (Bitar et al., 2007; Galil, 2007; Rilov, 2016; Rilov and Galil, 2009b), defined as an increase in temperature and salinity trends approaching those prevailing in the Red Sea. These hydrological changes have induced ecological changes in the Levantine marine ecosystems, namely in the biodiversity following the Lessepsian migration of several marine species from the Red to the Levantine Sea (Rilov, 2016; Zenetos et al., 2010) where environmental conditions are increasingly favorable to their establishment.

Lebanon's vulnerability to variability and to climate change has been demonstrated over the past few years by a number of extreme events: floods and landslides set off by extremely abundant rain, storm waves, heat waves and the resulting forest fires. The whole country is concerned by these events, which have serious economic consequences and lead to social disturbance. Specific studies on the impact of climate change on the marine ecosystems are scarce in Lebanon. A thirteen years time-series of SST and AT (2000-2012) was collected in one site located on the North-Central part of Lebanon showing interannual differences (Abboud-Abi Saab et al., 2013).

In May 2007, a massive, exceptional efflorescence of a centric diatom *Skeletonema costatum* and of an ichthyotoxic raphidophyceae *Heterosigma akashiwo* was observed for the first time in shallow waters in the Zouk-Nahr el Kelb area (north of Lebanon) close the Zouk electric power station with consequences on the plankton and on pelagic fish like sardines (Abboud-Abi Saab et al., 2008a). It was hypothesized that this phenomenon was fostered by the rise of SST as mentioned that the temperature was between 21.8°C and 24°C on the surface during the heat-

wave. Eutrophication is not considered as a major stressor along Lebanese coastline, an ultra-oligotrophic region (Abboud-Abi Saab et al., 2008b).

Sea warming may increase the virulence of pathogens, as observed for *Vibrio shiloi*, responsible for the whitening of the coral *Oculina patagonica* (Fig. 5) in the Eastern Mediterranean (Kushmaro et al., 1998).

The fieldwork performed for my PhD thesis allowed to observe the same phenomenon at a depth of 4 m of the vermetid reef of Nakoura (south of Lebanon).

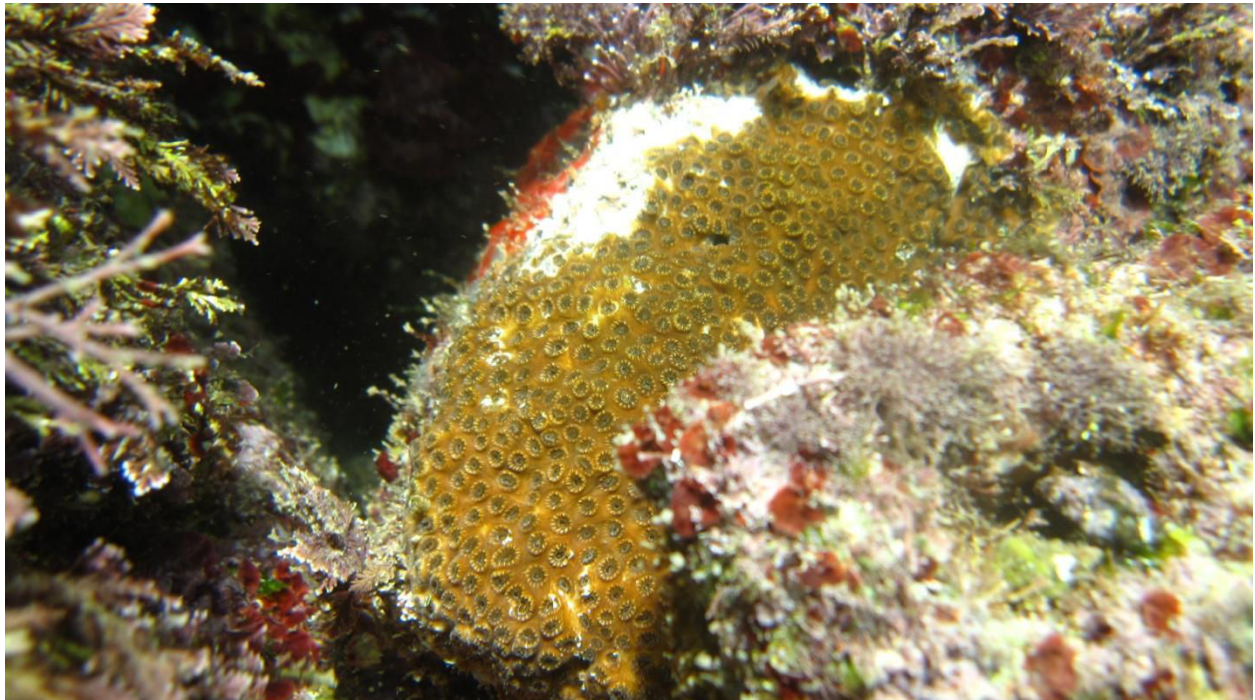


Fig. 5: The effect of climate change including sea warming on benthic communities. *Oculina patagonica* under the virulence of *Vibrio shiloi*, observed at Nakoura (south of Lebanon).

The sea warming can be responsible for the expansion of toxic dinobionts such as *Ostreopsis ovata*, which produces palytoxins and can cause health problems to people frequenting the beaches. Detailed studies on this emergent phenomenon allowed to describe a new species, *Ostreopsis fattorussoi* (Accoroni et al., 2016).

Furthermore, the effect of climate change induced a rise of the sea level (Blanfuné et al., 2016b; Giorgi and Lionello, 2008) of 10.5 cm in the past two decades; the predictions of sea level rise range up to 1 m by the end of the century. The Lebanese coastline is also concerned by this phenomenon (Ghaleb and Abi Rizk, 2008). The shallow habitats will be the more affected: as an

example, the seawater is expected to submerge the vermetid reefs. *D. anguliferum* could not afford a sufficient growth rate to counteract such variation, resulting in the platform erosion and potentially the extinction of these characteristic bioconstructions, eroding them over time Eastern (see chapter 4 for more details).

2.4.3 - Alien species: serious threats to biodiversity and natural ecosystem functioning

Over the past hundred years, the Eastern Mediterranean, including Lebanon, has undergone several environmental changes. The inauguration of the Suez Canal in 1869 opened the path to the migration of many marine organisms from the Red Sea to the Mediterranean. Indeed, since then, new species from the Red Sea are constantly being discovered in the Mediterranean, particularly in the Eastern basin, a phenomenon aptly named after the builder of the Suez Canal, Ferdinand de Lesseps, Lessepsian migration (Gravel, 1931; Por, 1978).

The Mediterranean Sea is highly concerned by species introductions (Rilov and Galil, 2009b; Zenetos et al., 2012). Based on updated checklists (Zenetos et al., 2012; Zenetos et al., 2010, 2011), a total of 986 alien species were known in the Mediterranean by December 2012: 775 in the Eastern basin, 308 in the Western basin, 249 in the Central basin and 190 in the Adriatic Sea. The Levantine part of the Eastern Mediterranean is particularly susceptible to the invasion of alien species from subtropical environments, due to its aforementioned warm temperatures (Galil, 2007). The opening of the Suez Canal in 1869 constituted a corridor for the spreading of thermophilic species, largely affecting local biodiversity (Mannino et al., 2017). Other practices such as aquaculture, shipping and leisure boating are increasing the magnitude of this problem, which is also worsening under climate change, particularly in the Eastern Mediterranean basin (Mannino et al., 2017). The Lebanese coast which at its southern end is about 400 km distant from the Suez canal, is fully exposed to the arrival of marine “lessepsian” species immigrating from the Red Sea via the Suez Canal (Bitar et al., 2007; Ramos-Esplá et al., 2014). The number of alien species is still increasing along the Lebanese waters (Bitar et al., 2017; Crocetta et al., 2013; Harmelin et al., 2009; Harmelin et al., 2016; Ramos-Esplá et al., 2014). In a study of the benthic communities associated to the vermetid reefs in 2008, 37% of total collected macroinvertebrates species in the region of Tyre (south Lebanon) resulted to be alien species (unpublished data). Invaders represent a threat to local flora and fauna, as in the case of *Mytilus*

galloprovincialis abundant in Lebanon in the past according to Gruvel (1931) are now totally replaced by the tropical *Brachidontes pharaonis* and *Cerithium scabridum* (Fig. 5).

It is worth noting that marine alien species may become invasive and have significant effects on the environment (biodiversity loss, habitat modifications and alterations in community structure), economy and human health (Boudouresque and Verlaque, 2002; Katsanevakis et al., 2014; Mannino et al., 2017).

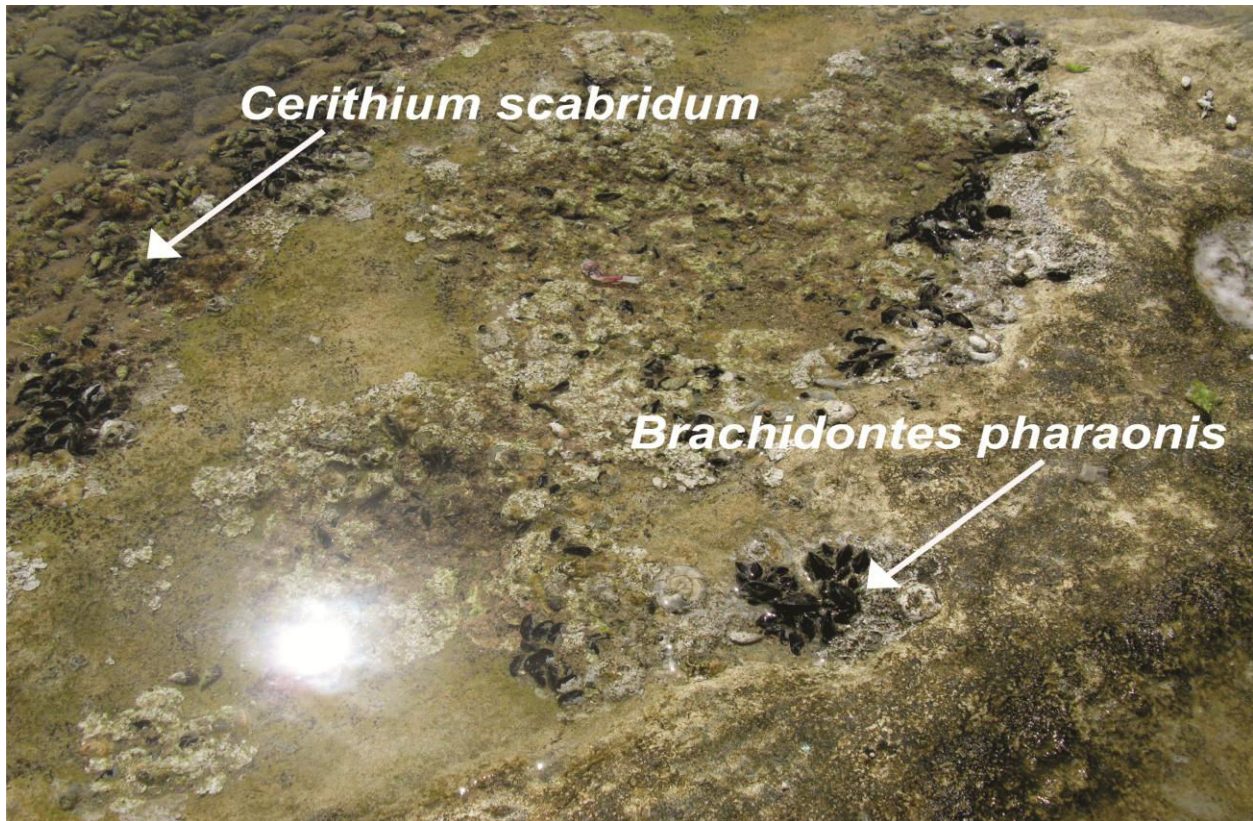


Fig. 6: A vermetid reef from Tyr (south of Lebanon) colonized by the two lessepsian mussels *Brachidontes pharaonis* and *Cerithium scabridum*.

Recently, the Mediterranean Sea has been considered as a hotspot of biological invasions (Boudouresque et al., 2017). Indeed, the rate of species invasions is expected to increase favored by the climate change (e.g. sea warming, Mannino et al., 2017), shipping (Zenetos et al., 2012) and overfishing (Boudouresque et al., 2017). It is worth noting that the ongoing enlargement of the Suez canal will likely accelerate the introduction of new (Galil et al., 2015) tropical Red Sea species entering the Mediterranean, the so-called Lessepsian species, first concentrated within

the Levantine Basin, to steadily spread westwards and northwards (Boudouresque, 1999; Katsanevakis et al., 2014; Lejeusne et al., 2010).

Table 2

Number of alien species recorded along the Lebanese coastline, according to the available data.

Groups	Number of species	References
Macroalgae	28	(Bitar et al., 2017)
Macrofauna	108	(Bitar, 2014; Crocetta et al., 2013; Harmelin et al., 2016)
Fish	46	(Bitar, 2013)

2.5 - Current marine protection and perspective

The Lebanese government has signed or ratified several international conventions and agreements that support the increase in water quality and the protection of marine organisms and habitats. These conventions include: the Convention for the Protection of the Mediterranean Sea Against Pollution (Barcelona Convention); the Convention on Biological Diversity (CBD); the United Nations Convention on the Law of the Sea (UNCLOS), the Convention on Wetlands (Ramsar Convention); the African-Eurasian Migratory Water bird Agreement (AEWA); the Agreement on Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous Atlantic area (ACCOBAMS); and the UNESCO Convention Concerning the Protection of the World Cultural and Natural Heritage (World Heritage Convention).

At the national level, Lebanon has implemented two marine protected areas (MPAs), representing Palm Islands Park and Tyre Coast Nature Reserve. The former was created in 1992, covers an area of 5 km² and was recognised as a Ramsar Site in 2001 (Ramsar, 2017a). It is formed by a group of three islets that lie roughly 5.5 km northwest of Tripoli-Palm, Sanai and Ramkin, which are important for Vulnerable and Endangered marine turtles according to IUCN (loggerhead turtle and green turtle, respectively) and migratory birds. Endangered monk seals were also regularly recorded in the area in the past, but such sightings have since become very rare. The Tyre Coast Nature Reserve was created in 1998, it occupies an area of 3.8 km² and consists of private agricultural land, freshwater springs and the last remaining sandy beach ecosystem in the country. As with the Palm Islands, its geographical situation places it along a major migratory route for birds, and for nesting sea turtles. It has been designated as a Ramsar Site (Ramsar, 2017b), an Important Bird Area (IBA), and a UNESCO World Heritage Site.

Despite these legal texts to manage coastal and marine ecosystems, the current set up is still characterized by a lack of transparency in policy making, allocative and productive inefficiencies, ineffective management, inadequate laws, misinterpretation of legal texts and poor compliance, as well as weak governance and corruption. Since the Lebanese coastline hosts a wide variety of important Mediterranean ecosystems (e.g. *Cystoseira* forest, vermetid reefs and coralligenous assemblages), but is situated in a vulnerable zone of the Eastern Mediterranean Sea, being located at nearly 450 km north of the Suez Canal, the main vector of introduction of alien species into the Mediterranean Sea (Boudouresque et al., 2017; Mannino et al., 2017). It is now well known that the Lebanese coastline is under multiple stressors leading to an increase in awareness of the need of integrating coastal zone management program in future actions. In view of the upcoming oil and gas discovery offshore Lebanon, new threats to the marine environment are expected to arise related to the construction and operation of offshore installations (oil spills, accidents and blow-outs). In this context of rapid changes, it is recommended first, to perform a detailed cartography of the entire Lebanese coast allowing to locate and identify important habitats, including accurate information on the distribution and abundance of coastal communities, especially of those deserving protection (e.g. *Cystoseira* forests, vermetid reefs, coralligenous and seagrass beds) allowing a baseline for monitoring their evolution in the future. Habitats deserve regular monitoring, as much as alien species, in order to detect early signal of deterioration/invasion of Mediterranean habitats. The creation of Marine Protected Areas (MPA), increasing the percentage of protected sea surface is also a useful tool. Protection cannot stop a biological invasion or an oil spill, but can increase the biodiversity and guarantee a production of propagules that can increase the resilience of a wider area than its limits or make possible ecological restoration actions.

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Chapter 3 – First assessment of the Ecological Status in the Levant Basin: application of the CARLIT index along the Lebanese coastline

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A belt of *Sargassum vulgare* in the infralittoral fringe of Nakoura, south of Lebanon (eastern Mediterranean Sea). Photo: Badreddine A.

Abstract

Macroalgae is one of the Biological Quality Elements (BQE) used by several indexes conceived in the European Water Framework Directive (WFD) for the assessment of the Ecological status of coastal water bodies. Among them, CARLIT index, based on the cartography of rocky-shore littoral communities, has been extensively and successfully applied in the Western Mediterranean Sea. In this study CARLIT was applied for the first time in the Levantine Sea, along the Lebanese shoreline in order to test the suitability of this method in the peculiar ecological conditions of the Levantine Sea and have a first assessment of its ecological status. The choice of proper reference sites is a focal point in the fulfillment of the WFD. In order to ensure accurate calculation of the ecological status of the Lebanese coast, the calculations of the reference conditions (RC) were performed using the values calculated in the Lebanese reference area, the Northwestern (NW) Mediterranean RC proposed in the first application of the CARLIT method and the Adriatic Sea RC. The results showed that the calculated ecological quality ratio values (EQR) based on Lebanese RC is particularly important when considering the principle of the WFD to reach and maintain a good Ecological Status. Overall, the EQR values were well correlated with anthropogenic pressures, as assessed by the LUSI and MA-LUSI indexes. In addition, this method allowed the collection of accurate information on the distribution and abundance of shallow-water communities, especially of those deserving protection (e.g. *Cystoseira* forests). Thus, the present paper represents a baseline for future studies and gives useful tools for the management of human impacts on the Lebanese coast.

Key-words: CARLIT, Ecological status, Water Framework Directive, Macroalgae, *Cystoseira*, Lebanese coast.

1. Introduction

Habitat loss and degradation, pollution, eutrophication, introduction of invasive species and, recently, climate change are the most important threats affecting coastal marine ecosystems and their ability to deliver ecosystem services at the global scale (Halpern et al., 2008; Waycott et al., 2009; Worm et al., 2006). The Mediterranean Sea is considered one of the first 25 global biodiversity hotspots (Myers et al., 2000) for its high biodiversity, the high level of endemism and the greatest proportions of species recorded (Bianchi and Morri, 2000). However, anthropogenic impacts are also relevant in the Mediterranean Sea (e.g. Bianchi and Morri, 2000; Costello et al., 2010; Lotze et al., 2006; Zenetos et al., 2012). The cumulative effects of human disturbances on marine coastal ecosystems worldwide and particularly in the Mediterranean Sea (Coll et al., 2012; Costello et al., 2010; Lotze et al., 2011), has led to the development of many methods and strategies to prevent a further deterioration of coastal ecosystems and to improve their ecological quality (Mann, 2000). The Water Framework Directive (WFD) 2000/60/EC, is one of the legislative monitoring networks that was adopted by the European Community in 2000, with the goal of using biota for assessing the water quality of inland surface waters, transitional waters, groundwaters and coastal waters. The objective of the WFD is that natural water bodies should reach and maintain a good ecological status (ES), i.e. the assemblages developing in the water bodies have to show low level of distortion resulting from human activities, deviating only slightly from those normally associated with those developing in undisturbed conditions (WFD, 2000). Within the WFD, several indices based on biological communities (phytoplankton, macroalgae, seagrasses, macroinvertebrates and fish) as bio-indicators (Biological Quality Elements or BQEs) have been developed along the Atlantic and Mediterranean coasts for the evaluation of the ES of marine coastal waters (for a review see Martínez-Crego et al., 2010). According to many ecological studies, macroalgal communities, one of the BQEs proposed in the WFD, are considered useful bio-indicators for the assessment of water quality worldwide and a wide range of indexes use them for the assessment of water quality: CCO index [Cover Characteristic Opportunistic species (Gall et al., 2016)], CFR index [Calidad de Fondos Rocosos (Guinda et al., 2008; Juanes et al., 2008)], the RICQI index [Rocky Intertidal Community Quality Index (Díez et al., 2012)], the MarMAT index [Marine Macroalgae Assessment Tool (Neto et al., 2012) and the RSL [Reduced Species List (Wells et al., 2007)] for the North East Atlantic, and the CARLIT index [Cartography of littoral and upper-

sublittoral rocky-shore communities (Ballesteros et al., 2007)] and the EEI index [Ecological Evaluation Index (Orfanidis et al., 2011; Taskin, 2015)] for Mediterranean coastal waters. In the Mediterranean Sea, the sensitivity of very shallow macroalgal communities to human disturbances is well known (Arévalo et al., 2007; Ballesteros et al., 2007; Orlando-Bonaca et al., 2008; Pinedo et al., 2007) and their distribution and status is assessed in the CARLIT index (Ballesteros et al., 2007) in order to calculate the ecological status of coastal waters. The communities are visually assessed and ranked according to their sensitivity to perturbation: Several *Cystoseira* species (Fucales, Phaeophyceae), which are particularly sensitive to water quality and other disturbances, are associated to the highest values of ecological status. In contrast, stress-resistant species (e.g. articulated Corallinales and Dictyotales), that are ubiquitous and tolerant, are associated to medium values. The lowest ES values are associated to very low structured communities dominated by opportunistic species such as green algae (e.g. *Ulva* spp. and *Cladophora* spp.) and cyanobacteria (Arévalo et al., 2007; Pinedo et al., 2007). The CARLIT methodology, developed in the Northwestern Mediterranean coast of Spain (Ballesteros et al., 2007) has been largely applied in other Mediterranean countries: France (Blanfuné et al., 2017), Italy (Asnaghi et al., 2009; Buia et al., 2007; Cecchi et al., 2009; Mangialajo et al., 2007; Sfriso and Facca, 2011), Malta (Blanfuné et al., 2011), Croatia (Nikolić et al., 2013), Tunisia (Omrane et al., 2010) and Albania (Blanfuné et al., 2016c). The CARLIT index has been widely used since: (i) it is a non-destructive method (no sample collection is needed); (ii) it potentially takes into consideration the entire rocky coastline of an area, although subsampling can be performed; (iii) it is time and cost-effective with almost no laboratory work needed; (iv) it is based on widely distributed communities that are relatively easy to identify and whose response to anthropogenic pressures is well-known (Ballesteros et al., 2007; Bermejo et al., 2013; Blanfuné et al., 2016c; Cavallo et al., 2016; Mangialajo et al., 2007; Nikolić et al., 2013; Torras et al., 2015). From a conservation point of view, the CARLIT index also provides valuable data concerning the distribution of shallow water Mediterranean algal forests, generally dominated by species of the genus *Cystoseira* C. Agardh and *Sargassum* C. Agardh (Fucales, Phaeophyceae), the main representatives of the order Fucales (Phaeophyceae, kingdom Stramenopiles) in several Mediterranean rocky-bottom communities (Blanfuné et al., 2016a; Cheminée et al., 2013; Hereu et al., 2008). These large brown seaweeds are ecosystem engineers as their canopy constitute highly structured and diverse communities (Thiriet et al., 2016),

forming dense forest habitats that offer shelter, food and nursery to other organisms (Cheminée et al., 2013). Like kelp forests in oceanic environments (Schiel and Foster, 2006), fucoid forests represent one of the more productive coastal habitats in the Mediterranean Sea (Mangialajo et al., 2012), providing valuable ecosystem goods and services to many organisms and to human kind (Cheminée et al., 2013; Salomidi et al., 2012; Thiriet et al., 2016). However, most of Mediterranean fucoids species are highly threatened and are currently disappearing or in regression in many coastal areas due to a complex mix of local and global impacts (Arévalo et al., 2007; Hereu et al., 2008; Mangialajo et al., 2008; Mineur et al., 2015; Thibaut et al., 2016; Thibaut et al., 2014a; Thibaut et al., 2014b; Thibaut et al., 2005). As a consequence, most Mediterranean fucoids are listed as endangered or threatened in the Annex II of the Barcelona Convention (1976, updated 2013) and their conservation and restoration is the object of several researches (reviewed by Gianni et al., 2013).

The application of CARLIT in the areas surveyed so far has provided valuable data on the ES of the water bodies, but also on the present distribution of shallow water forests dominated by fucoids. At present CARLIT index has been applied in most of the North-Western Mediterranean Sea and in part of the Adriatic Sea (Blanfuné et al., 2017 and references therein). The present study represents the first application of the CARLIT index in the Eastern-most part of the Mediterranean Sea (Levantine Sea, Lebanon) in order to i) test the applicability of CARLIT in this Basin, ii) assess the ES of Lebanese coastal waters, iii) calculate the relation between the CARLIT index and the anthropogenic pressures and iv) document and provide a baseline for the current distribution of fucoids forests and other valuable communities in Lebanon.

2. Material and methods

2.1. Study area

Lebanon has about 220 km of coastline which hosts 70% of the Lebanese population (Kouyoumjian and Hamzé, 2012). The continental shelf in the Lebanese Coastal Zone (LCZ) is narrow (Abboud-Abi Saab et al., 2012a), 3 to 7 km wide, and the coastline is characterized by the presence of a few bays (Bay of Beirut, Bay of Jounieh, Bay of Shekka and Bay of Akkar), 4 commercial ports and over 15 fishing harbors, dozens of sea pipelines for petroleum imports, various industries, three power plants and fuel tank farms (El Asmar and Taki, 2014) (Fig.1). Pebble beaches and rocky coasts are dominant, sandy beaches interesting only 20 percent of the coast (MOE/UNDP/ECODIT, 2011). Furthermore, the LCZ is suffering from many

supplementary sources of pollution such as illegal sewage discharge, rivers (generally characterized by torrential regime and carrying pollutants from agricultural, industrial and urban activities) and uncontrolled urban development, especially involving coastal artificialization (MOE/UNDP/ECODIT, 2011). Very few studies on macroalgal communities presence, abundance and patterns of distribution have been performed along the Lebanese coast (Basson et al., 1976; Kanaan et al., 2015; Lakkis and Novel-Lakkis, 2000) and *Cystoseira* species have never been the object of a detailed study although they have been mentioned in few benthic inventories and underwater visual census surveys (Bitar and Bitar-Kouli, 1995a; Ramos-Esplá et al., 2014).

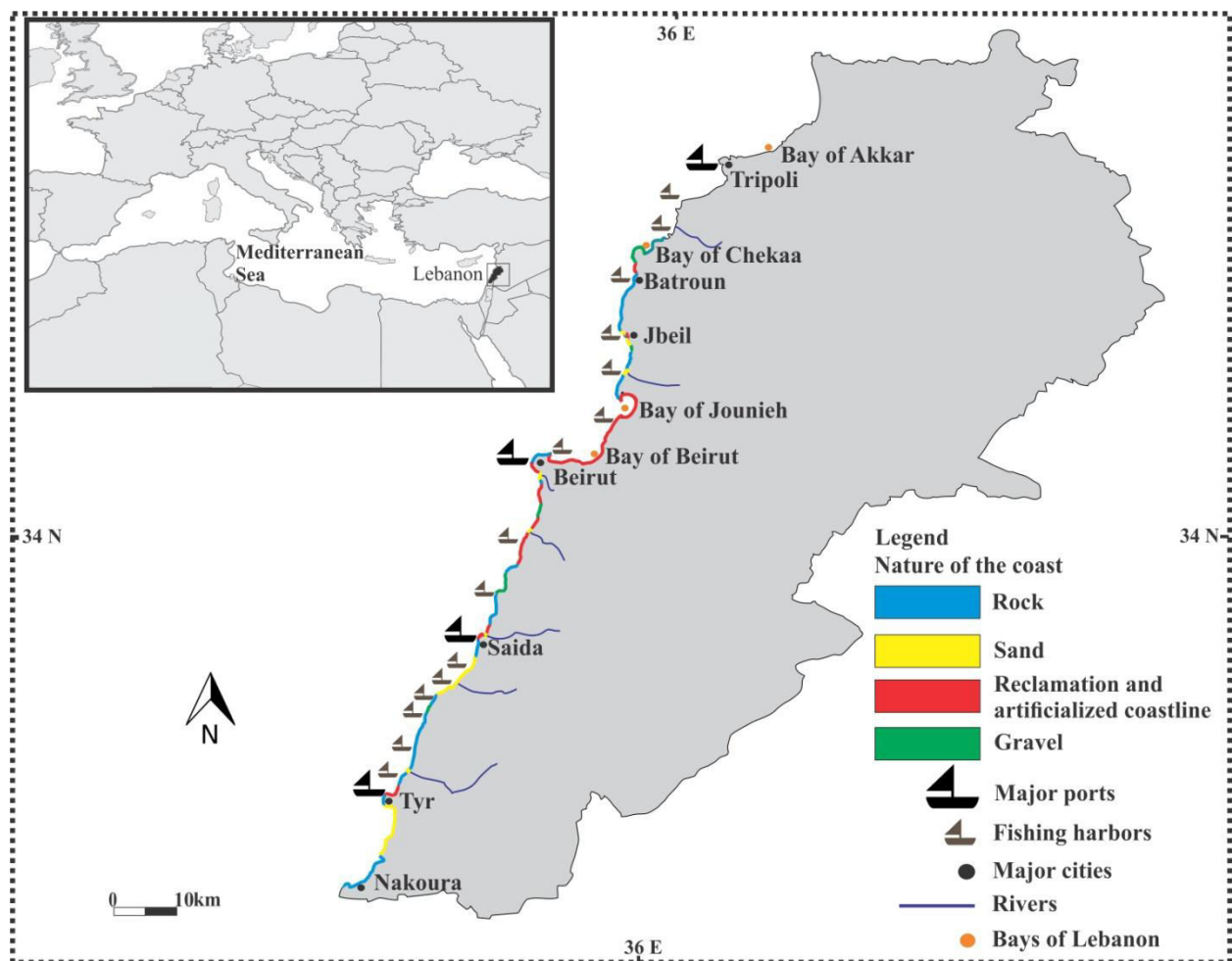


Fig. 1. Map of Lebanon, showing the location of the major cities, the 4 commercial and 15 fishing harbors, the main rivers, the 4 bays as much as distribution of rocky, sandy, gravel and reclamation and artificialized coastline in the study area.

2.2. CARLIT application

The study was performed along 164 km of the Lebanese coast, which represent about 75% of the entire coastline. Sandy beaches and highly modified areas such as marinas were excluded, according to Ballesteros et al. (2007) and Bermejo et al. (2013). As Lebanon does not belong to the European Union, no coastal water bodies were previously defined in an institutional framework. Then, the Lebanese coast was divided into 12 stretches of coast (Fig. 2) taking into account their catchment basin and typology.

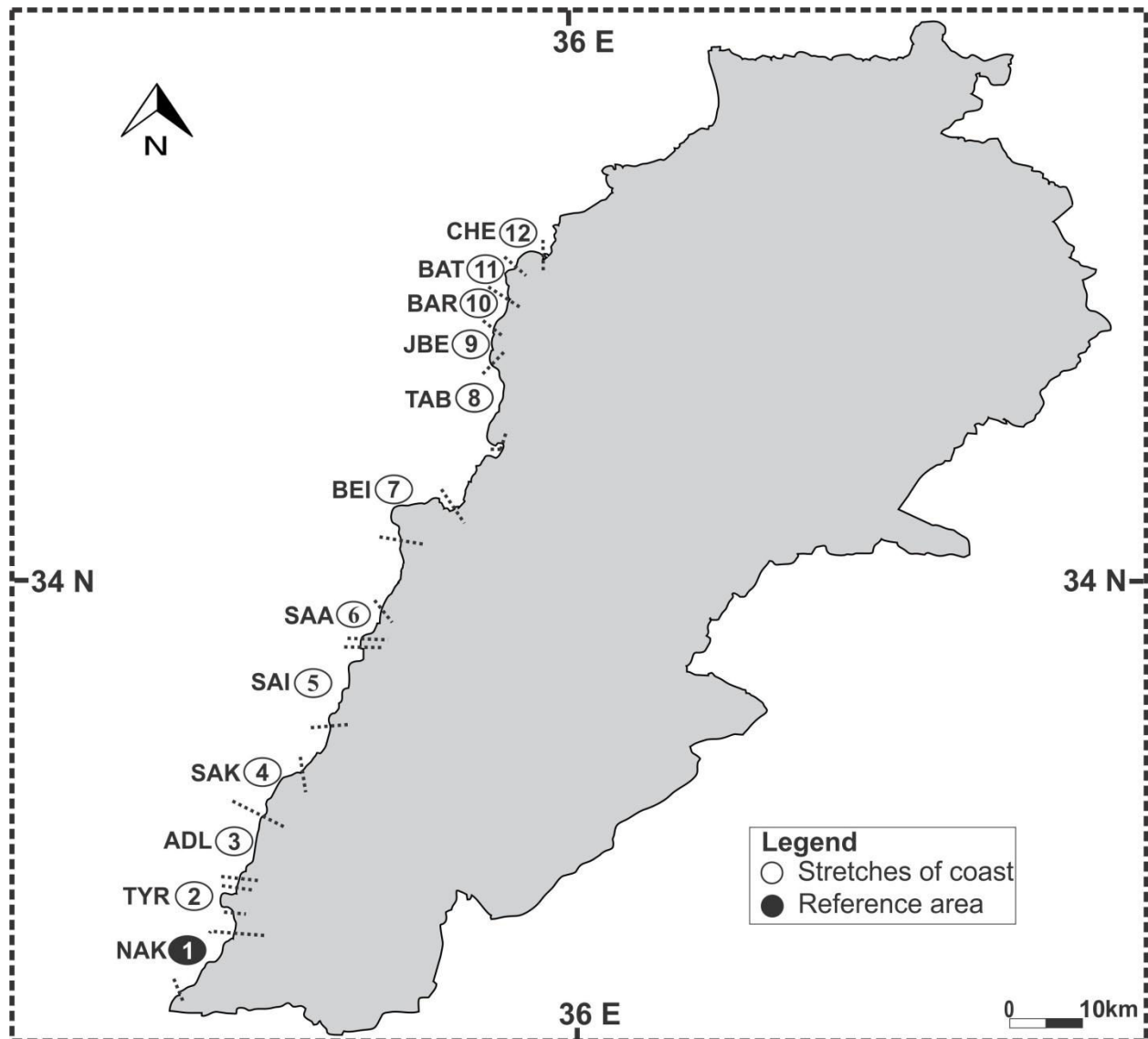


Fig. 2. Geographical distribution of the 12 stretches studied along the Lebanese coast. 1-NAK: Nakoura; 2-TYR: Tyr; 3-ADL: Adloun; 4-SAK: Saksakiyé; 5-SAI: Saida; 6-SAA: Saadiyet; 7-BEI: Beirut; 8-TAB: Tabarja; 9-BAR: Barbara; 10-JBE: Jbeil; 11-BAT: Batroun; 12-CHE: Ras-Chekaa.

The category table proposed by Ballesteros et al. (2007) and subsequently modified (e.g. Asnaghi et al., 2009; Bermejo et al., 2013; Blanfuné et al., 2017; Nikolić et al., 2013) was adapted to the Lebanese coast, as reported in Table 1. The same range of sensitivity values was considered (from 20, very sensitive to 1, not sensitive) and the simplified version with only three classes of *Cystoseira* belts was adopted (Nikolić et al., 2013).

Table 1

Summarized description and sensitivity levels of the main community categories taken into account for the application of CARLIT along the Lebanese coasts modified from Nikolić et al., (2013).

Category	Community description	Sensitivity level (SL.)	Acronym
<i>Cystoseira amentacea</i> 3	Continuous belts of <i>C. amentacea</i>	20	CYS3
Other sensitive <i>Cystoseira</i> species	Stands of other sensitive <i>Cystoseira</i> species (<i>Cystoseira rayssiae</i>)	20	CYSS
<i>Cystoseira amentacea</i> 2	Abundant patches of <i>C. amentacea</i>	15	CYS2
<i>Sargassum</i> spp.	Stands of <i>Sargassum vulgare</i>	14	SARG
<i>Cystoseira compressa</i>	Stands of <i>Cystoseira compressa</i>	12	CYSC
<i>Cystoseira amentacea</i> 1	Rare, scattered plants of <i>Cystoseira amentacea</i> ^a	10	CYS1
Ubiquitous photophilic algae	Stands of <i>Padina pavonica</i> , <i>Dictyota</i> spp., <i>Dictyopteris polypodioides</i> , <i>Halopteris scoparia</i> , <i>Taonia atomaria</i> , <i>Laurencia</i> complex	10	UPHO
Erect corallines	Stands of articulated Corallinales	8	ACOR
Tolerant photophilic algae	Community dominated by <i>Colpomenia sinuosa</i> , <i>Pterocliadiella capillacea</i> , <i>Hypnea musciformis</i>	6	TPHO
Green algae	Stands of <i>Ulva</i> spp. and <i>Cladophora</i> spp.	3	VTPH
Cyanobacteria	Stands dominated by cyanobacteria	1	CYAN

^a In the case of rare scattered plants of belt-forming *Cystoseira amentacea* (class 1), the dominant community is also recorded. (Sensitivity level: average value).

The list of geomorphological features and their categories (Table 2) used to describe the coastline sectors in the Lebanese coast, based on previous studies (Nikolić et al., 2013), consisted in coastline morphology (low coast/metric blocks), coastline slope (horizontal/subvertical), nature (natural/artificial) and type of the substrate (calcareous/sandstone) and degree of wave exposure (calm/exposed).

Table 2

Geomorphological feature data collected in the field for every sector.

Geomorphological features	Category
Coast morphology	Low continuous coast Metric blocks
Coastline slope	Horizontal (0 - 30°) Subvertical (30 – 60°)
Nature of the substrate	Natural Artificial
Substrate type	Calcareous (limestone) Sandstone
Wave exposure	Sheltered Exposed

The survey was conducted during April – May 2016, during the period of maximal development of macroalgal assemblages in the Lebanese coast. Each stretch of coast was previously divided into sectors of 50 m length using Quantum Geographical Information System (QGIS) software. The sampling consisted in a run of all the sectors, using a small boat, moving at low speed and proceeding as close as possible to the shoreline, in order to observe the shallow macroalgal communities. When hardly accessible by boat, some sectors were sampled by snorkeling or walking. In each sector, littoral/and upper littoral communities and geomorphological factors were visually recorded and noted directly into maps (scale 1:5000) previously prepared using aerial photographs taken from Google Earth®. Subsequently, data were transferred into geo-referenced maps using (QGIS) software.

In order to propose adequate reference conditions (RC) for the Lebanese coastline, potential reference areas were selected according to the criteria proposed by the Mediterranean Geographical Intercalibration Group (Bermejo et al., 2013; Nikolić et al., 2013): i) population density lower than 1000 ind/km² in the next 15 km and/or more than 100 habitats/km² in the next 3 km within that area (winter population); ii) no more than 10% of artificial coastline; iii) no harbors (more than 100 boats) within 3 km; iv) no beach regeneration within 1 km; v) no industries within 3 km; vi) no fish farms within 1 km vii) no desalination plants within 1 km. Along the studied Lebanese coast, only the relatively undisturbed area of Nakoura (black dot, Fig. 2), fulfilled the criteria selected.

The Ecological Quality (EQ) value was calculated for each Geomorphological Relevant Situation (GRS) in every stretch of coast, following the classical formula:

$$EQ = \frac{\sum(li * SLi)}{\sum li}$$

EQ: Ecological quality value of a particular coastline sector

li: Length of the coastline with the community category “i”

SLi: Sensitivity level of the community category “i”

According to the WFD, the ES has to be expressed in terms of ecological quality ratios (EQRs). The EQR of a stretch of coast is expressed as the ratio between the obtained EQ (EQ_{ssi}) and the EQ of reference sites. The EQR, expressed as a value (Table 5) ranging from 0 (bad ES) to 1 (high ES), is calculated as follows:

$$EQR = \frac{\sum \frac{EQ_{ssi} * li}{EQ_{rsi}}}{\sum li}$$

EQ_{ssi}: EQ in the study site for a situation i.

EQ_{rsi}: EQ in the reference sites for the situation i.

li: Coastal length in the study coast for a situation i.

The calculations of RC for the Lebanese coast were performed using the reference values calculated in the Lebanese proposed reference area, Nakoura (see results section), the Northwestern (NW) Mediterranean RC proposed in the first application of the CARLIT method (calculated in Corsica and Balearic Islands, Ballesteros et al., 2007, Table 3) and the Adriatic ones (calculated along Croatian coasts, Nikolić et al., 2013, Table 4). Class boundaries adopted are the same than previous studies (Ballesteros et al., 2007, Nikolić et al., 2013; Bermejo et al.,

2013; Blanfuné et al., 2016; Blanfuné et al., 2017): 0.75 for the high/good boundary, 0.6 for the good/moderate, 0.4 for the moderate/poor and 0.25 for the poor/bad.

Table 3

Ecological quality values under NW Mediterranean Reference Conditions (RC, Ballesteros et al., 2007).

Geomorphological situation	Coastal morphology	Coastline slope	EQ_{rsi}
1	Decimetric blocks	Artificial	12.1
2	Low coast	Artificial	11.9
3	High coast	Artificial	8
4	Decimetric blocks	Natural	12.2
5	Low coast	Natural	16.6
6	High coast	Natural	15.3

Table 4

Ecological quality values under Adriatic Reference Conditions (RC, Nikolić et al., 2013).

Geomorphological situation	Coastal morphology	Coastline slope	EQ_{rsi}
1	High coast	Horizontal	20
2	High coast	Sub-vertical	17.55
3	High coast	Vertical	12.96
4	High coast	Overhanging	10.00
5	Low coast	Horizontal	19.02
6	Low coast	Sub-vertical	17.72
7	Low coast	Vertical	14.62
8	Low coast	Overhanging	9.66
9	Blocks	-	12.76

2.3. Data analysis

In order to define which geomorphological features mostly influenced the distribution of macroalgal communities, a BEST analysis (Clarke and Gorley, 2006) was applied by combining each geomorphological feature and community category in the surveyed stretches of coast. The number of output geomorphological variables in the BEST analyses was limited to two. A non-metric multidimensional scaling (nMDS) was performed on the biological data, after calculation of the Bray-Curtis similarity matrix, separately for the two selected geomorphological features and for each stretch of coast. In order to better investigate multivariate patterns among stretches

and macroalgal assemblages along the Lebanese coast, a Factorial Correspondence Analysis (FCA) was performed on biological data, independently on the GRS. PRIMER 6 software package (Clarke and Gorley, 2006) and XLStat were used for statistical analyses.

2.4. Relationship of CARLIT index with anthropogenic pressures

The Land Use Simplified Index (LUSI; Flo et al., 2011), the Modified LUSI index (MA-LUSI-WB; Torras et al., 2015) and the Human Activities and Pressures Index (HAPI; Blanfuné et al., 2017), were used to analyze the relation between the CARLIT assessment of Ecological Status and the anthropogenic pressures. For each stretch of the surveyed coastline, land use category (urban, agricultural, industrial, population and artificial land) was assessed within 1500 m from the considered coastline using institutional (Lebanese Ministry of Environment) and QGIS data as follows:

$$\text{LUSI} = (\text{Urban score} + \text{Agricultural score} + \text{Industrial score} + \text{Typology score}) \times \text{Confinement}$$

Where Urban, Agricultural and Industrial represent the individual scores of the three land uses, typology represents the presence of sewage outfalls, commercial harbors, aquaculture or freshwater input and the Confinement represents a correction number depending on the shape of the coast (high for concave, low for convex). In our study the confinement correction number was not applied as it was assumed that the Lebanese coast is homogeneous and can generally be approximated to a line (confinement correction number = 1).

The MA-LUSI-WB index of the considered area was calculated by adding i) the number of inhabitants and ii) the percentage of artificialized coast, to the LUSI index results for each surveyed stretch of coast (Torras et al., 2015). It is expressed by the formula:

$$\text{MA-LUSI-WB} = \text{LUSI} + \log \left(\frac{\text{Inhabitants}}{\text{Coastline length}} \right) + \frac{\text{Length of artificial structure}}{\text{Length of rocky coastline}}$$

The HAPI index was applied according to Blanfuné et al. (2017): five land use pressures (urban, industrial, agriculture, artificialization and freshwater) were given a score (P_{si}) and a linear correlation was performed to define the coefficient of correlation (r) between the pressures factors and the EQRs results for each stretch of coast (the EQR based on the Lebanese RC calculated in Nakoura were applied). Finally, the result was divided by an annual seawater turnover score ($TS = 0.8$) that is the same for the whole Lebanese coastal zone, characterized by torrential rivers uniquely. The HAPI index is given by the following formula:

$$\text{HAPI} = \frac{\sum P_{si} * r_i}{TS}$$

The linear correlation between LUSI and MA-LUSI pressures index and the CARLIT index results in each stretch of coast was performed. No correlation was assessed with the HAPI index, which already includes the ES values in the calculations.

3. Results

The surveyed stretches of coast (Fig. 2) represent about 75 % of the entire coastline (164 km at a scale of 1:5000). The BEST analysis applied on the combination of the geomorphological features selected, showed the highest correlation between macroalgal community categories ($r = 0.380$) and the couple of geomorphological features “nature of substrate” (natural/artificial) and “slope” (horizontal/subvertical). Consequently, four different “Geomorphological Relevant Situations” (GRS) were obtained from the combination of these two most relevant geomorphological features (Table 5). The MDS performed on the community categories in function of the four GRS shows a clear segregation of points (Fig. 3), independently of the studied stretch of coast. On the basis of the 4 GRS obtained by the BEST analyses, corresponding EQ values were calculated on the unique possible reference area (Nakoura), as reported in Table 5.

Table 5

Lebanese RC, corresponding to the Ecological Quality values (EQ_i) calculated for the four Geomorphological Relevant Situations (GRS) resulting from the BEST analysis, in the reference area (Nakoura).

GRS	Type of substrate	Slope	EQ _i
1	Natural	Horizontal	12.9
2	Natural	Subvertical	9.3
3	Artificial	Horizontal	8
4	Artificial	Subvertical	8

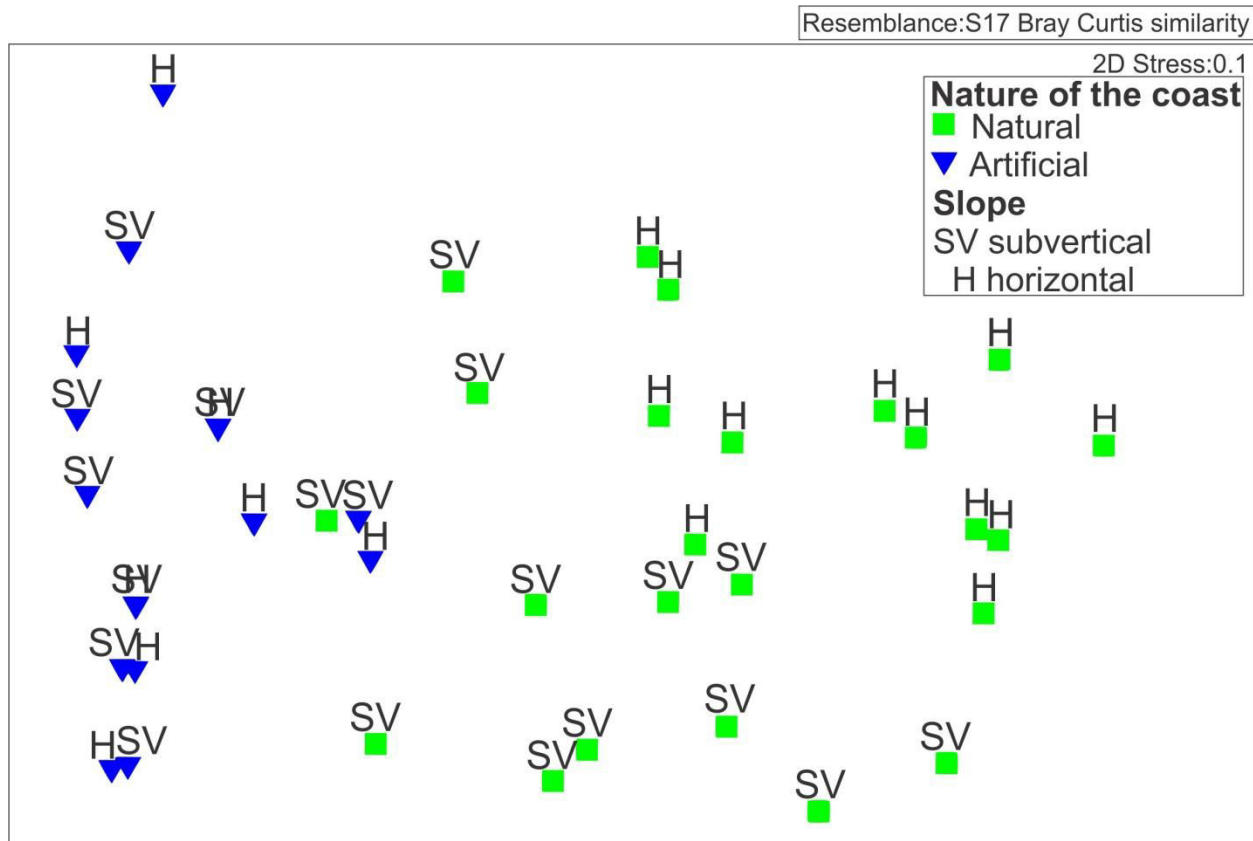


Fig. 3. Non-metric multi-dimensional scaling (nMDS) analysis on the community categories, in function of the 4 Geomorphological Relevant Situations, independently on the stretch of coast.

The assessment of the ES using the Lebanese RC proposed in this study (calculated in NAK), ranged from 0.16 in Beirut and 0.64 in ADL (Table 6, Fig. 4), with an average value of 0.44. The ES values calculated using the NW Mediterranean (Ballesteros et al., 2007) and Adriatic (Nikolić et al., 2013) RC are significantly and strongly correlated with the Lebanese results (respectively $R^2 = 0.93$ for Lebanese versus Adriatic-based values, $R^2 = 0.96$ for Lebanese versus North-West Mediterranean-based values, Fig. 5), even if these ES values are consistently lower than the Lebanese ones. A very high correlation is found between the ES values calculated with Adriatic versus NW Mediterranean-based values ($R^2 = 0.99$, Fig. 5).

Concerning the classification in ES classes (Fig. 4), the use of Lebanese RC calculated in NAK allowed the classification of 3 stretches of coast in the good ES class (ADL, BAR, CHE), 5 in the moderate (BAT, SAK, TYR, SAA, TAB), 2 in the poor (SAI, JBE) and one in the bad class (BEI). Based on the NW Mediterranean RC, 2 stretches were classified in good, 4 in moderate, 3 in poor and 3 in bad ES classes, while based on the Adriatic values 1 site was classified in good,

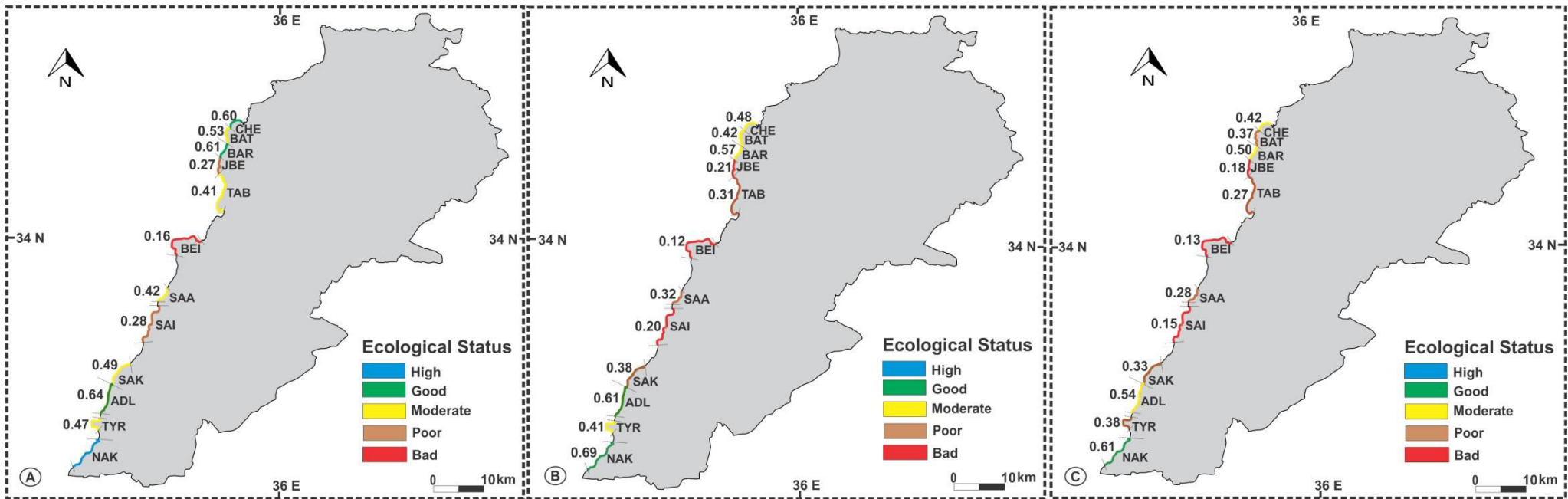
3 in moderate, 5 in poor and 3 in bad ES classes. Class agreement among the results of the three calculations was relatively low, with 4 matches out of 11 between the results based on Lebanese versus NW Mediterranean RC (1 good, 2 moderate and 1 bad), and no matches between results based on Lebanese versus Adriatic RC. On the contrary, 9 out of 12 matches were recorded when comparing results based on North-Western Mediterranean and Adriatic RC.

Table 6

Ecological quality and human pressures. EQR and ES CARLIT values calculated in the 12 stretches of the Lebanese surveyed coastline, under the three different reference conditions (RC) considered (Lebanese, this study, North-West Mediterranean, Ballesteros et al., 2007, and Adriatic, Nikolić et al., 2013). Values of LUSI index are according to Flo et al. (2011), MA-LUSI according to Torras et al. (2015) and HAPI according to Blanfuné et al. (2017) corresponding to the 12 stretches of the Lebanese coastline. *Reference area.

Stretches	Name	Length (m)	Lebanese RC (calculated in NAK)		NW Mediterranean RC (Ballesteros et al., 2007)		Adriatic RC (Nikolić et al., 2013)		LUSI	MA-LUSI	HAPI ^a
			EQR	ES	EQR	ES	EQR	ES			
NAK*	Nakoura	9500	1	High	0.69	Good	0.61	Good	1	1.3	-
ADL	Adloun	14300	0.64	Good	0.61	Good	0.54	Moderate	3.0	3.1	1.9
BAR	Barbara	6600	0.61	Good	0.57	Moderate	0.50	Moderate	2.2	1.3	2.0
CHE	Chekaa	5500	0.60	Good	0.48	Moderate	0.42	Moderate	3.3	2.5	3.0
BAT	Batroun	6950	0.53	Moderate	0.42	Moderate	0.37	Poor	7.0	6.8	2.0
SAK	Saksakiyé	8500	0.49	Moderate	0.38	Poor	0.33	Poor	5.1	5.7	4.7
TYR	Tyr	5450	0.47	Moderate	0.41	Moderate	0.38	Poor	3.7	4.7	2.6
SAA	Saadiyet	2900	0.42	Moderate	0.32	Poor	0.28	Poor	5.0	4.7	3.0
TAB	Tabarja	8950	0.41	Moderate	0.31	Poor	0.27	Poor	6.0	5.1	3.0
SAI	Saida	5050	0.28	Poor	0.20	Bad	0.15	Bad	8.7	10.5	3.8
JBE	Jbeil	5650	0.27	Poor	0.21	Bad	0.18	Bad	13.0	14.1	4.0
BEI	Beirut	8750	0.16	Bad	0.12	Bad	0.13	Bad	26.0	27.6	5.9

^aEQR values under Lebanese RC.



1

Fig. 4. Ecological quality Ratio (EQR) and Ecological status (ES) of the 12 studied stretches of coasts. EQR values calculated under the: A) Lebanese RC (calculated in Nakoura, assuming its ES as high), B) NW Mediterranean RC (Ballesteros et al., 2007) and C) Adriatic RC (Nikolić et al., 2013).

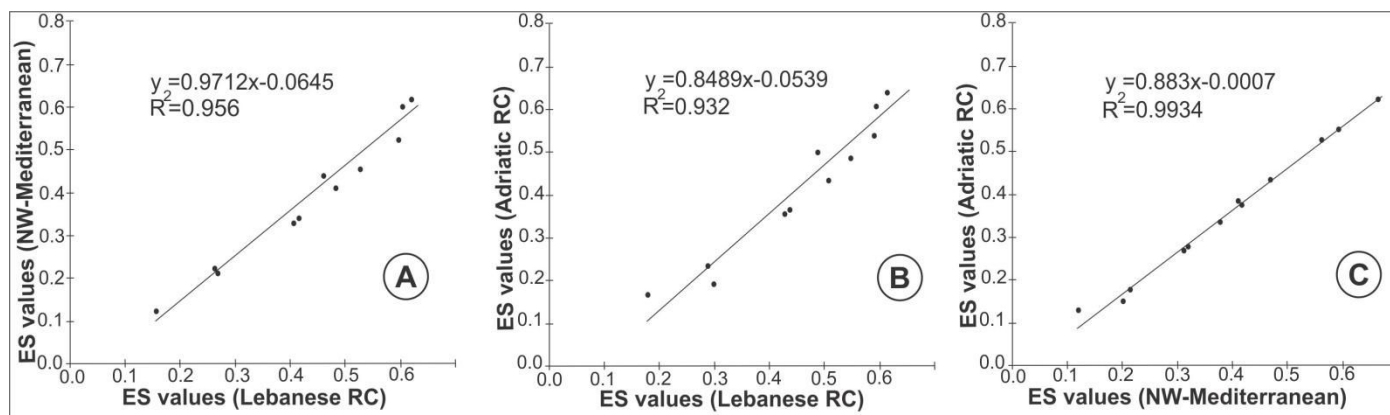


Fig. 5. Relation between the EQR values calculated under the three considered CARLIT RC: A) Lebanese RC, calculated in Nakoura, B) NW Mediterranean RC (Ballesteros et al., 2007) and C) Adriatic RC (Nikolić et al., 2013).

The pressure indexes LUSI, MA-LUSI and HAPI calculated in the 12 studied stretches of coast (Table 6) showed maximal values, corresponding to highest human impacts, in BEI area (LUSI: 26.0, MA-LUSI: 27.6 and HAPI: 5.9) and the lowest, corresponding to low human pressure, in NAK (LUSI:1, MA-LUSI:1.30, HAPI not calculated, as the EQR value calculated in the reference area is 1).

The ranking of human pressures scores is not always matching the ES ranking, but the linear correlation performed between the ES calculated with the three different RC and LUSI and MA-LUSI pressure indexes (Fig. 6), always highlighted significant strong relationships (Lebanese reference values: $n=11$; ES/LUSI $r = 0.85$, $p < 0.05$; ES/MA-LUSI, $r = 0.87$, $p < 0.05$; NW Mediterranean reference values: $n=12$; ES/LUSI $r = 0.79$, $p < 0.05$; ES/MA-LUSI, $r = 0.79$, $p < 0.05$; Adriatic reference values: $n=12$; ES/LUSI $r = 0.76$, $p < 0.05$; ES/MA-LUSI, $r = 0.76$, $p < 0.05$). A more detailed analyses of the ES and the relationships with the major pressure typologies (urban, industrial, agricultural, coastal artificialization, freshwater inputs), shows a high negative correlation with the urban pressure (table 7), followed by artificialization of the coastline, freshwater inputs (including rivers and sewage outfalls) and industrial pressure. The correlations with agricultural pressure and rivers were, on the contrary, not significant.

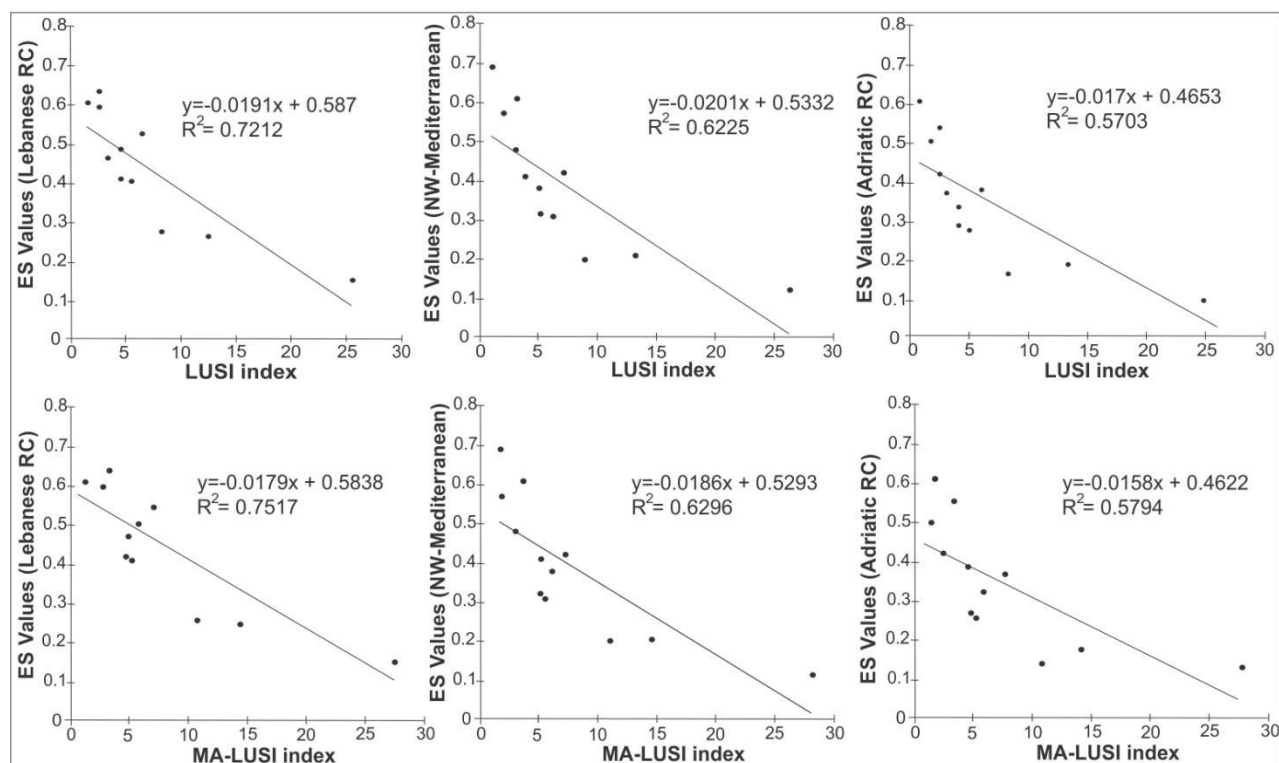


Fig. 6. Relation between the EQR values obtained by the three CARLIT RC (Lebanese, NW Mediterranean and Adriatic) and corresponding LUSI and MA-LUSI indexes of human pressures.

Table 7

Values of the correlation coefficient (r) from correlation matrix between the land uses pressures and EQR data for all the stretches of coast according to the three CARLIT methods (Significant correlation at $p < 0.05$).

CARLIT calculations	Pressure	Urban	Industrial	Agriculture	Artificialization	Freshwater (rivers)	Freshwater (rivers and sewage outfalls)
Lebanese RC	r	-0.819	-0.577	0.123	-0.750	-0.170	-0.720
	p-value	0.002	0.043	0.745	0.007	0.613	0.012
NW Mediterranean RC	r	-0.851	-0.610	0.102	-0.743	-0.169	-0.669
	p-value	0.000	0.035	0.750	0.005	0.599	0.010
Adriatic RC	r	-0.838	-0.584	0.113	-0.709	-0.153	-0.698
	p-value	0.001	0.040	0.720	0.004	0.698	0.012

The cartographic approach of the CARLIT method provides interesting insights on the distribution and conservation status of target communities. Large brown algae (*Cystoseira* and *Sargassum* species) covered the 31.8 % of the surveyed Lebanese coastline (see detailed distribution of these target species in Fig. 7). Other less sensitive photophilic algae, such as species belonging to the orders Dictyotales and Sphacelariales or to the *Laurencia* complex group represented the dominant community in 25.9% of the coastline, while erect Corallinales represented the dominant communities in 19.0 % of the coast. Green algae and Cyanobacteria, usually found in highly disturbed coasts, covered 23.1% of the surveyed coastline (respectively 18.7 % and 4.3 %).

The Factorial Correspondence Analyses (FCA) performed on the community categories shows a good association of the sites and the dominant categories (80 % of total variance represented by the first two axes, $p < 0.05$, Fig. 8). Cyanobacteria-dominated communities are associated to BEI area, characterized by a bad ES; Green algae, Tolerant Photophilic algae and Erect Corallinales are associated to stretches of coast with a moderate [e.g. Tabarja (TAB), Saadiyet (SAA), Saksakiyé (SAK) and TYR] to poor [e.g. Saida (SAI) and Jbeil (JBE)] ES; Ubiquitous Photophilic algae (UPHO) and *Cystoseira* communities are associated to stretches of coast characterized by good ES [e.g. Chekaa (CHE), Barbara (BAR), Adloun (ADL), Batroun (BAT) and to the reference area (Nakoura; NAK)].

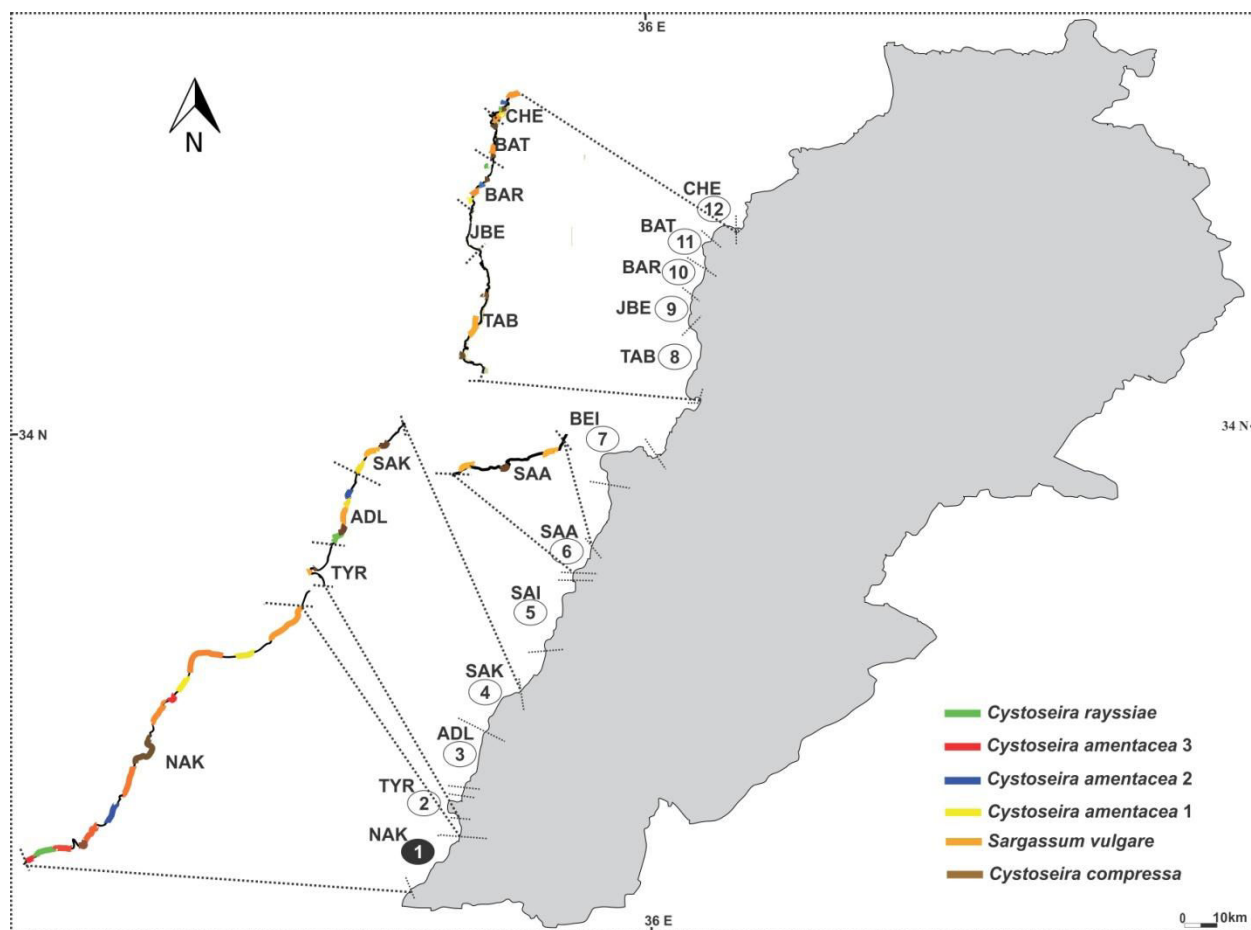


Fig. 7. The distribution of fucoids (*Cystoseira* and *Sargassum* species) along the Lebanese surveyed coastline.

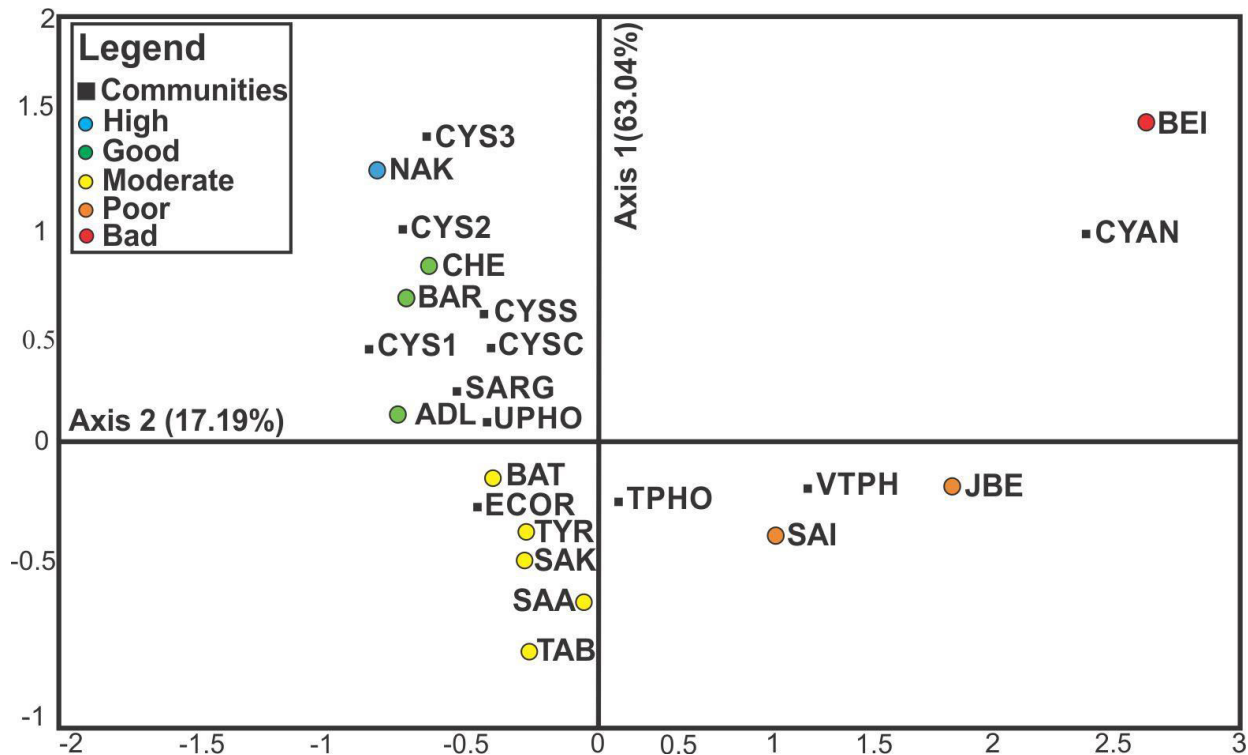


Fig. 8. Ordination of surveyed coastline stretches ($n = 12$) and community types derived from Factorial Correspondence Analysis (for abbreviations, see Table 1 and Table 6).

4. Discussion

The present application of the CARLIT (CARtography of LITtoral rocky-shore communities) index (Ballesteros et al., 2007) along Lebanese coasts represents the first assessment in the Levantine Sea of the Ecological Status (ES) of rocky shores, following the principles of the WFD 200/60/EU. The Lebanese coastline is currently subjected to several, often uncontrolled, human impacts, such as a fast urban development (MOE/UNDP/ECODIT, 2011), sewage outfalls (Abboud-Abi Saab et al., 2012a), industries (e.g. asbestos mines and factories producing phosphate fertilizers), overfishing by the use of illegal methods (Lteif, 2015) and an increasing spread of invasive lessepsian species (Bitar et al., 2017). Therefore, coastal ecosystems have suffered, in the recent decades (MOE/UNDP/ECODIT, 2011), important changes in species diversity and abundance and it is worth noting that deep water activities related to the oil and gas drillings have recently started. In counterpart, the awareness on the importance of reaching and maintaining a good ES is rising and poses a major challenge for setting up institutional monitoring programs. The Lebanese coastline is mostly characterized by rocky shores (70%, Kouyoumjian and Hamzé, 2012), making the indexes based on macroalgal communities very

adequate for the assessment of the ES. The CARLIT index was chosen because it is a fast, non-destructive and simple method that does not require further analyses in the laboratory, allowing wide scale studies: in the present study, 164 km of the Lebanese coastline were assessed.

The analysis of macroalgal community categories in function of the geomorphology of the coast revealed that coastal slope (e.g. horizontal/subvertical/vertical) and the nature of the substrate (natural/artificial) were the most relevant geomorphological features inducing changes in macroalgal assemblages. Nikolić et al. (2013) and Lasinio et al. (2017) proved that, in absence of anthropogenic pressures, the coastline slope could be the most relevant geomorphological feature in determining the distribution of shallow macroalgal communities such as *Cystoseira* species of the infralittoral fringe. The same studies (Ballesteros et al., 2007; Lasinio et al., 2017; Nikolić et al., 2013) also proved that the nature of the substrate (artificial versus natural) is a major source of variation for macroalgal communities. Such result is in agreement with a large amount of scientific literature on this topic, highlighting differences between artificial and natural substrates due to several interacting abiotic factors (i.e. reduced heterogeneity, unnaturally high anthropogenic disturbances) and biotic factors (i.e. increased herbivory and invasions) (Bulleri and Chapman, 2010; Ferrario et al., 2016; Firth et al., 2014), rather than to the physical features of each substrate. This generally results in less complex and less performant macroalgal assemblages on artificial substrates (i.e. Perkol-Finkel et al., 2006). Indeed, it is worth noting that in the Mediterranean Sea, *Cystoseira* species are rarely observed on artificial substrates (Gianni, 2016; Thibaut et al., 2016), and likely it occurs only when other ecological requirements of the species, such as good water quality, are guaranteed. This is in agreement with the results of the present study, in which no fucoids were recorded on artificial substrates.

In order to provide appropriate Ecological Quality Ratio (EQR) calculations for the Levantine Sea, characterized by more oligotrophic waters and lower species diversity than other Mediterranean areas (Martin et al., 2006), a search for potential reference sites was performed accordingly to the criteria applied in the framework of the MEDGIG (Mediterranean Geographical Intercalibration Group) for the implementation of the WFD 2000/60 EU. Ideally several reference sites should be selected in order to avoid biases due to the geographic position of the reference sites versus the studied sites, but unluckily this was not possible in Lebanon, as only one site included in the cartography (Nakoura) was compliant with the MEDGIG RC criteria. Based on the Lebanese RC, the results showed that, excluding the reference site Nakoura

covering 10.9 % of the surveyed coast, 29.9 % of the coast was assessed as belonging to the good, 37.1 % to the moderate, 12.1% to the poor and 9.9% to the bad ES. This result is particularly relevant when considering the principle of the WFD to reach and maintain a good ES. A comparison with the values calculated in the Northwestern Mediterranean (Ballesteros et al., 2007) and Adriatic reference sites (Nikolić et al., 2013) allowed to highlight relatively good correlations of EQRs, but some mismatches in the ES classes' agreement. This is due to the strict boundaries (no error assessment is allowed in classes attribution) and it highlights that appropriate reference conditions have to be chosen according to the area of study (Borja et al., 2012; Gaspar et al., 2012; Van Hoey et al., 2010). The extreme southern part of Lebanon (from NAK to SAK) is characterized by a good to moderate ES and it includes the most "pristine" zone, where the RC were calculated (NAK) and a good ES stretch (ADL). Agricultural discharges, polluted river runoff (e.g. Qasmiyé river) and solid wastes, in addition to illegal domestic/urban outfalls (Abboud-Abi Saab et al., 2008b) are most likely responsible of the moderate ES range of some stretches in the southern part of Lebanon (SAK, TYR). The southern and central zones of Lebanon, from SAI to BEI, are characterized by a moderate to bad ES. SAI has been affected by a thermal plant oil spill in 2006 (Khalaf et al., 2006) concerning about 140 km of coastline (from SAI, to JBE), likely responsible, together with urban and industrial influence, of the poor ES. The capital Beirut is the largest town of the Lebanese coastline. In Beirut water body the coastline urbanization is remarkable (> 450.000 inhabitants), the level of several pollutants in the sediments coming from industrial and urban wastewater sewages is high (Abi-Ghanem et al., 2016), it is affected by the runoff of the heavily polluted Beirut river (Abboud-Abi Saab et al., 2012a), by an intense maritime traffic (and consequent pollution from ships) and by large seafront dumpsites, altogether being the causes of the observed bad ES range. The northern zone (from TAB to CHE) is characterized by a good to moderate ES range, except for JBE, characterized by a poor ES, as it is heavily affected by urban and touristic activities (Byblos is a highly frequented cultural heritage destination), as well as intensive agricultural practices. In the same zone, several pollutants (oils and other noxious and hazardous substances) are accumulated in storage tanks with regular rejects in the seawater. Other stretches of the northern Lebanese coastline are characterized by a moderate ES (e.g. TAB and BAT) due to industrial activities [e.g. thermal and chemical discharges (Fakhri et al., 2008) and polluted river runoff (e.g. Naher Ibrahim; Abboud-Abi Saab et al., 2008)]. BAR and CHE are characterized by

a good ES. Rocky shallow communities, generally dominated by macroalgae, are known to be affected by several anthropogenic impacts (Crowe et al., 2000; Milazzo et al., 2004). The results of the present study shows that CARLIT-EQR results are well correlated to human pressure indicators (LUSI, MA-LUSI), in agreement with previous studies (Bermejo et al., 2013; Blanfuné et al., 2017; Nikolić et al., 2013; Torras et al., 2015). The present study allowed to show how urbanization, including artificialization of the coastline and sewage, are mostly affecting the very shallow communities, together with industrial impacts, as observed in other Mediterranean areas (Arévalo et al., 2007; Cavallo et al., 2016; Mangialajo et al., 2007; Pinedo et al., 2013). As a result, canopy-forming dominated assemblages tend to be lost as predicted (Benedetti-Cecchi et al., 2001; Mangialajo et al., 2008; Mineur et al., 2015; Thibaut et al., 2005) and to be replaced by less complex communities, characterized by stress tolerant, ubiquitous, opportunistic and ephemeral macroalgal species (Airoldi et al., 2014).

The CARLIT methodology also allows to perform a detailed cartography of the communities along the coastline. Such an assessment had never been performed before along the Lebanese coastline (and to our knowledge in neither part of the Levantine Sea). In the Mediterranean Sea, the highest complexity of shallow macroalgal assemblages is represented by furoid (*Cystoseira* and *Sargassum*) forests, generally considered locally threatened (Airoldi and Beck, 2007; Mineur et al., 2015; Strain et al., 2014). The application of the CARLIT method on the Lebanese coast provides an accurate description of the distribution and abundance of *Cystoseira* and *Sargassum* shallow forests. Four species of furoids have been recorded in the present study: *Cystoseira amentacea*, *Cystoseira compressa*, *Cystoseira rayssiae* and *Sargassum vulgare*. It is worth noting that *Cystoseira rayssiae*, endemic from the Levantine Sea (Ramon, 2000) has been recorded here for the first time along Lebanese coasts. *Cystoseira rayssiae* has been recorded in 4 stretches (NAK, ADL, BAR, CHE), covering 2% of the coast. *Cystoseira amentacea* has been recorded, in different abundance classes in 5 stretches (NAK, ADL, SAK, BAR, CHE), covering 9% of the coast. Most of the *Cystoseira amentacea* presence was recorded as isolated individuals, showing potentially suffering forests. Patches were abundant in 4 stretches (ADL, SAK, BAR, CHE), while continuous belts were recorded uniquely in NAK, the only site complying with the European criteria of a pristine area for the measure of RC. According to this study, *C. amentacea* was absent close to coastal artificialized areas (harbors and land reclamation zones) and severely polluted areas by urban and industrial sewage, as also reported in other

studies (Thibaut et al., 2014b). *Cystoseira compressa* and *Sargassum vulgare* were more abundant, present in all the stretches except SAI, BEI and JBE covering respectively 4 % and 17% of the coast, being absent uniquely in harbors and highly impacted areas. This is due to the fact that these species are less sensitive than most *Cystoseira* species (Mangialajo et al., 2012; Thibaut et al., 2005) and they have a higher recovery potential, due to their reproductive strategy (Guern, 1962; Steneck et al., 2002) involving drift of fertile portion of the ramifications and better dispersal. Since no long-term data series for benthic macrophytes are available for the Lebanese coastal waters, the present study represents the first assessment of the present state of macroalgal assemblages along the Lebanese coastline, allowing a baseline for monitoring their evolution in the future. This is highly important since loss of algal forests has already been recorded in several areas of the Mediterranean Sea (Airoldi and Beck, 2007; Mineur et al., 2015; Thibaut et al., 2014a; Thibaut et al., 2005) where historical data were present, but it is widely accepted that this loss may have happened without being noticed, due to the lack of past or even recent distribution data. For these reason, conservation and, when appropriate, restoration of marine forests should be seriously considered in several coastal zones (Gianni et al., 2013; Perkol-Finkel and Airoldi, 2010). The present study highlights that fucoids forests are still present in several Lebanese coasts and monitoring and conservation of such assemblages should be a priority in the framework of coastal zone management (Gianni et al., 2013). This is particularly important considering that the Lebanese coastline is under multiple stressors and about 32% of the surveyed coastline is already highly modified and artificialized. In addition, the entire Levant Basin is experiencing changes in marine assemblages at a very fast rate, due to the high impact of anthropogenic activities and the rise of seawater temperature (Doney et al., 2011), often associated with a continuous income of invasive species from the Suez Channel (Bitar et al., 2017; Galil et al., 2015). It is therefore of paramount importance to perform large scale assessment of marine assemblages in this Basin, in order to understand the magnitude of such changes and provide baselines for future assessments. The successful application of CARLIT method for the first time in a country of the Levantine Sea gives important insights on the ecological state of its coastal waters, and on the evolution of priority assemblages as marine forests of large brown seaweeds. Several advances have been performed in the evaluation of water masses at the European level (Birk et al., 2012; Hering et al., 2010), resulting in a potential recent improvement of the water quality (Borja et al., 2010; Pinedo et al., 2013). To go beyond

this approach it would be important to include in these studies non-EU countries, such as Lebanon, in order to improve the ecological status at the Mediterranean level.

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Supplementary data

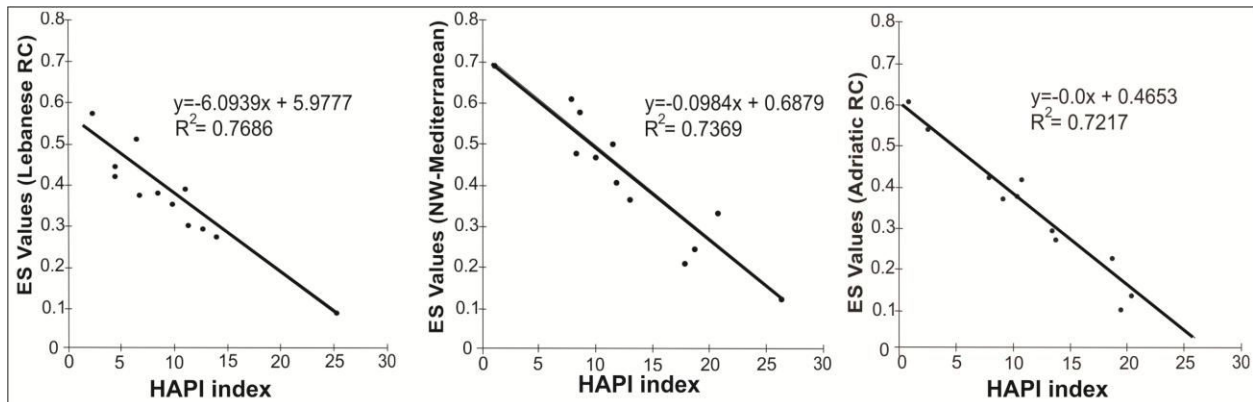
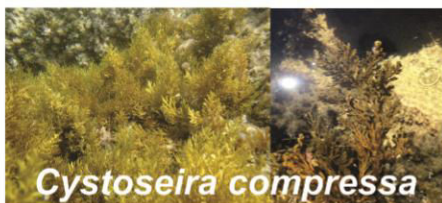


Fig. 9 Relation between the EQR values obtained by the three CARLIT RC (Lebanese, NW Mediterranean and Adriatic) and corresponding HAPI index of human pressures.

Box 1 Fucales (*Cystoseira* and *Sargassum*) species recorded during the application of the CARLIT index along the Lebanese coastline



Chapter 4 – Threatened biogenic formations of the Mediterranean: current status and assessment of the vermetid reefs along the Lebanese coastline (Levant Basin)

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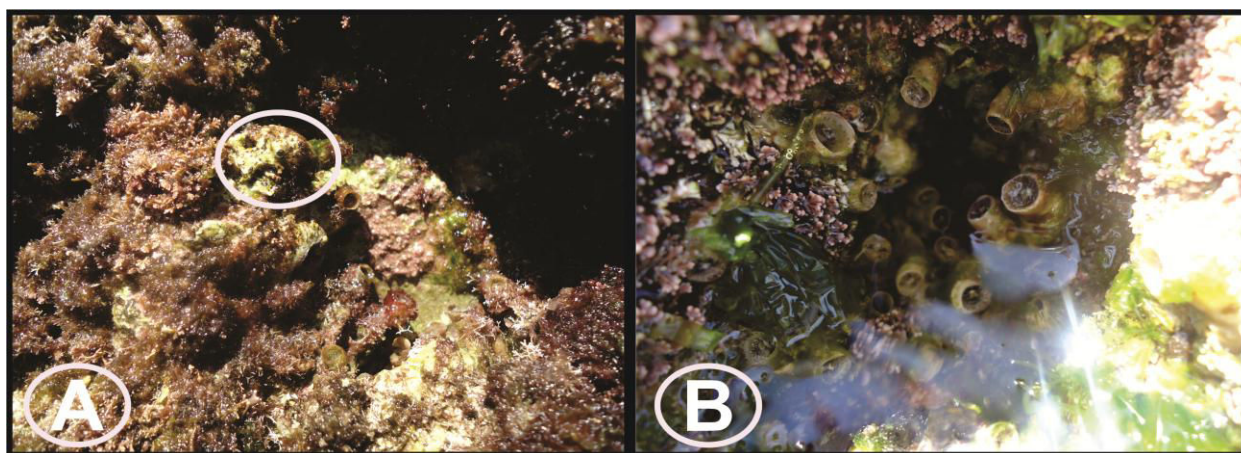
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Vermetids **A)** *Dendropoma anguliferum* and **B)** *Vermetus triquetrus* from the vermetid reef of Nakoura, south of Lebanon (eastern Mediterranean Sea). Photo: Badreddine A.

Abstract

Vermetid reefs are a key intertidal habitat in the warm-temperate part of the Mediterranean Sea and a few subtropical and tropical regions in the Atlantic and the Pacific ocean. These unique and highly diverse ecosystems are under siege due to both the high anthropogenic pressure and the global climate change, with documented local population declines in the Eastern Mediterranean. This study aims at evaluating the conservation state of vermetid reefs along the Lebanese coast (E-Med), where seawater warming, habitat degradation and coastal urbanization likely threaten their presence. We focused our surveys on the presence of living vermetids (*Dendropoma anguliferum* and *Vermetus triquetrus*), which shape the reef, and qualitatively compared our data with historical observations. Five sites were randomly selected among those belonging to three impact classes: i) undisturbed (i.e. protected), ii) moderately-urbanized, and iii) impacted, and two different non-destructive methods were applied to assess the conservation state of every reef and the associated communities. Our results highlight Lebanese vermetid reefs are highly vulnerable to human disturbances along the Lebanese coast. No living vermetid reefs were recorded in the impacted sites where evident signs of bio-physical erosion are already underway. Living individuals of *Vermetus triquetrus* were found in some undisturbed and moderately-urbanized sites, while living individuals of the endemic reef-builder *Dendropoma anguliferum* were found only at very low densities at the undisturbed (protected) site. Such findings corroborate preliminary observations of population decline in the Levantine Sea (E-Med), raise concerns about their near future persistence in the region, and represent a call for management and conservation actions to preserve this unique reef-building species in the Mediterranean Sea.

Key-words: Vermetid reefs, *Dendropoma anguliferum*, *Vermetus triquetrus*, *Neogoniolithon brassica-florida*, Levantine Sea, Lebanese coast.

4.1 - Introduction

Vermetid gastropods are important engineers in many coastal regions of the world (Breves et al., 2017; Milazzo et al., 2017; Miloslavich et al., 2010). These snails may form biogenic intertidal or shallow subtidal reefs and provide key ecosystem functions and services (Milazzo et al., 2017), by protecting the shoreline from wave erosion (Chemello and Silenzi, 2011 and references therein), sinking carbon, and being nursery and refuge habitats from predators for many diverse species assemblages (Chemello, 2009; Colombo et al., 2013; Donnarumma et al., 2014; Pandolfo et al., 1992a; Vizzini et al., 2012), including many invertebrates (Beneliahu, 1975; Chemello et al., 1998; Pandolfo et al., 1992b) and fish of commercial interest (Consoli et al., 2008; Goren and Galil, 2001).

In the Mediterranean Sea, the formation and persistence of vermetid reefs depend upon the actively rim-building gregarious gastropods of the genus *Dendropoma*, often in association with *Vermetus triquetrus* (Bivona-Bernardi, 1832), another solitary vermetid, and the crustose coralline alga *Neogoniolithon brassica-florida* Harvey (Setchell and Mason, 1943) which cements their tubular shells. Restricted to the warmest part of the Mediterranean Sea (Laborel, 1987; Safriel, 1974), vermetid reefs have been reported from several locations along the Mediterranean coasts (Milazzo et al., 2017 and references therein). Molecular analyses have recently revealed that the former *Dendropoma petraeum* species actually comprises a complex of four different cryptic species (Calvo et al., 2009; Golding et al., 2014; Usvyatsov and Galil, 2012) in the Mediterranean. As a result, it is now accepted that *D. petraeum* is a junior synonym of *D. cristatum* as previously proposed by (Scuderi, 1995), the westernmost Mediterranean species was named *D. lebeche*, while the easternmost one was ascribed to *D. anguliferum* (Templado et al., 2016).

Despite *Dendropoma* reefs are widespread along the warm-temperate part of the Mediterranean Sea, shaping the coastal seascape of many rocky areas, these unique biogenic reefs are rarely object of appropriate management and monitoring activities (Milazzo et al., 2017) as well as studies on are indeed rare, particularly in the Levantine basin (Galil, 2013). Likely following a precautionary approach, Mediterranean vermetid reefs are now listed as vulnerable habitats in the IUCN Red List (Gubbay et al., 2016), with many experts recognizing *Dendropoma* spp. and *Neogoniolithon brassica-florida* as species deserving protection (Abdulla et al., 2009; Fine et al., 2017; Langar et al., 2011; Relini, 2000; Scotti and Chemello, 2000).

Indeed, an example of such lack of information is represented by the significant *Dendropoma anguliferum* demise recently documented along the coast of Israel (Galil, 2013; Rilov, 2013, 2016; Usvyatsov and Galil, 2012). Such a rapid vermetid populations decline was hypothesized to be driven by multiple global (e.g. ocean warming, Rilov et al., 2016) and local impacts (e.g. coastal urbanization, Di Franco et al., 2011 and pollution, Rilov et al., 2016; Klerman et al., 2004) occurring in the last few decades in the region.

In the last decades, the Lebanese coastline have suffered severe anthropogenic pressures, including over-exploitation and pollution from different origins, making the current uses of coastal areas unsustainable (MOE/UNDP/ECODIT, 2011). These activities include, among others: marine sand and gravel extraction, sewage (Abboud-Abi Saab et al., 2012b) and oil dumping, unsustainable and illegal fisheries (Lteif, 2015), habitat degradation, recreational uses, coastal urbanization, invasive species (Bitar et al., 2017), along with large-scale impacts such as the effects of climate change. Events like the enlargement of the Suez Canal and the deep water activities related to the oil and gas drillings recently started, pose further major challenges to plan monitoring and management actions for this unique coastal ecosystem. By assessing the current conservation status of the vermetid reefs along the Lebanese coastline, where they represent the most dominant rocky formation (Sanlaville, 1977), we aim at contributing to fill a knowledge gap on population status of the vermetid reefs along the Levant Basin coastline. Specifically, we surveyed the vermetid reefs of five sites, along an established gradient of anthropogenic disturbance from south to north Lebanon. Therefore, we quantified the number of both living and dead *Dendropoma anguliferum* and *Vermetus triquetrus* individuals, along with the cover of *Neogoniolithon brassica-florida* and the composition and structure of the whole associated benthic communities. A comparison with historical data (particularly rare for the region) was also performed to assess the evolution of reefs in the recent decades.

4.2 - Material and Methods

4.2.1 - Study area

Lying at the northeastern tip of the Mediterranean Sea (Fig. 1), Lebanon has about 220 km of coastline, characterized by a narrow continental shelf, perpendicularly crossed by various canyon systems that connect coastal zones to deep-sea habitats. Eighty percent of the Lebanese coast is rocky with the remaining 20% reported to be sandy with some gravel (MOE/UNDP/ECODIT, 2011). Vermetid reefs, as the most dominant rocky formation along the Lebanese coast (Fevret

and Sanlaville, 1966; Kouyoumjian and Hamzé, 2012; Sanlaville, 1977), have never been the object of a detailed monitoring study. A literature survey of studies mentioning “vermetid reefs” (typology, description and ecology) in the sea coastline of Lebanon, has been conducted. These data included scientific papers (including non-peer-reviewed and/or non-indexed articles), books, reports submitted to international organizations (e.g. RAC-SPA and UNEP) and/or Lebanese environmental agencies. Only a few studies investigated the typology and the ecology of vermetid reefs or the associated benthic communities along the Lebanese coastline (Bellan-Santini et al., 2015; Bitar and Bitar-Kouli, 1995a, b; Dalongeville, 1977; Fevret and Sanlaville, 1965, 1966; Gruvel, 1931; Pergent et al., 2007; Sanlaville, 1977; Sanlaville et al., 1997). Generally they consisted in general descriptions (Bitar and Bitar-Kouli, 1995a, b; Sanlaville, 1977) and/or benthic fauna species inventories (Lakkis and Novel-Lakkis, 2000; Ramos-Esplá et al., 2014), whilst evidence of living vermetid reefs along the Lebanese coastline have only been reported in one study (Morhange et al., 2006). The study was performed along five sites from the south to the north of Lebanon (Fig. 1). The selection of sites was performed according to the presence of large vermetid reefs and different levels of human pressure. Each level of human impact was assessed by applying the LUSI index (Land Use Simplified Index (Flo et al., 2011), as reported in Badreddine et al. (2018) (see Table 1). LUSI index integrates several impacts (i.e. urbanization, agricultural and industrial activities, sewage outfalls, commercial harbors, aquaculture or freshwater input). Subsequently, scores were assigned to each type and level of pressure and added up to produce the final LUSI value (Badreddine et al., 2018; Flo et al., 2011). Two sites were considered as highly impacted (Beirut and Tripoli), two others as moderately urbanized (Tyr and Batroun) and two as undisturbed (Nakoura and Palm Island). Unluckily due to logistic (and political) reasons, the Marine Protected Area of Tripoli (Palm Island, North Lebanon) was not accessible and therefore only the Nakoura site was sampled.

Table 1

Sites considered for the assessment of vermetid reefs along Lebanese coast, their coordinates, the LUSI index calculated and the corresponding categories and conditions (see Flo et al., 2011 for further details).

Sites	Latitude, longitude	LUSI	Conditions
Nakoura	33° 8'25.15"N, 35° 9'14.82"E	0.00	Undisturbed
Tyr	33°16'33.58"N, 35°11'34.64"E	3.00	Moderately - urbanized
Beirut	33°54'9.15"N, 35°29'2.02"E	26.00	Impacted
Batroun	34°15'1.26"N, 35°39'23.97"E	7.00	Moderately - urbanized
Tripoli	34°26'15.77"N, 35°48'40.03"E	29.00	Impacted

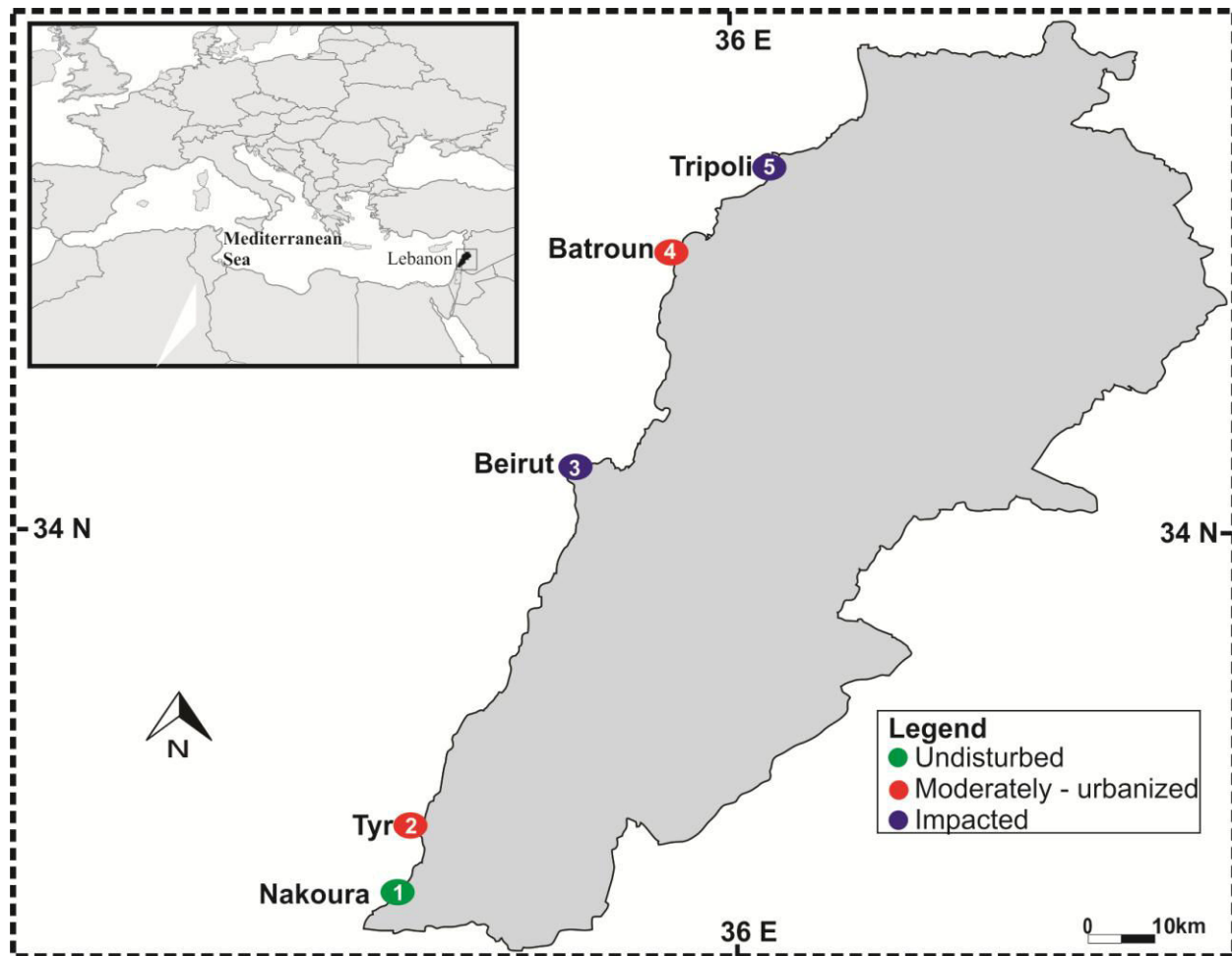


Fig. 1: Map of Lebanon showing the location of the five monitored sites. 1- Nakoura (Undisturbed); 2- Tyr (Moderately - urbanized); 3- Beirut (Impacted); 4- Batroun (Moderately - urbanized) and 5- Tripoli (Impacted).

2.2 - Sampling procedures

The surveys were conducted at low tide and under calm water conditions. At each sites, a qualitative description of the reef was performed, considering the following variables: (i) reef width from the inshore towards the open sea, (ii) presence of the “cuvettes” between edges of each vermetid platform and (iii) height of the inner and the outer margins. The most representative species in each zone of the vermetid reef were also noted.

The assessment of the whole benthic assemblages and of living and dead vermetids (*D. anguliferum* and *V. triquetrus*) was performed by point intercept transects and random 10 x 10 cm quadrats. Since the vermetid distribution can be very patchy particularly when disturbed, and the spatial scale of the different anthropogenic impacts we considered was unknown, these two

techniques were employed to avoid underestimation of vermetids presence. At each sampling site, 10 random 5 m long transects, parallel to the coastline were laid along both the inner edge (i.e., 5 transects) and the outer edge (5 transects) of the reefs. Species were identified every 20 cm on 25 points for each 5m transect. The percentage cover of living vermetids (*Dendropoma anguliferum* and *Vermetus triquetrus*), the calcareous encrusting algae *Neogoniolithon brassica-florida* cementing their shells, and of other algae and invertebrate species were then calculated for each replicated transect. The visual census of the benthic communities allowed us to identify 17 species (or higher taxonomic levels), which were regrouped in 11 Operational Taxonomic units (OTUs) of algae and invertebrates (Table 2). In addition to this, ten 10 x 10 cm plots, were randomly placed both in the inner (i.e. 5 photo - replicates) and the outer edges (5 photo - replicates) of the reefs and photographed with a digital camera (Sony, DSC-W550). In the lab, the density of living vermetid individuals was estimated on each photo by counting the shell opercula, which protect the living animal from predation, desiccation and wave impact, while get lost in dead individuals. Empty shells were also counted to assess the density of dead vermetid individuals. Density counts were performed using the open access ImageJ software (Schneider et al., 2012).

Table 2

List of Operational Taxonomic Units (OTUs) and corresponding species used for the community analyses

OTU designation	Species	Taxonomic group
DEN	<i>Dendropoma anguliferum</i>	Gastropod
VER	<i>Vermetus triquetrus</i>	Gastropod
PATE	<i>Patella</i> spp.	Gastropod
BRACH	<i>Brachidontes pharaonis</i>	Bivalve
CHTH	<i>Chthamalus</i> spp.	Cirriped
ECOR	<i>Corallina</i> spp., <i>Jania rubens</i>	Algae
SAR	<i>Sargassum vulgare</i>	Algae
UPHO	<i>Padina pavonica</i> , <i>Dictyota</i> spp., <i>Dictyopteris polypodioides</i> , <i>Taonia atomaria</i> , <i>Laurencia</i> complex,	Algae

ULVA	<i>Ulva</i> spp.	Algae
NEOG	<i>Neogoniolithon brassica-florida</i>	Algae
CYAN	<i>Rivularia</i> spp.	Cyanobacteria

2.3 - Data analyses

The multivariate patterns of the benthic assemblage composition and structure of the transects data were visualized by non-metric multidimensional scaling (nMDS) ordinations performed on the Bray-Curtis similarity matrix applied to square root transformed data. Two separate analyses were run for the two edges (inner and outer) in all the sites surveyed. Statistical differences in the benthic assemblages were tested by permutational multivariate analysis of variance (PERMANOVA, Anderson, 2001) based on Bray-Curtis resemblance matrix of square-root transformed data. A two-way orthogonal model was used, with Site (Si, 5 levels: Nakoura, Tyr, Beirut, Batroun and Tripoli) as a fixed factor and Edge (Ed, two levels: outer and inner) as a fixed orthogonal factor. To test the differences between Sites (Si), the density data of both living and dead vermetids (*Dendropoma anguliferum* and *Vermetus triquetrus*) were analysed by one - way PERMANOVA based on Euclidean distance matrix of untransformed data. For all the PERMANOVAs, P-values were obtained from 9999 permutations. Pair-wise t tests were performed in order to discern eventual differences among levels of significant factors or their interaction. Monte Carlo tests were also considered in case of low numbers of unique permutations. The PRIMER 6, PERMANOVA package was used to perform statistical analyses (Clarke and Gorley, 2006).

3 - Results

3.1 - General description of the Lebanese vermetid reefs

The vermetid reefs of the Lebanese coast form an intertidal platforms (Fig. 2), with widths from 70 m (Tyr) to nearly 170 m (Batroun). A general scheme of the reef topography is reported in Fig. 2, while a detailed description of the five monitored sites is reported in Fig. 3. Moving seaward, the platforms can be divided into three typical morphological zones: the outer edge, the “cuvettes” and the inner edge (Fig. 2). The outer edge is wide, flattened with some crevices in Nakoura (Fig. 3.1), Tyr (Fig. 3.2) and Batroun (Fig. 3.3) reefs, while is thin and sometimes absent in the platform of Beirut (Fig. 3.5) and Tripoli (Fig. 3.4). The inner edge is irregular with many tidal pools in Nakoura (Fig. 3.1), Tyr (Fig. 3.2) and Batroun (Fig. 3.3) platforms, and is mostly shallow and often lacking “cuvettes” in Tripoli (Fig. 3.4) and Beirut (Fig. 3.5). The

macrobenthic species identified on the Lebanese vermetid reefs were typically the lichen *Verrucaria amphibian*, the littorinids (*Melarhappe neritoides* and *Echinolittorina punctata*), and the isopoda *Ligia italica* in the supralittoral zone. The sessile fauna was mostly represented by *Chthamalus depressus* and *C. montagui*, whereas mobile species such as *Patella ulyssiponensis* and *P. rustica* and the intertidal crab *Pachygrapsus marmoratus* were found in the upper midlittoral zone. The lower midlittoral rock was characterized by *Vermetus triquetrus* occurring in the inner edge and *Dendropoma anguliferum* only present in the outer edge of the Nakoura reefs; along with other mobile invertebrates like the gastropods *Patella ulyssiponensis* and *Phorcus turbinatus*, and the crab *Pachygrapsus marmoratus*. Often vermetid species were in association with the red encrusting alga *Neogoniolithon brassica-florida*. Shallow tidal pools or “cuvettes”, considered an infralittoral enclave, were frequent in the Lebanese vermetid reefs and were mostly dominated by macroalgae (e.g., Corallinales, Dictyotales, Sphacelariales and Ulvales) (Fig. 2).

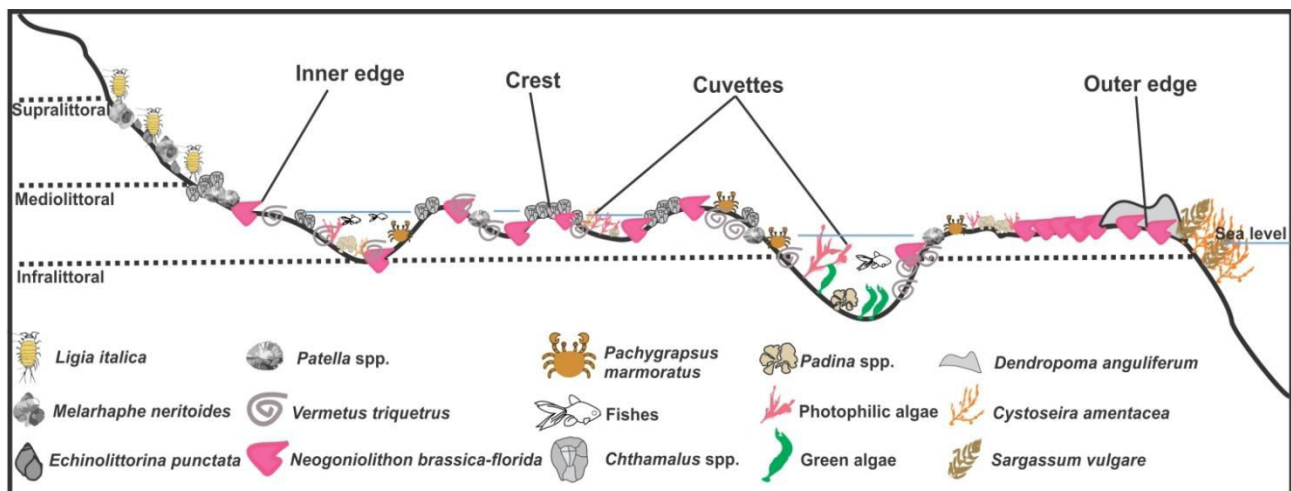


Fig. 2: Schematic illustration of a typical vermetid reef along the Lebanese coast, reporting the relative position of the reef according to the sea level (supralittoral, upper and lower mediolittoral and infralittoral, following the Mediterranean scheme (Pérès and Picard, 1964), and some characteristic species.

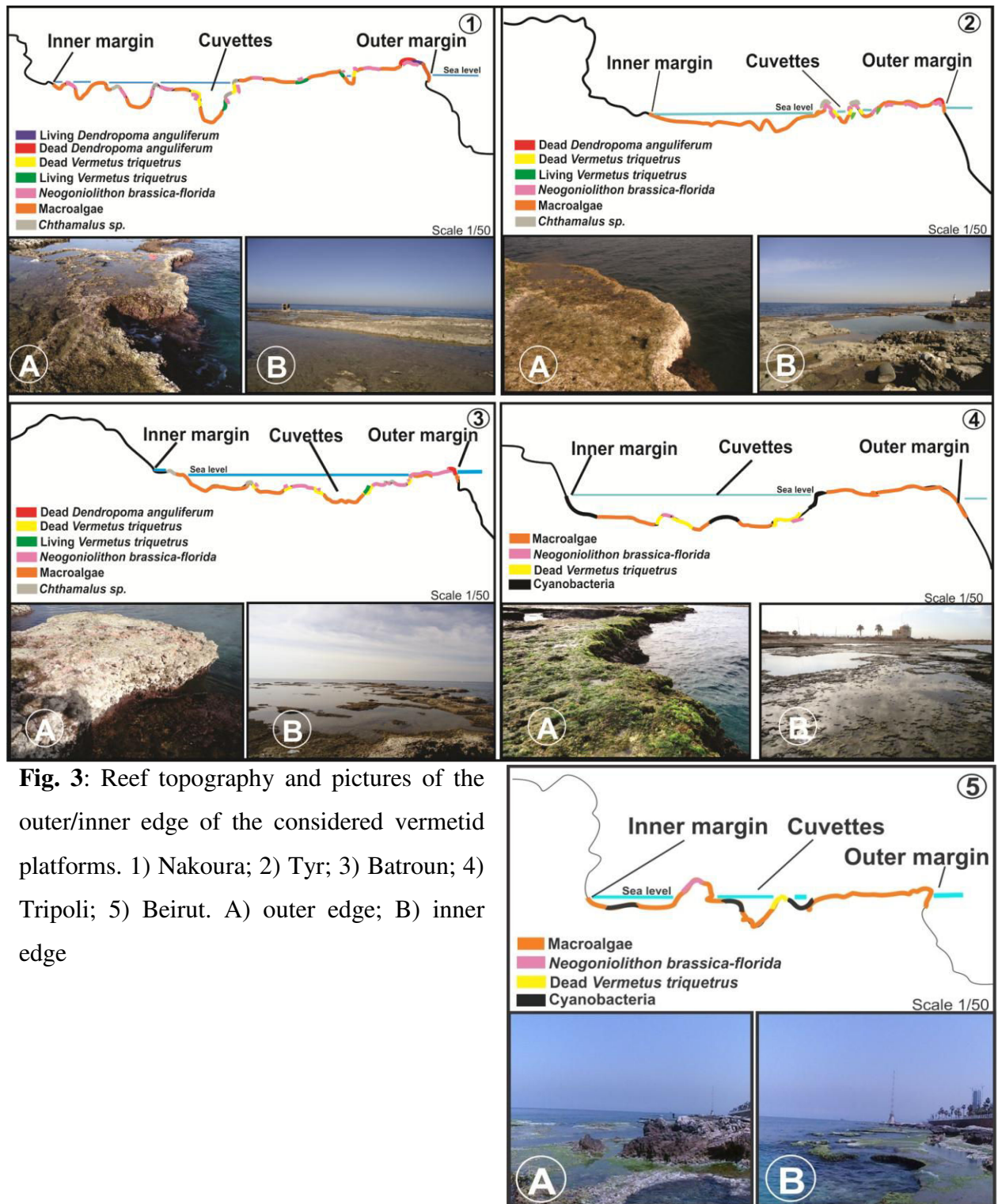


Fig. 3: Reef topography and pictures of the outer/inner edge of the considered vermetid platforms. 1) Nakoura; 2) Tyr; 3) Batroun; 4) Tripoli; 5) Beirut. A) outer edge; B) inner edge

3.2 - Assessment of benthic assemblages and vermetid population densities along the Lebanese coast

Composition and structure of the benthic assemblages of both the outer and inner reef edges strongly differed among the five sites subjected to different levels of anthropogenic pressures (Fig. 4).

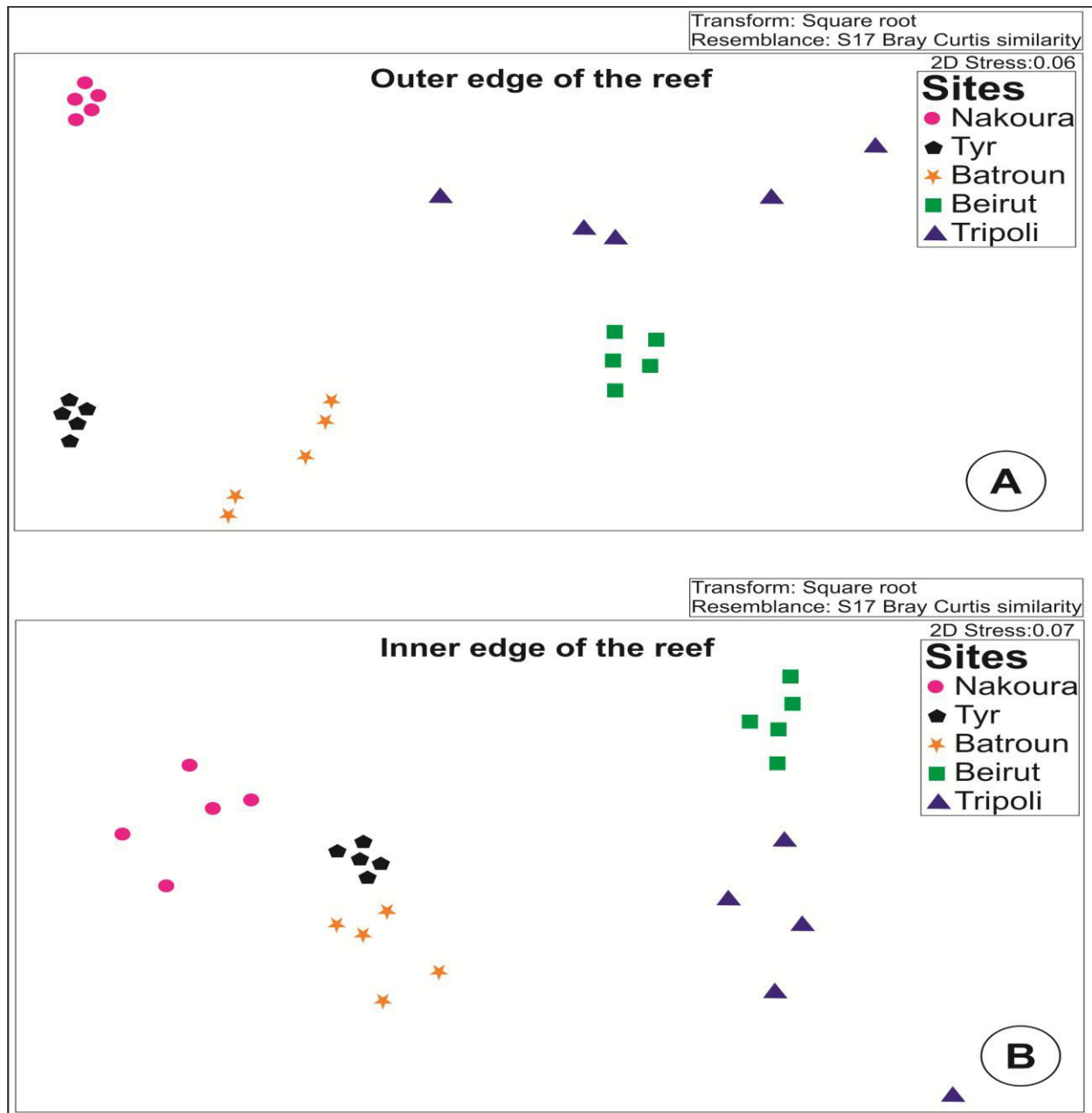


Fig. 4: Non-metric multi-dimensional scaling (nMDS) on benthic assemblages, using the transect method at the five studied sites. nMDS as a function of A) outer edge and B) inner edge.

PERMANOVA showed a significant ‘Edge x Site’ effect on the benthic assemblages (Pseudo-F: 23.873; $p < 0.001$; Table 3) and every pair-wise comparison supported highly significant difference between sites either in the outer or the inner edge (Pair-wise t tests, Table S1).

Table 3

PERMANOVA analysis on the benthic assemblages censused by the transect method. Ed: reef Edges; Si: Sites. Statistically significant values are in bold.

Source	df	SS	MS	Pseudo-F	P(perm)
Edge (Ed)	1	34805	34805	181.39	0.0001
Site (Si)	4	45639	11410	59.463	0.0001
EdxSi	4	18323	4580,8	23.873	0.0001
Res	40	7675,2	191,88		
Total	49				

In the inner edge, the reef-building encrusting red alga *Neogoniolithon brassica-florida* dominated in the undisturbed site of Nakoura and at the moderately disturbed sites of Tyr and Batroun (with average values ranging between 40% to 50%) (Fig. 5). Similar patterns were observed on the outer edge, but the Tyr vermetid reefs, where macroalgae were the most dominant group with on average more than 60 % cover (Fig. 5). Cyanobacteria and green turf algae mostly characterized the heavily impacted reefs of Beirut and Tripoli, where % cover of nude rock, likely covered by biofilm was also very high (Fig. 5).

More importantly, living individuals of *Dendropoma anguliferum* were only recorded at the outer edge of Nakoura (with an average 14.5 % cover), while *Vermetus triquetrus* was recorded in patches in the inner edge of the undisturbed site of Nakoura, and the moderately - urbanized sites of Batroun and Tyr reefs (with average values ranging from 16 % to 40 %, Fig. 6).

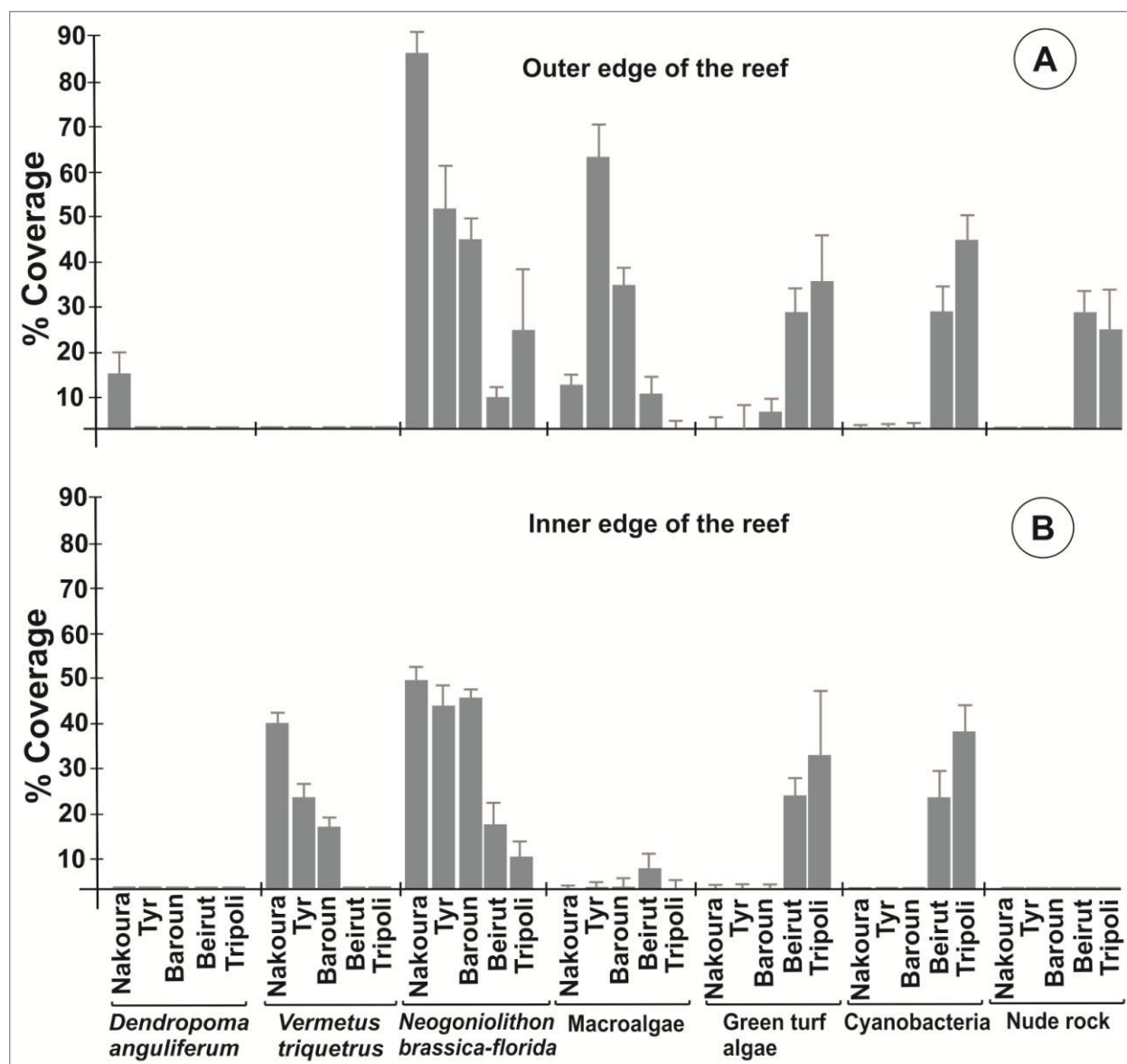


Fig. 5: Average \pm standard error (S.E.), of the most representing benthic assemblages data collected using transects methods at A) the outer edge and B) the inner edge.

Photo-sampling to assess the vermetid population density over the five sites spanning the Lebanese coast revealed that the maximum vermetid density recorded was on average 11 individuals per 100 cm^{-2} of *V. triquetrus* in the inner edge of the Nakoura reefs (Fig. 6). By contrast, very low average density of *Dendropoma anguliferum* (i.e., ~ 1 individuals per 100 cm^{-2}) was recorded on the outer edge of the undisturbed Nakoura reefs (Fig. 6). Both vermetid species were absent at the impacted sites of Beirut and Tripoli, and only *V. triquetrus* showed low densities in the moderately - urbanized reefs of Tyr and Baroun (Fig. 6). The statistical

analyses (PERMANOVA and pair-wise t tests) provided consistent results for the two vermetid species (Table 3), showing significant differences among Nakoura and Batroun, Beirut and Tripoli sites. The Tyr site was not significantly different from the other 5 sites, showing therefore an intermediate position, meanwhile for Beirut, Tripoli and Batroun the denominator was equal to zero. Densities of dead vermetids peaked in Batroun, Tyr and Nakoura for *Dendropoma anguliferum* and in Tripoli and Batroun for *Vermetus triquetrus*, showing no difference among sites (Table 4).

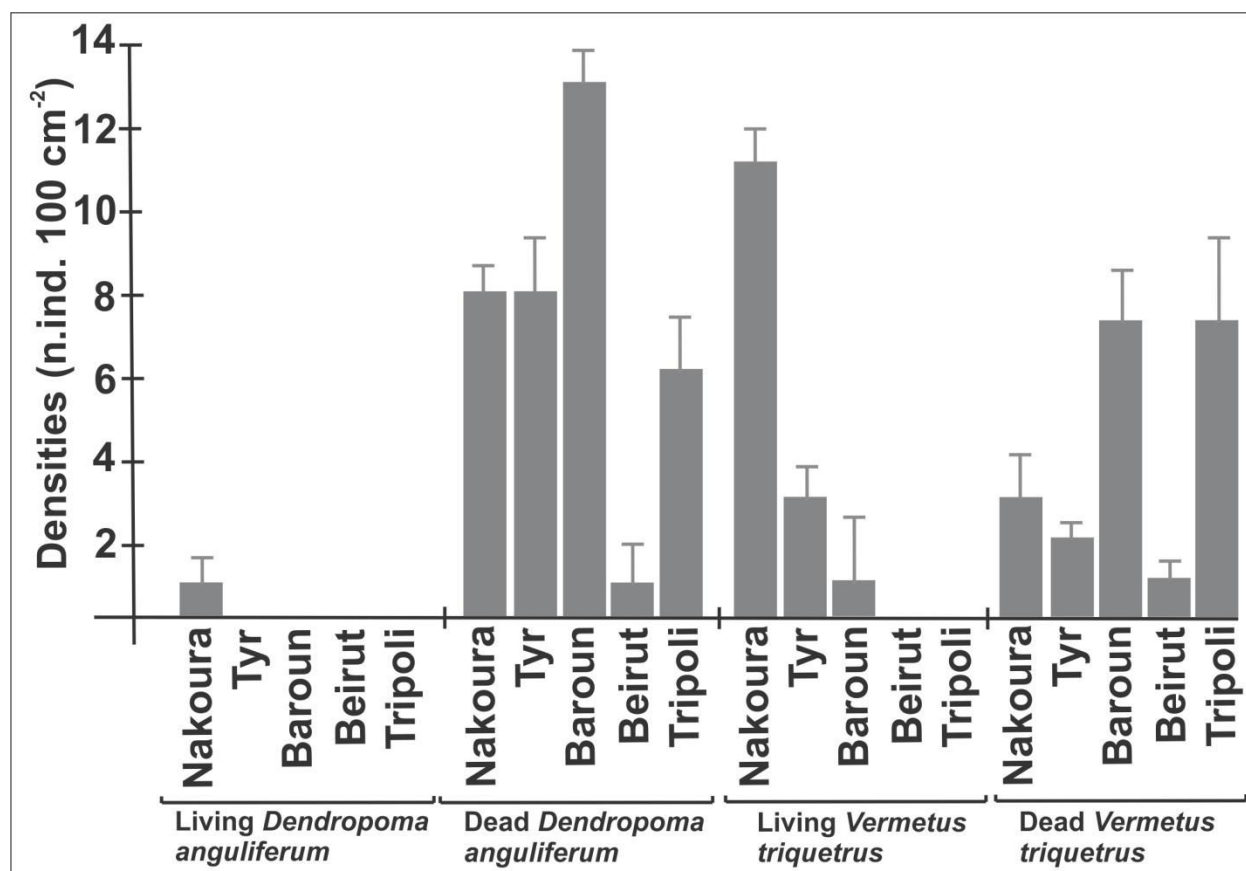


Fig. 6: Mean (\pm standard error) density (number of individuals per 100 cm⁻²) of living and dead vermetids (i.e., *Vermetus triquetrus* and *Dendropoma anguliferum*) at the five monitored sites.

Table 3

One - way PERMANOVA and pair wise t tests (only significant comparisons are presented) on the densities of *Dendropoma anguliferum* and *Vermetus triquetrus* (n. ind. 100 cm⁻²). Si: Sites. MC: Monte-Carlo. Statistically significant values are in bold.

Living <i>Dendropoma anguliferum</i> vermetids						<i>Vermetus triquetrus</i>					
Source	df	SS	MS	Pseudo -F	P(MC)	df	SS	MS	Pseudo- F	P(perm)	
Si	4	1.36	0.34	3.4	0.0272	4	750.72	187.68	4.1246	0.0071	
Res	45	2	0.1			45	2047.6	45.502			
Total	49	3.36				49	2798.3				
Pairwise test (Si)	t	P(MC)				Pairwise test (Si)	t	P(MC)			
Nakoura vs. Beirut	2.4495	0.0376				Nakoura vs. Beirut	2.3313	0.0308			
Nakoura vs. Tripoli	2.4495	0.0367				Nakoura vs. Tripoli	2.3313	0.0309			
Nakoura vs. Batroun	2.4495	0.0364				Nakoura vs. Batroun	2.3313	0.0325			

Table 4

One-way PERMANOVA on the densities of dead individuals (i.e. empty shells) of *Dendropoma anguliferum* and *Vermetus triquetrus* (n. ind. 100 cm⁻²). Si: Sites.

Dead <i>Dendropoma anguliferum</i> vermetids						<i>Vermetus triquetrus</i>				
Source	df	SS	MS	Pseudo- F	P(perm)	df	SS	MS	Pseudo- F	P(perm)
Si	4	693.3	173.3	1.563	0.1978	4	750.72	72.23	1.383	0.236

Res	45	4991	110.9	45	2047.6	52.229
Total	49	5684		49	2798.3	

4 - Discussion

The present study represents the first quantitative assessment of vermetid populations along the Lebanese coast and one of the few for the Levantine Sea (Eastern Mediterranean). It meets the urgent call for addressing the potential impacts of anthropogenic activities on the intertidal reefs built by *Dendropoma anguliferum*, an endemic species of the Levantine Sea, whose local extinction is presently underway (Galil, 2013; Rilov, 2016). The observations performed prove that Lebanese vermetid reefs have a similar general morphology to the one described along Israeli (Lipkin and Safriel, 1971; Safriel, 1974), Syrian (Al-Nimeh and Ellassafin, 1996) and Maltese (Azzopardi and Schembri, 1997) coasts, showing very large intertidal platforms between the reef edges (Fig. 2) (Chemello and Silenzi, 2011; Sanlaville, 1977). Along the Lebanese coast, *Dendropoma anguliferum* individuals in association with the encrusting alga *Neogoniolithon brassica-florida* are found in the seaward outer edge of the reef, exposed to higher wave energy. By contrast, the landward inner edge, exposed to a longer period of emersion during low tide and higher desiccation stress in the warmest months, is mostly characterized by *Vermetus triquetrus*. Remarkably, the presence of living individuals of *Dendropoma anguliferum*, at very low densities, was observed uniquely at the outer edge of the undisturbed reef of Nakoura. Living individuals of *Vermetus triquetrus*, occurring the inner edge of the reefs, were recorded at the undisturbed reef of Nakoura and, again at lower densities, at the moderately-urbanized reefs of Tyr and Batroun. The present study also shed light on the distribution of the encrusting calcareous algae *Neogoniolithon brassica-florida*, considered as a significant Mediterranean reef-builder (Milazzo et al., 2017), along the surveyed Lebanese reefs. As result, a high percentage coverage of *Neogoniolithon brassica-florida* was recorded at the undisturbed reef of Nakoura and the moderately-urbanized reefs of Tyr and Batroun, where living individuals of vermetids are still present. While *N. brassica florida* was mostly absent at the impacted sites of Beirut and Tripoli, where only dead vermetids were recorded. The potential decline of *N. brassica florida* along disturbance gradients have also been reported along the Israeli (Fine et al., 2017) and Tunisian coast (Langar et al., 2011), confirming the sensitivity of *N. brassica-florida* to both natural (e.g. calcification, Fine et al., 2017 and sea warming, Rilov et al., 2016) and human pressures. Furthermore, the observed changes in the composition and structure of the

benthic assemblages suggested, in both the internal and the external edges, a global decreasing in community complexity and species diversity from the undisturbed to the impacted sites. More specifically, the canopy-forming *Sargassum vulgare* (Fucales, Phaeophyceae) was only recorded at the undisturbed site of Nakoura, whereas less complex algae represented by Dictyotales and Corallinales dominated the moderately-urbanized reef of Tyr and Batroun. Green algae, small turfs and cyanobacteria characterized the impacted sites of Beirut and Tripoli. These results are in agreement with the general trend of fucoids loss and replacement by turf algae (Airoldi et al., 2014; Connell et al., 2014; Mancuso et al., 2017; Mangialajo et al., 2008; Strain et al., 2014) well described along Mediterranean coasts by several studies (Ballesteros et al., 2007; Blanfuné et al., 2016c; Orlando-Bonaca and Rotter, 2018) and with a recent assessment of littoral benthic communities carried out along the Lebanese coasts (Badreddine et al., 2018).

The loss of individuals of *Dendropoma anguliferum* in the moderately and highly impacted Lebanese sites seems to have happened in a recent past, as living individuals (referred as *Dendropoma petraeum*) were reported for the Tyr reef in 2002 (Morhange et al., 2006). A further evidence for a recent process of population loss is represented by the observed high density of dead shells in the undisturbed and the moderately-urbanized sites (personal observation). It is worth stressing that the natural recovery of reefs where *Dendropoma* is completely lost is very unlikely, because of the low recruitment from adjacent healthy reefs (Milazzo et al., 2017): *Dendropoma* species show a peculiar reproduction characterized by low connectivity and dispersal range (Calvo et al., 1998), as snails brood their young and the hatchlings crawl only a short distance before becoming a sessile individual (Milazzo et al., 2017). The presence of living *Vermetus triquetrus*, at low densities, in other moderately urbanized sites (Tyr and Batroun reefs), is likely due to the fact that *Vermetus triquetrus* is less sensitive to human pressures (Calvo and Templado, 2005; Schiaparelli et al., 2003) and that his dispersal potential is higher (Bieler, 1995; Calvo and Templado, 2005; Schiaparelli et al., 2006; Schiaparelli and Cattaneo-Vietti, 1999; Schiaparelli et al., 2003). A similar phenomenon has been observed along the Italian (Di Franco et al., 2011; Graziano et al., 2007), Spanish (Donnarumma et al., 2014) and Israeli coasts (Usvyatsov and Galil, 2012): the highest densities (>50000 individuals per m²) of *Dendropoma petraeum* were recorded at the outer edge of the surveyed reefs, in absence of anthropogenic pressures. Subsequently, the total abundance (100 individuals per m²) of all living vermetids recorded only at the undisturbed and the moderately-urbanized Lebanese surveyed

reefs is very low when compared to the work of Di Franco et al., (2011) that showed around 10000 individuals of living *Dendropoma cristatum* (as *D. petraeum*) at a disturbed site in Italy. The causes of such ongoing loss are still unknown (Milazzo et al., 2017). Several hypotheses have been proposed to explain such large mortality events, which seem to be led by the combined multiple natural and human stressors (Rilov, 2016). The Lebanese coastline, as the entire Levant Basin, is experiencing major ecosystems-wide change, due to **the multiple and massive** anthropogenic and natural pressures, such as climate change (e.g. the rise of the SST, Abboud-Abi Saab et al., 2013), overfishing (Lteif, 2015) and coastal urbanization and artificialization involve 32% of the Lebanese coastline (Badreddine et al., 2018).

A supplementary potential threat is the trampling of tourists and fishermen that may affect vermetid recruits survival and settlement success (Milazzo et al., 2017) as well as the associated benthic assemblages (Milazzo et al., 2004; Milazzo and Ramos-Esplá, 2000). It is also likely that, the prolonged exposure to solar radiation and to higher documented air temperatures, particularly during the warmest summer months and at low tide particularly in the inner edge (Franzitta et al., 2016), could have been lethal for *Dendropoma* recruits. It is also worth noting that the vermetid platform is a place of choice for the deliberate or accidental settlement of introduced species, the development of which is rarely controlled. For example, the lessepsian bivalve *Brachidontes pharaonis*, replaced the *Mytilus galloprovincialis* in Lebanese vermetid reefs (Bitar, 2008; Gruvel, 1931) and may represent an additional direct threat to the vermetid persistence (Milazzo et al., 2017 and references therein). However, such hypothesis still have to be confirmed by experimental evidences as according to Rilov (2016) *D. petraeum* does not have obvious non-indigenous competitors or predators.

In summary, the present study corroborates the initial hypothesis that the endemic *Dendropoma anguliferum* is under local extinction throughout the Levantine Sea (Galil, 2013; Milazzo et al., 2017). The living individuals observed in Nakoura should be classified as “Critically Endangered” and protection measures along with regular monitoring surveys (using non-destructive methods) should be implemented. Further studies should be also performed, especially in remote areas of the Levantine basin (i.e. offshore small islands) in order to assess whether living populations of *Dendropoma anguliferum* are present and potentially may be used as parent populations for replenishment of lost areas in the framework of ecological restoration actions once causes of loss have been identified and removed.

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4.6 - Supplementary data

Threatened biogenic formations of the Mediterranean: current status and assessment of the vermetid reefs along the Lebanese coastline (Levant Basin).

Table S1

Pairwise test on the factor Edge (Ed.) and the factor Sites (Si) at the five monitored sites (PERMANOVA on the benthic assemblages censured by the transect method). Statistically significant values are in bold.

Pairwise test (Ed)	t	P(perm)
Nakoura	14.151	0.0075
Tyr	24.475	0.0079
Beirut	8.2900	0.0030
Batroun	7.8205	0.0067
Tripoli	3.4831	0.0090

Pairwise test (Si)	Within level extern of factor Edge (Ed)		Within level intern of factor Edge (Ed)	
	t	P (perm)	t	P (perm)
Tyr, Nakoura	20.121	0.0087	3.8810	0.0076
Tyr, Beirut	18.638	0.0083	9.6752	0.0093
Tyr, Tripoli	7.9115	0.0084	4.2975	0.0081
Tyr, Batroun	4.0983	0.0083	2.3353	0.0083
Nakoura, Beirut	17.842	0.0067	10.122	0.0086
Nakoura, Tripoli	7.8189	0.0073	5.6720	0.0086
Nakoura, Batroun	8.1200	0.0077	4.6381	0.0085
Beirut, Tripoli	2.6339	0.0083	2.5072	0.0077
Beirut, Batroun	5.3645	0.0088	9.0888	0.0090
Tripoli, Batroun	5.089	0.0066	3.6287	0.0086

Chapter 5 - General discussion

Human impact on marine ecosystems is widespread: no area is unaffected by human influence and a large fraction of the oceans is strongly affected by multiple drivers (Halpern et al., 2015). In particular, the Mediterranean Sea is considered one of the biodiversity hotspots (Coll et al., 2010), but at the same time is subject to multiple human impacts (Coll et al., 2012) both acting at the local or the global scale, such as urbanization (Halpern et al., 2008), overfishing (Boudouresque et al., 2017), biological invasions (Katsanevakis et al., 2014; Mannino et al., 2017) and climate change effects (Lejeusne et al., 2010).

The eastern basin of the Mediterranean Sea seems to be even more prone to rapid ecosystem transformation than the western basin, as its coastal water conditions are naturally more extreme, being the hottest and the saltiest in the Mediterranean (Coll et al., 2010). It is also warming faster than the western basin (Abboud-Abi Saab et al., 2004; Sisma-Ventura et al., 2014), with a sea surface temperature (SST) increase of 2–3°C in the past three decades (Rilov, 2016) and its highly invaded (Bitar et al., 2017; Boudouresque et al., 2017; Rilov et al., 2017a; Zenetos et al., 2010). Human impacts, such as urbanization and overfishing are also widespread in this basin (Sala et al., 2012), where environmental regulations are not always implemented (or respected).

Coastal communities, due to their shallow position, are subject to various threats worldwide, both of terrestrial and marine origin (Barange et al., 2010; Grech et al., 2015; Halpern et al., 2015). In the Mediterranean Sea, very shallow communities such as large brown algae forests (Airoldi et al., 2014) and vermetid reefs (Milazzo et al., 2017) are submitted to multiple potentially interacting pressures.

5.1 – The Lebanese coast

Along the coast of Lebanon (south-eastern Mediterranean), rocky shores dominate the shallow continental shelf (chapter 2). Most of the bedrock on the Lebanese coast is covered by complex biogenic structures made of shells of organisms (e.g. vermetid reefs) and macroalgal crusts (e.g. large brown algae forests). However, Lebanese marine ecosystems, as the entire Levantine sea, are exposed to the most extreme temperature (e.g. ocean warming, Abboud-Abi Saab et al., 2012) and salinity (Abboud-Abi Saab et al., 2005) conditions, and to the high impact of anthropogenic activities such as coastal development (MOE/UNDP/ECODIT, 2011), fishery

(Lteif, 2015) and pollution (Abboud-Abi Saab et al., 2008b), often associated with a continuous income of invasive species from the Suez Canal (Bitar et al., 2017; Crocetta et al., 2013; Harmelin et al., 2016; Ramos-Esplá et al., 2014; Rilov and Galil, 2009a). It is now well known that Lebanese marine ecosystems had no effective protection from multiple stressors, except two small protected areas (chapter 2), as the application of the CARLIT index along the Lebanese coastline (chapter 3) allowed to prove that 32% of the surveyed coastline is already artificialized. The research disclosed in this manuscript represents the first comprehensive work on shallow large brown algae forests and vermetid reefs conservation in a relatively poorly known region of the Mediterranean Sea: the Lebanese coast.

5.2 - The CARLIT index, a useful tool for the assessment of the Ecological Status (ES) and the conservation of *Cystoseira* forests

The CARLIT (CARtography of rocky-shore LITtoral communities) index was conceived in the framework of the European Water Framework Directive (WFD 2000/60/EU) and it is applied in the north-western Mediterranean Sea since 1999. At present it has been applied in several areas of the western basin and of the Adriatic Sea (Spain, France, Italy, Malta, Croatia, Albania; see chapter 3 for more details). The application of CARLIT index along 164 km of the Lebanese coastline (chapter 3), represents the first application in the eastern basin of the Mediterranean Sea. The assessment of Ecological Status (ES) showed that 29.9 % of the coast belongs to the good ES class, 37.1 % to the moderate, 12.1% to the poor and 9.9% to the bad. The calculation of ES is strongly related to the reference values chosen and it is suggested that appropriate reference conditions have to be chosen according to the area of study (Borja et al., 2012; Gaspar et al., 2012; Van Hoey et al., 2010). In the present application a reference site in Nakoura was selected, as complying with the standard levels of human impact recognized by European expert groups; the results were coherent when calculated in relation to the value of a Lebanese reference site (Nakoura) or in relation to north-western Mediterranean reference sites (Ballesteros et al., 2007; Bermejo et al., 2013; Nikolić et al., 2013). The correlation of ES results with human pressures was performed in relation of commonly used indexes such as LUSI (Flo et al., 2011), MA-LUSI (Cavallo et al., 2016) and HAPI (Blanfuné et al., 2017). The results give important information on the conservation state and the threats acting along Lebanese coasts, as much as the potential modification of coastal ecosystems. The CARLIT index, in fact, provide important

data on the distribution of shallow benthic communities, allowing to establish a baseline of their distribution, in order to follow their evolution in time. The research performed allowed to quantify the presence of large brown algae forests (*Cystoseira* and *Sargassum* species), key ecosystems in shallow habitats, providing ecosystem function and services. Several studies showed that the loss of *Cystoseira* forests may lead to a dramatic change in the whole benthic community, increasing the relative abundance of tolerant species such as algal turfs and thus decreasing benthic communities complexity (Mangialajo et al., 2008; Orlando-Bonaca and Rotter, 2018). Several local and global factors have been suggested to drive the loss of *Cystoseira* spp., including urbanization and eutrophication (Mangialajo et al., 2008; Mineur et al., 2015; Thibaut et al., 2005), increase in water turbidity and sedimentation (Perkol-Finkel and Airoidi, 2010; Strain et al., 2014), over-grazing (Agnetta et al., 2015), climate change related effects (Asnaghi et al., 2013), and likely combinations of multiple stressors in the most impacted regions (Strain et al., 2014). In addition, it has been demonstrated that sea urchin (Guidetti et al., 2003) and herbivorous fishes (Vergés et al., 2016) can contribute to the consumption of *Cystoseira* species in several areas of the Mediterranean Sea (Gianni et al., 2013; Vergés et al., 2009).

Four species of Fucales have been recorded in this study: *Cystoseira amentacea*, *Cystoseira compressa*, *Cystoseira rayssiae* and *Sargassum vulgare*. They dominate in 11% and 31.8% of the high/good ES surveyed areas, continuous belts being recorded uniquely in the reference site (Nakoura), where human impact can be considered negligible (see detailed distribution of these target species in Fig. 7, chapter 3). Such low percentages show that large brown algae forests are potentially regressing along Lebanese coastline, highlighting the need of setting up regular monitoring in order to plan conservation plans. For instance, coastal urbanization was the most important factor explaining the current distribution of *Cystoseira* populations, in agreement with other *Cystoseira* species from the Mediterranean Sea (Thibaut et al. 2005, Mangialajo et al. 2008, Sales et al. 2011), for other furoids from the Canary Islands (Riera et al., 2015) and, in general, for habitat-forming brown algae worldwide (Wahl et al., 2015). It is plausible that the temperature rise (SST, chapter 2) and the spread of invasive tropical herbivorous fishes (e.g. the invasive *Siganus* spp.) has contributed to the depletion of *Cystoseira* forests. But the lack of historical data do not allow providing evidence of the adverse effect of warming and herbivores fishes on Lebanese marine forests.

All the Mediterranean species of the genus *Cystoseira* are included in the list of endangered or threatened species of the Annex II (recently amended by the decision IG.21/09, UNEP/MAP, 2013) of the Barcelona Convention (UNEP/MAP, 1995), except for *C. compressa*, which is considered relatively tolerant to human pressures compared to other species of *Cystoseira* (Thibaut et al., 2005; Mangialajo et al., 2008). Indeed, *C. compressa* is the only species relatively common in Lebanon, occurring at 9 out of 12 studied sites.

Unluckily such legislation is generally not implemented but management plans are increasing in several Mediterranean countries. The baseline provided in this research will be useful for the assessment of *Cystoseira* forests evolution in Lebanon and will allow the implementation of future management plans (protection, defense from herbivores and ecological restoration).

5.3 - The Lebanese vermetid reefs: threatened key shallow ecosystems

In Mediterranean Sea, the best-studied calcifying bioconstructions on shallow rocky coast are vermetid reefs, occurring from the upper intertidal to the upper subtidal zone (Paoli et al., 2017). These biogenic reefs are built up by sessile gastropods species belonging to the genus *Dendropoma*. The ecological importance of reef-building vermetids is due to gregarious habit and massive settlement on the rocky shore, performing many ecological services (e.g. sheltered refuges, nursery areas, chapter 4) and promoting biodiversity (Milazzo et al., 2017).

Vermetid reefs are commonly distributed along the warm-water coasts of the southern part and their largest bioconstructions can be found along the Levantine Sea (Milazzo et al., 2017), including the Lebanese coast (see chapter 4 for more details).

The research performed in my PhD represents one of the first detailed description and health status assessment of vermetid reefs in the Levantine basin. In particular, the data gives important insight of what pristine nearshore reefs looked like in the Levant (see vermetid reef of Nakoura, chapter 4), and confirms the sensitivity of vermetids reefs to human pressures. The situation is similar in the whole south-eastern Levant concerning urbanization and modification of the coastline, overfishing, bioinvasions and climate change, and we suggest that these findings are likely to be representative of a much larger area. A monitoring survey along the Israeli coast, suggest that Levant reef is highly degraded (Rilov, 2016).

The study performed allow to prove the enigmatic decrease (risk of local extinction) of *Dendropoma anguliferum*, an endemic species of the Levantine Sea (only few living individuals

have been observed in Nakoura. From a conservation point of view this finding is very important, as *Dendropoma* reproduction is characterized by a very low dispersal, as snails brood their young and the hatchlings crawl only a short distance before becoming a sessile individual (Milazzo et al., 2017). The recruitment from adjacent areas is therefore particularly unlikely.

From a biogeographic-conservation perspective, as both warming and bioinvasions continue in the Mediterranean (Boudouresque et al., 2017), it is expected that this degraded reef state will gradually advance westward. Alleviating human pressures with marine reserves might make the reefs more resilient to global pressures, but other conservation actions, such as ecological restoration, may be necessary to reduce the erosion of vermetid reefs.

5.4 - Conclusion and perspectives

The Lebanese coastline is under multiple stressors affecting marine ecosystems: the few community surveys and several experiments along the Israeli (Rilov, 2016) and the Turkey (Sala et al., 2012) coasts suggest that the entire Levant has gone through profound coastal ecosystem phase shifts. The awareness of the need of integrating coastal zone management program in future actions is increasing, the priority being preventing further deterioration of important coastal ecosystems, in order to provide the associated ecosystem function and services (Paoli et al., 2017).

In view of the upcoming oil and gas discovery offshore Lebanon, new threats to the marine environment are expected to arise related to the construction and operation of offshore installations (oil spills, accidents and blow-outs). In case of oils spill accident (from platforms or tankers), it is important to know the distribution of such sensitive ecosystems, in order to plan coastal protection actions or manage the emergency (move the tanker, install floating protections). The knowledge acquired in the research performed in this thesis allows addressing this timely issue and highlighting the importance in continuing the effort in finding efficient indicators. From a regional view, a fine knowledge of the presence, distribution and conservation status of brown algae forests and vermetid reefs, is the first essential step for an appropriate long-term managing of marine resources and contribute to fill the knowledge gaps on this often neglected marine animal ecosystems. The results presented in this study highlight that *Cystoseira* forests and vermetid reefs are threatened along Lebanese coasts, as already observed along the Israeli coast concerning vermetid reefs (Rilov, 2016) and in Kos reefs (at the south-eastern end

of the Aegean Sea, just outside of the area defined as the Levantine basin) concerning *Cystoseira* forests (Bianchi et al., 2014). The current conservation state of important coastal ecosystems is now available to the general public and more importantly to sea users. They can support the institution of MPAs along the Lebanese coast. However, MPAs alone are not sufficient to guarantee the protection of important coastal ecosystems since regional or global physical and climatic factors, such as global warming (Lejeune et al., 2010), species invasion (Mannino et al., 2017) ocean acidification (Gattuso et al., 2015) and increased water turbidity (Parravicini et al., 2015a), cannot be prevented by the implementation of individual MPAs or other small-scale protection measures (Parravicini et al., 2013). Hence a continuous long-term monitoring should be a priority for a better assessment of the effects of human impacts on the evolution of marine ecosystems. In this context, it is necessary to maintain the good ES of the existing coastal ecosystems (e.g. large brown algae forests, vermetids reefs) allowing to conserve current population, including restoration programs.

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Chapitre 5 – Discussion générale

L'effet des impacts humains sur les écosystèmes marins côtiers ne cesse d'augmenter: aucune zone a échappé de cet effet et une grande partie des océans est fortement affectée par plusieurs facteurs (Halpern et al., 2015). En particulier, la mer Méditerranée est considérée comme l'un des points chauds de la biodiversité (Coll et al., 2010), mais en même temps elle est soumise à de multiples impacts humains (Coll et al., 2012) agissant à l'échelle locale ou globale, comme l'urbanisation (Halpern et al., 2008), la surpêche (Boudouresque et al., 2017), les invasions biologiques (Katsanevakis et al., 2014; Mannino et al., 2017) et l'effet du changement climatique (Lejeune et al., 2010).

Le bassin oriental de la Méditerranée semble être encore plus sujette à une transformation rapide de l'écosystème que le bassin occidental, car ses eaux côtières sont exposées naturellement à des conditions plus extrêmes, étant les plus chaudes et les plus salées de la Méditerranée (Coll et al., 2010). Il se réchauffe également plus vite que le bassin occidental (Abboud-Abi Saab et al., 2004; Sisma-Ventura et al., 2014), avec une augmentation de la température de surface de la mer (TS) de 2–3°C au cours des trois dernières décennies (Rilov, 2016) et il est hautement soumis à l'arrivée des espèces exotiques (Bitar et al., 2017; Boudouresque et al., 2017; Rilov et al., 2017a; Zenetos et al., 2010). Les impacts humains, tels que l'urbanisation et la surpêche, sont également répandus dans ce bassin (Sala et al., 2012), où les réglementations environnementales ne sont toujours pas mises en œuvre (ou respectées).

Les communautés côtières, en raison de leur présence au niveau du médio-infralittorale, sont soumises à diverses menaces, d'origine terrestre et marine (Barange et al., 2010; Grech et al., 2015; Halpern et al., 2015). En Méditerranée, ces communautés telles que les grandes forêts d'algues brunes (Airoldi et al., 2014) et les trottoirs à Vermets (Milazzo et al., 2017) sont affectés par l'interaction de multiples pressions d'origine diverses.

5.1 – La côte Libanaise

Le long de la côte Libanaise (bassin Levantin de la Méditerranée), les côtes rocheuses dominent le plateau continental (chapitre 2) dont la plus grande partie est couverte de structures biogéniques complexes, telles que les trottoirs à Vermets et les grandes forêts d'algues brunes. Cependant, les écosystèmes marins Libanais, comme ceux de la mer Levantine en général, sont

exposés aux conditions les plus extrêmes de température (e.g. réchauffement des océans, Abboud-Abi Saab et al., 2012) et de salinité (Abboud-Abi Saab et al., 2005), ainsi qu'aux effets des activités anthropiques telles que le développement côtier (MOE/UNDP/ECODIT, 2011), la pêche (Lteif, 2015) et la pollution (Abboud-Abi Saab et al., 2008b), souvent associées à l'introduction continue d'espèces invasives via le canal de Suez (Bitar et al., 2017; Crocetta et al., 2013; Harmelin et al., 2016; Ramos-Esplá et al., 2014; Rilov and Galil, 2009a). Il est maintenant bien connu que les écosystèmes marins Libanais n'étaient pas efficacement protégés contre les multiples facteurs de stress naturel et humain, à l'exception de deux petites aires marines protégées (chapitre 2) et l'application de l'indice CARLIT le long des côtes Libanaises (chapitre 3) a aussi montré que 32% de la côte Libanaise est artificialisée.

La recherche décrite dans ce manuscrit représente le premier travail complet sur les grandes forêts d'algues brunes et la conservation des trottoirs à Vermets dans une région relativement peu connue de la mer Méditerranée: la côte Libanaise.

5.2 - L'indice CARLIT, un outil utile pour l'évaluation de l'Etat Ecologique (EE) et la conservation des forêts de *Cystoseira*

L'indice CARLIT (CARtographie des communautés benthiques du LITtorale) a été conçu dans le cadre de la Directive des Eaux Européennes (DCE 2000/60/UE) et il est appliqué dans le nord-ouest de la Méditerranée depuis 1999. Actuellement, appliqué dans plusieurs zones du bassin occidental et de la mer Adriatique (Espagne, France, Italie, Malte, Croatie, Albanie, voir le chapitre 3 pour plus de détails). L'application de l'indice CARLIT sur 164 km du littoral Libanais (chapitre 3) est la première dans le bassin oriental de la Méditerranée. L'évaluation de l'EE a montré que 29,9% de la côte appartient à l'EE de bonne classe, 37,1% à la classe moyenne, 12,1% aux pauvres et 9,9% à la mauvaise. Le calcul de l'EE est fortement liée aux valeurs de référence calculées et il est suggéré que les conditions de référence appropriées doivent être choisies en fonction du domaine d'étude (Borja et al., 2012; Gaspar et al., 2012; Van Hoey et al., 2010). Dans cette première application, un site de référence à Nakoura a été sélectionné, en conformité avec les niveaux standards d'impact humains reconnus par les groupes d'experts européens; les résultats calculés sont cohérents par rapport aux valeurs du site de référence Libanais (Nakoura) et à celles calculées des sites de référence du nord-ouest Méditerranéen (Ballesteros et al., 2007; Bermejo et al., 2013; Nikolić et al., 2013)

La corrélation des résultats de l'EE obtenus avec les pressions humaines a été réalisée en utilisant les indices couramment utilisés tels que le LUSI (Flo et al., 2011), le MA-LUSI (Cavallo et al., 2016) et le HAPI (Blanfuné et al., 2017). Les résultats obtenus fournissent des informations importantes sur l'état de conservation et les menaces agissant le long des côtes Libanaises, autant que la modification potentielle des écosystèmes côtiers. L'indice CARLIT, en effet, fournit des données importantes sur la distribution des communautés benthiques côtières, permettant d'établir une base de référence de leur distribution, aboutissant au suivi de leur évolution dans le temps. La recherche effectuée a permis de quantifier la présence de grandes forêts d'algues brunes (espèces de *Cystoseira* et de *Sargassum*), comme habitats clés des écosystèmes côtiers, fournissant plusieurs fonctions et services. Plusieurs études ont montré que la perte des forêts de *Cystoseira* peut entraîner un changement de la communauté benthique, augmentant l'abondance relative des espèces tolérantes et réduisant ainsi la complexité des communautés benthiques (Mangialajo et al., 2008; Orlando-Bonaca and Rotter, 2018). Plusieurs facteurs locaux et globaux ont été suggérés pour entraîner la perte de *Cystoseira* spp., y compris l'urbanisation et l'eutrophisation (Mangialajo et al., 2008; Mineur et al., 2015; Thibaut et al., 2005), l'augmentation de la turbidité et la sédimentation (Perkol-Finkel and Airoidi, 2010; Strain et al., 2014), le surpâturage (Agnetta et al., 2015), les effets liés aux changements climatiques (Asnagli et al., 2013) et les interactions probables entre différents facteurs de stress (Strain et al., 2014). En outre, il a été démontré que les oursins (Guidetti et al., 2003) et les poissons herbivores (Vergés et al., 2016) peuvent contribuer à la consommation d'espèces de *Cystoseira* dans plusieurs zones de la mer Méditerranée (Gianni et al., 2013; Vergés et al., 2009).

Quatre espèces de Fucales ont été enregistrées dans cette étude: *Cystoseira amentacea*, *Cystoseira compressa*, *Cystoseira rayssiae* et *Sargassum vulgare*, dominant dans 11% et 31,8% des sites étudiés de classe hautes et bonnes EE, les ceintures continues étant enregistrées uniquement sur le site de référence (Nakoura), où l'impact humain peut être considéré comme négligeable (voir la distribution détaillée de ces espèces cibles sur la figure 7, chapitre 3). Des pourcentages si faibles montrent que les forêts de grandes algues brunes peuvent régresser le long des côtes Libanaises, soulignant la nécessité de mettre en place un suivi régulier afin de planifier les plans de conservation. Par exemple, l'urbanisation côtière était le facteur le plus important expliquant la répartition actuelle des populations de *Cystoseira*, en accord avec d'autres espèces de *Cystoseira* de la Méditerranée (Mangialajo et al., 2008; Sales and E., 2009;

Thibaut et al., 2005) et les fucoïdes des îles Canaries (Riera et al., 2015) et, en général, pour les algues brunes formant des habitats marins clés dans le monde entier (Wahl et al., 2015). Il est plausible que l'élévation de la température (e.g. SST, chapitre 2) et la propagation de poissons herbivores tropicaux envahissants (par exemple l'espèce lessepsienne invasive *Siganus* spp.) aient contribué à la perte des forêts de *Cystoseira*. Mais le manque de données historiques ne permet pas de mettre en évidence les effets néfastes du réchauffement et des herbivores sur les forêts marines Libanaises.

Toutes les espèces Méditerranéennes du genre *Cystoseira* figurent sur la liste des espèces menacées ou en danger de l'Annexe II (récemment modifiée par la décision IG.21/09, UNEP /MAP, 2013) de la Convention de Barcelone (PNUE/PAM, 1995), à l'exception de *C. compressa*, qui est considérée comme relativement tolérante aux pressions anthropiques par rapport aux autres espèces de *Cystoseira* (Mangialajo et al., 2012). En effet, *C. compressa* est la seule espèce relativement commune au Liban, sur 9 des 12 sites étudiés.

Malheureusement, une telle législation n'est généralement pas mise en œuvre, mais les plans de gestion sont en augmentation dans plusieurs pays Méditerranéens. La base de référence fournie dans cette recherche sera utile pour l'évaluation de l'évolution des forêts de *Cystoseira* au Liban et permettra la mise en œuvre des futurs plans de gestion (protection, défense des herbivores et restauration écologique).

5.3 - Les trottoirs à Vermets Libanais: importants écosystèmes côtiers menacés

En mer Méditerranée, les bioconstructions calcifiantes les mieux étudiées sur la côte rocheuse sont les trottoirs à Vermets, qui se trouvent de la zone médiolittorale à la zone infralittorale supérieure (Chemello et al., 2014; Paoli et al., 2017). Ces formations biogéniques sont construits par des espèces de gastéropodes sessiles appartenant au genre *Dendropoma*. Leur importance écologique est due à au peuplement massif sur le rivage rocheux, assurant de nombreux services écologiques (refuges, nurseries, chapitre 4) et favorisant la biodiversité (Milazzo et al., 2017).

Les trottoirs à Vermets sont communément répartis le long des côtes d'eau chaude de la partie sud et leurs plus grandes bioconstructions se trouvent le long de la mer Levantine (Chemello and Silenzi, 2011; Milazzo et al., 2017), y compris la côte Libanaise (voir chapitre 4 pour plus de détails).

La recherche effectuée dans ma thèse représente l'une des premières descriptions détaillées et évaluation de l'état de santé des trottoirs à Vermets du bassin Levantin. En particulier, les données donnent un aperçu important de ce que ressemble les trottoirs saines de la côte Levantine (voir le trottoir à Vermets de Nakoura, chapitre 4), et confirment la sensibilité de ces trottoirs aux pressions humaines. Etant donné que la situation est similaire au niveau de la côte Levantine en ce qui concerne l'urbanisation et la modification du littoral, la surpêche, les invasions biologiques et le changement climatique, et nous suggérons que ces résultats sont susceptibles d'être représentatifs d'une superficie beaucoup plus grande. Une étude de surveillance le long de la côte Israélienne suggère que les trottoirs du Levant sont fortement dégradés (Rilov, 2016).

L'étude réalisée permet de démontrer l'extinction énigmatique (risque d'extinction locale) de *Dendropoma anguliferum*, une espèce endémique de la Mer Levantine (seuls quelques individus vivants ont été observés à Nakoura). D'un point de vue conservatoire, cette constatation est très importante, car la reproduction de cette espèce (*Dendropoma*) se caractérise par une très faible dispersion, car les jeunes couvent leurs parents et les parents ne rampent que très peu de temps avant de devenir des individus sessiles (Milazzo et al., 2017).

D'un autre point de vue conservatoire mais biogéographique et alors que le réchauffement et la bioinvasion se poursuivent en Méditerranée (Boudouresque et al., 2017), on s'attend à ce que cet état dégradé de ces formations biogéniques importantes avance progressivement vers l'ouest. Comme solution, une diminution des pressions humaines sur les réserves marines pourrait rendre les trottoirs plus résistants aux pressions mondiales, mais d'autres actions de conservation, telles que la restauration écologique, pourraient être aussi nécessaires pour réduire l'érosion des trottoirs à Vermets.

5.4 – Conclusions et perspectives

La côte Libanaise est soumise à plusieurs facteurs de stress affectant les écosystèmes marins: les recherches fragmentaires sur les communautés côtières et plusieurs expériences le long des côtes Israéliennes (Rilov, 2016) et Turquie (Sala et al., 2012) suggèrent que l'ensemble du Levant est sous une profonde dégradation de phase côtière. La prise en conscience de la nécessité d'intégrer le programme de gestion des zones côtières dans les actions futures augmente, mais la priorité est

de prévenir la détérioration des écosystèmes côtiers importants, afin de fournir la fonction et les services associés (Paoli et al., 2017).

Compte tenu de la prochaine découverte de pétrole et du gaz au Liban, le milieu marin sera affecté par de nouvelles menaces en relation avec la construction des plateformes pétrolières (ex. déversements de pétrole, accidents et éruptions). En cas d'accident de déversement d'hydrocarbures (provenant des plateformes), il est important de connaître la répartition de ces écosystèmes sensibles, afin de planifier les actions de protection côtière ou gérer l'urgence (ex. déplacer le pétrolier, installer des protections flottantes). Les connaissances acquises dans la recherche effectuée dans cette thèse permettent d'aborder cette question primordiale et de souligner l'importance de poursuivre l'effort pour trouver des indicateurs biologiques efficaces. D'un point de vue régional, une bonne connaissance de la présence, de la répartition et de l'état de conservation des algues brunes et des trottoirs à Vermets est une première étape et essentielle pour une gestion appropriée des ressources marines à long terme et contribue à combler les lacunes en matière de connaissances des écosystèmes animaux marins. Les résultats présentés dans cette étude soulignent que les forêts de *Cystoseira* et les trottoirs à Vermets sont menacés le long des côtes Libanaises, comme déjà observé le long des côtes Israéliennes concernant les trottoirs à Vermets (Rilov, 2016) et dans les récifs de Kos (à l'extrémité sud-est de la mer Egée) juste à l'extérieur de la zone définie du bassin Levantin) concernant les forêts de *Cystoseira* (Bianchi et al., 2014). L'état de conservation actuel des écosystèmes côtiers importants est maintenant disponible pour le grand public et, plus important encore, pour les utilisateurs de la mer. Ils peuvent aussi soutenir l'institution des AMP le long de la côte Libanaise. Cependant, les AMP ne sont pas suffisantes pour garantir la protection des écosystèmes côtiers importants depuis que les facteurs physiques et climatiques régionaux ou mondiaux, tels que le réchauffement climatique (Lejeune et al., 2010), l'invasion des espèces (Mannino et al., 2017), l'acidification (Gattuso et al., 2015) et l'augmentation de la turbidité de l'eau (Parravicini et al., 2015a), ne peut être prévenue et limitée par la mise en œuvre d'AMP individuelles ou d'autres mesures de protection à petite échelle (Parravicini et al., 2013). Par conséquent, un suivi continu à long terme devrait être une priorité pour une meilleure évaluation des effets des impacts humains sur l'évolution des écosystèmes marins. Dans ce contexte, il est nécessaire de maintenir le bon EE des écosystèmes côtiers existants (par exemple les grandes forêts d'algues brunes et

des trottoirs à Vermets) permettant de conserver la population actuelle, y compris les programmes de restauration.

5.5 – Références

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