

Enhancing eco-engineering of coastal infrastructure with eco-design

Moving from mitigation to integration

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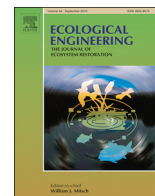
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Enhancing eco-engineering of coastal infrastructure with eco-design: Moving from mitigation to integration



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ABSTRACT

Eco-design aims to enhance eco-engineering practices of coastal infrastructure projects in support of ecological functions before these projects are developed and implemented. The principle is to integrate eco-engineering concepts in the early phases of project design. Although ecological losses are inherent in any construction project, the goal of eco-design is to introduce environmental considerations upfront during technical design choices, and not just afterwards when evaluating the need for reduction or compensatory mitigation. It seeks to reduce the negative impacts of marine infrastructure by introducing a new reflexive civil engineering approach. It requires a valuation of nature with the aim of reducing impacts by incorporating intelligent design and habitat-centered construction. The principle advocated in this paper is to design coastal infrastructures, at micro- to macro-biological scales, using a combination of fine and large scale physical and chemical modifications to hard substrates, within the scope of civil engineering requirements. To this end, we provide a brief introduction to the factors involved in concrete-biota interactions and propose several recommendations as a basis to integrate ecology into civil engineering projects, specifically addressed to concrete.

1. Introduction

Approximately 60% of the world's human population live within 100 km of a sea coast (e.g., Vitousek et al., 1997). On the public coast of France human occupation rate of the coastal zone doubled between 1965 and 1980 (MEDAM, 2015). Between 2000 and 2006, no less than 6.809 ha were destroyed for coastal parking, harbor construction, sea-wall protections and other human facilities (Ibid). For instance, in the Languedoc Roussillon Region of southern France close to the Mediterranean Sea, the urbanization level within a 15 km length of coastline is close to 70%. The phenomenon of increasing shoreline development is growing worldwide. In recent literature, this is often referred to as

'coastal squeeze', a term introduced by Doody (2004) in recognition of the threat to the existence of coastal habitats caused by the compound impacts of sea-level rise and human activities. The phenomenon is very prominent in developed countries (INSEE, 2013) such as Spain, Italy, Belgium, Japan, China, and the USA, but it is also becoming more prominent in the developing world (e.g., Vietnam, Thailand, Philippines, Myanmar, India and Indonesia) (Phan et al., 2014). It develops rapidly, especially in a context of emergency poverty alleviation and economic development where environmental governance is weak. Around the Mediterranean, urbanization increased from 54% to 66% between 1970 and 2006 (Halpern et al., 2008). Furthermore, the situation is likely to worsen; the world's population is forecast to

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approach 7.5 billion people living within 100 km of a coast by 2050 (Lussault, 2013), and this will necessarily coincide with a growing need for increased coastal development and associated disturbance of essential coastal habitats.

The consequences of coastal urbanization are synergistic with other anthropogenic impacts on the nearshore environment, i.e., climate change, rising sea level (including subsidence), recurrent pollution, habitat degradation and overfishing. Faced with these escalating impacts, it is critical to develop sustainable long-term management of our coasts based on well-informed decision making and public education. But it is clear that the driving issues are global: social, economic, and ecological, and moreover deeply linked with our model of society based on perpetual growth. Obviously, there is no “magic” solution. However, in the short term, pragmatic approaches are required to avoid or reduce destruction of natural capital (Kiesecker et al., 2010) by a better integration of Coastal Infrastructure (CI) projects with natural ecosystems. Ecological design of infrastructure is a way to reconcile urbanization with protection of the natural environment from which essential goods and services are drawn.

Eco-design is a new approach developed in response to the cumulative impacts of CI on the ecology, biodiversity, and natural resources of coastal areas. It involves introducing ecological considerations in new CI construction based on eco-engineering solutions. It is similar to the classic eco-engineering concept, rooted in both ecological theory and knowledge and engineering practices. In defining ecological engineering, Mitsch and Jørgensen (2004) remind us that its goal is to design, create, or restore “ecosystems that integrate human society with the natural environment that will be of benefit to both”. As used today in the field of work design, eco-engineering is primarily a corrective approach to address problems that require mitigation. It tries to incorporate understanding of ecological phenomena to simultaneously repair and enhance biodiversity and ecosystem function. But, its insights are in general only poorly applied by civil engineers, especially during the early phases of work, such as the design and planning processes, where avoiding and reducing ecological impacts should be prioritized. In most cases, ecological engineering knowledge and know-how are restricted to applications at the latter phase of work, and are intended to offset negative environmental ecological impact from the CI construction through compensatory mitigation. In contrast, eco-design by definition aims to better associate and reconcile ecology and design, from the onset of the work design process, when the basic size and shape of a structure are defined (Fig. 1). It is a mix between eco-engineering design and work design processes, begun in the earliest stages of construction planning. Furthermore, if we consider that, in current use, civil engineers are working in the early phase of work design planning (preliminary design, detail scheme design, and general design), and eco-engineering at the end, when the general design is approved by financial and technical trustees, the only way to associate them is to incorporate an eco-design approach. Thus, a modernization of both construction and ecological approaches in civil work processes starts with marrying the two words “ecology” and “design”. The hesitations of civil engineers to apply ecological concepts and solutions during initial phases of design should be eliminated, or at least reduced. Eco-design requires a full collaboration of civil and ecological engineers working together during the same planning phases; this should ensure a

better environmental integration for the project (Fig. 1).

This approach is close to “building with nature” in the EU (De Vriend and Van Koningsveld, 2012) and in the win-win insight proposed by “reconciliation ecology” between humans and nature (Rosenzweig, 2003). It finds its roots at the end of the 19th century with the famous “re-culturation of nature and re-naturalization of culture” of K. Marx as a concept to link the future of humans with the fate of the natural world (Berque, 2014). In addition, there is an increasing perception that nature can help provide viable solutions to problems of CI by taking into account the properties of natural ecosystems (Coombes et al., 2015). Moreover, concept of nature-based solutions (NBS) has been developing in recent years. The IUCN defines this as “actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits”. “It can also help to create new jobs and economic growth, through the manufacture and delivery of new products and services, which enhance the natural capital rather than deplete it” (EU Horizon H2020 Policy).

As Aronson et al. (2016) reminded us, “Engineers and ecologists must work together and learn from each other if our work is to generate significant societal benefits”, and Mitsch (2014) asked “When will ecologists learn engineering and engineers learn ecology?” The current lack of integration between these two professions is one of the reasons why the creation of new infrastructures that successfully integrate both ecological and technical concerns is so challenging. Based on our experience, although some engineering schools or training programs are developing courses and research programs on marine ecology, currently, most civil engineers are not fully aware or attuned to relevant ecological concerns when they are tasked to develop projects or when asked specifically to try to “build with nature”. This is not simply due to a lack of knowledge of ecological issues and lack of proper training, but also due to the current philosophy of building in natural areas. Consideration of technical, economic, or social concerns have high precedence over environmental (bio-physical) ones during the design of infrastructure.

In this paper, we try to review some of the most important marine biological phenomena, to be taken into account at the early phase of project of CI, to try to bring together civil and ecological engineers in a process of eco-design.

Historically in ecology (cf. Table 1), research about coastal colonization or settlement phenomena reflected mainstream literature about the use of artificial substrates during the 1970’s through the 1990’s (e.g. Zobel, 1972; Relini, 1993). However, since the 2000’s, traditional coastal infrastructures have been implicated as major risk factors in reducing local biodiversity in comparison with surrounding natural ecosystems (Bulleri and Chapman, 2004; Bulleri et al., 2005; Jackson et al., 2008; Bulleri and Chapman, 2010). There have been multiple reports about the toxicity of concrete infrastructures, problems with using smooth surfaces in the marine environment, landscape disruption, and indirect impacts due to the carbon dioxide production in concrete fabrication and habitat destruction due to rock or sand extraction (Hillier et al., 1999; Wilding and Sayer, 2002; Moschella et al., 2005; Terlizzi and Faimali, 2010). Further, novel habitat (artificial hard substrata) can influence and even alter local and regional biodiversity by modifying natural patterns of species dispersal or by facilitating the

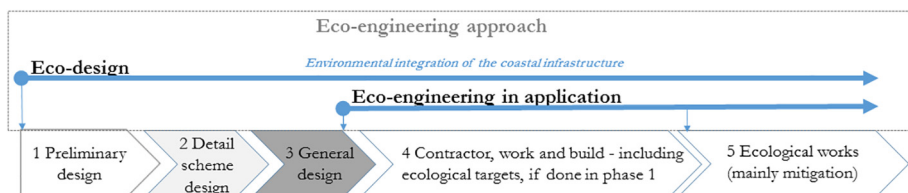


Fig. 1. Eco-design application within civil engineering projects in comparison to present eco-engineering application. The eco-design approach begins in the early phase of the work design planning. In comparison with usual eco-engineering treatments, which are based on compensatory mitigation resulting from environmental impact assessments or ecosystem damage. They are mainly considered after the design of coastal infrastructure to reduce or offset negative impacts, reducing environmental integration of CI.

Table 1
Timeline of research concerning artificial coastal infrastructures and marine ecosystem relationships (selected publications).

Coastal Infrastructure Research	Selected Literature	Phases-period	Impact
Coastal infrastructure colonization, settlement phenomena	ZoBell, 1972; Relini, 1993	1970s–1990 s	Few studied
Risk factors in reducing local biodiversity	Bulleri and Chapman, 2004; Bulleri et al., 2005; Jackson et al., 2008; Bulleri and Chapman, 2010	2000–present	Negative on biodiversity
Toxicity of concrete infrastructures, landscape disruption, indirect impacts (Carbon dioxide, rock or sand extraction ...)	Hillier et al., 1999; Wilding and Sayer, 2002; Moschella et al., 2005; Terlizzi and Faimali, 2010		
Invasive species, modifying natural patterns of species dispersal	Glasby et al., 2007; Airoldi and Bulleri, 2011; Dafforn et al., 2012; Jacob et al., 2015; Firth et al., 2016		
Enhance biodiversity (composition chemistry, roughness, surface treatment, pits or holes)	Wilding and Sayer, 2002; Lee et al., 2008; Martins et al., 2010; Chapman and Underwood, 2011; Coombes et al., 2011; Pioch et al., 2015; Souche et al., 2016; Evans et al., 2016	2000–present	Positive on biodiversity
Bio-protective role of biofouling community	Moschella et al., 2005; Coombes et al., 2013; La Marca et al., 2014; Coombes et al., 2015; Perkol-Finkel and Sella, 2015	Late 2000–present	Positive on biodiversity and construction lifetime
Associate ecological consideration in coastal engineering construction, eco-design	Lacroix and Pioch, 2011; Firth et al., 2014; Phan et al., 2014; Coombes et al., 2015; Dafforn et al., 2015; Sella and Perkol-Finkel, 2015; Patranella et al., 2016; Coombes et al., 2017; Perkol-Finkel et al., 2017	2010–present	Positive on biodiversity and construction objectives

NB: current publications are still describing the negative impacts of CI, we only develop here new research topics for CI in relationship with marine ecosystems.

establishment and spread of exotic, and in some cases invasive, species (Glasby et al., 2007; Airoldi and Bulleri, 2011; Dafforn et al., 2012; Firth et al., 2016). These should be pertinent arguments for engineers or policymakers, who may tend to ignore eco-design in the belief “everything will turn green in the sea”. ‘Green’ does not necessarily mean that ecological function or species assemblages that develop following construction are equivalent with the biota that existed prior to impact (Jacob et al., 2015). In contrast, research that incorporates ecological consideration in the design of CI has clearly demonstrated that it is feasible to enhance biodiversity by changes in composition chemistry, roughness, surface treatment, or inclusion of variously-sized pits or holes (Wilding and Sayer, 2002; Martins et al., 2010; Chapman and Underwood, 2011; Pioch et al., 2015; Souche et al., 2016; Evans et al., 2016). Interestingly, research has also indicated that physical alteration and damage to artificial structures due to natural processes (weathering, wave action, chemical erosion) could be reduced by the bio-protective role of the biofouling community (Moschella et al., 2005; Coombes et al., 2013; La Marca et al., 2014; Coombes et al., 2015; Perkol-Finkel and Sella, 2015). Pragmatically, most current CI cannot be readily removed, but there is now an increasing research effort into ways that new infrastructure can be designed and built to meet engineering requirements while also increasing its value as replacement habitat (Lacroix and Pioch, 2011; Firth et al., 2014; Phan et al., 2014; Coombes et al., 2015; Dafforn et al., 2015; Sella and Perkol-Finkel, 2015; Patranella et al., 2016).

2. Definition of marine eco-design

This paper briefly explores some of the factors involved in eco-design of marine structure by taking into account specific relationships between micro- and macro-concrete artificial habitat and natural marine ecological processes, and thus follows the steps used in civil engineering to design CI (cf. Fig. 1). It is not the purpose here to provide an in-depth review of the major factors that must be addressed in eco-engineering. There are a number of excellent reviews addressing the subject and the interested reader is referred to them for a more extensive coverage (Dyson, 2009; Firth et al., 2014; Evans, 2015; Sella and Perkol-Finkel, 2015; Firth et al., 2016). The goals of this paper are to: 1) briefly explore some of the factors that must be taken into account by engineers relative to the complex relationships between micro- and macro- concrete artificial structure and natural marine ecological processes during the preliminary phase of CI project design and 2) to provide recommendations on how to proceed to take into account environmental goals as functional requirements as soon as possible in civil

engineering projects.

An eco-designed CI is a project that incorporates ecosystem conservation objectives into its functions at the same level of study and prioritization as the usual technical, economic or social objectives. Eco-design is thus part of the design of a project from the earliest stages (preliminary design or feasibility studies; first box in Fig. 1), when defining the functions of the structure and its ecosystemic objectives (Fig. 1).

The conservation objectives of the eco-design relative to the impacted ecosystems have to take into account, at least, the identified impacts on the ecosystem, but can and should go well beyond that. The design should take into account, as much as possible, the integration of the infrastructure with the environment and which natural habitats, processes, or components thereof are affected, which habitats to preserve or re-establish, and how to incorporate creation of such habitats in the design conceptualization phase, taking into account both a conservation of habitats and minimization of impacts. Mitigation hierarchy, avoidance, reduction and, finally, offset proposals and adaptation actions are not central to eco-design, although they must also be fully taken into account by a specific ‘Environmental Impact Assessments’ (EIA) (Kiesecker et al., 2010). Similarly, the notion of ‘no net loss’, an effort to balance losses by increasing biodiversity or productivity to offset project-related impacts, is integrated into eco-design. This is because even when every effort is made to avoid, minimize and offset the impacts of construction, human activities can or will inherently negatively impact biodiversity to some extent (Maron et al., 2015; Moreno-Mateos et al., 2015). Jacob et al. (2016) has shown that these activities are mainly related to port infrastructure and coastal defense, waste water collection and discharge, and sediment dredging and disposal. The idea that damages resulting from human activities must be balanced by equivalent gains is a necessary step in the right direction, but is not completely sufficient and can still be improved upon. Indeed, eco-design of a structure should not be defined solely in response to anticipated or unavoidable impacts, but should include ecosystem conservation objectives as well.

Consideration of the ecosystem requires an intellectual approach integrating many parameters (Babcock et al., 2005). In particular, the notion of “habitat” is a key concept for population development (Rice, 2005). In relation to ecology, the bio-geographical approach gives primacy to the configuration of sites on a broad basis, and thus to general distribution of habitat, and to the distribution of species, whereas an ecological approach rather insists on the local interrelations between species and their immediate habitat (Woiillez, 2007). When a new CI construction takes place in a natural area, it will create a new


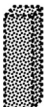
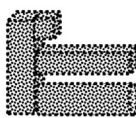
Concern and scale	Design	Mainstream consideration
Micro-structure material (μ)		<ul style="list-style-type: none"> - Concrete implementation - Physic-chemical - Biological interaction - Colonization
Micro-structure external (cm)		<ul style="list-style-type: none"> - Mold for concrete - Colonization - Bio mimicking
Macro-structure (cm to m)		<ul style="list-style-type: none"> - Mold for concrete & implementation - Hydrodynamic - Artificial reef / habitat function - Bio mimicking

Fig. 2. Submerged concrete creating habitat at three scale: 1) micro-structural (μ m) consideration creating micrometric habitat with the “material” (figure filled with dots); 2) micro-structural (cm) creating centimetric habitat “external” (dotted line on the surface); 3) macro-structural (cm to m) creating centimeter to meter habitat (volume by assembled figures).

habitat (at a minimum as a hard substratum supporting settlement), with a colonization of every submerged surface being in direct proportion to the surface area of the deployed structure (assuming the deployment is not a biocide) (Nakamura, 1985). For the purpose of this paper, habitat is somewhat arbitrarily divided into micro-habitat and macro-habitat, with divisions at micrometric, centimetric and pluricentimetric scales (cf. Fig. 2).

It has been established that artificial structures which have rougher surfaces, more closely matching natural topography, will experience better colonization than smooth concrete surfaces. The presence of ledges, ridges and crevices has also been found to have some influence on improving the colonization and biodiversity of artificial marine structures. At microscopic and macroscopic scales of material and structures (external shape), several biological and physico-chemical factors directly influence colonization (Relini, 1993; Kakimoto, 2004; Bulleri and Chapman, 2010). By exploring these three scales, we have attempted to formulate some initial recommendations for engineers based on biological process.

Eco-designed habitat elements typically do not require any special maintenance to maintain colonization enhancement effect. Indeed, similar to ecological restoration (SER, 2004), the natural auto-regeneration processes should be favored by initial design choices. These processes should not generate any human interventions *a posteriori*. In the end, three main questions have to drive CI eco-designed projects: 1) What are the ecosystem functions that the structure could support? 2) What habitats will be impacted by the project? 3) How could the current ecosystem functions, both locally and regionally, be maintained or developed? An eco-based design also needs to mimic the original habitat as closely as possible, guided by the following principles: 1) to improve the ecological integration of its surfaces by bio-mimicry/nature-based solutions with naturally occurring ecosystems, and 2) to create complexity at micro-, meso-, and macro-habitat levels (Fig. 2), to provide support for flora, fauna, juveniles and adults.

Of course, creating artificial habitat can also facilitate the spread and support population growth of invasive exotic species. Thus, if the infrastructure also causes an area of impact on the sea-bed, this sea-bed area typically cannot be replaced. However, if one looks at the footprint from the perspective of surface area, then replacement is possible with material of higher roughness, i.e., boulders versus sand. Likewise, ecosystem services can be replaced, but seldom with full equitability.

3. Substratum composition and microstructural aspects for marine eco-design

In this section, we focus on material composition and micro-structural scales of CI, linked to the early stages of substrate colonization, from biofilm formation to substrate effects on larval settlement, and conversely the influence of fouling organisms on the characteristics on

the substrate surface. These considerations will drive the selection of construction material (concrete) and external shape of CI to enhance colonization. All the positive effects described hereafter are cumulative.

3.1. Development of biofilm

Every submerged surface in the marine environment is immediately covered by a thin layer of biofilm, which is the first phase of biological settlement. Biofilm development mechanisms, its structure, and its specific composition depend on substrate surface characteristics (Taylor et al., 1994).

The biofilm development model in marine environments includes several phases (i.e., attachment, colonization, growth, and dispersion) that are modulated over time by a wide range of biological, physico-chemical, and environmental factors (see also description in ZoBell, 1972). Soon (minutes-hours) after a surface is submerged in seawater, pioneering biofilm micro-organisms (mainly bacteria) begin to colonize it. From there, it takes much longer (from a few days to a few weeks, depending on the season and immersion environment) before a specific bio-diversity begins to develop and a biofilm layer becomes visually detectable (Salta et al., 2013).

Since there are so many different kinds of substrates and since periphytic species (microbes found on any kind of solid or semi-solid substrate) differ so widely in their responses to substrata under diverse environmental conditions, ranges of tolerance to different substrata can be assessed only in general terms (Ibid.). The suitability of a substratum for a particular periphyte is usually determined by the physical as well as the chemical nature of the substrate. In various ways, the depth and distribution of surface depressions influence the attachment of both inanimate and living materials. Likewise, substratum with chemoattractant coatings can enhance initial colonization (Lee et al., 2008). But after a few months, different substratum, more commonly used in marine construction, such as concrete and also metal, rock, wood or fiber-glass, may present the same assemblage (Anderson and Underwood, 1994; Choi et al., 2006; Coombes et al., 2011; Green et al., 2012). Nonetheless, high surface roughness is generally considered to increase the extent of bacterial accumulation (Borsje et al., 2011). Adhesion occurs at surface irregularities; the absence of micro cracks and crevices can significantly decrease microbial biomass (Terlizzi and Faimali, 2010). Characklis et al. (1990) noted microbial colonization increases with surface roughness. Biofilm development generally creates the conditions promoting the settlement of macrofouling organisms, which will proceed with surface colonization.

3.2. Biofouling

Submerged concrete surfaces undergo biofouling as biota, both sessile and vagile, settle onto a substratum and create an assemblage of

marine organisms. This association typically begins immediately upon submergence into the aquatic environment. Biofouling cannot be defined from an ecological point of view as a distinct and univocal entity because it varies according to different environmental situations. In other words, the species composition of the community changes from one site to another. The term fouling implies “dirt” or “filth”, and also includes the concept of damage because the presence of fouling can alter the technological characteristics and the possibilities of utilizing the structure onto which it has settled. Marine substrates, including concrete structures, demonstrate a great diversity of accumulated microfoulers and macrofoulers (Salta et al., 2013). In the Mediterranean Sea hundreds of macrofouling species have been recorded (Relini, 1993).

There are two current models for the formation of the biofouling assemblage. The successional model involves distinguishable temporal/seasonal sequences and biotic succession (Redfield and Deevy, 1952; Relini, 1974, Connell and Slatyer, 1977; Relini and Faimali, 2004). This is the classical successional model of biofouling on a substrate, implying causality from stage to stage of settlement. Another widely accepted model of biofouling settlement (Maki and Mitchell, 2002) is probabilistic or dynamic. All fouling stages are assumed to run continuously, leading to dynamic and complex interactions between water and substratum, water and specific biofouling organisms, and interspecifically among biofouling organisms, which, again, may interact with physical forces such as water flow or gravitation (Terlizzi and Faimali, 2010).

Regardless of the model used, it is clear that in any case the biofilm formation can be a crucial step, and the physical nature of the surface such as roughness, color, thermal capacity, composition, mechanical properties, surface chemistry, and surface tension of the concrete substrate can influence species composition and the amount of biofouling (Pioch et al., 2011). However, *in situ* studies have shown that the nature of the substrate influences settlement of micro- and macro-foulers during the early stages of colonization. Souche et al. (2016) and Perkol-Finkel and Sella (2015) have shown that pH or additional chemical fertilizer added into concrete mixtures can directly influence the diversity and abundance of algae. The slope of the substratum can also influence biofouling development; vertical slopes are less effective than other orientations (Somsueb et al., 2001). Thus, roughness diversity is, similar to biofilm, the most important factor for a positive colonization (Souche et al., 2016; Borsje et al., 2011). However, these positive influences for substratum colonization could be masked soon after the first exposure and become modulated by complex interactions of environmental variables, including biological, chemical and physical cues, light, food availability, and the presence of conspecific adults (Terlizzi and Faimali, 2010).

So, biofouling is a complex phenomenon dependent upon several inter-related processes, and the rate and extent of these processes are influenced by numerous physical, chemical and biological factors in the immediate proximity of the surface. For the purposes of this paper it is important to understand that biofouling can have dramatic influence on, and interaction with, the invertebrate and vertebrate assemblages associated with the structure.

3.3. Protection of biofouling against corrosion and leaching of concrete

The presence of some encrusting organisms, such as algae, barnacles, annelid worms and mollusks, can also improve conservation of the surfaces on which they grow, giving rise to the process of ‘bioprotection’ (La Marca et al., 2014). This refers to the direct or indirect ability of organisms to limit the efficiency of deteriorative processes such as erosion, weathering, and corrosion (e.g., Coombes et al., 2013). To facilitate their development, adapted material (pH close to what is found in the marine environment between 8.2 and 8.5) and roughness are key factors as well as position of CI in the landscape (i.e., depth and current orientation) (Firth et al., 2016). Thus, barnacles on the concrete

surface may represent a physical barrier that reduces salt ingress and subsequent crystallization below the surface. Such a bioprotective effect on the underlying surface appears to be proportional to the extent of the barnacle cover; bioprotection by barnacles is likely to be greatest where cover is more complete. The observations of La Marca et al. (2014) agree with the other studies, suggesting that barnacles can limit salt ion penetration within materials in the tidal zone and thus improve their resistance to corrosion (Iwanami et al., 2002; Maruya et al., 2003; Kawabata et al., 2012). In addition, Risinger (2012) found that biogenic growth of oysters makes concrete 10-fold stronger over time compared to concrete without oysters.

In urban coastal environments where disturbance may be frequent, facilitating the establishment and/or recovery of bio-protective species on engineered structures could enhance the durability of the construction materials, as well as support conservation for biodiversity enhancement. Using seaweed as an example, Coombes et al. (2013) developed a conceptual model of the relationship between biological cover and microclimate in the intertidal zone. Disturbance events that remove or drastically reduce seaweed cover mediate shifts between relatively stable and unstable states with respect to mechanical decay and ecological stress associated with heat and desiccation.

3.4. Settlement and substrate

Larvae of most sessile marine organisms metamorphose when they encounter a suitable settlement cue (Rodríguez et al., 1993). This transformation is usually irreversible and happens relatively quickly, being completed within a day or two. For sessile organisms, settlement is particularly crucial because the site of attachment of the larva determines the fate of the adult and the initial spatial distribution within populations. Eventual recruitment of individuals into a population of animals in a particular area or habitat will therefore depend not just on the arrival of larvae (i.e., their “supply”), but also on their rates of settlement at that particular location and the availability of suitable settlement substrate.

As larvae of benthic species (bryozoans, tunicates, sponges, cnidarians, echinoderms and others) encounter the substratum, they may show exploratory behavior, moving over the substrate as they search for a suitable settlement location. The substrate itself may provide a stimulus, with larvae capable of responding to its texture, color, or light intensity. Benthic substrates present complex chemical cues derived from the substrate itself, from the matrix of micro-organisms and particulate organic matter (collectively, biofilm and biofouling) and from other macro-organisms. Settlement induction is probably done by direct contact of marine larvae with almost unknown bacterial ligands (Hadfield, 2011) rather than by soluble compounds (Hadfield et al., 2014).

After larvae are settled and metamorphosed, the earliest stages of benthic life are subject to various disturbances. Some disturbances are physical, such as wave action, but many of these disturbances can be offset. For example, the snail *Littorina neritoides* wedges itself into tiny crevices in the rock and then swells its shell to fit tightly. Thus, recruitment will be in greater numbers where the surface of the CI can provide suitable crevices and holes.

For the settlement of algae, den Hartog (1972) suggested that a physical factor of decisive importance is the texture of the substratum. The attachment of algae to a rough rock surface is much easier than to a smooth rock. On smooth surfaces plant growth is usually limited to fissures and small irregularities of the rock surface. In the intertidal belt, where the water-retaining capacity of the substrate is largely dependent on its surface texture, the influence of the latter is very obvious (Coombes et al., 2011). By the end, small holes and pits creating refuges against predators, especially for juveniles, are also positive factors (Menge et al., 1983).

Table 2

Recommendation to select construction material and external shape at a small scale, for engineer and constructor to enhance colonization on CI.

	Material (concrete)	External shape (micro-structural)	To avoid	Positive additional effect
1 Development of biofilm	<ul style="list-style-type: none"> ● Chemoattractant coatings 	<ul style="list-style-type: none"> ● Roughness (texture) 	<ul style="list-style-type: none"> ● Metal leaching ● pH (far from sea pH) 	<ul style="list-style-type: none"> ● Bio-protection of surfaces (durability)
2 Biofouling	<ul style="list-style-type: none"> ● pH ● Fertilizer ● Seashell crushed 	<ul style="list-style-type: none"> ● Roughness diversity ● Grooved texture ● Slope 	<ul style="list-style-type: none"> ● Smooth surface ● Unfavorable external conditions 	<ul style="list-style-type: none"> ● Aesthetic (natural sea-scape integration)
3 Settlement and recruitment		<ul style="list-style-type: none"> ● Hole, pits 	<ul style="list-style-type: none"> ● Only vertical structure 	

NB: Effects are cumulative, for each column and line, e.g. recommendation from line 1 + L2 and column 1 + C2 are better than only line 3 from column 2.

3.5. Micro-habitat complexity and role of roughness of the substrate

The importance of physical habitat complexity and the effect of various engineering design features on the ecology for rocky shore species (e.g. Moschella et al., 2005; Chapman and Blockley, 2009) has led to considerable work worldwide to test various engineering designs for ecological gain (see Table 2 and Chapman and Underwood, 2011). The importance of micro-habitat complexity in determining the abundance and diversity of epibiota has been assessed at different spatial scales (Moschella et al., 2005) and the effect of crevices and fractures of the rock surface (around a centimeter wide) on epibiotic species diversity is clear (Chapman and Bulleri, 2003).

On natural rocky shores, fine-scale habitat heterogeneity is created by weathering, involving the wetting and drying of rocks, salt crystallization, chemical breakdown, erosion, and biological processes (Coombes, 2014). Further, there is substantial experimental evidence of the importance of fine-scale texture for the development of marine biofilms, the settlement of invertebrate larvae and spores, recruitment of juveniles, and the nature of community interactions on rocky substrata (e.g. Menge et al., 1983; Chabot and Bourget, 1988; Walters and Wethey, 1996; Decho, 2000). Yet, limited research has examined enhancement opportunities of roughening the concrete of the infrastructure to finer scales (millimeters). Most ecological enhancement trials in the intertidal zone have focused on increasing physical habitat complexity at the centimeter-meter scale (Coombes et al., 2015). Concrete, when produced using standard molding techniques, typically lacks fine-scale topographic complexity. Certain concrete chemistries may also limit (via exclusion and/or delay) the development of epilithic communities via pH effects and metal leaching (Hillier et al., 1999; Spieler et al., 2001; Wilding and Sayer, 2002). Coombes et al. (2015) tested the hypothesis that the settlement and recruitment of a dominant early colonist (barnacles) on marine-grade concrete would vary between treatments with different fine-scale (millimeter) surface textures. Their data demonstrated that, relative to smooth materials, hard coastal infrastructure with a fine, grooved texture could support a population of barnacles comparable to those found on naturally weathered rock. This, in turn, would be expected to lead to the faster establishment of a greater range of invertebrate species which would, in turn, provide a forage base for higher trophic levels. Ideally the eco-design would incorporate a multitude of textures at varying scales (millimeter-centimeter, centimeter-meter) to provide habitat for a diverse biota. Thus, the simple and inexpensive manipulation of concrete surface texture can provide habitat for enhancing the conservation value of urban marine infrastructure. Surface microstructure is also important for the microbial biofilm and biofouling. Many of the geochemical and biological processes which are mediated by microorganisms occur within microenvironments which can be measured in a spatial scale of micrometers. These processes are localized by cells within a matrix of extracellular polymeric secretions (EPS), collectively called a “microbial biofilm” (Decho, 2000). Special admixtures containing biogenic aggregates (crushed seashells), organic or inorganic activators (fertilizer, chemoattractant) can also alter the surface texture and chemistry and should positively affect settlement (Lee et al., 2008; Devillers et al.,

2010; Souche et al., 2016). Finally, aesthetic integration in the sea-scape of the CI (color, species diversity, texture) will be better if the submerged part of the structure is covered by biofouling.

4. Macro-structural aspects for eco-design

Assemblages of marine organisms (micro and macro) live on natural and artificial substrates. At the same time marine structures are habitat for fishes and it could be incorporated into macro-structural aspect for eco-designed CI. Whereas there are a host of algae and invertebrates that are associated with macro-habitat, this section focuses on the colonization of the structure by fishes as, from an artificial structure perspective, as most likely more has been done with this group than any other. Obviously, fishes targeted by fisheries provide ecosystemic service of provisioning, an important economic indicator in environmental public policy. Thus, most of the main species targeted by fisheries are predators at the top of the food web and as such can be used as indicators of the health of the entire food web (Myers and Worm, 2003; Pauly et al., 2005). We will use these predators as sentinel species (Sergio et al., 2008). Nonetheless, our purpose is not to substitute the assessment of a few species, usually delivering affordable ecosystemic services, as the priority for biodiversity management. Considering a whole ecosystem with a systemic approach is the only way to ensure its conservation (Elliott et al., 2007). For example, Kilfoyle et al. (2013) clearly showed that a boulder reef used as mitigation for coastal low-relief hard bottom in Florida was more useful for generating an assemblage of predatory fisheries-important species than as equitable replacement of juvenile habitat. Large fishes attracted by large artificially enhanced overhangs and holes replaced the native assemblage that was previously dominated by juveniles associated with small refuges within the surrounding natural ecosystem. However, as top predators are under pressure of human fisheries, eco-design that supports their habitat could attract local stakeholders and introduce the idea of re-thinking the design of CI. Economically valuable species could facilitate the arguments for eco-design and ensure, indirectly, the concept of designing infrastructure to minimize impact to the whole ecosystem. Of course, concentrating on hard substrate associated species, because concrete is the material most commonly used for coastal construction, and species targeted by fisheries, is not enough. The approach needs to be balanced with soft substratum species, and not just those targeted by fisheries. Our concerns are to enhance biodiversity for species locally present in the eco-region.

4.1. Marine assemblages on natural and artificial substrates

Beginning in the 1950's, much work has been carried out that highlights the main differences between biological assemblages on artificial and natural substrata. Basically, urban marine infrastructure supports different epibiota and associated assemblages and does not function as a surrogate for natural rocky habitats. Generally, epibiotic communities of low-crested coastal defense structures are qualitatively similar to those on natural rocky shores, as both habitats are regulated by the same physical and biological factors (Bacchiocchi and Airoidi,

2003). However, there are, minimally, quantitative differences in the diversity and abundance of epibiota on artificial structures. Typically, epibiotic assemblages on artificial structures are less diverse than those associated with natural rocky shore communities (Moschella et al., 2005; Coombes et al., 2015). Further, introduction of artificial structure in the intertidal zone or in nearshore waters can cause fragmentation and loss of natural habitats which can alter local and regional biodiversity by modifying natural patterns of species dispersal or by facilitating the establishment and spread of exotic species (Bulleri and Chapman, 2010). The generalized spread of non-indigenous species and management of biological invasions is an increasing worldwide concern for the conservation of marine biodiversity at local and regional scales (Bulleri, 2005; Bulleri and Airoldi, 2005; Li et al., 2005; Glasby et al., 2007; Tyrrell and Byers, 2007; Vaselli et al., 2008; Lam et al., 2009; Airoldi and Bulleri, 2011; Dafforn et al., 2012; Airoldi et al., 2015). Understanding the drivers of these differences could improve our ability to design artificial structures that more closely mimic natural habitats, potentially mitigating some effects of loss and fragmentation of coastal habitats in urban areas.

4.2. Volume

All marine species are vulnerable to environmental disturbance (e.g., pollution, over-fishing, sedimentation, artificialization or invasive species) but especially if their living ecosystem is small (surface and volume) and low in species diversity (Worm et al., 2006). According to Dempster et al. (2002), the marine productivity (abundance, biomass, and species richness) of artificial structures is proportional with their size. According to Bohnsack and Sutherland (1985), the minimum volume of a complex artificial marine ecosystem in the case of artificial reefs should be around 400 m³ for temperate water. This minimal volume is well within the reach of large marine projects and could be a starting-point for creating and maintaining a functional ecosystem, but the size could be far less if the issue is to enhance biodiversity integration at the project site. Multiple smaller modules with variably-sized refuge have been used in the past to acquire differing assemblages of fishes (Pioch et al., 2011).

4.3. Sizing effective habitat in the artificial infrastructure

The volume (surface × depth) of the coastal infrastructure could be enhanced by providing cavities for refuge-seeking species (surface × depth × # of cavities). In recent years, it has been shown that complexity of an artificial substratum was linked with higher levels of biodiversity (Charbonnel et al., 2002; Sherman et al., 2002). This principle is true, but could be nuanced by the inclusion of ecological objectives wherein species-specific complexity is created for a species group with size-specific refuge (Diamond, 1975). Thus, providing a mix of appropriately sized micro- and macro-habitats could produce a more diverse assemblage of targeted predators and juveniles, as well as increased invertebrate forage resources (Kilfoyle et al., 2013; Patranella et al., 2016). The ecological function of different size, depth, and orientations of macro-structure habitats has to be carefully analyzed as in nature they are correlated with ecological function at different spatio-temporal scales. Three essential habitat functions need to be considered for fishes: refuge, feeding, and breeding (Grove et al., 1994). These functions vary among species and life-stages. The empirical observations of targeted species, in their natural habitat, provide the insight into size-effective artificial habitat (Baine, 2001). Ethological studies about the relationships among species on natural and artificial habitats are important (Fréon and Dagorn, 2000). Such studies focus on the spatial relationship between animals (or a group) of differing species and is based on a decision by at least one of the two individuals to maintain contact with the other associate with other objects or topographic structures (natural or artificial) (Ibid.). Research in this area was developed early in Japan, where fisheries tried to maximize the fish

stock exploitation in relationship with the fishes' natural habitats (Ogawa, 1982). In several studies there, the depth, orientation, height, and internal volume of artificial habitat were constructed to mimic certain aspects of the natural habitat as determined by *in situ* observations (Ogawa, 1982; Nakamura, 1985; Tanoue et al., 2015). Contemporary authors have largely used the principles stemming from this research (Seaman, 1995; Relini et al., 2002; Bortone, 2006; Seaman, 2007; Bortone et al., 2011). This work tends to confirm common general ethological concepts that the types of species or groups can be classified according to their behavior with respect to their habitat (Gerino et al., 2003). According to Nakamura (1985) and modified by Kakimoto (2004), three homogeneous groups of fisheries-important species can be determined by their relationship to habitat. Type A species living within cavities, type B staying close to the structure, and type C positioned above or around natural or artificial hard substrate habitats. In addition, many species, including those not of fisheries interest, prefer holes within artificial structure slightly larger than their body diameter. Some species are found in tunnels, although straight tunnels may not be preferred, and only a few families appear to prefer blind tunnels. Likewise, many fishes use horizontal shaded areas for predator avoidance and thus artificial structure with overhang that provides shade can be successful in providing refuge. Vertical structure can be used to avoid large predators that cannot turn as fast as their prey; it can also provide a hydrologic front which aids planktivory or as a retreat from strong current (for references see: Spieler et al., 2001). These considerations should be used to avoid destruction or fragmentation of the habitat (mainly by disrupting biological corridors or isolation of production zones), and the ecological functions it ensures (Farina, 2008). Spatially creating connectivity between artificial substrates and neighboring natural habitats should also be developed (Kakimoto, 2004). According to Nakamura (1985) the optimum distances between natural and artificial substrates is less than 200 m for benthic species and 300 m for pelagic species. Studies on artificial reefs have shown that beyond a certain distance, biological exchanges (flows) between two units are weaker (Santos and Monteiro, 2001; Seaman, 2007). For a separation distance of about 1000 m or more, two hard substrates (natural or artificial) are considered to be quasi-independent because the biological fluxes are lower. Of equal concern is creating habitat or corridors for invasive or site-detrimental species (i.e., refuge for predators in a nursery area) (Kilfoyle et al., 2013; Airoldi et al., 2015; Patranella et al., 2016) (see Table 3).

5. Discussion

This paper has provided a brief overview of some of the bio-physical factors interacting with concrete structures in the marine environment. Incorporating multi-scale design of both, material, micro- and macro-habitat into hard marine infrastructure is likely to prove the most effective approach to maximizing the potential to support ecosystems and biodiversity in urban coastal regions. However, regardless of the design, if pollution levels are high, oxygen levels are low, or food is limited (due to anthropogenic impacts, for instance), the structure will not be effective in maintaining biodiversity.

At this time several CI have been done using an eco-design approach (Pioch et al., 2011; Coombes et al., 2015; Perkol-Finkel et al., 2017) and incorporated ecological concerns at the early stage of design. Ecological targets were taken into account as well as socio-economical and technical considerations, i.e., choice of material and structural shape of the construction. At Mayotte Island, an eco-designed water pipe line about 2.5 km in length has been working since 2009, supplying fresh water for people as well as new habitat for local species, increasing species diversity 5-fold post-construction after 1.5 year (Bigot, 2010). In 2013, 52 eco-designed moorings were installed in Deshaies (Guadeloupe, French overseas). After 4 years, the assessment showed targeted species, such as juvenile lobsters and groupers, settled in the eco-designed artificial habitat that mimicks local natural habitats (Pioch, in prep.). Most likely

Table 3
Recommendation for macrostructural design, for engineer and constructor to enhance colonization on CI.

	Macro-structural aspects	To avoid	Positive additional effect
1 Marine assemblage	<ul style="list-style-type: none"> ● Mimic natural habitat (diversity) as a basic for CI aspect 	<ul style="list-style-type: none"> ● Habitat fragmentation ● promote invasive species 	<ul style="list-style-type: none"> ● Fisheries enhancement or conservation area
2 volume	<ul style="list-style-type: none"> ● Over 400 m³ available habitat (temp. water) ● Variably-sized refuge 	<ul style="list-style-type: none"> ● Low diversity of habitat volume ● isolation of production zones 	<ul style="list-style-type: none"> ● Aesthetic (natural sea-scape integration)
3 Sizing effective habitat in the artificial infrastructure	<ul style="list-style-type: none"> ● Different size, depth, and orientations: horizontal shaded areas, vertical structure creating hydrologic front, tunnels and blind tunnels ● Targeting refuge, feeding, and breeding size of natural and local habitats (mimicking) 	<ul style="list-style-type: none"> ● Disrupting biological corridors (connectivity) 	

NB: Effects are cumulative, for each column and line.

due to the engineering design, these facilities and their associated biota survived essentially unscathed the 6 m high waves associated with Hurricane Irma in September 2017 (diving survey made in November 2017).

But, these examples also pointed out two fields where it is clearly needing research: knowledge to mimic natural ecosystem and adaptive management.

6. Knowledge to mimic natural ecosystem

It is clear from an ecological perspective that smooth vertical concrete CI in the marine environment is essentially without positive ecological value and should only be used as an absolute last resort. Roughness of the substrate is fundamental for effective settlement of a diverse assemblage of marine organisms. Ideally it is advised to include the presence of fine-scale textures and grooves/furrows of different sizes and orientation. There has also been extensive research on the positive effects of minor, inexpensive surface modifications and changes in composition of concrete on associated assemblages and biodiversity, without hampering the concrete's structural performance (Perkol-Finkel and Sella, 2014; Sella and Perkol-Finkel, 2015). Ideally, such modifications should be done in all marine construction. Further, there exists a wealth of literature on artificial reefs on the interaction of specifically constructed macro-habitats and associated biological assemblages (Nicoletti et al., 2007).

Such habitats could readily and inexpensively be incorporated into designs for CI. The fact that it has, to date, not become common practice calls for a fundamental cultural change in the world of construction (see below).

Yet it must be admitted that despite a rapidly growing body of literature, we still cannot reliably design and create a specifically desired ecosystem that functionally provides ecological goods and services as well as a natural ecosystem. A great deal of research is still required. However, we do not recommend large investments in a global research approach to eco-design because the interactions of biota with concrete structures are often very site specific. Rather, research should be local and initiated at the specific construction site at the earliest opportunity, when the site is selected and before the preliminary structural designs are initiated (Fig. 1). Potential substrates, in terms of micro- and macro-habitat should be tested with replication and for as long as possible prior to general design (final design) and construction. Because the assemblages associated with a structure are not static, but rather depend on a host of stochastic natural processes (Nicoletti et al., 2007), we recommend all new projects incorporate some experimental research to allow for knowledge based adaptive management to determine whether modification of the project design is required. As the technical knowledge increases, civil engineering scholarly education needs to be developed with ecological and eco-engineering issues in mind and with components on how to integrate complexity and cost-effectiveness when addressing environmental and ecosystem approaches in eco-design.

7. Adaptive management

Related to the issues of current knowledge as well as economics, is the apparent desire of everyone involved to avoid further involvement once the project is completed. This is common throughout both the developed and developing world and is understandable from several perspectives. The resource manager may not wish to see the project monitored for fear that if the results are not as good as anticipated, or worse, the loss of public support and the outcry related to misspent tax dollars could impact the resource managers' jobs. For them it can be better to 'let sleeping dogs lie' and merely continue to cite the expected results rather than to undertake post-construction monitoring and find out otherwise. Likewise, the entity paying for the construction may not want to know exactly how well it is performing vis-a-vis expectations because that could leave the construction/renovation costs open-ended if corrections are demanded by resource managers. Nonetheless, without analyzing results and making efforts to correct or improve them, progress in understanding the problems and solutions that are bound to occur in a nascent discipline like eco-design and eco-engineering will be slow. Thus, an adaptive management approach should be applied to every project; every project should be monitored for several years until relative equilibrium is achieved and corrective action undertaken during that time period as needed. Moreover, culturally, it is not surprising that construction engineers may not feel enticed to design-with-nature. On the one hand, it is a new approach, not business as usual, demanding incorporation of a foreign discipline, e.g. ecology, into a traditional, well-established business. On the other hand, some engineers may falsely believe ecosystem loss is already being adequately addressed by a host of burdensome mitigation and replacement regulations and a demand for new approaches is unlikely to be well received. However, there is a lot of literature showing that by and large mitigation does not adequately compensate for ecosystem loss (Moreno-Mateos et al., 2015). Likewise, there exists a self-protective attitude on the part of some resource managers that leads them to always rely on mitigation approaches that have been implemented elsewhere to provide an excuse if something does not work. This provides a standard approach that is not adapted to achieve the environmental goals. Ecosystem repair will by its very nature always be site specific, and finding something that works at one site might not work at another.

8. Summary and conclusions

Eco-design calls for a modernization of both construction and ecological approaches in civil work processes, starts with marrying the two words "ecology" and "design", and requires a full collaboration of civil and ecological engineers working together during the same planning phases. To ensure dialogue and collaboration, considerations for the design of CI should be taken into account at the early stage of project design. Indeed, eco-design of CI tries to accommodate in the design planning stage a logical and practical implementation of concepts from both sides of two complex approaches: technical and ecological. From

material composition (i.e. concrete) to micro- and macro-structure, ensuring a parallel and reciprocal exchange to define the general design of CI, associating ecological and technical parameters, one needs to incorporate a review of studies and experimental results since eco-engineering has been studied and improved for less than 20 years (proposed in sections 2 and 3).

Clearly, reconciling both human and non-human use of the near-shore marine environment in a sustainable way represents a major challenge for the 21st century and beyond. It is a challenge society must come to grips with lest we face continued loss of a multitude of essential ecosystem goods and services. With the forecasted increase in both coastal population and sea-level rise, coastal construction will at best continue unabated for the foreseeable future. At worst, it will increase in response to short-sighted economic priorities or in efforts to ameliorate natural disasters. Moreover, there is a lack of clear policy developments or applications in administrative agencies, applicable to both environmental (in charge of EIA authorization) and civil engineering (in charge of construction permitting), to develop coastal infrastructures targeting better environmental integration, with better construction solutions and within acceptable costs. There is a growing need for development, in clear administrative terms, of references on coastal civil works that incorporate environmental performance enhanced by eco-design approaches. In conclusion, we believe fully implemented eco-design protocols could dramatically reduce the impacts of coastal construction and it is needed now more than ever. It requires, simply, an ambitious political will.

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