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Viewpoint

Eco-engineering and management strategies for marine infrastructure to reduce establishment and dispersal of non-indigenous species

Katherine A. Dafforn[1,2]
[1]*University of New South Wales, School of Biological, Earth and Environmental Sciences, Sydney, NSW 2052, Australia*
[2]*Sydney Institute of Marine Science, Mosman, NSW 2088, Australia*
E-mail: *k.dafforn@unsw.edu.au*

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Editor's note:

This study was first presented at the 9th International Conference on Marine Bioinvasions held in Sydney, Australia, January 19–21, 2016 (http://www.marinebioinvasions.info/previous-conferences). Since their inception in 1999, ICMB series have provided a venue for the exchange of information on various aspects of biological invasions in marine ecosystems, including ecological research, education, management and policies tackling marine bioinvasions.

Abstract

Habitat modification and the introduction and establishment of non-indigenous species (NIS) are two of the greatest threats to global biodiversity. Human modifications of marine habitats include the introduction of boating infrastructure, coastal defences and offshore energy installations that are occurring at an increasing rate. These artificial structures are now widely recognised as providing opportunities for the establishment and dispersal of non-indigenous fouling species in new regions. This is driving increased interest into how structures might be designed and built to limit their suitability for invasive species. At the same time the potential for artificial habitats to provide habitat to native and threatened species means that the control of NIS on these structures should not just rely on antifouling. Green or eco-engineering aims to incorporate ecological theory and principles into the design of engineered structures. When combined with other management strategies that aim to increase the resistance of recipient environments there is the potential to enhance practical barriers against invaders in an increasingly developed ocean. Here I explore examples of NIS facilitation by artificial structures and the ecological theories that could be used to reduce opportunities for NIS establishment and spread. Examples include (1) manipulating the physical and chemical properties of structures to enhance native recruitment over NIS, (2) enhancing resource use of structures by native species through "pre-seeding", (3) providing opportunities for native grazers and predators to easily access structures, and (4) considering the timing of construction/maintenance/decommissioning for artificial structures such that resources are not made available when propagule pressure is also high. These examples are not exhaustive, but rather provide a discussion point for managers of biological invasions to generate further research and application over larger spatial scales.

Key words: artificial structure, estuary, coast, offshore, community ecology, invasion theory

Introduction

Successful invasion is generally thought to comprise of three main stages; (1) a species must be transported outside of its native range (donor region) and (2) establish a self-sustaining population that is (3) able to disperse throughout a new area (recipient region) (Williamson 1996; Kolar and Lodge 2001). The introduction of non-indigenous species (NIS) is a common problem in a world increasingly connected through infrastructure and growing transport networks (Ruiz et al. 2000; Gollasch 2002; Minchin and Gollasch 2003) and is posited as the biggest threat to biodiversity after habitat loss (Vitousek et al. 1997; Wilcove et al. 1998). As a result, there has been significant investment in reducing invasion opportunities (Hulme 2009), but where efforts to manage transport vectors or border control fail, then eradication can be costly (Pimentel et al. 2000). Hence there is a pressing need to think outside the box of conventional controls and investigate novel solutions to reduce the invasion opportunities for NIS in our ports and harbours.

Different natural and anthropogenic selection filters act on NIS at different stages of the invasion process (Williamson and Fitter 1996; Piola et al. 2009). At the transport stage, NIS are selected for a wide environmental tolerance as they must survive entrainment and subsequent changes in environmental conditions from the donor to recipient region (Johnston et al. 2009; Keller et al. 2011). Successful establishment will then depend on them finding a "niche opportunity" within the new region (Tilman 1997; Shea and Chesson 2002). As a result only a subset of transported species is actually able to establish and persist. This has also been defined in statistical terms as the "tens" rule (Williamson et al. 1986; Williamson and Fitter 1996) and refers to the probability that only one in every ten species transported is likely to arrive at a new destination, and only one in ten of those arrivals will establish and disperse in the new region. While we have some idea of the selection agents acting on species introductions (Williamson and Fitter 1996), further investigation is needed to determine how these selection agents could be manipulated in marine developments for the management of invasions.

The increasing construction of estuarine, coastal and offshore infrastructure provides novel habitat that has been shown to increase "niche opportunity" for NIS (Bulleri and Airoldi 2005; Bulleri et al. 2006; Glasby et al. 2007; Dafforn et al. 2009b; Airoldi and Bulleri 2011; Dafforn et al. 2012; Simkanin et al. 2012; Airoldi et al. 2015). This has been extensively reviewed elsewhere (Mineur et al. 2012; Johnston et al. 2017), but briefly can occur through the provision of physical and chemical conditions that match the environmental tolerance of arriving NIS, increased availability of limiting resources and reduced resistance in the form of natural enemies. Ecological strategies are increasingly being considered by marine developers in efforts to build and marine infrastructure in a more environmentally sustainable way. Most examples where ecological theory has been used to enhance engineered structures are related to manipulations of physical properties such as material, complexity, or microhabitat addition ("green" or "eco-engineering" e.g. Chapman and Blockley 2009; Browne and Chapman 2011; Chapman and Underwood 2011; Browne and Chapman 2014; Dafforn et al. 2015a; Firth et al. 2016b; Firth et al. 2016c; Morris et al. 2016; Mayer-Pinto et al. 2017). There is also a growing number of strategies to manage marine infrastructure that could be applied to reduce NIS threats including marine spatial planning (Gilbert et al. 2015), water quality improvement (Piola et al. 2009; Johnston et al. in press) and implementation of regulatory drivers (Naylor et al. 2012) . These strategies together with interdisciplinary approaches to marine development provide significant capacity to design, build, and manage structures that not only fulfil their major objective as physical infrastructure, but also reduce "niche opportunities" for NIS (Sella and Perkol-Finkel 2015).

Below are examples where built infrastructure (or artificial structures) have supported the establishment and dispersal of marine NIS. I use community ecology theory (Shea and Chesson 2002) as a framework for identifying the properties of built infrastructure that (1) have facilitated the establishment and dispersal of NIS, and (2) could be manipulated through eco-engineering to prevent future invasions. I provide practical small-scale examples that have been or could be incorporated into the construction or retrofit of artificial structures and outline future directions for research.

Marine infrastructure facilitates the establishment and dispersal of non-indigenous species

In areas of Europe, the United States, Australia and Asia large sections of the coastline is now modified by the addition of built infrastructure such as seawalls, breakwaters, pilings and marinas (Bulleri and Chapman 2010; Dugan et al. 2011; Dafforn et al. 2015a). Together with this, global demand for resources has driven exploration and extraction offshore where aquaculture and energy platforms are creating an increasing footprint in the ocean (Wilson and Elliott 2009; Wilson et al. 2010; Firth et al. 2016a; Heery et al. in press). Duarte (2012) refers to this collectively as "ocean sprawl" because human activities once confined to land continue to expand into ocean ecosystems. Since NIS are closely associated with artificial structures, ocean sprawl has been and will continue to be a major factor in their global spread.

Marine infrastructure, including ports, marinas, breakwaters, oil and gas platforms, has been found to be highly susceptible to NIS establishment. This is reviewed extensively in Mineur et al. (2012), but some examples include boating infrastructure (pilings and pontoons), which has previously been found to support up to 2.5× more NIS than natural reef (Glasby et al. 2007), with pontoons in particular acting as invader hotspots (Dafforn et al. 2009b). Moreover, energy infrastructure (oil platforms and rigs) can support communities comprising between 20–30% NIS (Ferreira et al. 2006; Hopkins and Forrest 2010). Apart from the provision of local habitat for the recruitment of NIS, recent research has highlighted the role of artificial structures in their spread. For example, the northward range shift of the non-indigenous coral *Oculina patagonica* along 400 km of Mediterranean coastline is thought to have occurred more rapidly on artificial than natural habitats (Serrano et al. 2013). Similarly, the non-indigenous alga *Undaria pinnatifida* has experienced a northward range expansion from its southernmost introduction point in France to Northern Ireland in just 40 years (Minchin and Nunn 2014). While the initial introduction is thought to have been with the oyster aquaculture industry, the spread of the alga through Europe has been linked to recreational craft and the European network of marinas. Airoldi et al. (2015) also provide compelling evidence that coastal infrastructure along 500 km of coastline in the North Adriatic sea has influenced the regional spread of non-indigenous ascidians. Together these examples provide a convincing argument for designing infrastructure in more ecologically-sustainable ways, specifically to limit the establishment and dispersal of NIS.

"Niche opportunities" provided by artificial structures

Following the framework proposed by Shea and Chesson (2002), artificial structures potentially facilitate invasion through a number of processes. Firstly, through the construction of habitats with physico-chemical conditions, which match the characteristics of individual or multiple NIS (habitat suitability, Moyle and Light 1996). Secondly, through the provision of space that may be limiting in the recipient region (resource availability, Davis et al. 2000), and thirdly, by reducing biotic resistance from native species and natural enemies (biotic resistance and enemy release, Keane and Crawley 2002; Levine et al. 2004). These processes also have the potential to act and interact throughout the life cycle of an artificial structure, from construction and operation to decommissioning.

The construction of infrastructure adds substrates to the marine environment that are physically and chemically different to natural habitats. Artificial structures are often oriented vertically and shaded artificially (Glasby and Connell 1999), therefore they can experience less light than natural habitats (Glasby 1999). The design of artificial structures has also been linked to changes in currents around them, predominantly reduced flow which could increase encounter probabilities for NIS and the chance of establishment (Glasby et al. 2007). These properties are especially relevant since a large majority of NIS are fouling invertebrates and benefit from reduced algal competition under low light conditions (Dafforn et al. 2012). Lower levels of sedimentation and slower flow under these conditions also benefit invertebrates that rely on filtering apparatus to obtain food (Ostroumov 2005). Similarly NIS establishment and spread on marina structures like pontoons can be explained by their depth range and floating position in the water column (Glasby et al. 2007), which together create physical (e.g. floating) or chemical (e.g. metal contamination in the water column) conditions for marine invaders that are analogous to the boat hulls upon which they may have arrived (Dafforn et al. 2009b). The materials used in construction may also be toxic e.g. pilings treated with copper chromated arsenate (Weis and Weis 1992) or chemically inhibit biological recruitment due to high surface alkalinity e.g. Portland cement used in breakwaters (Sella and Perkol-Finkel 2015). While copper is widely accepted to facilitate NIS dominance over native species, the potential for concrete mixtures to enhance recruitment of target species on artificial structures has only recently begun to be explored (Sella and Perkol-Finkel 2015).

Artificial structures also increase the availability of a limiting resource in marine environments, i.e. space through the provision of hard substrates (Dayton 1971; Buss 1979; Bullard et al. 2004; Glasby et al. 2007). Since many fouling NIS are fast-growing or opportunistic (r-strategists), free space could be enough to facilitate their establishment over slower growing native species (k-strategists) (Grime 1977). In other instances, the provision of resources needs to also match the physico-chemical requirements of the NIS. For example, establishment of the non-indigenous alga *Codium fragile* ssp. *tomentosoides* in the North Adriatic Sea has been linked to the space provided by breakwaters, particularly on sheltered (landward) sections and with disturbances that reduced biotic resistance from dominant native mussels (Bulleri and Airoldi 2005).

During operation and decommissioning, artificial structures also change the local environmental conditions and may create conditions that favour NIS. For example, Rivero et al. (2013) found that the construction of a breakwater around a marina can reduce flow by 30%. This traps contaminants leaching from antifouling paints and has the potential to entrain the larvae and spores. Enclosed boat harbours and marinas can therefore facilitate transport of a native species to a new region, where it is non-indigenous, but also can act as a propagule source for regional dispersal (Floerl and Inglis 2003). Furthermore, boat harbours contaminated with metals from antifouling paints have been shown to facilitate invader dominance over native species

(Piola and Johnston 2008). When in combination, the presence of metal-tolerant NIS in low flow conditions at contaminated sites (e.g. marinas) can contribute to these systems being more invaded and acting as a major source of intraregional dispersal (reviewed by Johnston et al. 2017).

Hydrodynamic modelling of energy platforms in the North Sea have also shown that changes to flow as a result of the underwater scaffolding may trap propagules (larvae) that would otherwise be lost offshore, and when these propagules are non-indigenous, then potentially facilitate establishment and dispersal through oil fields (Adams et al. 2014). The trapping of propagules in areas where artificial substrate is readily available (space is not limiting) and shaded (physico-chemical conditions are suitable for fouling species) could further facilitate NIS establishment over the propagules of any native species that might also be present. Furthermore, there is a continuing argument as to whether non-operational energy platforms should be decommissioned or remain are reefs (Macreadie et al. 2011) that could potentially support NIS.

Eco-engineering and other management strategies to reduce "niche opportunities" for non-indigenous species on marine infrastructure

There are increasing opportunities for marine researchers, managers and developers to work together to reduce marine invasion through ecologically-informed design, construction and management of artificial structures (Naylor et al. 2012). At its most base level this could include regulations that control the timing of different stages of marine developments. For example, the construction of a new structure in the marine environment could consider major recruitment patterns of NIS and avoid providing an important resource at times when free space might increase the chance of successful settlement (Lockwood et al. 2005; Clark and Johnston 2009; Hedge and Johnston 2012). Given the cost and scale of many developments, timing controls at the initial construction stage might not be logistically possible. The ongoing maintenance of existing artificial structures offers more possibilities for timing control to prevent disturbances that free up resources when NIS can take advantage of them (Airoldi and Bulleri 2011). Physical cleaning practices, such as in-water cleaning, should be carefully considered in maintenance scheduling to avoid causing NIS to spawn in reproductive periods and increase local propagule pressure (Hopkins and Forrest 2008).

There is a long history of biofouling control in the marine environment and much of this has been driven by shipping, aquaculture and port industries, where the removal of all fouling species is desirable to prevent damage to important infrastructure and avoid economic costs (Dafforn et al. 2011). Strategies have included non-discriminant antifouling applications, chemical control and physical removal. While there have been demonstrated examples that these strategies can be effective controls of fouling and NIS (Champ and Pugh 1987), negative impacts (e.g. from metal pollution) on native species have also occurred (Terlizzi et al. 2001). Increasingly research suggests that manipulating substrate composition, micro- and macro-topography might offer a non-toxic alternative for directly preventing NIS recruitment while facilitating native species (Tyrrell and Byers 2007; Sella and Perkol-Finkel 2015; Strain et al. unpublished data). Furthermore, manipulations of substrate can indirectly affect the recruitment of NIS and native species in several ways, including facilitation of native species that compete with NIS for space (Sella and Perkol-Finkel 2015), and changes to the biofilm (Tan et al. 2015). The potential for microbial assemblages to be manipulated to prevent NIS recruitment is an important area of research, and molecular advances now give us an opportunity to understand how eco-engineering designs might influence fouling communities from the biofilm upwards.

Larger-scale physical manipulations of artificial structures could also be used to manage NIS recruitment and spread. For example, there is significant evidence that shading from artificial structures facilitates a predominantly invertebrate community (Miller and Etter 2008; Dafforn et al. 2012), and that NIS comprise a significant proportion of these shaded communities (Wasson et al. 2005). Therefore designs that aim to reduce shading, such as "skylights" in foreshore boardwalks composed of metal grills or transparent materials (Dyson and Yocom 2014), could go some way to encouraging native algal recruitment and NIS exclusion. Similarly, building structures such as seawalls on a more gentle gradient could create conditions more similar to natural reefs systems (Department of Environment and Climate Change 2009), reduce shading, and therefore create physico-chemical conditions that are more suitable for native than NIS establishment (Dafforn et al. 2015a).

On a larger scale, the placement of artificial structures locally, regionally and internationally should be incorporated into marine spatial planning (Dafforn et al. 2015b; Domínguez-Tejo et al. 2016). Further research is needed to e.g. determine appropriate densities, sizes and connectivity of artificial structures that could potentially allow them to provide a pathway for climate migrants (species extending their ranges due to climate change Vergés et al. 2014), but not act as stepping stones (Airoldi et al. 2015) for the dispersal of NIS (Bishop et al. in press). Breakwaters, locks and weirs are often used to protect important infrastructure, and while they have been linked to conditions with reduced flow and propagule entrainment (Floerl and Inglis 2003; Rivero et al. 2013), there is also the potential that at ecologically-sensitive sites such as marine protected areas, they could be used to physically prevent NIS spread by trapping propagules or containing them during an eradication effort (e.g. Willan et al. 2000). An important trade-off associated with these physical interventions is the build-up of contaminants such as the metals from antifouling paints used on boats that creates degraded conditions (Sim et al. 2015).

Ports and harbours are particularly impacted by chemical contaminants (Warnken et al. 2004; Dafforn et al. 2008; Dafforn et al. 2009a). The sources of these include land-based stormwater inputs such as metals and nutrients (Birch 2000), legacy inorganic and organic contaminants from past industrial practices (Birch 2000; Jones 2000; Maguire 2000), and marine-based contaminants from antifouling paints and vessel discharges (Schiff et al. 2004). Chemical disturbance in estuaries is posited to be a major factor in the loss of native species' resistance to invasion (Piola and Johnston 2008; Johnston et al. in press) and can be beneficial for opportunistic invaders that have arrived on the hulls of vessels and already been selected for metal tolerance (Piola et al. 2009). Measures that are increasingly being incorporated into foreshore developments include water sensitive urban design that often aims to trap and recycle all contaminants through measures such as artificial wetlands and filtration systems (Hatt et al. 2006; Davis and Birch 2009; Madhani and Brown 2015; Prosser et al. 2015; Greenway in press). Copper contamination in particular has been implicated in the establishment of NIS (Piola et al. 2009). Apart from being a major contaminant in stormwater runoff, copper is also the primary component of many antifouling paints, and wooden pilings are often treated with copper chromated arsenate to prevent fouling (Weis et al. 1993). Limiting the use of copper in antifouling products would go some way to reducing chemical advantages for NIS establishment and dispersal, and helping to rebuild native species resistance to invasion (Piola et al. 2009; Johnston 2011; Johnston et al. in press).

Apart from physical and chemical manipulations, the biotic characteristics of artificial structures could be directly manipulated to increase resource use and enhance biotic resistance, thereby decreasing opportunities for NIS. "Pre-seeding" artificial structures with native species is gathering traction in eco-engineering (Perkol-Finkel et al. 2012) and has analogous principles to the cultivation of native plant communities on green roofs or walls (Johnson and Newton 1996; Oberndorfer et al. 2007). Research has demonstrated that pre-empting space with dominant species such as canopy-forming algae can reduce invasion by hard substrate invertebrates (Dafforn et al. 2012) and also provide a refuge for threatened native species (Perkol-Finkel et al. 2012). The lack of natural enemies, such as benthic grazers and predators, on many artificial structures has also been experimentally shown to influence successful utilisation of these habitats by NIS (Dumont et al. 2011; Forrest et al. 2013; Simkanin et al. 2013). Relocating mobile species and "pre-seeding" structures with key grazers or predators appropriate to the system e.g. gastropods and/or echinoderms could go some way to enhancing biotic resistance on artificial structures. Building structures with a gentle gradient or that enhance connectivity with the benthos (Bishop et al. in press) might also provide more natural opportunities for benthic predators to extend their feeding range to artificial structures.

Below are examples of how experimental findings from invasion ecology could be applied in an eco-engineering context. These include small-scale experimental examples that demonstrate the potential for building structures with specific physical and chemical properties that directly or indirectly reduce colonisation by NIS; manipulating assemblages on structures to reduce resource availability; and improving biotic resistance of the resident community to reduce NIS establishment, while also supporting native species:

1. Building with natural substrates instead of artificial substrates can reduce space occupation by NIS up to 54% and increase native species by 45% over time (Tyrrell and Byers 2007);
2. Building with natural bedrock (e.g. sandstone in Sydney Harbour) can reduce NIS richness by ~ 30% compared to concrete or wood (Glasby et al. 2007);
3. Building with specially formulated concrete (e.g. ECOncrete®) compared to standard concrete can reduce NIS richness by up to 50% and increase native species richness by ~ 43% (Sella and Perkol-Finkel 2015);
4. Building fixed rather than shallow, floating (e.g. pontoon) structures can reduce NIS richness by 28% (Dafforn et al. 2009b);

5. Reducing shading (e.g. by building on a gentle gradient or adding light penetrating features to over-water structures) could reduce NIS dominance by 50–90% (Kim and Micheli 2013);
6. Controlling metal contaminant inputs (e.g. stormwater management, antifouling regulations) could increase native species richness by 34% and reduce NIS dominance (space occupation) by up to 29% (Piola and Johnston 2008);
7. "Pre-seeding substrates" with native fouling species (e.g. habitat forming algae) can reduce occupation by NIS by up to 33% (Dafforn et al. 2012);
8. Increasing native predator abundance on artificial structures (e.g. by increasing connectivity to benthos) can reduce NIS dominance (e.g. ascidians) by ~ 50% (Simkanin et al. 2013).

While these examples provided above show great promise for application in marine developments, so far most have only been investigated at a small-scale and require testing over larger spatial scales. Furthermore, the logistical difficulties of each strategy to apply over a large-scale will vary with location. For example, the application of natural substrates (sandstone) in the eco-engineering design at Headland Park, Sydney Harbour required a significant rock supply to build 1.4 km of intertidal foreshore. This was cut from the headland during construction of a nearby underground car park because local sandstone supplies are limited. Where natural substrates are not an option, specially formulated concrete could provide a more readily available alternative and this has already been investigated at the scale of breakwater sections (Sella and Perkol-Finkel 2015). In comparison, biological manipulations such as "pre-seeding" are likely to prove more difficult than physical manipulations to apply over large spatial scales due to e.g. mortality during transport and the difficulty of establishment at target sites. Despite this, breakwater-scale testing has been done with a threatened algal species (Perkol-Finkel et al. 2012) and restoration projects show increasing success at large-scales (Campbell et al. 2014).

Conclusion

Evidence so far that eco-engineering could be used to control NIS success is largely experimental and small-scale. Eco-engineering will not provide a rapid solution for managing NIS establishment and dispersal. For it to become widely adopted and effective over the longer term requires a change in management principles, policy and regulation, interdisciplinary communication and co-ordination. Practical solutions for reducing niche opportunities on artificial structures therefore need to be explored over longer timescales and larger spatial scales. Future research should investigate reducing niche opportunities at each stage of a marine development (construction, operation, decommissioning), and also at each at stage of a fouling community development. The latter will benefit from (1) advances in molecular techniques that can characterise the "unseen" and unculturable diversity on these structures to improve understanding of how the early biofilm development might determine later dominance of native or NIS, and (2) new strategies to inoculate or "pre-seed" structures with relevant species and/or communities. Future population growth and resource demand will place increasing pressure on our marine environment and better integration of ecological theory and principles has the potential to mitigate invasion and provide positive benefits.

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