Can Biomimicry and Bioinspiration Provide Solutions for Fouling Control?

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Abstract
Biomimicry, modeling biological systems to find engineering methods, and bioinspiration, improving upon or repurposing the biological model, may provide direction for the development of new antifouling solutions. Despite being subject to constant pressure from foulers, many organisms maintain a clean surface. The challenge lies in selecting the most effective and reproducible antifouling mechanisms from nature and mimicking or modifying them to provide a realistic engineered solution.

Keywords: natural antifouling, marine coatings, biomimicry, bioinspiration, antifouling, foul release

Introduction
Antifouling is changing. The ban on tributyltin (TBT), arguably the most effective and yet environmentally damaging antifouling precipitated an increase in research to develop new technology (Swain, 1999; Omae, 2003). The immediate response was to return to copper as the antifouling of choice. However, high levels of copper in many ports and harbors has led to concern and even the banning of copper based antifouling (i.e., San Diego, Washington State; Carson et al., 2009; Nehring, 2001; Qian et al., 2010; Thomas et al., 2001). The use of toxic coatings may also be linked to the transport of biocide tolerant non-indigenous species (Dafforn et al., 2008). Some users have switched to biocide-free silicone antifouling coatings for improved hydrodynamic and environmental performance. However, these coatings may foul, which necessitates cleaning, and there may be an increased risk of transporting non-native species. They are mechanically weak and can be damaged more easily than traditional coatings (Chambers et al., 2006; Nehring, 2001; Swain, 2010; Swain et al., 2007; Yebra et al., 2004). An ideal coating will be hydraulically smooth and control fouling for the lifetime of the vessel, be environmentally compliant, control invasive species, be easily applied, repaired and maintained, be compatible with materials and methods of hull construction and decommissioning, and be cost effective (Swain, 2010).

In the decades since a ban on TBT was proposed, research has been directed towards new solutions to the fouling problem. Some of the discoveries have been in the form of new booster biocides to improve the performance of copper based antifouling against biofilms (slimes). These include Irgarol 1051, Seanie 211, diuron, pyrithiones, and many others. Unfortunately, some of these boosters may parallel TBT in terms of environmental impact. For example, Irgarol 1051 is a photosynthesis inhibitor that reduces plants’ ability to create energy causing growth to slow, reproduction to stop and eventually death of the plant. It has a long half-life and does not partition into sediment so it is found primarily in the water column. It has been found to occur in estuaries, ports and harbors at elevated levels and is highly toxic to non-target marine plants (Hall et al., 1994; Thomas & Brooks, 2010; Thomas et al., 2001; Yebra et al., 2004). Recently, it has been detected in water samples collected from the Caribbean, Bermuda, Florida and Australia in the vicinity of seagrass beds and coral reefs where the effects could be devastating (Carbery et al., 2006; Owen et al., 2002; Scarlett et al., 1999). Researchers must be careful to avoid any chemistry that may impact the environment and non-target organisms. One source of new technology is to understand how organisms prevent fouling and then mimic or draw inspiration from these biological models to create an engineering solution.

Organisms that are unfouled or only lightly fouled provide insights into the mechanisms that have evolved to prevent surface colonization or epibiosis (Wahl, 1989). These “clean” organisms are the focus of research into biomimetic and bioinspired solutions to fouling on human structures. Biomimicry refers to the study of the structure and function of biological systems as models for the design of engineering solutions (dictionary.com) while bioinspiration expands on biomimicry by not only copying or imitating nature but also improving them or...
repurposing the biological model for an idealized engineering solution.

This review will discuss the methods by which nature controls fouling and characterize natural antifouling and engineered solutions in terms of chemical, physical, mechanical, behavioral and combined mechanisms.

Natural Antifouling
Organisms have evolved several different strategies to prevent fouling. These natural antifouling methods include chemical, physical, mechanical, behavioral and a combination of more than one of the others (Bers & Wahl, 2004; Pawlik, 1992; Wahl, 1989).

Chemical
Chemical antifouling has a long history of research and has been the subject of many reviews (Armstrong et al., 2000; Clare, 1996; Fusetani, 2004; Omae, 2006; Pawlik, 1992; Qian et al., 2010; Raveendran & Mol, 2009; Rittschoff, 2000; and others). To date, thousands of active natural products have been identified (Pawlik, 1992). The activity of natural chemistries includes low pH, detergents, aesthetics, attachment and morphogenesis inhibitors, or toxic chemicals. The chemicals may be surface bound or water soluble (Omae, 2006; Rittschof, 2000; Wahl, 1989). Despite issues with the ecological relevance of some of the chemicals, active natural products have been isolated from an algae, sponges, soft corals and a limpet that are either available at the surface or released into the water column when the organism is disturbed (de Nys & Steinberg, 2002; Fusetani, 2004; Hay, 1996; Hellio et al., 2002). The mucus of dolphins, echinoderms, fish and corals contain antifouling chemicals that have been found to dissolve glue, prevent attachment or act as antimicrobial toxins (Baum et al., 2002; Bavington et al., 2004; Ebran et al., 2000; Ritchie, 2006; Shephard, 1994; Videler et al., 1999). Many tunicates have acidic body pH and low epibiosis, especially in areas where density of acidic vacuoles is high (Hirose et al., 2001; Stoeker, 1980). Additionally, when looking at whole animal extracts, some tunicates contain chemicals that are cytotoxic, antimicrobial and antiviral (Davis & Wright, 1989). The eggs of many organisms, including fish and coral, are well protected with antimicrobial chemistries (Marquis et al., 2005, Ramasamy & Marugan, 2007). Terrestrial plants have also yielded interesting chemistries such as tannins, pyrethroids and capsaicin (Feng et al., 2009; Perez et al., 2007; Xu et al., 2005).

More recently, attention has turned to microorganisms. Antifouling metabolites that had been attributed in the past to algae, sponges, corals, etc., have been found on closer study, to be produced by surface associated bacteria and cyanobacteria (Armstrong et al., 2000; Clare, 1996; Krug, 2006). These surface associated microorganisms are distinct from the communities in the water column, often found in higher densities than the water column community and are often highly pigmented (Dobretsov et al., 2005; Faimali et al., 2004; Holmstrom et al., 1992). Deterrent biofilms prevent fouling by toxic or deterrent chemistries (Dobretsov et al., 2006; Pawlik, 1992).

Physical
The two primary physical means identified to prevent fouling are surface energy and surface texture. A surface energy range of 20-30 dynes/cm (Baier, 1972; Dexter, 1979) has been shown to minimize adhesion and favor the removal of epibionts. Such surface energy values have been measured on the surface of killer whales (Baier & Meyer, 1986), gorgonians (Vrolijk et al., 1990) and healthy teeth (Baier & Meyer, 1986; Glantz et al., 1991). Surface energy also affects settlement of some organisms, albeit in a species specific manner (Anderson et al., 2003; Meyer et al., 1988; Molino & Weatherbee, 2008; Rittschof & Costlow, 1989). For example, it has been found that barnacles and bryozoans prefer to settle on different surface energies (Dahlstrom et al., 2004; Rittschof & Costlow, 1989). Diatoms and the green algae Ulva have different adhesion strengths on surfaces with different wettability. Diatoms are more easily removed from hydrophobic surfaces, whereas Ulva releases more easily from hydrophobic surfaces (Finlay et al., 2002; Kishnan et al., 2006). Low adhesion surfaces in nature are associated with waxes, oils, surfactants, mucus or fluorinated or methylated compounds (Baum et al., 2003; Krug, 2006; Shephard, 1994; Wahl, 1989).

The antifouling properties of surface topography have received extensive attention and review (Scardino & de Nys, 2011; Scardino et al., 2008). The effectiveness of topography as antifouling appears to be the relationship of scale between the texture and the settling organism. An ultra-smooth surface offers no refuge from predation or hydrodynamic stresses and is therefore unattractive (Kohler et al., 1999; Walters & Wethey, 1996). Surfaces with textures that are smaller than the settler reduce settlement and/or attachment strength, the “attachment point theory” (Scardino et al., 2008). Textures that are the same size or
slightly larger than the propagules offer the greatest number of attachment points, the strongest attachment and the best protection to settling organisms (Callow et al., 2002; Scardino et al., 2006). Organisms that have only one attachment point (barnacles, arborescent bryozoans, etc.) are more specific in searching for high quality pits than colonial organisms with multiple attachment points, likely because the colonial organisms outgrow the “refuge” of the pit quickly and can survive partial mortality (Walters & Wethey, 1996). The use of hairs in mussel spat (Dixon et al., 1995), spicules in gorgonian coral (Scardino & de Nys, 2011; Vrolijk et al., 1990) and spines in some colonial organisms (Dyrynda, 1986; Wahl, 1989) has been shown to prevent fouling and overgrowth of fouling organisms. It has been suggested that many other organisms including crabs, brittle stars, molluscs, marine mammals and sharks (adult skin and dogfish egg cases), use textured surfaces with one or more scales of complexity to prevent micro- and macro-fouling (Baum et al., 2002; Bers & Wahl, 2004; Scardino & de Nys, 2004; Scardino & de Nys, 2011).

**Mechanical**

Grooming is a common antifouling mechanism found in nature. Grooming involves specialized structures that either pick or sweep an animals surface clean (Wahl, 1989). Decapod crustaceans have evolved brushes used to remove epibionts and parasites from specific parts of their bodies like the gills and carapace (Acosta & Poirrier, 1992; Batang & Suzuki, 2003; Bauer, 1981). Historically, echinoderms and bryozoans were thought to use specialized structures to clean their surfaces (Campbell & Rainbow, 1977; Dyrynda, 1986), but recently this has been called into question as the pedicellaria of the crown of thorns starfish (*Acanthaster planci*) were found to be too unresponsive and widely placed to be effective in keeping their surfaces clean (Guenther et al., 2007). Many organisms use ciliary cleaning in conjunction with mucus to keep surfaces clean (Wahl et al., 1998). Symbiotic or mutualistic relationships such as fish visiting “cleaning stations” (Poulin & Grutter, 1996), mutualistic grazing of snails within populations (Wahl & Sonnichsen, 1992; Wahl et al., 1998) and branchiobdellid annelids that feed on epibionts in the gill chamber of crayfish (Brown et al., 2002) are examples of beneficial relationships that may prevent fouling.

The other mechanical method of antifouling is surface renewal via shedding or molting of outer layers. Crustaceans, stone fish and algae all molt, either the entire surface simultaneously or in patches, which removes all attached fouling (Bakus et al., 1986; Keats et al., 1997; Wahl, 1989). Additionally, many organisms use mucus as membrane to separate themselves from their environment. The mucus sloughs off removing foulers, makes adhesion difficult and fouls sensory and attachment apparatus of epibionts (Brown & Bythell, 2005; Davies & Hawkins, 1998; Denny, 1989; Dyrynda, 1986; Shephard, 1994; Wahl, 1989; Wahl et al., 1998).

**Behavioral**

Behavioral antifouling is the direct or indirect active avoidance of fouling organisms (Becker & Wahl, 1996). Burrowing into sediment, moving into the air, between fresh and salt water or into areas with very different oxygen contents and nocturnal activity or hiding in crevices are all mechanisms that remove less tolerant epibiotic organisms (Becker & Wahl, 1996; Wahl, 1989; Wahl et al., 1998). Organisms with a similar range of tolerances to their hosts will be unaffected by these behavioral methods (Brock et al., 1999).

**Combination**

Most organisms that are well studied use a combination of methods to prevent surface fouling. This was highlighted in reviews by Ralston and Swain (2009) and Scardino and de Nys (2011). Crustaceans groom and shed their shells and use behavioral mechanisms like burrowing and moving among habitats to ensure clean surfaces (Becker & Wahl, 1996; Wahl et al., 1998). Echinoderms groom, slough, excrete anti-adhesive mucus, have chemical antifoulants and may even use a strong negatively charged cuticle to prevent surface colonization (Bakus et al., 1986; Bavington et al., 2004; Bryan et al., 1996; McKenzie & Grigolava, 1996). Corals use antibacterial mucus, select specific microbial colonists which in turn protect them from other microbes, slough mucus and surface layers and secrete secondary metabolites to keep their surfaces clean (Brown & Bythell, 2005; Ritchie, 2006; Targett et al., 1983). Dolphins and whales are hypothesized to use microtopography in conjunction with an enzymatically active zymogel to prevent attachment of macrofoulers (Baum et al., 2003; Meyer & Seegers, 2004) and surface sloughing, skin compliance and a critical surface tension in the preferred range for minimal adhesion combined with breaching may remove fouling at an early stage (Baum et al., 2003; Fish & Rohr, 1999; Scardino & de Nys, 2011). Algae have provided many
new chemical metabolites that prevent fouling, shed their outer layers and may remove settled epibionts by flexing beyond what their epibionts can withstand (Nylund & Pavia, 2005; Scardino & de Nys, 2011; Walters et al., 2003; Wikstrom & Pavia, 2004).

### Biomimetic and Bioinspired Engineering Solutions

#### Chemical

Due to our vast experience with incorporating chemicals into coatings, it is not surprising that natural products are the most investigated biological antifouling. SeaNine 211 is a booster biocide added to copper coatings to boost efficacy against fouling plants. It degrades quickly in water and sediment, binds strongly to sediment, has low environmental toxicity and has an excellent performance record from lab and field tests and ship trials (Thomas & Brooks, 2010; Yebra et al., 2004). SeaNine 211 is based on the natural product isothiazolone originally isolated in the 1980s from the soft coral *Eunicella* (Raveendran & Mol, 2009). Econea is a halogenated pyrrol that is the active ingredient in copper-free antifouling paints from manufacturers such as Petit, Interlux, Sea Hawk and others. Halogenated pyrrols are common secondary metabolites in bacteria and sponges (or possibly surface bacteria associated with sponges) and are potent settlement and metamorphosis inhibitors for barnacles and other animal foulers (Dahms et al., 2006; Omae, 2006). Because of its specificity against animal fouling, Econea is often combined with a booster like SeaNine to prevent plant fouling as well.

Perhaps the most studied natural chemistry is the halogenated furanone originally isolated from the red algae *Delisea pulchra*. The chemical is present on the surface of the plant in concentrations that prevent fouling and the coverage of epibionts corresponds to concentrations of the furanone (de Nys & Steinberg, 2002). It has not yet been successfully incorporated into a long-lasting ship hull coating (Chambers et al., 2006); however, some have reported that it is available products called “Netsafe” and “Pearlsafe” marketed in Australia for use in commercial aquaculture (Raveendran & Mol, 2009). We were unable to find any record of these products for sale at this time so they may no longer be available. Many other natural chemicals from marine macroorganisms show promise for non-toxic or low-toxicity antifouling paints and are being investigated (see reviews by Armstrong et al., 2000; Fusetani, 2004; Omae, 2006; Qian et al., 2010; Raveendran & Mol, 2009).

Terrestrial plants have also yielded promising chemistries for antifouling. These include products like tannins, pyrethroids and capsaicin (Feng et al., 2009; Perez et al., 2007; Thomas & Brooks, 2010; Xu et al., 2005). Pyrethroids, synthetic analogs of pyrethrin from chrysanthemum flowers, are of particular interest because they are already approved for use as environmentally safe insecticides. These insecticides have low toxicity to mammals, do not persist, do not bioaccumulate and are available in industrial quantities (Feng et al., 2009). Tannin is present in terrestrial plants, mangroves and in some marine algae, primarily as an anti-herbivory chemical. However, some have found it to have antifouling properties as well (Brock et al., 2007; Lau & Qian, 1997; Perez et al., 2007; Wikstrom & Pavia, 2004). The long-term efficacy of tannin isolated from the quebracho tree was improved by precipitating it with aluminum forming a salt which increased the life span of the coating to 1 month in the field (Perez et al., 2007).

Another avenue of research is isolating chemicals from microorganisms and using the microorganisms themselves. There are many benefits to this strategy including culturability, abundance and ability to trick or stress the organisms into producing large quantities of the necessary chemical (Dobretsov et al., 2006; Holmstrom & Kjelleberg, 1994). Holmstrom et al. (2000) were able to keep bacteria alive in a coating for 14 days in the laboratory. Microencapsulation is another strategy being investigated, not just for microorganisms but for all natural products, as a way to increase length of efficacy. Coatings with microencapsulated living bacteria were able to prevent fouling up to 7 weeks in field trials (Chambers et al., 2006; Yee et al., 2007).

The use of enzymes and hormones that are commercially available is another strategy for chemical antifouling. Many patents have been awarded and there is an enzymatic coating available on the Danish yacht market, although little scientific evidence of effectiveness exists (Olsen et al., 2007). Enzymes may act directly by dissolving glues, lysing cells or decomposing exoskeletons of barnacles (Abarzua & Jakubowski, 1995; Evans & Clarkson, 1993; Olsen et al., 2007). They may also act indirectly by increasing the effectiveness of an antifoulant or by acting on the coating to improve release or polishing rates (Olsen et al., 2007). Hormones, such as noradrenaline, may also be used as a non-toxic deterrent in antifouling coatings (Gohad et al., 2010). However, both enzymes and hormones have several drawbacks to their widespread use.
including expense, instability, potentially specific response and need for environmental approval (Gohad et al., 2010; Olsen et al., 2007; Rittschof, 2000).

There are several challenges in getting new chemicals approved for use in antifouling paints. The environmental problems associated with TBT have increased awareness of the potential risks associated with introducing new chemistries and attention must be given to proving environmental compliance. This greatly increases the time and the cost to go from the identification and isolation of a chemical to commercialization, which can cost millions of dollars and take over 10 years to get approval. Furthermore, many natural products are structurally complex and only available in small amounts in the organism so there are issues with obtaining or synthesizing the active chemicals (Fusetani, 2004; Rittschof, 2000; Rittschof, 2001). Natural products tend to have a short life span as they cannot be toxic to the organism. This leads to issues when incorporated into a coating as coatings need to maintain efficacy for 3-12 years of service life (de Nys & Steinberg, 2002; Fusetani, 2004; Ingle, 2007; Marechal & Hellio, 2009; Rittschof, 2000; Rittschof, 2001). Conversely, the short life span is beneficial for environmental compliance as one of the characteristics of an ideal chemical antifoulant is short half life (Clare, 1996). Other factors for an ideal chemical antifoulant include non-toxicity, activity against a wide variety of fouling organisms, easy incorporation into a controlled release coating and should come from a cultural organism or have an active chemistry that can be industrially synthesized (Clare, 1996; Hellio et al., 2002; Marechal & Hellio, 2009; Ravendran & Mol, 2009; Rittschof, 2000; Yebra et al., 2004).

Physical

Slippery coatings are not new technology. Commercially available fouling release coatings have been available since the mid-1970s and are proving to be an increasingly successful method for fouling control. These coatings combine polydimethylsiloxane silicone with low surface energy, oils and compliance to reduce the adhesion strength of organisms to a surface. Fouling is removed by hydrodynamic shear forces or with gentle cleaning (Anderson et al., 2003). There are several lanolin based waxes on the market for use on ship hulls and propellers. While the wax may provide short-term antifouling, the main purpose is to lessen attachment strength and make cleaning easier. These products are often used over a tough epoxy, however the duration of effect is unknown and we were unable to find any published data in a peer-reviewed journal to back the claims of manufacturers. Results obtained from these coatings may vary depending on the fouling communities. Effects of surface energy and wettability on surface colonization are species specific with some responding favorably to hydrophobic surfaces and some to hydrophilic or intermediate surfaces (Callow et al., 2002, Dahlstrom et al., 2004). Additionally primary colonizers often change the surface energy of surfaces which will change the effect on subsequent settlers (Scardino & de Nys, 2011).

Mimicking the surface texture of marine organisms has been investigated as an environmentally friendly antifoulant. “Sealcoat” is a commercially available antifouling coating that is flocked with fibers mimicking the fur of a seal. According to the company’s website, fouling is prevented for up to 5 years. However, no scientific data exists to back this claim. Other studies looking at flocked or furred coatings found mixed responses with green and brown algae, encrusting barnacles and barnacles deterred, red algae and hydroids unaffected and solitary tunicates and tube worms increased by these coatings (Phillippi et al., 2001). It must also be remembered that seals do not only depend on their fur to keep them fouling free but also groom and spend large amounts of time out of the water.

Mimics of topographies from other organisms such as crustose coralline algae, molluscs, crabs, brittle stars, soft corals and dogfish egg cases, have been investigated for antifouling activity and have shown short-term efficacy in laboratory assays. Additionally, topographies from pilot whale and shark skins have been characterized and had an antifouling activity attributed to the microstructures. These active topographies range in scale from 1 to 300 μm with multiple length scales occurring on natural surfaces (Baum et al., 2002; Bers & Wahl, 2004; Scardino & de Nys, 2004; Scardino & de Nys, 2011). The “Sharklet” is an example of a biomimetic texture used as an engineered surface to prevent fouling. It has performed well in laboratory assays against Ulva spores and Balanus amphitrite cyprids (Carman et al., 2006; Schumacher et al., 2007). In order to improve the effect of this and other topographies, a mathematical model was created called the “Engineered Roughness Index”; this index can also be used to predict settlement of marine organisms on the engineered topographies (Long et al., 2010). Engineered surfaces with hierarchically wrinkled surfaces...
have shown promising results in field trials, especially against barnacles (Efimenko et al., 2009; Scardino & de Nys, 2011).

Sound has been suggested as an antifouling method. However, there are no published field test data that scientifically prove that it can provide long-term antifouling. This is not a truly biomimetic method as it is not reported as a natural antifouling mechanism. Sound is used by competent larvae of fish and invertebrates like crabs to navigate to appropriate settlement sites (Radford et al., 2010; Simpson et al., 2008; Stanley et al., 2010). Specific habitats have different auditory signatures and larvae can use these to differentiate and pilot to their adult habitats (Radford et al., 2010).

Both high- and low-frequency sound waves have been shown to be effective at inhibiting settlement of barnacles and mussels (Branscomb & Rittschof, 1984; Donskoy & Ludyanskiy, 1995; Guo et al., 2011). Additionally, ultrasound waves have been used to destroy barnacle larvae via cavitation for ballast water treatment (Seth et al., 2010). The use of low-frequency sound is limited because it is audible to humans and other organisms and therefore noise pollution is an issue. Several companies worldwide (Ultrasonic Antifouling, ASM, Sonihull and others) offer ultrasonic units that can be installed that are purported to prevent fouling or conversely to kill settling fouling organisms thereby making them easy to remove. However, this method is variable in effect, with settlement rates ranging from 1% up to 55% for low and high frequency, respectively (Branscomb & Rittschof, 1984; Guo et al., 2011). Guo and colleagues (2011) reported a settlement rate for barnacle cyprids in the laboratory of about 20% for their best ultrasonic treatment compared to a rate of around 70% for the control so the method is not perfect. Additionally, Sonihull reports changes in fish behavior when their ultrasonic units are in use so there are noise pollution concerns with high-frequency sound as well.

Physical methods of antifouling are often inferred but seldom proved due to challenges associated with testing living materials. Surface topography effects are scale dependent (Scardino et al., 2006; Schumacher et al., 2007) and effectiveness in fouling prevention may vary geographically (Bers et al., 2010). Finding a universal physical antifoulant may be difficult and the results are often short lived, lasting a month or less in field testing (Holm et al., 1997).

Mechanical

Mechanical cleaning is performed on ships, aquaculture nets, instruments and other marine structures when they become fouled, either because an antifouling coating was not used or if that coating becomes fouled. The U.S. Navy cleans their vessels when a set level of fouling is reached as set out in the Naval Ships’ Technical Manual (Cologer, 1984; NSTM, 2006). Cleaning is reactive and has been shown to speed the rate of re-colonization and increase the risk of transport of nonindigenous species (Floerl et al., 2005). Additionally, commercially available brush cleaning devices (i.e., SCAMP, Mini-Pamper, etc.) are harsh and may damage the antifouling coating. A new direction for mechanical antifouling is to mimic natural grooming. This is the idea behind the HullBUG (Hull Bioinspired Underwater Grooming), an autonomous robot that will proactively pass over a hull while a ship is in port. Its mode of action is a gentle wiping or brushing of the surface on a frequent schedule sufficient to remove fouling at its earliest stages before it can become established (Borchardt, 2010; Tribou & Swain, 2010). Results from field testing of fouling release and copper-coated panels subjected to grooming are so promising that further experiments and scale up on this method are being investigated.

Ecospeed is a commercially available hull coating system. It is a tough glass flake reinforced vinyl ester coating. When combined with hull cleaning, this non-toxic coating is purported to maintain a fouling free surface with no repainting for up to 25 years. Additionally, the coating smooths during cleaning, decreasing drag. Again, no scientifically published data exists to back the claims made by the manufacturer.

Surface renewal has been attempted as an antifoulant for ship hull coatings. Polymers were developed that hydrolyze in seawater leaving a clean surface as they dissolve (Candries et al., 2000). To date, however, these coatings have only been successful when combined with biocides as the rate of dissolution and thickness of the coating required would be too great without the help of toxic chemicals.

Mechanical antifouling has proven to be an effective but imperfect method of keeping submerged surfaces clean. Cleaning requires the deployment of equipment and usually divers, which increases both the expense and human risk factor of this antifouling mechanism. When applied to toxic coatings, cleaning may increase the release of biocides, at least in the short term (Schiff et al., 2004). Cleaning may cause damage to coatings which increases the rate of re-colonization.
and may increase the risk of transport of invasive species (Floerl et al., 2005; Piola & Johnston, 2008). Mechanical antifouling works better when combined with another antifouling method such as a biocidal coating or a fouling release surface. Grooming, however, is proactive and more closely matches many of the behavioral activities found in nature. Many organisms benefit from self or mutual grooming to maintain their surfaces free of fouling.

**Behavioral**

Behavioral methods include removing a vessel from the water when not in use or moving between fresh and salt water. The former is commonly practiced by recreational boat owners; however, removing a large vessel from the water is impractical, especially if that ship is frequently used. Moving vessels between fresh and salt water, by traversing through the Panama Canal, for instance, is performed occasionally and has been credited with preventing the unobstructed movement of Caribbean and Pacific species between the two bodies of water. Brock and colleagues (1999) found that moving a ship into fresh water for 9 days was sufficient to remove 90% of fouling from the hull. However, tolerant fouling organisms will not be affected by this antifouling method as shown by the survival and subsequent introduction of the mussel *Mytilus galloprovincialis* to Oahu, Hawaii, from Washington. The mussel was one of the 10% of fouling organisms remaining on the *USS Missouri* after its Pacific transit and was seen spawning shortly after arrival in Pearl Harbor and later found colonizing the ballast tanks of a submarine (Apte et al., 2000).

**Combined**

It is unlikely that any one antifouling mechanism will be sufficient to prevent all fouling in all situations that may be encountered by submerged structures. Indeed, every organism that is well studied with regards to natural antifouling uses a combination of strategies to maintain a clean surface. The most effective coatings in use today also use more than one antifouling mechanism; antifouling coatings use a biocide combined with self-polishing or ablative mechanism to keep an active layer at the surface. Fouling release coatings combine low surface energy, oils and compliance to maximize self-cleaning. To date, most researchers investigating a biomimetic solution to antifouling have focused on only one method. However, that is beginning to change with the recent publication of reviews focusing on combined antifouling mechanisms (Ralston & Swain, 2009; Scardino & de Nys, 2011).

**Bioinspired Approaches**

The examples highlighted above represent biomimetic solutions for biofouling control. Very little research exists that takes lessons from nature and adapts or alters them for a true bioinspired solution. It has only been recently that novel uses have been proposed from biological models. For example, the dopamine based adhesive system in mussels, a common fouling organism, has been investigated as a way to obtain better adhesion of non-stick coatings to a substrate. The dopamine adhesive allows testing on polyethylene glycol (PEG) and other slippery polymers where before it was not possible because the polymers would not stick to anything. Those coatings using the bioinspired PEG-DOPA system outperformed traditional silicone fouling release coatings in laboratory assays, comparing both the settlement and adhesion of a common fouling diatom and alga (Statz et al., 2006).

**Conclusions**

Marine organisms can achieve long-term protection from fouling using short-lived renewable mechanisms. This is attributed to using a combination of chemical, physical, mechanical and behavioral mechanisms. Much research has been published investigating the specific ways that organisms maintain a clean surface but frequently focus on only one mechanism without considering the efficacy of a holistic combined method. The challenge, for us, is to identify and select the best natural systems to solve the problem of biofouling. Through improved knowledge of natural systems, we will be better able to both mimic and innovate using biological models to find engineering solutions. Results so far have been promising but better interactions between biologists, ecologists, engineers, chemists and materials scientists are needed and publishing of results is vitally important. Despite some issues, biomimetics and bioinspiration hold great promise for new antifouling solutions. For example, the HullBUG grooming method now being developed by the Office of Naval Research demonstrates how a proactive grooming method will enhance the long-term effectiveness of the presently available commercial antifouling or fouling release surfaces.

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Recent progress and future perspectives.


