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Integrated Pest Management for Fouling Organisms on Boat Hulls

Carolynn S. Culver[1]
Leigh T. Johnson[2]
Henry M. Page[3]
Jenifer E. Dugan[4]
Christen A. Santschi[5]

[1]California Sea Grant Extension Program, Marine Science Institute, University of California, Santa Barbara, CA 93106-6150, 805.893.4530, c_culver@lifesci.ucsb.edu
[2]University of California Cooperative Extension – San Diego County, 9335 Hazard Way, Suite 201, San Diego, CA 92123, ltjohnson@ucanr.edu
[3]Marine Science Institute, University of California, Santa Barbara, CA 93106-6150, 805.893.7568, mark.page@lifesci.ucsb.edu
[4]Marine Science Institute, University of California, Santa Barbara, CA 93106-6150, 805.893.2675, jenny.dugan@lifesci.ucsb.edu
[5]Marine Science Institute, University of California, Santa Barbara, CA 93106-6150, 805.905.5972, christensantschi@gmail.com

Running head: Management of hull biofouling

Abstract

Boating is a major vector for aquatic invasive species that cause significant economic and ecological impacts, necessitating biofouling control that goes beyond simply maintaining boat operations. However, new regulations restricting the use of antifouling paints, a common control tactic along with hull cleaning, have not considered the consequences to invasive species management. As a result, there is a critical need for a biofouling control strategy that both protects water quality and minimizes invasive species transport. We compared recruitment of fouling organisms to experimental plates: 1) treated with hull coatings after 1 month and, for copper-based paint, after 1, 3, 6, and 12 month submersion times, 2) after application of California's in-water hull cleaning practices, and 3) among locations within and between geographically separated harbors. Copper-based paint was initially effective at reducing fouling, but lost effectiveness over time and was fouled heavily within 12 months. On plates with copper-based paint, non-native species typically recruited first and facilitated the recruitment of other species. Nontoxic coatings were readily fouled and invasives, *Watersipora subatra* and *Hydroides* spp., settled more often on the epoxy and/or slick coatings. Recruitment was higher in the harbor in the warmer water region. Depending on the harbor, *W. subatra*, *Ciona* spp., and *Filograna implexa* recruitment was correlated with water flow and/or the presence of conspecifics on the docks. Strong seasonal recruitment was evident for *Ciona* spp., *F. implexa* and *Bugula neritina*. Algae dominated light-exposed surfaces and invertebrates dominated shaded surfaces of plates. California's hull cleaning practices did not stimulate fouling, which contradicted findings from elsewhere. Our findings informed the development of an integrated pest management framework for biofouling control on boat hulls adaptable to different regions and boater needs. This novel approach balances effective boat operations and protection of ecosystem health while simultaneously addressing water quality and invasive species transport.

Introduction

Fouling organisms, biota that attach and grow on manmade surfaces, such as boat hulls, pilings, cables, pipelines and docks, have been long considered pests by many who work in or enjoy aquatic habitats. Biofouling is an accumulation of these organisms, including a variety of soft and hard sessile species of algae and invertebrates. When these marine and freshwater fouling organisms attach to and accumulate on boats they interfere with hydrodynamics. This creates frictional drag that slows vessels, diminishes ship maneuverability, and reduces fuel efficiency, increasing costs and hydrocarbon emissions (Champ 2000; Yebra et al. 2003; Schultz 2007). Thus, controlling fouling organisms is critical for boat maintenance.

The need to control biofouling on boats has intensified with the identification of boat hulls as a primary vector for aquatic invasive species (AIS). AIS can affect humans and the environment, causing economic and/or ecological impacts as have been reported worldwide (Pimentel et al. 2000, 2005; Ehrenfeld 2010). Historically, ships have been considered the main vector for moving fouling species across oceans to large international ports. Boats are now recognized as a vector for spreading non-native species from large ports to small craft harbors, and among inland lakes and reservoirs (Johnson et al. 2001; Wasson et al. 2001; Floerl et al. 2009; Ferrario et al. 2017). Countries such as Australia, New Zealand (NZ), Canada and the United States (US) (e.g., California, Hawaii) propose to limit new introductions of saltwater AIS from boating, fishing and other recreational activities because of their detrimental impacts on human and natural systems (Godwin 2005; CDFW 2008; Australian DAWR 2015; Maritime NZ 2015; Canadian Minister of Justice 2015; McKenzie et al. 2016). Several regions, including many US states, already have implemented regulations making it illegal to transport freshwater AIS, such as aquatic weeds and Eurasian mussels, via boats and trailers (e.g., State of Michigan 2019).

Chemically active coatings known as antifouling paints are used to deter biofouling on hulls of recreational and commercial boats and ships. Toxic copper-based paints are currently used as a primary biofouling control method around the world (Piola et al. 2009). However, there are growing concerns about the impacts of these toxic paints on water quality and ecosystem health. In particular, leaching of copper from boat hulls has contributed to elevated levels of dissolved copper in some saltwater habitats, including several harbors in California (e.g., Schiff et al. 2007; Singhasemanon et al. 2008; Kiaune and Singhasemanon 2011). These elevated copper levels are known to affect the health of many marine organisms (Martin et al. 1981;

McIntyre et al. 2008; see also review by Eklund and Watermann 2018). Nonetheless, some non-native fouling organisms have been found to tolerate elevated copper levels (e.g., Floerl et al. 2004; Crooks et al. 2011; see also review by Lande et al. 2011; Osborne et al. 2018). Piola and Johnston (2006) reported a high prevalence of non-native species in a copper-polluted harbor, thereby representing a high proportion of the fouling organisms available to attach to vessels in the harbor. Dafforn et al. (2008) also suggested that boats with copper-based coatings may facilitate transport of these non-native, copper tolerant fouling species. These findings suggest that copper-based antifouling paints may be increasing the risk of transporting non-native species via boat hulls, potentially impacting ecosystem health, and adding to the concerns about using these paints for biofouling control.

Negative impacts of copper-based antifouling paints on water quality and ecosystem health have resulted in governmental actions by several domestic and foreign agencies, with subsequent effects on boat owners and boating industries around the world, particularly in the US, Australia, NZ, and the Baltic and North Seas. In the US, actions include restricting allowable copper levels in and leaching rates of antifouling paints (Washington State Legislature 2011; CDPR 2014a, 2014b; US EPA 2010), and setting a state (California) standard for allowable concentration of dissolved copper in marine waters (US Environmental Protection Agency 2000). Reductions in copper emissions from antifouling paints are required in boat basins that exceed the standard (e.g., CRWQCB-SDR 2005, 2006). Further, the US Environmental Protection Agency (EPA) (2016) is examining national water quality criteria for copper in estuarine and marine waters. In the Baltic Sea, a multi-national, interdisciplinary program is being conducted by a northern European consortium of academic, government and private research organizations to reduce toxins from antifouling paints used on recreational boats (Change 2014). Some countries already regulate copper antifouling paints on smaller boats operating in saltwater and freshwater (Sweden, Eklund and Karlsson 2010; Denmark, Danish EPA 2015).

Integrated Pest Management Strategy for Hull Fouling

New and planned regulations on copper emissions will certainly help address water quality issues arising from copper-based antifouling paints on boats in regulated areas. However, they do not consider the potential consequences of AIS transport and biofouling control more broadly. An adaptive Integrated Pest Management (IPM) approach, using a combination of tactics (chemical, physical, cultural) for multiple pest life stages, can inform development of an effective and balanced fouling control strategy that simultaneously considers boat operations and ecosystem health, both water quality and AIS. Development of this type of control strategy requires understanding the complexity and interaction of factors that influence the settlement, growth, reproduction and accumulation of fouling organisms on boat hulls.

To develop an IPM framework for biofouling control we investigated recruitment responses of fouling organisms to select factors. Our research objectives were to: 1) Assess the influence of hull coatings on recruitment of fouling organisms, 2) Assess the influence of aging copper-based antifouling paint on recruitment of AIS and native fouling organisms, 3) Experimentally evaluate the influence of standard hull cleaning practices used in California on the accumulation of biofouling on boat hulls, and 4) Evaluate temporal and spatial recruitment patterns to determine the potential effects of time of year, location among and within harbors, and environmental factors on the recruitment of fouling organisms to boat hulls.

By addressing these objectives we gained insights for controlling biofouling on boats and in harbors. We identified settlement preferences (Crisp 1984; Pawlik 1992) of fouling organisms for different types of hull coatings and ages of copper-based antifouling paint, information needed to determine which fouling species required control. We also evaluated the efficacy of California's in-water hull cleaning practices for reducing fouling that was questioned following reports that it stimulated attachment of fouling organism in Australia (Floerl 2002; Floerl et al. 2005). Evaluation of environmental variables that may influence fouling, including water temperature (Stachowicz et al. 2002; Scheibling and Gagnon 2009; Sorte et al. 2010), salinity (Lambert and Lambert 2003), water motion or flow (Leichter and Witman 1997), shading (Glasby 1999a; Miller and Etter 2008), proximity to the seafloor (Glasby 1999b) and the presence of nearby conspecifics (Jensen and Morse 1984; Minchinton 1997), enabled us to develop predictions about the intensity and timing of fouling at locations within and among harbors. This in turn helped us to evaluate how various fouling control tactics might be incorporated into a hull fouling control strategy.

Based on our key findings and those of related work, we developed an IPM framework for managing hull fouling that considers boat and harbor operations, water quality and invasive species. Aspects of this framework focus on reducing spread of non-native fouling AIS specifically, as these species are highly abundant in harbors worldwide (Cohen et al. 2001, 2005; Paulay et al. 2002; Hewitt et al. 2004), contributing substantially to the available fouling assemblages that accumulate on boat hulls. AIS control is thus essential for overall fouling control on boat hulls to minimize drag, extend the service life of hull coatings, and maintain the integrity of native ecosystems where boats are taken. Although our work concentrates on saltwater conditions of specific regions, the resulting IPM framework for hull fouling can be broadly applied to other locations, including freshwater systems, if it is adjusted to local conditions and fouling biota. The general IPM fouling control framework and associated information is intended to inform technically, ecologically and economically sound decision and policy making for controlling fouling on boat hulls while maintaining boat operations, protecting water quality and minimizing the spread of AIS.

[A]Methods

We focused our study on saltwater boating, where boats typically travel from location to location without being removed from the water. This differs from freshwater boating where boats often are hauled out of the water and transported on a trailer to other locations. We further focused our study on small recreational and commercial vessels and did not include saltwater ships (large vessels), such as those used in commerce and the military, as they differ in operational parameters and economics that influence the approach required for fouling control. We also concentrated on factors influencing fouling for boats that rarely move from their harbors, as our earlier research indicated that this represents half of California boaters (Johnson and Fernandez 2011).

*[C]*Study sites.–Our field studies were conducted in two small craft harbors on the southern California coast: Santa Barbara Harbor (SBH), Santa Barbara (34.405811, -119.691254); and Shelter Island Yacht Basin (SIYB) of San Diego Bay, San Diego (32.711111, -117.235278) (Fig. 1). These harbors are frequented by commercial and recreational boats in Santa Barbara and by recreational boats in San Diego. These two harbors are located, respectively, in the northern and southern portions of the Southern California Bight within two marine biogeographic provinces. The Santa Barbara region is within the "California Transition Zone" where warm and cold waters of the Californian and Oregonian provinces mix, whereas the San Diego region is influenced by the warm waters of the San Diegan province (Dawson 2001).

The effects of hull coating, time of year, location (among and within harbors), and environmental variables on recruitment of fouling organisms were examined at 28 stations in the two study harbors. Stations 1 through 16 were in Santa Barbara Harbor (SBH) (Fig. 1a) and Stations 17 through 28 were in Shelter Island Yacht Basin (SIYB) (Fig. 1b). For most analyses, the SBH stations were further grouped into four locations along a gradient from the inner to outer harbor across the width of the harbor. The SIYB stations also were grouped along a gradient from the inner to outer basin in association with three separate marina locations: inner, Half Moon Anchorage (HMA) (stations 17-20), middle, Southwestern Yacht Club (SWYC) (stations 21-24) and outer, Kona Kai Marina (KKM) (stations 25-28).

Two other field studies were conducted at a subset of the above stations. We investigated the effects of aging of copper-based paint on fouling at two locations in SIYB: at the inner (HMA) (Stations 17-20) and outer basin (KKM) (Stations 25-28) (Fig. 1b). An assessment of hull cleaning methods on accumulation of fouling was conducted at three locations: one in SBH (stations 13-16) and two in SIYB [HMA (Stations 17-20) and KKM (Stations 25-28)] (Fig. 1).

[C]Experimental set-up.–We conducted these studies on floating docks in the harbors and marinas described above. At each station, we deployed a PVC frame with 15 cm x 15 cm fiberglass experimental plates attached vertically to the inside of the frame (Fig. 2). Plates were randomly assigned to positions along the frame. The side of the plate facing out into the slip represented the 'front' and the side facing the dock was the 'back.' Frames were attached to the northern (SBH) or the northwestern (SIYB) facing side of the floating docks, with the plates at a depth of 1 meter below the surface of the water where hull cleaners have noted extensive fouling. Four replicate frames were deployed at each location for each experiment. Prior to attachment of the frame to the dock, fouling organisms were removed from the area directly behind the frames and a small (~ 5 cm) buffer zone around the frames.

Hull coatings representing typical brands used in California at the time of the study were applied to the experimental plates by a commercial boat repair yard in San Diego. All plates were initially coated with Cook Composites polyester gel base coat (gel or gel coat), as is done on boat hulls prior to application of toxic antifouling paints and nontoxic (nonbiocidal) coatings. Depending on the experiment (Table 1), treatment-coatings were applied over the initial gel coat. The treatment coatings were: 1) copper-based antifouling paint, Interlux Epoxy Modified Antifouling ('copper'); 2) nontoxic, ceramic-epoxy, CeRamKote Marine ('epoxy'); 3) nontoxic, siliconized epoxy, Eco-5 Marine ('slick'); and 4) nontoxic, gel, Cook Composites polyester ('gel'). Note, herein we refer to nontoxic, siliconized epoxy coatings as 'slick' coatings, not 'foul-release' coatings; terminology appropriate for the recreational boating milieu. Coatings were black in color because this was the only available color common to the types of paints and coatings used for the studies.

The size of the experimental frames, the number of plates on each frame, the type of coating on the plates, and the duration and time frame of the experiments differed for each field experiment (Table 1; Fig. 2). Details of each experiment follow.

Hull Coatings: The evaluation of the effect of hull coating on recruitment of fouling organisms included four treatment plates, one for each type of coating described above (one toxic and three nontoxic coatings) (Fig. 2a). The nontoxic gel coat plates in this experiment also were used for the Time of Year and Location studies (see below).

Aging Copper-Based Antifouling Paint: The assessment of the effect of aging of copper-based paint on the recruitment of fouling organisms on plates included three experimental plates with the same copper-based antifouling paint (Interlux Epoxy Modified Antifouling paint) used in the Hull Coating Experiment (Fig. 2b). Each plate was assigned to one of three submersion time treatments: 3, 6 or 12 months.

Hull Cleaning: The evaluation of the effect of hull cleaning methods on accumulation of fouling organisms included three sets of three plates (nine plates total) with three coating types and three cleaning treatments (Fig. 2c). The same coatings (copper, epoxy and slick applied over a gel-coat base) used in the other experiments were used for this experiment. Three cleaning treatments, 1) frequently cleaned, 2) cleaned once and 3) not cleaned (new), were applied to plates on each frame. Plates undergoing the 'frequently cleaned' treatment were submerged and cleaned frequently for a three-month period. At the same time, the 'cleaned once' treatment plates were allowed to continually accumulate fouling over the three-month period. At the end of the third month, plates from both of these treatments were cleaned and returned to the water along with a third treatment consisting of a set of new plates ('not cleaned') that had not previously been submerged in the water. None of the plates were cleaned during the fourth month when fouling was allowed to accumulate on the treatment plates. The amount and type of fouling were evaluated on the front side of the plates in each treatment at the end of the fourth month.

California best management practices (BMPs) for hull cleaning, developed by the California Professional Divers Association (CPDA), were followed whenever plates were cleaned in this experiment. The least pressure and softest cleaning tool were used first (Johnson and Gonzalez

2004). Pressure was gradually increased and more abrasive tools were used as needed, with plates cleaned in a container of saltwater. In accordance with the California BMPs for warm water areas (i.e., San Diego), plates in the ‘frequently cleaned’ treatment were cleaned every two weeks for the nontoxic coated plates and every three weeks for the plates with copper-based antifouling paint. The same BMPs were also used for the ‘cleaned once’ treatment, but (as noted above) these plates were cleaned only once at the end of the three months.

During each cleaning, the type of fouling growth was rated visually for each plate, whether cleaned or not, using the Five-Point Scale of the California BMPs (Johnson and Gonzalez 2004). Light “silting” (biofilm) represented the lowest rating (1) and substantial hard growth represented the highest rating (5). For all plates that were cleaned, we also recorded the cleaning tool and effort required to remove the fouling growth in accordance with the Five-Point Scale. In this case, the lowest rating (1) was defined by the least abrasive tool and the lightest pressure, with the highest rating (5) indicating use of the most abrasive tool and highest degree of physical effort.

Temporal and Spatial Recruitment Patterns: Our studies evaluating time of year, location and environmental factors used the same frames and gel-coated plates as used in the Hull Coating Experiment. To assess temporal and spatial recruitment patterns we analyzed monthly recruitment of fouling organisms to the gel-coated plates for 15 months and 12 months, respectively.

We measured several environmental variables at all stations including water temperature, salinity, water flow, light, water depth and the abundance of nearby conspecifics. These data were used to explore potential relationships between environmental variables and the recruitment of fouling organisms. Water temperature was measured with continuously recording temperature loggers (HOBO™) attached to the experimental frames deployed at each station for the Hull Coating Experiment. The data loggers recorded water temperature every 15 minutes. The data were downloaded monthly. Surface salinity was measured weekly at each station using a temperature-compensated refractometer. We also assessed relative differences in water motion (flow) among stations by measuring the dissolution rate of SLOD™ cards -- slow-dissolving, gypsum plaster molded to a standard size and fixed to a base -- that also were attached to the experimental frames (Hart et al. 2002). SLOD™ cards were deployed and retrieved monthly. We used plate side (front - facing out, or back - facing the dock) as a proxy to evaluate the influence of light level (shading) on recruitment of fouling organisms on the gel-coated plates. Water depth was measured at each station since proximity to the bottom could influence turbidity and the availability of sediment-bound contaminants. Water depth at each station is expressed as a "relative depth": the deviation in depth from the overall mean depth. The abundance of nearby conspecifics, which may attract settlers or provide larvae, was assessed by photographing three 15 cm x 15 cm quadrats (photoplots) situated on the dock floats at each station prior to deploying the experimental frames.

[C]Sample retrieval and analysis.–Upon collection from frames (see Table 1 for schedule), all plates were photographed, both front and back, and then placed in a plastic Ziploc™ bag that was filled with air to protect samples from being crushed. Bags were placed in large Tupperware™ containers and transported in a chilled cooler to the laboratory where they were frozen for subsequent processing and analysis (see Sample Analyses). One exception to this was the plates from the Hull Cleaning Experiment, which underwent a different process. Details of specific protocols for each experiment follow.

Hull Coating and Aging of Copper-Based Antifouling Paint: We visually identified and measured the proportional cover of all sessile organisms attached to the front and back of the plates using point-contact sampling (Underwood and Anderson 1994). A clear plastic grid with 50 randomly distributed holes was placed over each plate and a 1 mm diameter pin was inserted through each hole to contact the organism on the plate below it. Every organism the pin touched was identified and recorded. To calculate proportional cover of a species, the number of pin contacts was then multiplied by two. In cases where species overlapped and layering occurred there was more than 100% total cover on a plate. Counts of non-colonial species also were recorded. Organisms growing within 0.4 cm of the edge of the plate were not analyzed to avoid potential influences by conditions that might occur only near the edge.

Species/taxa on the plates were identified to lowest possible taxonomic level, with voucher samples sent to appropriate taxonomists for confirmation of identifications. In some cases, it was only possible to identify organisms to the level of genus as the species has not been fully resolved by taxonomists (Table A.1, A.2). We grouped the polychaetes, *Hydroides elegans* and *H. gracilis,* because it is difficult to distinguish between these species without microscopic inspection of each individual worm. A subsample of this worm complex was analyzed and a mix of species was present, with far more *H. elegans* (non-native) present than H. *gracilis* (native) in the sample. However, it is unknown whether this was the case for all colonies of these worms that we encountered. We also grouped *Ciona intestinalis* and *savignyi*, two non-native solitary tunicates. When possible, each species recorded on the plates was categorized by origin (native, non-native, cryptogenic) based upon the California Aquatic Non-native Organism Database that is managed by California Department of Fish and Wildlife (CDFW 2011). We categorized *Diplosoma listerianum* as non-native instead of cryptogenic, however, because of conclusions detailed in Ruiz et al. (2000).

Hull Cleaning: All plates were cleaned and the fouling growth, cleaning tool and cleaning effort were recorded at the end of the experiment as described above. In addition, we assessed the amount of fouling (accumulated biomass) on each plate by collecting all the fouling growth that had accumulated over the one-month period (between months three and four) at the end of the experiment. The collected fouling growth was taken to the laboratory for processing. Samples were filtered through a Whatman Cat No 1004 090 filter (#4 paper filter), dried in a drying oven at 15.5°C for 48 hours, and weighed to the nearest 0.0001 grams.

Temporal and Spatial Recruitment Patterns: Annual means were calculated for water temperature, salinity and SLOD™ card dissolution rate. The composition and proportional cover of macroalgae and invertebrates attached to the docks was determined from the photoplots by projecting the image and scoring contacts on 100 uniformly spaced points (similar to how the plates were scored).

[C]Statistical analysis.–The statistical analyses were conducted using Excel, SAS 9.2, SYSTAT 13 and SPSS 19. Details of specific analyses for each experiment follow.

Hull Coating: To evaluate the effect of hull coating on fouling, we compared the recruitment of organisms among three nontoxic hull coatings (epoxy, slick and gel) for the two different harbors (SBH, SIYB) using a multivariate analysis of variance (MANOVA), with individual species/taxa as the dependent variables. The toxic coating type (copper-based antifouling paint) was not included in these statistical analyses because the data for this coating violated the assumptions required for the analysis. We focused our analysis on non-native, cryptogenic or unresolved taxa as they represented the dominant organisms. We constrained the analysis to better meet the mathematical assumptions of MANOVA by excluding rare taxa, which kept the number of variables (taxa) less than or equal to the number of stations. To be included, a taxon needed to occur on at least 45% of the plates and the average annual proportional cover needed to exceed 0.010 (1%). All proportional cover data were arcsine-transformed prior to analysis. Individual count data were log-transformed. Analyses were run using SAS 9.2.

Aging of Copper-Based Antifouling Paint: We analyzed the effect of aging of copper-based antifouling paint on fouling of experimental plates using the proportional cover of all sessile organisms and individual counts of solitary organisms, measured as described above. In this experiment, data from the front and back surfaces of the plates were combined due to the low occurrence and coverage of most species encountered. Differences in the proportional cover of non-native and native species after 12 months at each location were analyzed using the paired Student T-test on arcsine-transformed data. Because the data for the two shorter submersion times (3 and 6 months) violated the assumptions required for statistical analyses (normally distributed data, homogeneity of variance), only general trends are discussed for these data. Analyses were run using SAS 9.2.

Hull Cleaning: The effect of cleaning practices on fouling biomass was analyzed using Kruskal-Wallace non-parametric rank test to evaluate differences in rankings of fouling growth type, cleaning tool and cleaning effort among locations, coating type, and cleaning treatment. To test for differences in accumulated biomass (amount of fouling) among locations, coating type and cleaning treatment we used Analysis of Variance (ANOVA). Biomass data were log (x+1) transformed prior to analysis (Zar 1999). Analyses were run using SAS 9.2.

Temporal and Spatial Recruitment Patterns: The effect of time of year on recruitment of fouling organisms was described by the dispersion in recruitment computed as the coefficient of variation (CV) in monthly cover during the 15 months of the study. The influence of location and environmental parameters on fouling including the effects of plate side (front versus back) and location within the harbors (outer to inner harbor) on the abundance (as proportional cover) of the more common algae and invertebrates were explored using multivariate analysis of variance (MANOVA). Plate surface and location were designated as fixed factors and the cover of algal and invertebrate taxa as the response variables. The assumptions of normality and homogeneity of variances were explored using Shapiro Wilks' test and Levene's test, respectively. The tests showed that these assumptions were typically violated for ~25% of the taxa within each location x side combination. However, MANOVA is generally considered robust to violations of these mathematical assumptions (Lindman 1974, Bray and Maxwell 1985). If the multivariate test statistic Wilks' λ was significant ($P<0.05$), significant effects of side and location for individual taxa were identified using univariate F-tests. MANOVA analyses were run using SYSTAT 13 and SPSS 19. Proportional cover data were arcsine-transformed ($p' = \text{arcsine}\sqrt{p}$) prior to analysis as recommended by Zar (1999).

We used correlation and regression analyses to examine relationships between the annual means of environmental variables for each station and linear distance from the outer to inner harbor. Distance was measured for each station from an arbitrary point established in the outer harbor (SBH: 34.405811, -119.691254; SIYB: 32.711111, -117.235278, Fig. 1). Within each harbor, we explored potential correlation among values of water temperature, salinity, flow, and water depth measured at each station. For variables that were cross-correlated, we selected the variable that showed the fewest significant correlations with the other variables or those that we viewed as most likely to help explain observed patterns for use in subsequent correlation and regression analysis.

For those invertebrate taxa showing significant location effects with MANOVA, we used correlation and regression analysis to explore potential relationships between monthly mean cover of these taxa averaged across 12 months, and the measured environmental variables, which included the cover of the taxa of interest on the dock. Only those taxa that could be satisfactorily identified in the photoplots were used in this analysis. Correlation analyses were run using SYSTAT 13.

[A]Results

[B]Hull coatings

More than 35 taxa of fouling organisms from 8 phyla recruited to the plates with new nontoxic coatings and reached high cover over one-month intervals at both harbors (Table A.1). When all taxa are included, percent cover of fouling organisms on the plates with nontoxic coatings over the short time intervals was quite high averaging 71.3% to 91.4% with more fouling observed at the southern harbor. Dominant species on the experimental plates with nontoxic coatings included a few taxa of unresolved taxonomy and several AIS (Figs. 3-5). Nearly half of the cover on plates at both harbors consisted of one or two algal taxa, *Enteromorpha* and *Cladophora*, and tube worms in the family Spirorbidae (Figs. 3, 4). Spirorbid tube worms were very dense at the southern harbor as compared to the northern harbor over the three coating types (Fig. 4). The dominant non-native species observed on the plates included branching and encrusting bryozoans, *Bugula neritina, Watersipora subatra (formerly W. subtorquata* in our region; Vieira et al. 2014)*,* and *Cryptosula pallasiana*, a tube worm, *Hydroides elegans*, the solitary tunicates *Ciona* spp., and the colonial tunicates, *Diplosoma listerianum* and *Botrylloides violaceus* (Fig. 3). At the southern harbor (SIYB), two additional primary invertebrate species were observed on the plates: the tube worm, *Filograna implexa*, and the colonial tunicate, *Botryllus schlosseri* (Fig. 3b).

At the southern harbor (SIYB), recruitment of fouling organisms was significantly affected by the type of nontoxic coating on the plate for both colonial (proportional cover) (λ value, 0.327, *F* = 2.68, *P* < 0.001; Fig. 3b) and non-colonial (counts) species (λ value, 0.663, *F* = 2.91, *P* = 0.006; Fig. 4b). Recruitment of the invasive *W*. *subatra* was significantly higher on plates with epoxy and slick coatings as compared to the plates with only gel coat (p < 0.001). Also, recruitment of *Hydroides* spp. (*H*. *elegans* and *H*. *gracilis*) was significantly higher on the epoxy nontoxic coating compared to the slick coating (proportional cover, *P* = 0.022; counts, *P* = 0.008; Figs. 3b, 4b). At the northern harbor, recruitment was lower overall compared to the southern harbor, and it was not significantly affected by type of coating for either colonial (proportional cover) (λ value, 0.684, *F* = 1.06, *P* = 0.395; Fig. 3a) or non-colonial (counts) species (λ value, 0.904, *F* = 0.89, *P* = 0.523; Fig. 4a).

Fouling was extremely limited on plates with copper-based antifouling paint submerged in both harbors over one-month intervals (Tables A.2). Fouling on these plates consisted of just a few individuals or very small colonies of a few species of tube worms (including the non-native *Hydroides elegans*) and sabellid worms, a couple of algal taxa of unresolved taxonomy, one non-native tunicate (*D*. *listerianum*) and one cryptogenic tube-building amphipod (*Laticorophium baconi*).

[B]Aging of Copper-Based Antifouling Paint

Over the 12 months of the experiment, twenty-two different organisms from six taxa were detected on the plates with copper-based antifouling paint (Table A.2). Almost half (45%) of these organisms were rare, occurring on only one plate for a single submersion time at one or both locations at the southern harbor. Several other fouling organisms were more common, occurring throughout the experiment.

Fouling organisms recruiting to the plates with copper–based antifouling paints over intermediate submersion times (3, 6 months) were primarily AIS, along with two cryptogenic species (*L. baconi* and *Bowerbankia* sp.) and tube worm (*Spirorbis* sp.) of unresolved taxonomy (Figs. 6-8). Non-native fouling species appeared earlier than native species on these plates. The AIS observed on the experimental plates with copper-based antifouling paint at both inner and outer harbor locations included *H. elegans*, *F. implexa* (Figs.7b, c), *B. neritina* (Fig. 6a), *W. subatra* (Figs. 6a, b), D. *listerianum* (Fig. 6b), and *Ciona* spp. (Table A.2).

The proportional cover of the principal space occupiers increased substantially over time on the experimental plates with copper-based antifouling paint at both locations, with these plates becoming heavily fouled within 12 months of submersion (Fig. 6). The cryptogenic amphipod, *L. baconi*, occupied the most space at the end of the experiment at both inner and outer harbor locations, with the non-native tunicate, *D. listerianum*, occupying the second and third highest amount of space at the inner (HMA) and outer (KMA) locations respectively. Further, non-native species occupied more than twice as much space as native species on plates with copper-based antifouling paint submerged for 12 months at both locations (Figs. 6-8). At the outer location (KKM), proportional cover was significantly greater for the four primary non-native species compared to the three primary native species (KKM: t = 3.22, $P = 0.049$). A similar trend was evident at the inner location (HMA), although these results were not statistically significant (HMA: t = 2.86, $P = 0.065$) with only one native species (*Aplidium californicum*) versus four non-native species (*D. listeranium*, *F. implexa*, *W. subatra* and *B. neritina*) recruiting to these plates.

Some species recruited on top of other species. We observed that at times *D. listerianum* recruited on top of the tube mats of *L. baconi*. At six months at one of our southern locations (KKM), we found the native alga species, *Rhodymenia pacifica*, recruited onto the non-native bryozoan, *W. subatra*, rather than the plate itself, with direct recruitment onto the plates with copper-based antifouling paint occurring only after 12 months of submersion. The native bryozoan *Bugula californica* also recruited onto *W. subatra* and directly onto some of the plates with copper-based antifouling paint, but not until the plates had been submerged for 12 months.

[B]Hull Cleaning

Hull cleaning did not stimulate the recruitment of fouling organisms, even during the peak period for their recruitment and growth at our three study locations (Fig. 9). Plates that had never been cleaned or that had been cleaned once accumulated just as much fouling growth as plates that were frequently cleaned using the California BMPs ($X^2 = 2.56$, $P = 0.083$). We found no difference in the type of fouling among locations ($X^2 = 0.009$, $P = 0.995$) or cleaning treatments ($X^2 = 0.009$, $P = 0.995$). Similar types of organisms were found on plates at the three locations (SBH, KKM, HMA) whether they were cleaned or not. The type of tool and the amount of effort needed to remove fouling growth also did not vary among locations (tool: $X^2 = 2.01$, $P = 0.366$; effort: $X^2 = 2.49$, $P = 0.287$), with the least abrasive tools and similar light to moderate effort used on plates at all three locations. However, plates that were cleaned once or frequently cleaned required a slightly more abrasive tool (rank 2 versus 1) and a little more effort (rank 1 versus 2 or 3) to remove the fouling growth than plates that were new and had never been cleaned (Tool: $X^2 = 17.0$, $P = 0.0002$; Effort: $X^2 = 6.20$, $P = 0.045$). A slightly more abrasive tool and moderate effort was typically required to remove a dark green algal film or calcareous organisms. Even though the light calcareous growth was fairly easily removed, some scratches on the plates resulted from the process.

A slightly more abrasive tool (rank 2 versus 1) and more effort (rank 2 and 3 versus 1) were required to remove the fouling growth from the plates with nontoxic coatings than from the plates with a copper-based paint (tool: $X^2 = 32.9$, $P < 0.0001$; effort: $X^2 = 79.9$, $P < 0.0001$). Significantly less fouling accumulated ($X^2 = 50.8$, $P < 0.0001$; Fig. 10) and significantly different types of fouling ($X^2 = 107$, $P < 0.0001$) occurred – slime layer (siltation) versus green algae and light growth of calcareous organisms – on the plates with the toxic antifouling paint as compared to those with nontoxic coatings.

Fouling was significantly less at the northern harbor (SBH) compared to the two southern locations at SIYB ($X^2 = 28.5$, $P < 0.0001$; Fig. 10). Water temperatures at the time of the experiment were higher at the southern location, averaging 21.9˚ C and 22.2˚ C at the outer (KKM) and inner (HMA) locations respectively as compared to 18.8˚ C at the northern (SBH) harbor.

[B]Temporal and Spatial Recruitment Patterns

Seasonality was evident at both harbors, but the mean recruitment of all our focal species was more seasonal and less dispersed, as reflected in a higher coefficient of variation (CV) value, at the northern harbor (SBH) (1.8 ± 0.2) compared with the southern harbor (SIYB) (1.3 ± 0.1) ($t = 3.685$, $df = 11$, $P = 0.004$). Overall recruitment was lowest during late fall, winter, and early spring. We found strong seasonal recruitment of *F. implexa*, *B. neritina* and *Ciona* spp. on nontoxic coatings over one or more summer months at our study harbors (Fig. 10).

Spatial variation in recruitment of some taxa was evident within the harbors. At the northern harbor, recruitment of *Ciona* spp. increased ($P = 0.017$), whereas recruitment of *Watersipora* ($P < 0.001$) and *Spirorbid* sp. ($P = 0.044$) decreased from the outer to inner locations within the harbor (Fig. 11). At the southern harbor spatial variation in recruitment was evident for five of the 12 taxa, including: *D. listerianum* ($P < 0.001$); *W. subatra* ($P = 0.017$); *Spirorbid* sp. ($P = 0.015$), *Hydroides* spp. ($P = 0.002$), and *F. implexa* ($p < 0.001$) (Fig. 12). Recruitment of these taxa increased (*F. implexa*) or decreased (*D. listerianum, Spirorbid* sp.) from outer (KKM) to inner (HMA) harbor locations or highest at the intermediate location (SWYC) (*W. subatra*, *Hydroides* spp.).

The recruitment of many algal and invertebrate taxa was significantly influenced by orientation of the plate surface at both the northern (SBH: $P \leq 0.01$) and southern harbors (SIYB: $P \leq 0.05$) (Figs. 11, 12). The front side of the plate, facing away from the dock and exposed to light, was colonized primarily by algae (*Cladophora, Enteromorpha*), whereas the back side, that faced the dock and was shaded, had little macroalgae, but was colonized by a suite of invertebrates dominated by ascidians, bryozoans, and tube worms.

Environmental conditions and the distribution of conspecifics within harbors partially explained the spatial patterns in recruitment documented in our study. Recruitment of three of the fouling taxa (*F. implexa, Ciona* spp., *W. subatra*) was influenced by water flow rates. Water flow was negatively correlated with recruitment for both *Ciona* spp. at the northern harbor ($r^2 = 0.49$, $P < 0.05$; Fig. 13) and *F. implexa* at the southern harbor ($r^2 = 0.62$, $P < 0.05$; Fig. 14). The strong, negative response of *Ciona* spp. recruitment to enhanced flow found in a complementary manipulative field experiment supports the hypothesis that water flow can influence the distribution and abundance of this taxon (Santschi 2012). Recruitment of *W. subatra* was positively correlated with water flow at the southern harbor ($r^2 = 0.54$, $P < 0.05$; Fig. 14). In contrast, at the northern harbor *W. subatra* recruitment was correlated with the cover of conspecifics on the dock floats ($r^2 = 0.64$, $P < 0.05$; Fig. 13).

[A]Discussion

An effective IPM strategy to control hull fouling requires tactics that target one or more life stages of these diverse organisms. Such tactics include chemical, physical and cultural approaches that can be used in combination as companion methods. Our research results have implications for applying various fouling-control tactics.

[B]Chemical Tactics

Chemical tactics to control hull fouling include toxic hull coatings and the use of liquid chlorine contained within a slip liner (not a focus of our study). Toxic hull coatings, such as copper-based antifouling paints, are the most widely used chemical tactic for fouling control. They are quite effective at inhibiting recruitment and early survival of fouling organisms. However, we illustrated that they pose a risk for transporting AIS because the effectiveness of the toxic paint diminishes over a relatively short amount of time (within 6 months) and non-native species are among the first to recruit to plates with toxic paint. AIS that recruited to the plates can form large colonies that out compete native species for space and food, particularly in disturbed habitats (Page et al. 2006; Piola and Johnston 2008). Some of the species also can be a nuisance for boaters, as they form calcareous colonies that are difficult to remove from boat hulls. Depending on the species, their removal may result in damage to hull coatings if they are not removed when small and easier to dislodge. Our results add to the evidence of copper tolerance of non-native species documented elsewhere (e.g., Floerl et al. 2004; Crooks et al. 2011; see also review by Lande et al. 2011; Osborne et al. 2018) and support the hypothesis of Dafforn et al. (2008) that boat hulls with copper-based antifouling paints may facilitate selective transport of copper-tolerant non-native organisms.

For boat hulls with toxic copper-based antifouling paint that are submerged for periods greater than six months, the risks of spreading AIS may be substantially higher. These boats may contain a number of non-native species that have grown and likely are reproducing (although this was not measured), thereby increasing the chance of spreading them to other areas. Further, the copper-tolerant species may provide a foundation on which other fouling species can settle, thereby enabling less-tolerant species to be carried to new areas more readily than would otherwise be possible (Floerl et al. 2004). Crooks et al. (2011) noted this secondary settlement adaptation among invasive fouling species in San Francisco Bay. We observed that the tube-dwelling amphipod *L. baconi* tolerated the copper-based paint, and that it may have also facilitated recruitment of a non-native tunicate (*D. listerianum*). Alternatively, the tube it produced may have protected the amphipod from the toxic effects of the paint and *D. listerianum* may simply have been overgrowing the tube mats, not using them for "protection" from the antifouling paint. We also documented recruitment of the non-native bryozoan *W. subatra,* a species known to be a foundation to which other organisms, including AIS, can attach (Floerl et al. 2004). Further investigations of secondary settlement of fouling organisms on substrates with toxic antifouling paint will help elucidate the importance of foundation species for facilitating spread of AIS.

[B]Physical Tactics

Physical tactics for controlling hull fouling include using barriers or changing physical factors that alter settlement or attachment of fouling organisms. Well known physical tactics include storing a boat on a trailer, a lift, or in a slip liner (Culver and Johnson 2012). Nontoxic hull coatings, including the epoxy and slick coatings we tested in our experiments, also represent a physical tactic, albeit less recognized as such. While these coatings are not designed to prevent fouling organisms from settling, their surface characteristics can influence recruitment and/or attachment strength of fouling organisms (Pomerat and Weiss 1946; Crisp 1984; Aldred and Clare 2009; Townsin and Anderson 2009). Another tactic is the physical removal of organisms, by hand or with the aid of mechanical equipment, from the boat via hull cleaning both in and out of the water (sometimes defined as a 'mechanical' tactic).

Biofouling by certain taxa may be reduced by a boater's application of certain hull coatings. For example, we found the slick coating, but not the epoxy coating, attracted tube worms (*Hydroides* spp.) in some areas. Theoretically, application of the less preferred epoxy coating would therefore help to reduce hull fouling by these tube worms in those areas. Enhanced nanotechnology that characterizes surfaces is expected to lead to the development of new coatings that consider and exploit settlement preferences of fouling organisms (Callow and Callow 2009). In addition, silicone-based (slick) coatings are designed to reduce the strength of attachment of fouling organisms (Anderson et al. 2003; Townsin and Anderson 2009), something we did not investigate during our study. Often referred to as "foul release" coatings, the weaker attachment results in fouling organisms that are easier to remove and/or slough off when a vessel reaches a certain speed. These coatings were initially developed for use on commercial ships that operate at speeds over 15 knots (Townsin and Anderson 2009). However, Kovach and Swain (unpublished data) found that at least partial sloughing can occur at a speed of only 4 knots, a speed that is reached within harbors. These findings suggest that slick coatings may facilitate removal of at least some fouling taxa on boats at low speeds. This outcome would be good for reducing fouling on individual boats. However, the released organisms, depending on their survival and reproductive state after release, could serve as a source for reseeding boats and docks. This could hinder fouling management or lead to new introductions and spread AIS, especially if released outside the harbor. The coatings industry is working to improve the ability of these coatings to slough off slime (Townsin and Anderson 2009), an early fouling stage, which might enhance the usefulness of this physical tactic if fewer organisms are able to recruit.

In-Water Hull Cleaning

In-water hull cleaning is a companion practice used worldwide. Its effectiveness, however, has been questioned because studies conducted in Australia found that cleaning practices stimulated fouling (Floerl 2002; Floerl et al. 2005). The potential for stimulating fouling is further supported by the intermediate disturbance hypothesis (Grime 1973; Horn 1975; Connell 1978) that states recolonization may be more rapid following moderate disturbance such as hull cleaning. We, however, found that the CPDA's cleaning practices did not stimulate the recruitment of fouling organisms. The disparity among the studies likely is due to fundamental differences in the practices employed, including the intervals between cleanings and the types of tools used. Floerl (2002) allowed plates to accumulate fouling growth for seven months before they were cleaned for the first time. In contrast, we cleaned experimental plates much more frequently *as per* CPDA recommendations for the warm season in Southern California (Johnson and Gonzalez 2004): every three weeks for plates coated with copper-based antifouling paints and every two weeks for plates coated with nontoxic coatings. Floerl (2002) also cleaned plates with a more abrasive tool, a paint scraper, whereas we cleaned the plate surfaces with 3M™ pads (soft- and medium-grade).

Longer cleaning intervals, like those used in the Australian studies, can increase the suitability of the surface for recruitment of fouling organisms. Fouling organisms are able to grow and some taxa become tougher or harder in texture as they mature. As a result, a more aggressive tool and greater effort are required to remove them, increasing the likelihood of scratching and/or chipping the protective hull coating. In addition, total removal of older, more developed organisms is more difficult and fragments of fouling organisms may be left attached to the surface. Consequently, there is an increase in the rugosity of the coating's surface, a characteristic that many organisms prefer when searching for a place to settle (Crisp and Barnes 1954; Petraitis 1990). Also, remnants of the fouling organisms could create a chemical signal, attracting propagules to settle (Burke 1986; Pawlik 1992; Bryan et al. 1997, 1998). In fact, Floerl (2002) found that prospective recruits to scraped plates were strongly influenced by the types of fouling species that were on the plates prior to scraping. While we noticed very small scratches on some of our experimental plates where small calcareous growth had been removed, there were no noticeable deep scratches or fragments of organisms. In contrast, Floerl and colleagues (2005) deemed sterilization was necessary to remove all traces of the fouling assemblage to reduce subsequent fouling. These factors, at least in part, likely explain the finding that hull cleaning stimulated fouling as reported in the Australian research. Our results illustrate that the use of hull cleaning BMPs similar to those used in California can avoid stimulated fouling. Other studies support our findings and the use of frequent and gentle hull cleaning (Bergman and Ziegler 2018; Hunsucker et al. 2018, 2019).

Shorter cleaning intervals have the added benefit of not allowing fouling organisms to grow and mature. As a result, the fouling organisms typically will be small and readily damaged when cleaning occurs, likely not surviving the process. They also will have less time to develop, reducing the likelihood that they will reach maturity. This is beneficial for two reasons. First, if they are mature they can serve as a source of larvae that could potentially reseed boats and slips in the area, thereby hindering fouling management. Second, boats leaving the harbor with mature fouling organisms represent a higher risk of transporting AIS to other areas with suitable environmental conditions for the species.

Concerns have been raised about in-water hull cleaning as organisms removed during cleaning activities are not typically contained and disposed on land (CDFW 2008). Instead the removed material is allowed to sink to the bottom of the harbor. This practice could pose ecological risks when a boat is cleaned at the home port after having visited another area where AIS may have attached to the hull and been transported back to the home port. Some of this risk could be avoided if boats are cleaned at the visiting port before returning to home port. In-water cleaning of sedentary resident boats in their home port likely poses less ecological concern as the attached fouling organisms already occur in the harbor. Nonetheless, dislodging adult fouling organisms without lethal damage could allow these species to persist and continue to reproduce on the harbor bottom, hindering biofouling management and potentially increasing the risk of spreading AIS. Evaluating the survivorship of removed fouling organisms of different taxa, ages and of those sinking to the bottom of the harbor would help determine whether this concern is warranted. If survivorship of removed fouling organisms is documented, then research will be needed to develop practical, cost-effective collection technologies.

For boaters, durability of hull coatings is an important factor when considering hull cleaning frequency. The primary benefit of slick coatings for recreational boat owners is ease of cleaning, not hardness (aka durability). In contrast, nontoxic epoxy and ceramic-epoxy coatings neither prevent nor reduce the strength of fouling organisms' attachment. Instead, they offer the benefit of durability for boats whose hulls must be cleaned often (Lewis 2009). Watermann (1999) discusses applying a hard, smooth anticorrosive system and maintaining it for several years with regular underwater hull cleaning. Johnson and Gonzalez (2004) conducted a field demonstration of frequently cleaned, nontoxic coatings on recreational boats in San Diego Bay and follow-up surveys found that the tested epoxy coating lasted eight years and the ceramic-epoxy coating lasted over five years. In contrast, copper-based antifouling paints are replaced every two to three years on recreational boats in that location (Carson et al. 2009). It may be that more frequent cleanings using less abrasive tools (i.e., California-based hull cleaning practices) could help extend the life of all coatings; a topic requiring further study.

[B]Cultural Tactics

Cultural tactics include practices that prevent or delay pest outbreaks, such as choosing sites that do not favor the pest, scheduling management tactics, and increasing efficacy by removing sources of the pest (FAO 2016; Flint 2012; Dafforn 2017). For hull fouling-control, these include practices associated with maintenance, like renewing hull coatings, scheduling hull cleaning, and removing sources of pests from dock floats.

[C]*Timing maintenance practices*.–As generally known, and further illustrated in our study, toxic hull coatings, such as copper-based antifouling paint, are most effective following initial application (< 6 months). Given this short time interval, application will be most effective at reducing hull fouling if applied just before peak recruitment when fouling organisms' larvae are most abundant and likely to settle on and attach to hard surfaces. Applying fresh toxic coatings to boat hulls at this time should greatly reduce fouling and the risk of spreading AIS at least for a few months.

Hull cleaning efficacy can be increased through careful planning of cleaning frequency and timing based on: 1) Type and age of hull coating, 2) Time of year, 3) Harbor location and 4) Slip location and conditions. Our results support the use of different hull cleaning frequencies for toxic copper-based antifouling paints versus nontoxic hull coatings. Boats with copper-based antifouling paint should be cleaned within the first 6 months after the toxic paint has been applied, with more frequent cleaning as the paint ages and fouling accumulates more readily. In comparison, nontoxic coatings require cleaning shortly after application and submersion of the boat, and frequently from that time forward. Epoxy and slick coatings also may require more frequent cleaning if certain taxa (*Watersipora subatra*, *Hydroides* spp.) are abundant where the boat is kept.

Hull cleaning frequencies will be more efficient if they are adapted to seasonal variation in recruitment of fouling organisms within a biogeographic area. Our earlier field demonstration on boats in San Diego Bay (Johnson and Gonzalez 2004) and results presented here and elsewhere (e.g., Underwood and Anderson 1994; Bullard et al. 2013) illustrate the high degree to which fouling accumulation varies seasonally, supporting the use of different cleaning frequencies throughout the year. When recruitment is low, the frequency of hull cleaning activities could be reduced. In contrast, when recruitment of fouling organisms is high, frequent cleanings would be most beneficial. The hull cleaning schedule could also be adjusted to coincide with AIS recruitment patterns, especially those species with limited (1-3 months) recruitment periods (e.g., *F*. *implexa*, *B*. *neritina*, *Ciona* spp.). Further, under California BMPs, cleaning frequency is typically adjusted according to the coastal area where the boat is kept (Johnson and Fernandez 2011; Johnson et al. 2012). Our findings support this adaptive approach based on biogeography. Species in temperate regions are known to reach reproductive maturity sooner and reproduce more often in warmer waters (Sastry 1963; Dugan et al. 1991). Thus, more frequent hull cleaning is needed in temperate areas with warmer water. This was evident during our study; experimental plates at the northern harbor were less fouled and thus could have been cleaned less frequently than prescribed by the CPDA BMPs for warmer southern waters.

On a finer spatial scale, slip location and associated conditions within a harbor may also need to be considered when determining cleaning frequencies, particularly if AIS are present. For example, the strong, negative response of *Ciona* spp. recruitment to enhanced flow found in a related field experiment supports the hypothesis that water motion, and thus location in the harbor, can influence distribution and abundance of this taxon (Santschi 2012). Similarly, published and unpublished observations on *W*. *subatra* support the potential importance of established colonies and water motion in influencing recruitment and early growth of this bryozoan. *W*. *subatra* produces larvae with a very short planktonic life (24 hours or less) and thus has limited dispersal ability. Page et al. (2006, 2019) and Simons et al. (2016) found that this bryozoan recruited to settling plates deployed at offshore oil platforms with existing colonies, but not to plates on platforms without these colonies. Our contrasting results on the importance of environmental variables for recruitment and growth of *W*. *subatra* at our two study locations may be related to differences in the range or magnitude of variation in these variables between the different sized harbors, suggesting additional study of these responses is needed.

The influence of environmental factors on recruitment of fouling organisms signifies that boats kept in different locations within the same harbor may require different hull cleaning schedules to control biofouling and limit AIS transport. Boats kept in slips far from the mouth of the harbor where water flow typically is restricted may need to be cleaned more often when non-native invasive tunicates (e.g., *Ciona* spp.) are recruiting. Similarly, hulls of boats kept near the mouth where flow is higher (or where the docks have higher cover of conspecifics) may need to be cleaned on a schedule that is based on recruitment of the non-native bryozoan *W. subatra*. Identifying areas within harbors where AIS and other species of concern to boaters are persistent will help inform hull cleaning best management practices.

Light conditions within a slip may influence hull cleaning frequency. Light is required for algae to grow and this was the primary fouling taxa occurring on the front of the plates, with invertebrates dominating the back of the plates. These results are consistent with published studies that found a dramatic effect of algal cover on invertebrate recruitment (Coyer et al. 1993; Raimondi and Morse 2000). However, the lower recruitment of invertebrates to the front of the plates could also be related to a preference of some settling invertebrates for shaded surfaces (Miller and Etter 2008). Regardless of the mechanism, boats kept in shaded areas may experience higher recruitment of invertebrates, many of which are AIS, and consequently need more frequent hull cleaning to reduce damage to hull coatings and the risk of transport of non-native species.

[C]*Removal of biofouling source on docks*.–Development of a system-wide control program should include tactics that target harbor infrastructure. Fouling organisms attached to dock floats, pier pilings and other structures provide a source of larvae that can re-infest cleaned boat hulls. Knowing which species are present on these structures can help identify ‘hot spots’ – locations where species of concern, including non-native species and other fouling species that are difficult to remove or cause damage when removed from boat hulls – occur. If hot spots are found, harbor managers can concentrate removal efforts to reduce larval production while minimizing the need to clean infrastructure frequently throughout the harbor.

Our investigation of dock floats indicated that only a small amount of this space was occupied by fouling organisms other than algae. It is likely, however, that invertebrate fouling species were present and more abundant on nearby surfaces of the docks and pilings where we were not able to photograph or sample. Light exposure declines on the undersides of docks and with water depths on the pilings, providing shaded surfaces where a higher proportion of fouling invertebrates may be present. For this reason, surveying the undersides of docks and shaded depths of pilings could be used to identify hot spots for specific fouling species, and allow for targeted removal of these organisms. This approach could increase the efficiency of efforts to reduce populations of fouling organisms in a harbor.

To implement this potentially useful tactic, cost-effective methods are needed for removing fouling organisms from docks and pilings. Frequent dock scraping may be an option at smaller harbors, but it is too labor intensive to be feasible in many areas. As noted earlier, research also is needed to determine whether organisms scraped from hulls and docks into the water survive and continue to reproduce in the harbor. If so, systems to remove and dispose fouling organisms will need to be considered. Biological control agents that consume different stages of fouling organisms are being evaluated and show some promise for controlling specific species of concern (Culver et al. this issue; Culver et al. unpublished data) and fouling communities as a whole (Atalah et al. 2014, 2016). No matter which tactic is used to remove fouling, efforts focused at hot spots within harbors will help minimize costs. Ideally, removals from docks should also coincide with recruitment periods for native species to help minimize the colonization of the newly cleaned open space by non-native taxa, particularly AIS.

<B>IPM Framework for Hull Fouling Control

A summary of our hull fouling control framework is presented in Figure 15. It is based upon an IPM pyramid designed for the built environment (Underwood and López-Uribe 2019). Our pyramid applies basic principles of IPM, including the use of multiple tactics (represented by the tiers) that target all life stages of the pest and using more benign methods when possible. To be effective, these tactics should be used in combination as companion methods. The framework offers guidance to boaters for designing a fouling control strategy with tactics that address biofouling dynamics and factors associated with the boat and its use. A few additional tactics exist and new ones may be developed, all of which should be considered and incorporated into an IPM strategy as necessary (Culver and Johnson 2012).

IPM strategies seek to limit the use of toxic chemicals by applying them only when needed and in a way that minimizes their impacts on people and the environment (Flint 2012). Thus, they appear at the top of the pyramid. Although toxic copper-based antifouling paints are detrimental to water quality, their use will likely continue worldwide because they effectively inhibit fouling of many species for at least six months. Considering water quality impacts and the growing evidence for copper tolerance by fouling taxa, an IPM strategy could require a reduced use of copper-based paints in areas where they have not already been prohibited. Specifically, toxic hull coatings could be restricted to use only on boats that frequently travel long distances. These boats represent a higher risk for transporting and spreading AIS to new locations. If they are frequently out of port, such boats also represent a lower risk for contributing to copper pollution in marinas. An important and notable exception is boats that travel short distances to offshore islands, as islands are especially vulnerable to invasions (Brockie et al. 1988; Reaser et al. 2007). Further, toxic antifouling paint could be applied only to areas on boats that are critical for boat operations and difficult to clean manually (e.g., water intakes, housings for outdrive units). Scheduling toxic paint application (a cultural tactic) just prior to the season when many fouling organisms recruit will also help maximize the effectiveness of this strategy. In addition boats with toxic antifouling paint could be strategically located (another cultural tactic) in slips with high water circulation so that copper leached from coatings is less likely to accumulate in the harbor.

Avoiding the use of toxic antifouling paint for boats that travel infrequently or only short distances will further reduce impacts to water quality. These boats stay in the slip for extended periods and would be a source of leached toxins if toxic antifouling paint were applied. When considering the many available types of hull coatings, boaters will benefit by knowing whether a specific coating is more or less attractive to AIS or other species of concern. Importantly, while use of nontoxic hull coatings may be beneficial for water quality, when used alone they represent a substantial risk for transporting AIS via boats even when newly applied. As previously noted, many of these AIS can form dense aggregations and are difficult to remove from boat hulls. This also is the case for boats with antifouling paints that have been submerged for longer periods of time. These results reinforce the need to employ several tactics that work together as companion methods to control hull fouling and the spread of non-native species.

Companion fouling-control tactics are expected to become more important as the use of nontoxic and less-toxic hull coatings increases in response to growing regulation of copper antifouling paints. While tactics such as boat lifts and slip liners (with or without chlorine) are an effective option, they are expensive, require maintenance and are not permitted at certain harbors (Johnson and Fernandez 2011). This means that mechanical hull cleaning will remain an important component of a hull fouling IPM strategy. Because the cost of land-based hull cleaning, which requires lifting the boat out of the water and transporting it to a boat repair yard, is considerably more expensive (Johnson and Fernandez 2011), in-water hull cleaning is anticipated to remain the most common companion practice for boats kept in coastal harbors. The CPDA recommended BMPs tested here, which require frequent cleanings using less abrasive cleaning tools and effort, are beneficial for minimizing damage to hull coatings and reducing spread of AIS. The benefits of these ‘grooming’ practices (frequent and gentle hull cleaning) are also being reported for ships (Hunsucker et al. 2018, 2019).

As with chemical tactics, the efficacy of physical tactics can be enhanced through combination with cultural tactics. Adjusting the frequency and timing of hull cleaning to recruitment patterns of fouling organisms will enable boaters to better manage biofouling while also reducing potential transport of AIS. For example, in temperate regions or ports with species of particular concern, hull cleaning frequency may be increased during periods of intense fouling. In waters where less fouling occurs in general, slip locations and conditions (particularly water flow, shading and presence of conspecifics) may reveal areas within a harbor where more frequent hull cleaning will be beneficial. For boats with nontoxic coatings or older antifouling paint, frequent cleanings will be necessary. More generally, cleaning the hull just prior to leaving a port, especially if traveling far or to islands, is an effective cultural tactic for reducing the risk of transporting AIS and removing accumulated fouling (Culver and Johnson 2012). Cleaning harbor docks and other infrastructure is also an important cultural tactic to consider for system-wide hull fouling control. Integrating these tactics into fouling control strategies can address some of the complexities associated with fouling organism recruitment and the diversity of boating activities.

[B]Adoption of IPM for Boats

Application of an IPM approach for hull fouling control has only just begun. Discussions were initiated in response to realized and anticipated regulatory changes regarding copper-based antifouling paint and the need for hull fouling control methods that also considered risks associated with AIS transport. Beforehand, water quality and AIS transport had not been considered together. Previously developed measures often were beneficial for addressing only one issue, while being detrimental to the other. Although we have not determined whether the current IPM framework is being adopted, some marinas are taking steps that align with our framework components. For example, as of 2015, the hull coatings on 41 boats (1.8% of boats in the basin) had been converted to nonbiocidal coatings in response to a grant program in San Diego, California (SDUPD 2015). Additional steps, including the requirement for in-water hull cleaners to obtain a permit and follow the industry-recognized best management practices (SDUPD 2012) that were a topic of our research, have been implemented. Overall, copper loading has been reduced by an estimated 40.4% of the baseline (AFW 2016). It is anticipated that IPM for hull fouling control will receive more attention as compliance schedules proceed and more boaters switch to nontoxic coatings that require increased use of other fouling control tactics.

We also expect that adoption of this integrated approach will increase as more boaters and key community leaders learn and share the concept within the boating community (Rogers 2003). Johnson and Fernandez (2011) found that boating-industry customer awareness of nontoxic hull coatings significantly and positively influenced the use of these hull coatings. A majority

(76-100%) of participants in our educational workshops indicated that they intended to discuss the various tactics and IPM framework with others, with a small percentage (12-20%) already doing so. These results suggest that education may enhance dissemination of knowledge about IPM strategies for hull fouling control in the boating community. This could increase the likelihood that IPM will be adopted when regulations require boat owners to reduce use of copper antifouling paints and/or for boat owners seeking a more environmentally friendly fouling control strategy. Follow-up surveys of participants would provide further insight into actual adoption of the various tactics.

[B]Conclusions

Use of IPM to control biofouling on boat hulls is a new concept that requires evaluation and modification as scientific research continues, additional tactics become available, and more boat owners apply this approach. As a first step, we concentrated on factors influencing fouling for boats that rarely move; the case for half of all boaters in California. Additional research on the influence of boat use frequency and cruising speed on biofouling is critically needed to make an IPM strategy more broadly applicable. Nonetheless, an IPM framework as outlined here (Fig. 15) can provide a means for simultaneously addressing issues of water quality and AIS transport on boat hulls, while controlling biofouling. Adaptive in nature, it is not a “one size fits all” approach; it needs to be tailored to local conditions and individual boating patterns. As such, our IPM framework can be applied in areas where copper-based antifouling paints will continue to be used, as well as areas where the use of these toxic paints has been or will be restricted. Overall, this framework uses a sound and well-proven approach for pest management to facilitate an adaptive approach for biofouling control that balances the need for efficient boat operations while minimizing impacts to ecosystem health.

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Table 1. Design information for the field studies and experiments conducted for this study. Single asterisk (*) denotes that the same one-month gel treatment plates were evaluated for two of the experiments. Double asterisk (**) denotes that the front and back plate surfaces were combined for the analyses. Triple asterisk (***) denotes that only the front of the plates were analyzed. Four replicate frames were deployed at each location.

Study	Study sites (locations)	Frame size (instruments)	Treatments	Coatings	Fouling accumulation time intervals	Number of plates (surfaces)	Duration (months)	Time frame
Hull Coating	SBH (4) SIYB (3)	1m x 1m	4*	4 (all)	1 month	1340 (2680)	12	April 2008-March 2009
Aging copper-based antifouling paint	SIYB (2)	1m x 0.5m	3	1 (copper)	3, 6, 12 month	24 (48**)	12	July 2008-June 2009
Hull cleaning	SBH (1) SIYB (2)	1m x 1.5m	3	3 (all, less gel)	1 month	108 (108***)	4	June 2008-Sept 2008
Time of year	SBH (4) SIYB (3)	1m x 1m	1*	1 (gel)	1 month	419 (838)	15	April 2008-June 2009

Location and environmental factors	SBH (4) SIYB (3)	1m x 1m (SLOD™/ HOBO™)	n/a	n/a	1 month	n/a	12	April 2008-March 2009

Table A.1. Species recruiting to plates with nontoxic coatings submerged for one month at both the northern (Santa Barbara Harbor) and southern (Shelter Island Yacht Basin) harbors. Origin: C, cryptogenic; N, native; NN, non-native; Unr, unresolved, UnID, unidentified. Coating Type: E, epoxy; S, slick; G, gel base. "-", species absent. "x", species present. Single asterisk (*) denotes very rare species that were found on only one plate at one time at a site. Double asterisk (**) denotes rare species that were found on one to five plates.

			Coating type		
Phyla	Species	Origin	E	S	G
Algae					
Chlorophyta	*Cladophora* sp.	Unr	x	x	x
	Colpomenia sp.	Unr	x	x	x
	Ectocarpacea	Unr	x	x	x
	Enteromorpha sp.	Unr	x	x	x
	Ulva sp.	Unr	x**	x**	x**
Rhodophyta	*Rhodymenia pacifica*	N	-	-	x*
	Antithamnion sp.	Unr	x	x	x
Invertebrates					
Annelida	*Filograna implexa*	NN	x	x	x
	Hydroides spp. complex				
	H. elegans, *H. gracilis*	NN/N	x	x	x
	Myxicola sp. A - Harris	Unr	x*	-	-
	Sabellid				
	(likely *Pseudopotamilla* sp.)	UnID	x*	-	-
	Spirorbid sp.	Unr	x	x	x
Mollusca	*Mytilus* sp.	UnID	x*	-	-
Chordata	*Aplidium californicum*	N	x	x	x
	Ascidia ceretodes	N	-	-	-
	Ascidia zara	NN	-	-	-
	Botrylloides diegensis	N	x	x	x

	Botrylloides violaceus	NN	x	x	x
	Botryllus schlosseri	NN	x	x	x
	Ciona spp. *C. intestinalis or C. savignyi*	NN/NN	x	x	x
	Styela clava	NN	x	-	-
	Styela montereyensis	N	-	-	-
	Styela plicata	NN	x	x	x
	Diplosoma listerianum	NN	x	x	x
	Molgula sp. (most likely *M. ficus* or *M. verrucifera*)	Unr	x**	x**	-
	Unidentified tunicates (n=3)	UnID	x	x	x**
Crustacea	*Laticorophium baconi* (tubes)	C	x	x	x
Bryozoa	*Bugula californica*	N	x	x	x
	Celleporaria brunnea	N	x	x	x
	Crisulipora occidentalis	N	x	x	x
	Thalamoporella californica	N	x	x	x
	Tubulipora sp. (Either *T. tuba* or *T. pacifica*)	N	x	x	x
	Bugula neritina	NN	x	x	x
	Cryptosula pallasiana	NN	x	x	x
	Watersipora subatra	NN	x	x	x
	Bowerbankia sp.	Unr	x	x	x
	Membranipora sp.	Unr	x	x	x
Porifera	Unidentified sponges (n=2)	UnID	-	x**	x*

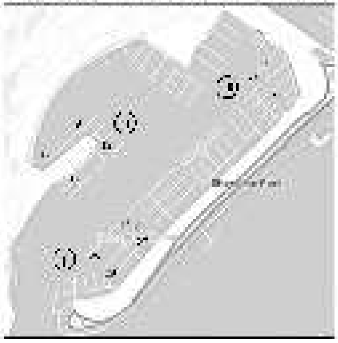
Table A.2. Species recruiting to plates coated with copper-based antifouling paint submerged for up to twelve months. The shortest submersion time (1 month) includes data from all locations at both harbors, with the longer submersion times (3, 6, 12 months) including data from two locations at the southern harbor (Shelter Island Yacht Basin). Origin: C, cryptogenic; N, native; NN, non-native; Unr, unresolved, UnID, unidentified. "-" species absent. "x", species present. Single asterisk (*) denotes very rare species that were found on only one plate at one time at a single site. Double asterisk (**) denotes species that did not recruit directly to the plates. Highlighted (bold) species occupied the most space over time.

			Submersion time (month)			
Phyla	Species	Origin	1	3	6	12
Algae						
Chlorophyta	*Cladophora* sp.	Unr	x*			
	Colpomenia sp.	Unr			x*	
	Enteromorpha sp.	Unr	x			
	Green monofilament	UnID		x*		
Rhodophyta	***Rhodymenia pacifica***	N			x**	x
Invertebrates						
Annelida	***Filograna implexa***	NN		x	x	x
	Hydroides spp. complex					
	H. elegans, H. gracilis	NN/N	x	x	x	x
	Sabellid	Unr	x			
	Spirorbid sp.	Unr	x	x	x	x
Chordata	***Aplidium californicum***	N				x
	Botrylloides diegensis	N				x*
	Botrylloides violaceus	NN				x*
	Ciona sp.					
	C. intestinalis or C. savignyi	NN		x*		x
	Diplosoma listerianum	NN	x	x*		x
Crustacea	***Laticorophium baconi***					
	(tube mats)	C	x	x	x	x
Bryozoa	***Bowerbankia* sp.**	Unr		x	x	x
	Bugula californica	N				x
	Bugula neritina	NN			x	x
	Celleporaria brunnea	N			x*	

	Crisulipora occidentalis	N		x*
	Cryptosula pallasiana	NN		x*
	Thalamoporella californica	N	x*	
	Watersipora subatra	NN	x	x
Porifera	Sponge	UnID		x*

(A) Santa Barbara Harbor

(B) Shelter Island Yacht Basin, San Diego Bay



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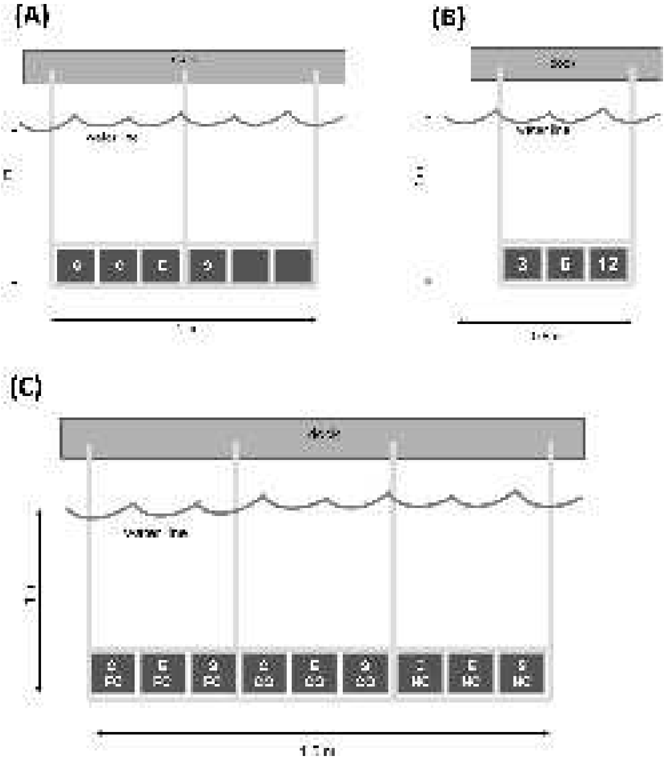

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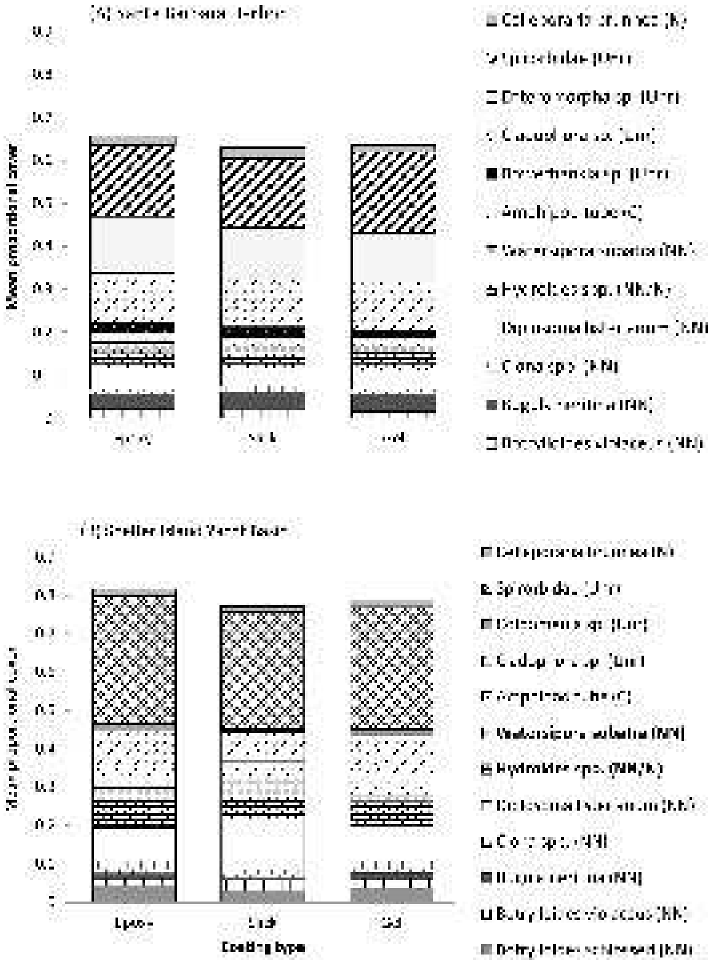

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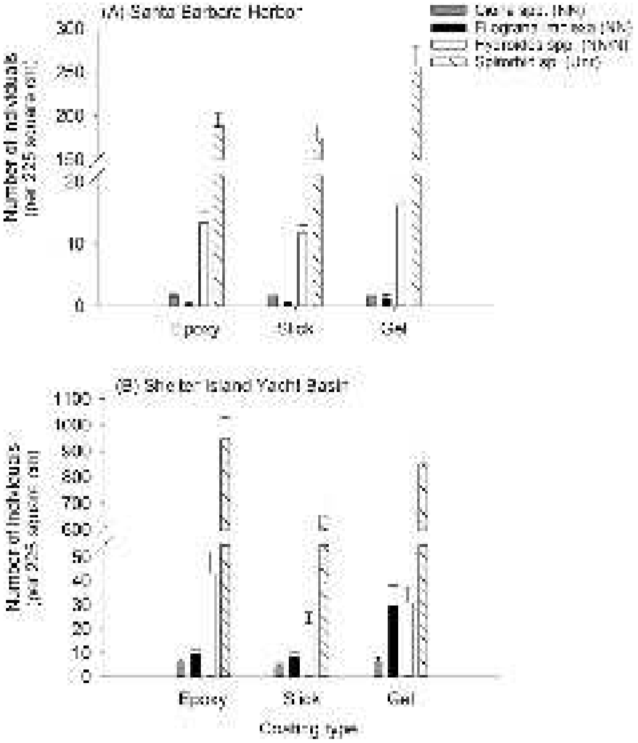

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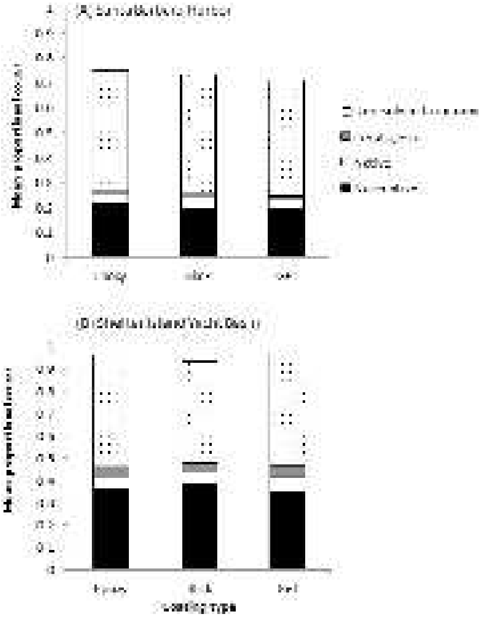

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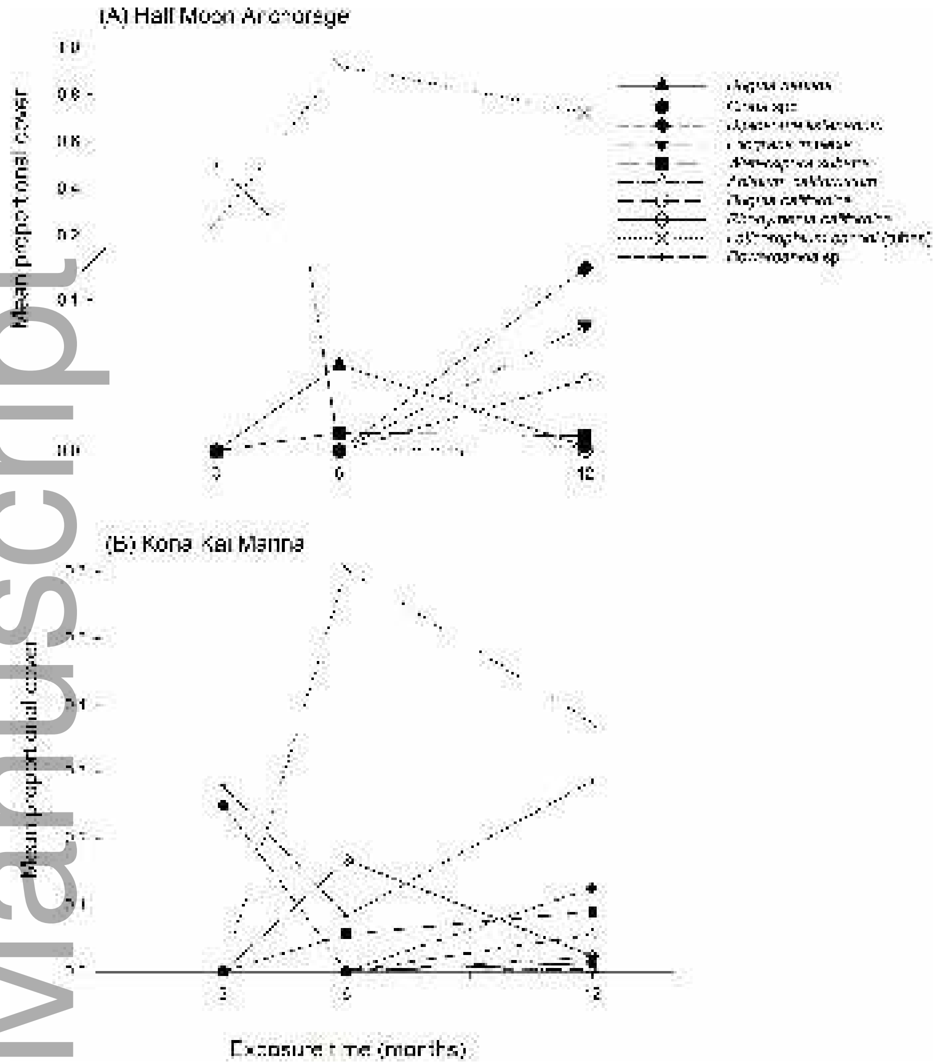

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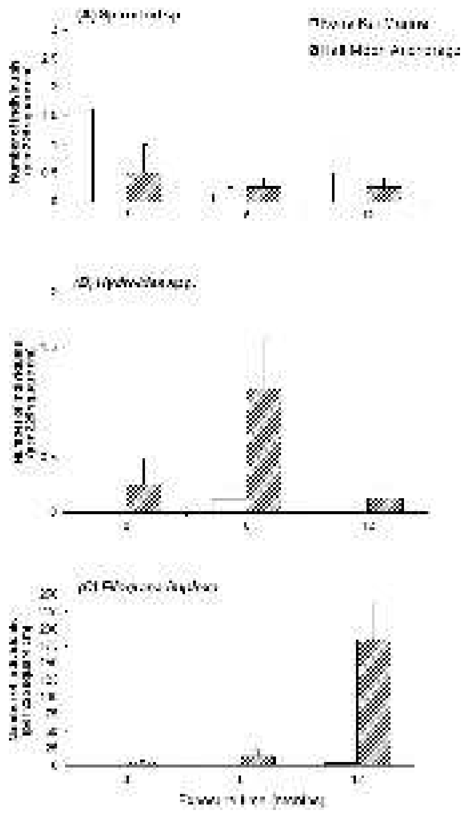

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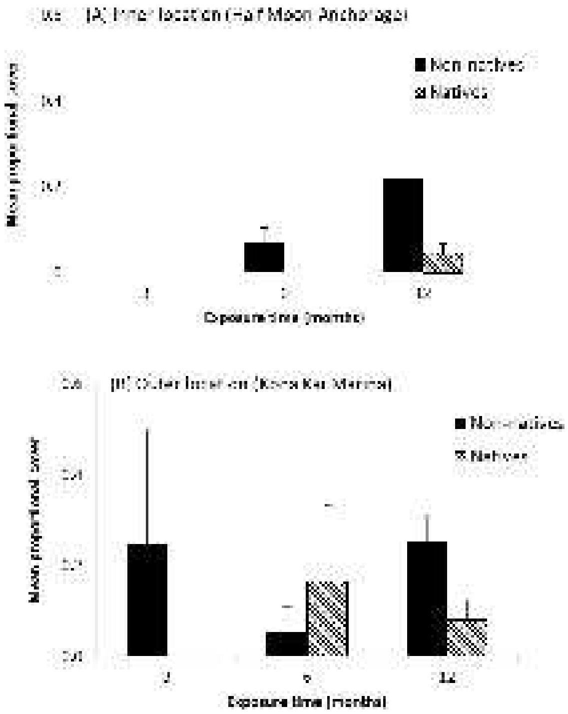

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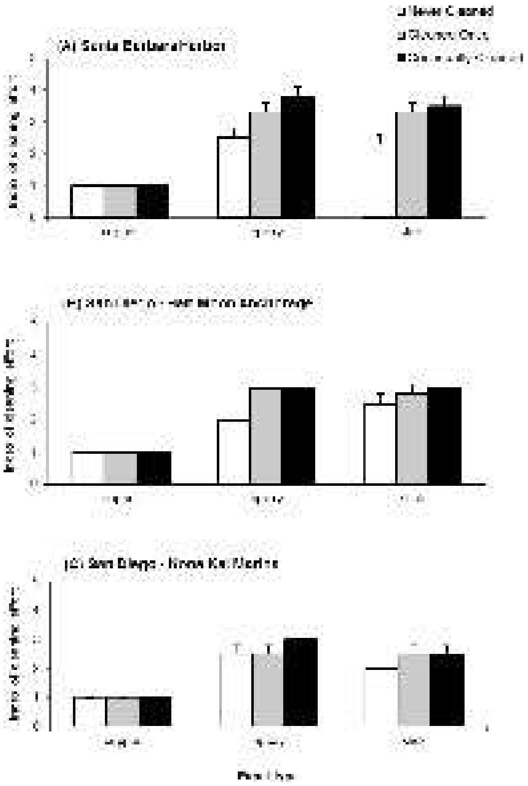

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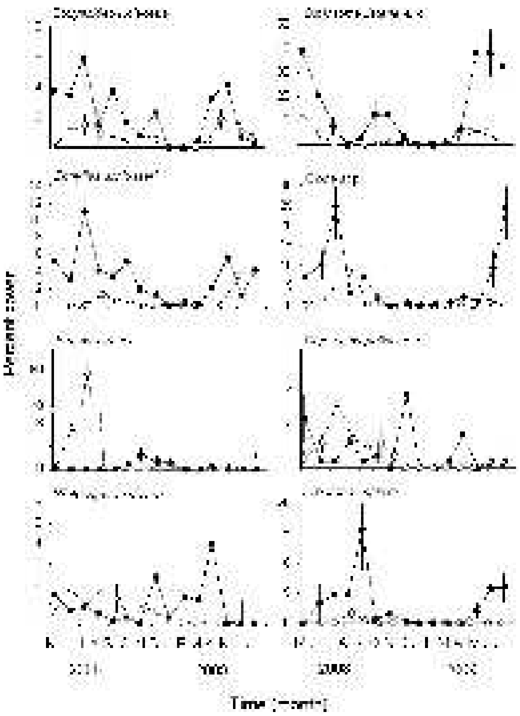

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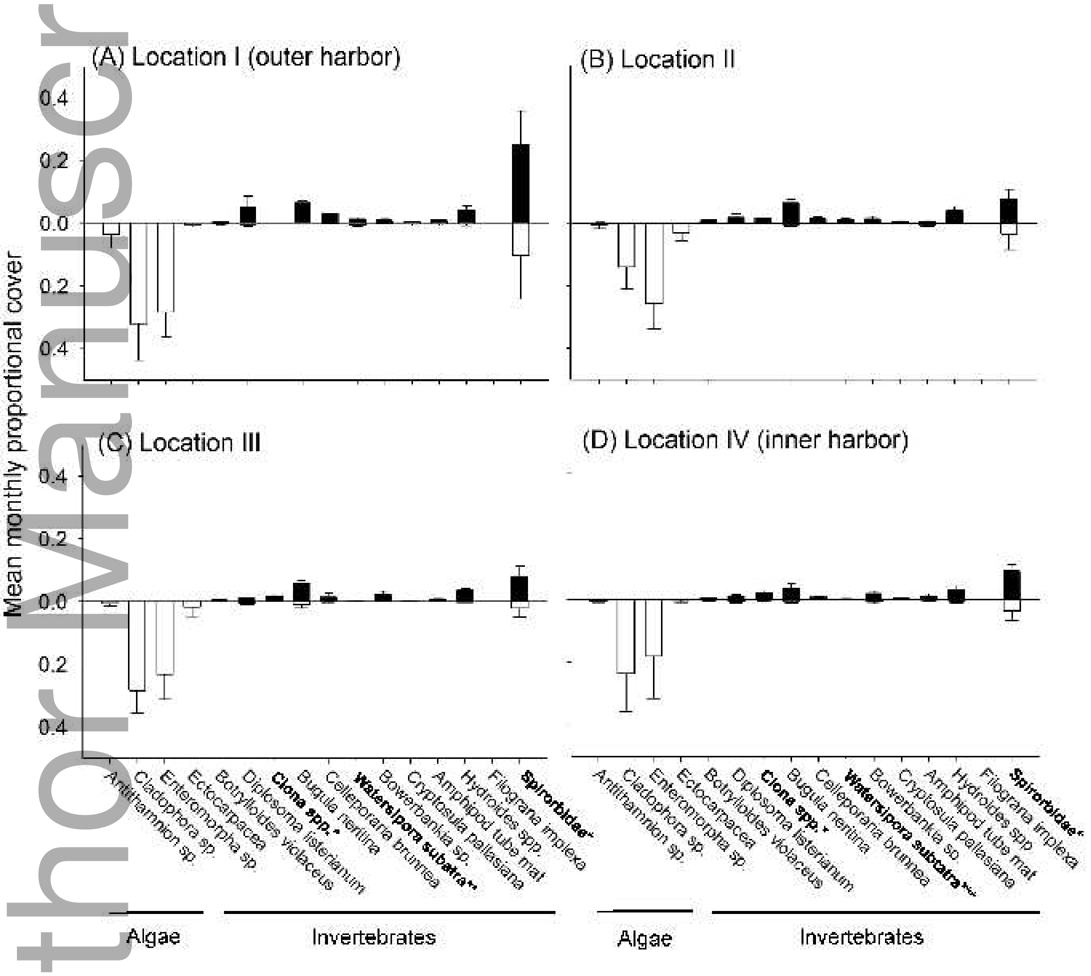

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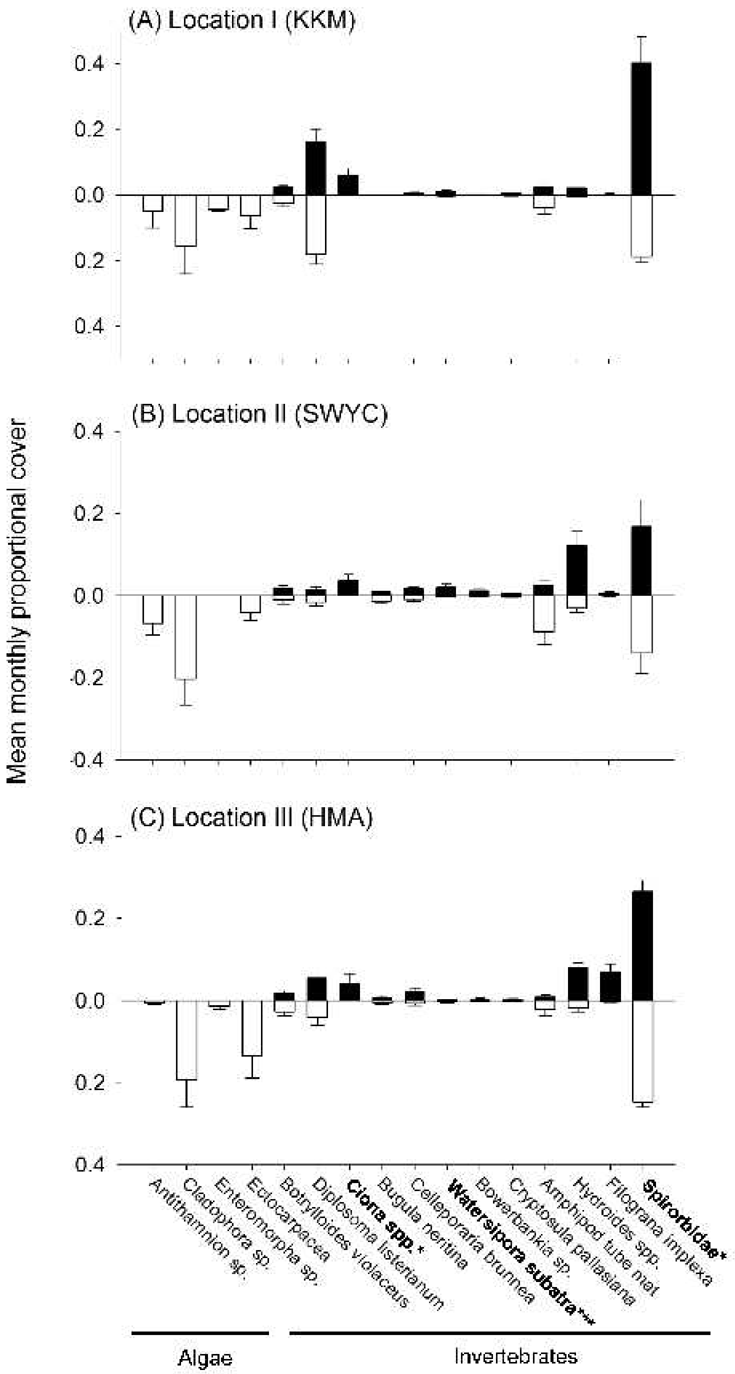

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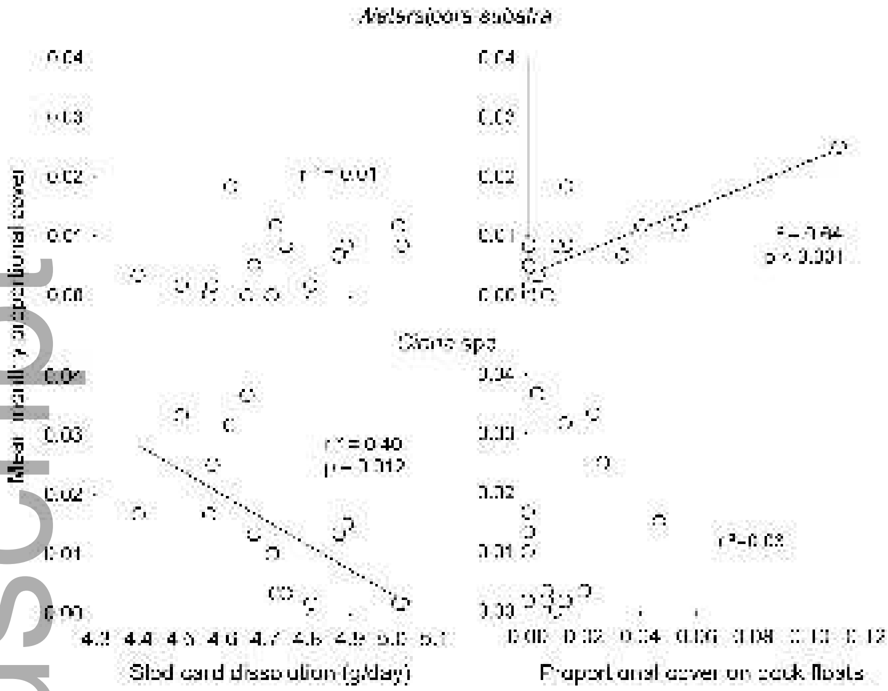

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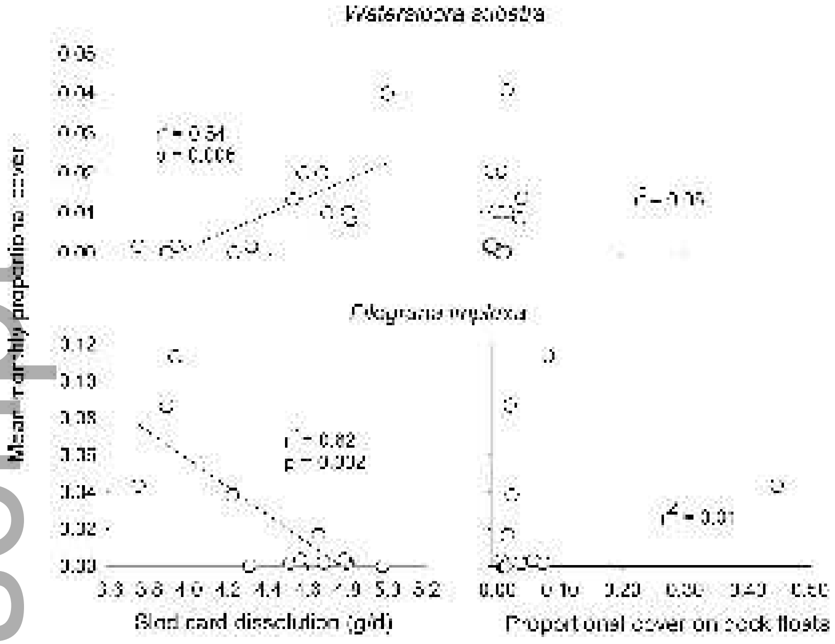

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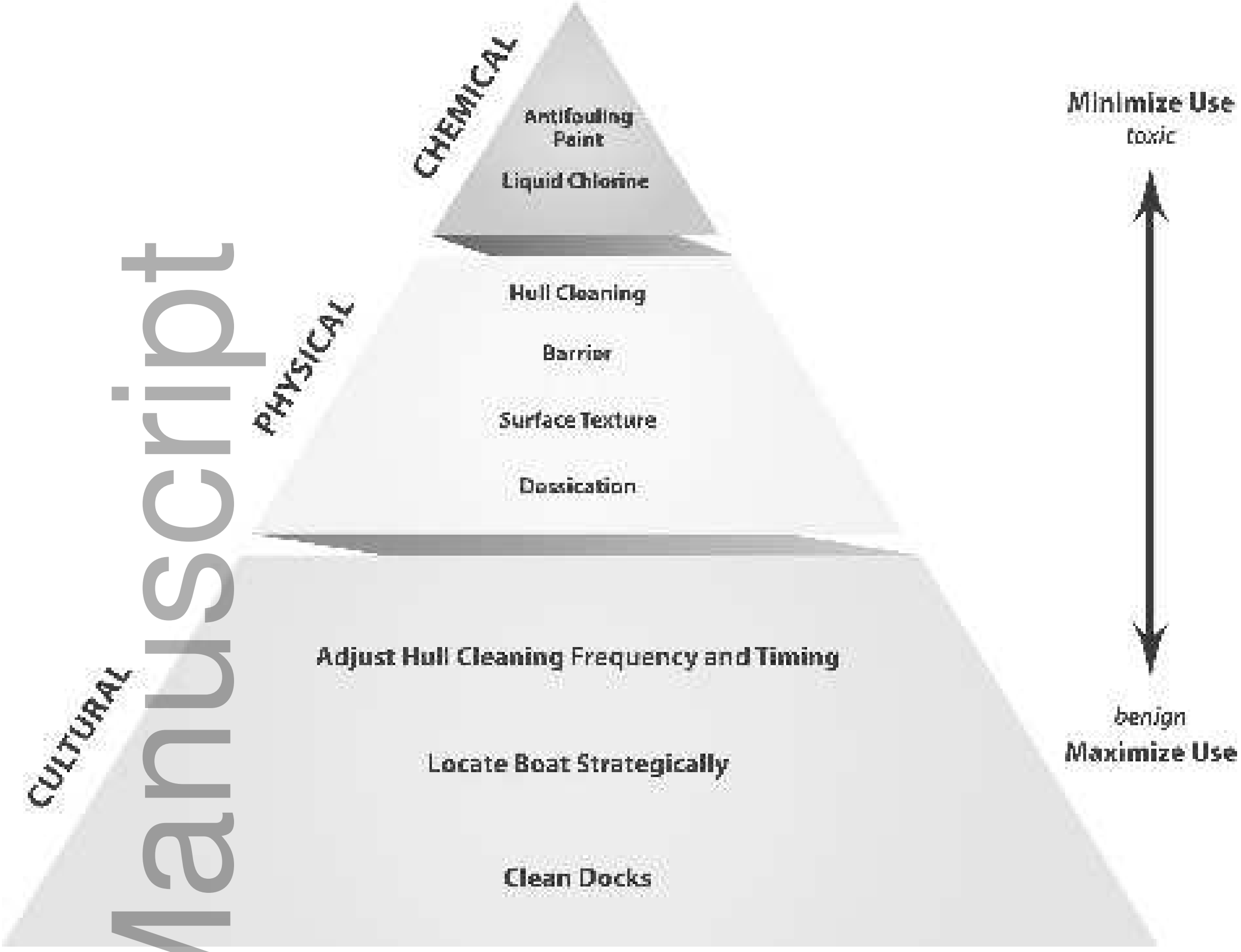

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