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Conceptual issues in designing a policy to phase out metal-based antifouling paints on recreational boats in San Diego Bay

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ABSTRACT

In marine areas throughout the world where recreational boats are densely located, concentrations of copper in the water are being found to be in excess of government standards, due to the hull coatings used on these boats. Copper-based hull coatings are intended to be antifouling in that they retard the growth of algae, barnacles and tubeworms; but alternatives exist that can eliminate the harm that copper contamination does to marine organisms. A variety of policy options are available to mandate or provide economic incentives to switch to these less harmful alternatives. This paper puts forth a conceptual framework for thinking about how to design and evaluate alternative policies to transition to nontoxic boat hulls, drawing from the authors' experience designing a policy for use in San Diego Bay. Many of the issues raised are broadly applicable to environmental problems where the solution involves a large-scale replacement of durable consumer goods.

1. Introduction

Toxic hull paints are used worldwide to control the growth of organisms such as algae and barnacles on boats. This growth, known as fouling, creates friction that can decrease a boat's speed, maneuverability, and fuel efficiency. To prevent these adverse effects of fouling, most bottom paints contain a copper biocide. Copper-based antifouling paints are designed to leach copper slowly into the water immediately surrounding a boat's hull. Copper is also released into the water when boat hulls are cleaned. Unfortunately, the copper is toxic not only to the potentially fouling organism but also to other organisms in the marine environment. This is particularly true when copper is present in high concentrations and there is growing concern that copper pollution poses a major threat to the marine environment. The problem is largely centered on major harbors where large numbers of recreational boats are densely located.

Regulatory agencies in California focusing on San Diego have determined that dissolved copper in some boat basins has reached levels that are toxic to some species and that antifouling paints on recreational boats are the primary source of this copper (California Regional Water Quality Control Board, San Diego Region, 2005; U.S. Environmental Protection Agency, 2002). As a result, these agencies are required to take regulatory action to reduce copper levels in San Diego by reducing the copper contamination coming from recreational boats. While the San Diego region is in the forefront of regulatory action, the California Regional Water Quality Control Board (CARWQCB) is also looking at copper pollution in Huntington Harbor and Newport Bay in Orange County, Marina Del Rey in Los Angeles County, and Santa Barbara.[1] This paper examines the policy options available to regulators from a conceptual standpoint.

Recreational boat owners have long coated the hulls of their boats with metal-based antifouling paints even though environmental problems associated with these paints have long been recognized. Indeed, the current generation of copper-based paints replaced the much more toxic tributyl tin-based paints, which were banned for use on most recreational boats by the U.S. Environmental Protection Agency in 1987. Now copper-based antifouling paints are facing regulation in the United States and a number of other countries. Sweden, the Netherlands, and Denmark have recently banned copper hull paints on recreational vessels in certain areas (Swedish Chemicals Inspectorate, 2006; Danish Environmental Protection Agency, Ministry of the

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[1] Copper contamination from boat hulls in the United States, is of course, not California-specific. Within the U.S., other areas of current concern to regulators include Chesapeake Bay, Maryland, Port Canaveral and Indian River Lagoon, Florida, and various harbors in the State of Washington. See Hall et al. (1988), Sheffield Engineering (1988), Trocine and Trefry (1993), and Stasch and Lynch (1999) for further discussion.

Environment, 2003; Netherlands Ministry of Housing, Spatial Planning, and the Environment, 2004; College Toelating Bestrijdingsmiddelen, 2004). Several European countries are now closely monitoring their levels of dissolved copper in boat basins, and antifouling paints applied in the United Kingdom, Sweden, the Netherlands, Belgium, Finland, and Austria must be registered under current pesticide laws (International Coatings Ltd., UK and International Paint Inc., 2004).

Regulatory agencies attempting to phase out toxic antifouling paints face a number of challenges, including the technological availability of nontoxic hull coatings, the cost to boat owners of converting to these alternatives, and the feasibility of implementing and enforcing a program to induce this conversion. This paper addresses these issues in the context of designing and evaluating policies to transition to nontoxic bottom coatings on recreational boats in San Diego Bay. We discuss policy objectives and evaluation criteria, and consider five primary policy options: an immediate "command-and-control" ban on copper; a command-and-control phase out in which copper paints are banned one marina at a time; two standard economic incentive policies, a tax on the use of copper and a marketable copper quota program; and a two-part regulatory phase out in which copper is immediately banned on new boats and prohibited on existing boats at a future date. A similar set of policy options is likely to be applicable in other situations where the government desires to phase out a component of a product that is deleterious from an environmental perspective in favor of one that is more benign.

We lay out the conceptual reasoning behind our favored policy for use in San Diego Bay – announcing copper paints will be banned in fifteen years, requiring all new boats to use nontoxic coatings, and educating boaters and boatyards as to the cost and properties of newly available nontoxic coatings. Such a policy is shown to be attractive along three main criteria that are important to policymakers; namely feasibility, minimizing costs incurred by boat owners, and minimizing the burden placed on other relevant parties such as boatyards, marinas, and regulatory agencies.

The reasoning behind our proposed approach is likely to hold in other pollution control contexts with similar properties, particularly when policymakers aim to induce large-scale replacement of polluting durable goods. For example, replacing diesel engines on city buses is analogous in many ways and similar approaches have shown to be effective in the U.S. and internationally.[2] Other programs, such as the removal of lead from gasoline and inducing adoption of low flush toilets also have similar properties, namely that a depreciating capital good or component must be replaced in order to achieve abatement objectives.

The paper is organized as follows. The next section provides background on the policy problem, focusing on regulation toward copper pollution in San Diego Bay. Section 3 discusses technologically viable alternatives to copper-based antifouling paints. Section 4 presents the primary conceptual issues a policymaker faces when designing a policy to induce boaters to switch to these alternatives, and lays out our policy's objectives and the criteria by which we evaluate alternate policy options. Section 5 discusses the four policy alternatives we consider and proposes recommendations for policy design stemming from our experience analyzing policy options for use in San Diego Bay. Section 6 concludes.

2. Regulatory background

Like many regulatory situations, ours begins with an environmental standard being violated and the need to find a way to meet the standard. Under the California Water Code, the California Regional Water Quality Control Board is responsible for protecting surface waters by regulating the discharge of pollutants into those waters, as required under the U.S. Clean Water Act (CWA). For any impaired water body, the CWA requires every state to establish Total Maximum Daily Load (TMDL) programs for specific pollutants to attain water quality objectives. The TMDL is intended to be set so that, once a pollutant's discharges have been reduced, water quality standards will be achieved.

Dissolved copper concentrations are elevated in many locations throughout San Diego Bay, especially in the southern reaches and enclosed yacht basins (Katz, 1988; VanderWeele, 1996; Valkirs et al., 1994). Numerous studies have indicated that these concentrations exceed the water quality criteria of 3.1 parts per billion (ppb) dissolved copper set as federal and state regulatory standards (U.S. Environmental Protection Agency, 2000). As early as 1980, dissolved copper concentrations in San Diego Bay were reported to be above 14 ppb, and the phytoplankton genera most sensitive to copper toxicity were found to be absent from the innermost waters of the Shelter Island Yacht Basin in northern San Diego Bay (Krett Lane, 1980). A study in the mid-1990s found dissolved copper concentrations of up to 12 ppb in the Shelter Island Yacht Basin (McPherson and Peters, 1995). A 1998 U.S. Navy study evaluating dissolved copper levels throughout the Bay found over half of the samples exceeded the water quality criteria of 3.1 ppb (Johnson et al., 1998).

Dissolved copper concentrations that exceed state and federal standards of 3.1 ppb are problematic to the marine environment at large because they affect various life stages of marine organisms including mussels, oysters, scallops, sea urchins and crustaceans.[3] When exposed to dissolved copper at concentrations from 3.0 to 10.0 ppb, these species showed reduced or abnormal embryo growth, development, spawning, and survival (Calabrese et al., 1984; Coglianese and Martin, 1981; Gould et al., 1988; Lee and Xu, 1984; Lussier et al., 1985; MacDonald et al., 1988; Martin et al., 1981; Stromgren and Nielsen, 1991).

According to studies conducted for CARWQCB's TMDL assessment, elevated levels of dissolved copper in San Diego Bay are due in large part to copper-based antifouling paints, particularly in areas where recreational boats are densely located. The largest of these areas is the Shelter Island Yacht Basin which holds over 2200 recreational boats and where 98% of the dissolved copper in this basin is thought to come from antifouling paints (CARWQCB, 2005).

The high concentrations of copper in these marinas stem from the technological nature of antifouling paints on boats that are kept there. Recreational boats typically spend most of their time at slips, where the antifouling paints continuously emit copper that accumulates in marinas with poor water circulation. This type of copper loading is referred to as "passive leaching". The contribution of passive leaching to the copper pollution problem in San Diego Bay has been estimated to range from 56% to 95% of copper loading (PRC Environmental Management, Inc., 1997; Schiff et al., 2003). The other major source of copper release is underwater hull cleaning, as scrubbing copper-containing paints release dissolved copper into

[2] A program was implemented in Delhi, India, where authorities mandated higher emission standards for new public buses, taxis and auto-rickshaws, and existing buses were required to convert to compressed natural gas or another clean fuel before 2004. Similar programs have been implemented in a number of U.S. cities including Atlanta, Los Angeles, and Sacramento.

[3] Phytoplankton and zooplankton, including bivalve larvae, are the organisms thought to be most sensitive to copper toxicity. See the California Regional Water Quality Control Board's (2005) Total Maximum Daily Load for Dissolved Copper in the Shelter Island Yacht Basin for further discussion.

the surrounding water.[4] Switching to nontoxic hull coatings would reduce copper loading from both passive leaching and underwater hull cleaning.

3. Nontoxic hull coatings: availability and properties

Interest in the copper pollution issue has surfaced due in part to the possibility of increased regulation to reduce copper levels, and the number of technological solutions has increased in recent years. Nontoxic hull coatings are currently available, but they are new to the market and most consumers generally know little about them (Carson et al., 2002).[5] However, the threat of future regulation and the possibility of developing a niche market for environmentally sensitive boaters have led most major marine paint companies to begin developing biocide-free paints (Kettlewell, 2000).

Understanding certain technological features of antifouling strategies is necessary for policymakers to understand costs of transitioning to nontoxic hull coatings. First, nontoxic coatings do not prevent organisms from attaching to boats' hulls, so they must be cleaned more often than traditional copper-based paints. An offsetting advantage is that the most common nontoxic hull coatings are more durable and last longer than copper-based paints, as the effectiveness of copper-based paints depends on cuprous oxide which leaches out of the paint over time. Costs of purchasing nontoxic coatings, preparing the hull, and applying the coating are presently higher than for copper-based paint, but this may change as more paint companies develop and market nontoxic coatings and as boatyards learn appropriate application procedures and cleaning protocols.

Currently available nontoxic hull coatings may be silicone-based, epoxy-based, water-based, or polymer-based. Epoxy coatings tend to be highly durable and require frequent cleaning[6]; in contrast, most San Diego area boat owners reapply copper-based coatings every two to three years. Silicone hull coatings also last longer than copper-based and are occasionally used on racing boats as they can provide a small increase in speed. The slippery nature of silicone coatings allows for fouling growth to be wiped off easily, and hull cleaners recommend especially frequent cleaning since later stages of fouling growth can penetrate the silicone and become more firmly established on the hull. Due to the slippery nature of silicone, boats with these coatings can require special handling during repairs at boatyards. Silicone-based paints are also somewhat less resistant to damage than epoxy-based paints; for the most part, however, the properties of these two types of paints are fairly similar.

Table 1 summarizes these general properties of alternate hull coatings. One major problem facing regulatory agencies making decisions involving transitioning to a new, less-polluting technology is that there will be substantial uncertainty concerning the properties of that technology. Much of the available information will come from its manufacturers, who have only modest real world experience with the new technology. They also have an incentive to over-emphasize its desirable properties and under-emphasize its disadvantages. Installers of the new technology will have even less real world experience with it and, because they will have to depreciate the value of their capital investments (including human capital) in installing the old technology, they also will have an incentive to over-estimate the cost and problems involved with switching to the new technology. Thus it is important to recognize that there may be substantial gains from having the government or universities provide independent information concerning the properties of the new technology.[7]

Independent sources of information can also help the regulatory process from being derailed by claims that there is too much uncertainty, while allowing regulators to recognize situations where an expensive switch in technology has a high chance of not working. Over the longer run, installation of the new technology in a number of "test" locations is itself likely to foster further research and development by manufacturers. One of the most interesting questions with regard to nontoxic paints is whether their cost will fall substantially as production is ramped up and application experience is gained.

4. Transitioning to nontoxic paints: policy objectives and evaluation criteria

To develop a policy toward copper-based hull paints in San Diego Bay, it first is necessary to specify the policy's objectives and the criteria for evaluating the merits of a specific policy. Following the language of California Senate Bill 315, we considered two complementary policy objectives:

1) Development of a plan that meets the California Regional Water Quality Control Board: San Diego Region's proposed (April 23, 2001) Total Daily Maximum Load (TDML) requirement of a 66% reduction in dissolved copper coming from recreational boats in Shelter Island Yacht Basin.[8]
2) Development of a plan that results in the eventual phase out of copper-based hull paints on recreational boats in San Diego Bay.

Any phase out of the use of copper-based hull paints will require that the 66% reduction required by the Regional Board's TDML be met first. The Regional Board's objective of a 66% reduction can therefore be seen either as an intermediate step toward a final phase out or as a final policy end point. The conceptual issues pertinent to the consideration of these two objectives will be equivalent, so for simplicity we considered policies to induce a complete phase out of copper.[9]

[4] The total amount of copper released during cleaning depends on a range of factors, including how frequently the hull is cleaned, the method of cleaning, the type and thickness of paint, and the frequency of painting. Ideally, cleaning is performed regularly so organisms do not have a chance to become firmly attached, but when hulls need to be scrubbed hard to remove fouling, the copper release problem can be greatly exacerbated. Professional underwater hull cleaners in San Diego are highly sensitive to San Diego Bay's copper pollution problem and employ Best Management Practices to minimize copper emissions.

[5] In general, current strategies combine a nontoxic hull coating and a "companion strategy" such as increasing the frequency of hull cleanings, storing the boat out of water, or surrounding it with a slip liner.

[6] Manufacturers of two nontoxic epoxy-based coatings report that their coatings have lasted from 6 to 12 years on test boats. Though independent testing is still scarce, initial anecdotal evidence supports this claim. For example an epoxy coating on a San Diego area sailboat that participated in the authors' field demonstration lasted eight years and was reported to have been in good condition when replaced with a newer product.

[7] In the particular case we examine, the University of California's Sea Grant Extension Program in San Diego County conducted a demonstration to provide preliminary information on nontoxic antifouling strategies. The project tracked the performance of one silicone-based and two epoxy-based coatings on six vessels in San Diego Bay for several years. From our perspective, the most notable result is that the epoxy coatings withstood intensive cleaning and showed promise of extended service life well in excess of the estimate used in our analysis.

[8] Since this analysis was completed, the regulatory agency has settled on a 76% reduction. The regulatory agency had considerable latitude with respect to the timeframe for meeting the standard as long as reasonable reductions are being made. On the basis of our analysis, San Diego authorities have since adopted a 15-year time horizon.

[9] It is beyond the scope of this study to consider the relative desirability of these two objectives.

Table 1
General properties of alternate antifouling strategies.

	Copper-based antifouling paint	Epoxy-based hull coating	Silicone-based hull coating
General description	Leaches cuprous oxide to act as preventative biocide	Hard, durable coating; does not contain a biocide	Smooth, slick surface; does not contain a biocide
Durability	Reapplied frequently to replace copper content	Lasts longer than copper-based paint	Lasts longer than copper-based paints
Maintenance properties	Hull should be periodically stripped of old paint accumulation	Hull should be cleaned frequently to scrub off attached organisms	Hull should be cleaned frequently to prevent growth from penetrating
Other properties		More resistant to damage than other coatings	Can increase boat speed Less resistant to damage than other coatings Slippery and sometimes difficult/dangerous for boatyards to handle

Policies can be evaluated along a variety of criteria ranging from cost minimization, effectiveness, impacts on various affected parties, perceived fairness, and feasibility, and policymakers often select policies based on satisfying some combination of these objectives. The relevance and weight of particular evaluation criteria generally depends on a policy's context and on objectives or expectations of relevant parties. For a thorough discussion of evaluation criteria in various contexts, see Bohm and Russell (1985), Hahn (1986), Sterner (2003), and Tietenberg (2006).

We considered the design of a copper control policy with respect to three main criteria that were deemed relevant to San Diego regulatory authorities[10]:

1) Feasibility,
2) Cost to recreational boat owners, and
3) The burden placed on other relevant parties (*i.e.*, boatyards, hull cleaners, marinas, the Port District and the State of California).

We first narrow our analysis to policies that can feasibly be implemented; then, policies that have lower costs and place lower burdens on other relevant parties are assumed preferred. We consider a policy strictly better than another if it is superior on all three of these dimensions. Since various stakeholders may place different weights on these criteria and thus judge different policies preferable, our approach remains agnostic as to tradeoffs between the different objectives, and only considers a policy to be strictly better than another if it is better along all three criteria.

Once a policy's objectives and evaluation criteria are established, policymakers can choose among a menu of policy instruments which can be customized and/or combined to meet the desired objectives. The remainder of this section lays out each of our three evaluation criteria, and the following section discusses the policy options we considered for phasing out copper in San Diego Bay, according to these criteria.

4.1. *Feasibility and the constraint of boatyard capacity*

Before evaluating options according to cost and other burdens imposed, we eliminate policy options that are infeasible. The limited capacity of boatyards serving San Diego Bay creates a practical constraint that essentially rules out an immediate ban on copper, or any other policy that aims to achieve a 100% phase out in less than seven years, with the following reasoning.

Because the toxic element constantly leaches out of copper-based paints, boaters with copper hulls need to reapply the paint approximately every 2–3 years at San Diego Bay.[11] Each repainting requires a boat to be hauled out of the water and is usually performed at a local boatyard. Because new coats of paint generally are applied directly on top of old coats, old paint accumulates and new coats become increasingly difficult to apply. After being repainted about six times, a boat's hull usually needs to be stripped entirely clean of the old paint to again be able to apply new coats. Essentially, a clean hull is a capital asset that depreciates over time until it needs to be replaced (*i.e.* stripped) on average every 15 years. Stripping is an expensive component of a boat's maintenance schedule, generally costing $150 per foot of a boat's length.

Nontoxic coatings cannot be applied directly on top of copper-based paints; a hull with any amount of copper paint accumulation needs to be stripped to be converted to a nontoxic coating. In addition to the considerable cost of application, this feature of nontoxic coatings makes a very quick paint conversion of an entire population of boats infeasible due to limited boatyard capacity. Boatyards routinely perform paint jobs and stripping jobs, and in San Diego Bay, boatyards serve a stable population of boats and operate at close to full capacity. Stripping and repainting a boat take more time than simply repainting it, so immediate conversion would in general create a demand that boatyards currently could not meet.

The ability to increase capacity by increasing labor and capital equipment is standard in many industries, but substantial increases in boatyard capacity are unlikely in this case. The fact that boats need to be stored on location, where space is limited, and the need for paints to dry, create physical constraints that make large capacity increases more difficult than is often the case. Moreover, while a policy requiring conversion to nontoxic coatings will create more maintenance work for boatyards in the short term, the use of nontoxic hull coatings implies less maintenance work in the long run since nontoxic coatings generally do not need to be reapplied as often as copper-based paints. Boatyards have a strong incentive against making the large capital expenditures that would be needed to substantially increase current maintenance capacity.

The minimum time horizon for any policy to phase out copper is determined by boatyard capacity, and this capacity constraint prevents immediate conversion of the current fleet of recreational boats; however, since nontoxic epoxy hull coatings need to be reapplied less often than copper-based paints, boatyard capacity is freed over time as boats in the population convert to nontoxic coatings. This additional capacity can be used for conversions over time. From interviewing boatyard operators and deriving a simple

[10] There are of course other criteria that regulators may deem relevant and important. Other commonly considered criteria include the perceived fairness of the policy's outcome, flexibility in the face of changing information, and relative ease of monitoring and enforcement. Bohm and Russell (1985), Hahn (1986), and Sterner (2003) lay out and discuss common evaluation criteria for environmental policies.

[11] Figures pertinent to maintenance requirements and their costs were obtained by surveying boatyards and boat owners. See Carson et al. (2002).

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dynamic model of conversion capacity, the quickest possible time horizon in which the objective of a 66% reduction in copper discharge could be achieved in San Diego Bay (after large-scale commercial application is viable) is estimated to be five years. The minimum time horizon necessary to achieve a complete phase out in San Diego Bay is seven years (Damon, 2007).

4.2. Costs to recreational boat owners

Once the set of practically feasible policies is determined (*i.e.*, policies that allow at least seven years for a phase out), we can consider ways to design a policy with the other policy objectives in mind. One of the most important criteria is the cost that recreational boat owners will bear under the new regulation. Any change in the overall cost of maintaining a boat will generally be borne by the boat owner, and the true economic cost of any policy can be thought of as the total change in hull maintenance costs.

When making hull paint decisions, an economically rational boat owner should consider the present discounted value of hull maintenance over a boat's remaining lifetime. Even if the current owner plans to sell the boat before it is permanently retired, its resale value in an efficient market will depend on features of the boat such as its current paint type and the ensuing maintenance costs. Evidence from surveys of boat owners in San Diego empirically demonstrates that this is indeed true for this population of boaters.[12]

To formally model the boat owner's cost minimization problem, we let $C(t;l,c_f,c_c)$ represent the stream, starting at time t, of an individual boat owner's cleaning costs, where c_c is the cost per foot of cleaning a hull each time it must be cleaned, c_f is the frequency with which it must be cleaned, and l is the length in feet of the individual boat. We similarly define $P(t;l,p_f,p_c)$ as the recurring cost of painting the boat and $S(t;l,s_f,s_c)$ as the cost of stripping its hull. An individual cost-minimizing boat owner therefore chooses T, the time to switch from a copper-based paint to a nontoxic hull coating (denoted with superscripts 0 and 1, respectively), to solve:

$$\min_T \int_a^T \left(C\left(t;l,c_f^0,c_c^0\right)+P\left(t;l,p_f^0,p_c^0\right)+S\left(t;l,s_f^0,s_c^0\right)\right)\mathrm{e}^{-r(t-a)}\,\mathrm{d}t + \int_T^E \left(C\left(t;l,c_f^1,c_c^1\right)+P\left(t;l,p_f^1,p_c^1\right)+S\left(t;l,s_f^1,s_c^1\right)\right)\mathrm{e}^{-r(t-a)}\,\mathrm{d}t \quad (1)$$

where a represents the age, in years, of the boat today, and E represents the age at which the boat will be retired.

Comparing a traditional copper-based paint and a nontoxic alternative such as epoxy will almost always show that the copper-based paint has lower initial costs. The cost advantage becomes even larger if one considers costs over the first couple of years since a copper hull needs to be cleaned less often. However, taking a longer-term perspective can reverse this conclusion, primarily because nontoxic coatings tend to last considerably longer than copper-based paints. When making rational cost calculations, this lower frequency of incurring repainting costs should be balanced against the higher initial painting cost and higher hull cleaning costs over the lifespan of the nontoxic hull coating.

As noted earlier, there is an additional cost that is highly significant when drawing these cost comparisons: the cost of stripping old accumulated paint. A hull that is always repainted with copper hull paint must be stripped periodically, and the owner of a copper hull who wishes to switch to a nontoxic coating also must strip the old copper paint from the hull. Stripping costs tend to be much larger than the painting costs (see Table 2), so a comparison of total lifetime costs between copper and nontoxic paints depends critically on whether the boat has to incur an additional stripping cost in order to apply a nontoxic hull coating.

Table 2
Standard maintenance cost properties: copper-based versus epoxy coatings.

Property	Copper-based paints	Epoxy hull coatings
Application frequency	Every 2–3 years	Every 7–8 years
Application cost (per application)	\$30/ft	\$40/ft
Cleaning frequency	14 times per year	22 times per year
Cleaning cost (per application)	\$1/ft	\$1/ft
Stripping frequency	Every 6th repainting	Every 6th repainting
Stripping cost	\$120/ft	\$120/ft

There are two situations in which an additional stripping is not required in order to apply a nontoxic coating. The first is when painting the hull of a new boat, since there is no accumulated paint to remove. New boats come with "gel coats" that usually are then coated with a traditional copper-based paint; alternatively, a nontoxic coating can be applied directly to the gel coat without additional preparation. The other situation in which copper paints and nontoxic coatings face identical stripping costs is when an older boat has an accumulation of old copper paint that must be stripped before new copper paint *or* a nontoxic coating will correctly adhere. More generally, the closer an existing boat with copper paint is to needing to be stripped, the more favorable the lifetime cost comparison between the copper paint and the nontoxic coating will be. In this sense, a new or newly stripped hull can be seen as an asset that depreciates over time, and a hull that needs stripping can be thought of as a fully depreciated hull. A policymaker's understanding of this intuition is crucial to identifying the lowest-cost way to design a policy, and we return to this point when discussing policy options in Section 5.

Lastly, when thinking about the nature of a boat owner's costs, it is important to balance the costs occurring in different time periods with an appropriate discount rate. Survey evidence found that boat owners in San Diego Bay tradeoff hull maintenance costs over time at a 5% discount rate, on average (Damon, 2007).

Total maintenance costs for a new 40-foot boat in San Diego Bay as a function of time horizon, are shown in Fig. 1.[13] This figure shows that using copper-based paint is less expensive in initial years but this cost advantage falls when considering total lifetime cost over longer time horizons. The nontoxic coating becomes the less expensive alternative at a time horizon of 18 years or longer and, for time horizons of 5 years or greater, the difference in the total lifetime cost profiles is fairly small. It should also be noted that the cost of nontoxic paints is likely to fall as their scale of production increases, and equipment and labor costs of application are likely fall with increased experience applying these paints.

4.3. Burden on other parties

In addition to economic costs imposed on boat owners, policy options will vary according to their impacts on boatyards, marinas, and regulatory agencies. The primary burdens that are likely to be imposed are monitoring, enforcement, training, and other financial costs that may not accrue to individual boat owners.

[12] A survey of San Diego boaters was conducted by the authors to understand how boat owners choose between different hull paint options. The methodology and results of this survey are discussed in Damon (2007).

[13] Baseline cost assumptions are summarized in Table 2; additionally, boats are assumed to be retired at age 30. All assumptions come from conversations with San Diego boatyards, marinas, and recreational boaters.

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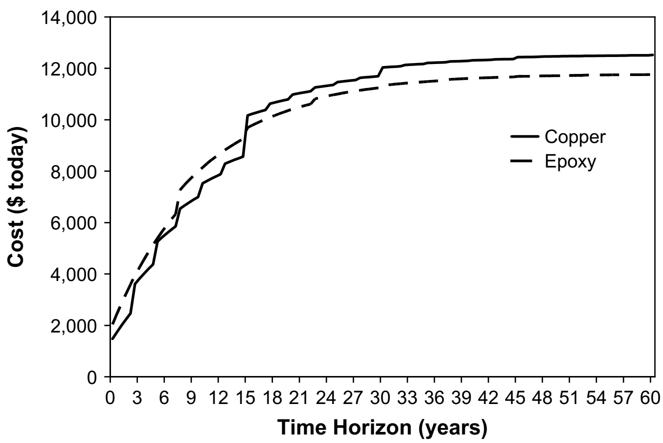

Fig. 1. The total lifetime cost of maintenance for a new boat.

The policies we considered generally require monitoring and enforcement actions with respect to one or more of the following:

(a) ensuring that only nontoxic hull coatings are applied to new boats,
(b) ensuring that only nontoxic hull coatings are on boats in San Diego Bay after a particular date,
(c) ensuring that only a specific total amount of copper is applied to recreational boats over some time period, and
(d) ensuring that a tax is collected on copper hull coatings when applied.

These issues will be addressed in our discussion of specific policy options in the following section.

Additionally, under any policy achieving a 100% reduction in copper use, boatyards are likely to face issues related to ramping up for large-scale application of nontoxic hull paints. For hull cleaners, special training and some special equipment will be needed to clean nontoxic hulls. Because the training and equipment are likely to make hull cleaners more efficient, particularly coupled with the need for more frequent hull cleaning, the long-run financial implications of this training and equipment are likely to be neutral if not advantageous. However, training and equipment requirements are likely to impose substantial "upfront" expenditures on hull cleaners. In contrast, boatyards eventually lose from any policy because of less frequently repainting of boats, although some of this cost is offset by more expensive maintenance when performed. We do not rigorously assess these two impacts further in our analysis because the impacts do not vary substantially across policy options, as the main difference is which boats are affected, not the number of boats.

5. Design of a policy for use in San Diego Bay

In general, policies fall into three broad categories: (1) educational efforts concerning the properties (*e.g.*, costs, environmental impacts, and performance) of relevant options available to individuals and industries, (2) command-and-control instruments which mandate standards and/or regulatory requirements to achieve objectives, and (3) market-based instruments which achieve the policy's objectives by affecting relative prices and altering economic incentives. Table 3 presents common pollution control instruments in each of these categories and examples of each. We also consider a new type of policy we call a 2-part ban which is discussed in detail later in this section.

As nontoxic hull coatings are a fairly new product without widespread commercial availability, educational efforts will be a key component of any long-term effort to phase out copper paints. Boatyards face uncertainty with respect to the application of nontoxic alternatives, and demonstration projects can exhibit the feasibility of undertaking particular actions or using particular technologies in order to achieve an efficient, large-scale commercial application of the new technology.[14] Boater education projects are also necessary, primarily to inform boaters that the copper hull paints they use cause pollution problems and to inform them of the long-term cost implications of copper versus nontoxic hull paint options. These educational efforts can be coupled with any policy instrument used to phase out copper. The remainder of this section is focused on the relative merits of alternate command-and-control and market-based policy instruments to achieve this objective.

In the previous section we determined that no policy can feasibly impose immediate conversion over the population of boats. The first policy option we consider, a command-and-control-style immediate ban on copper, thus does not meet our first criteria of feasibility and we do not consider it further in our analysis. Realizing that a 100% copper phase out will need a minimum of seven years, we next consider issues surrounding how our set of feasible policies – a marina-by-marina phase out, a copper tax, a tradable copper permit program, and a two-part regulatory phase out – could be used to meet the policy's objectives. An overview of this section's results is presented in Table 4.

5.1. Market-based measures

5.1.1. User fee on copper

The price of copper hull paints can be directly increased by imposing a user fee. As the price of applying copper would increase relative to nontoxic alternatives, boaters would have an incentive either to switch to a nontoxic alternative or to reduce the amount of copper that leaches off the hull over time. The latter can be accomplished by applying less copper initially to the boat's hull, given the same duration between repaintings, or by increasing the duration between repaintings. A successful user fee should be based directly on the cuprous oxide content of the paint to ensure that this incentive is provided and, for a 100% phase out of copper, should be set high enough that boaters will choose a nontoxic alternative.

An advantage of this approach is that, at each point in time, it "selects" as volunteers the boat owners that are closest to having their hulls stripped, which substantially lowers the overall cost of the policy when compared to a policy that induces a switch in a more random order from a cost perspective (*e.g.*, phasing out copper marina-by-marina, as discussed below). The cost comparisons in Section 4 highlight the fact that there are two types of boats for which an additional costly stripping need not be incurred to convert to a nontoxic coating: new boats and boats that need to be stripped before any other paint can be applied. Any least-cost policy should begin by targeting these boats. Given that a policy cannot feasibly impose immediate conversion, so some "ordering" of conversions must take place, a policymaker can substantially lower the cost of the policy by targeting the lowest-cost converters at each point in time. An appropriately set user fee on copper can accomplish this by reversing the cost differential between copper-based and nontoxic paints just enough such that the appropriate number of the lowest-cost converters will be induced to select nontoxic paints the next time their hulls are stripped.

[14] Such a demonstration project was undertaken in conjunction with our project in San Diego Bay. See Johnson and Gonzalez (2004) for further discussion.

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Table 3
Alternate policy instruments for pollution control.

Category	Possible instruments	Examples
Command-and-control	Immediate restriction	Ordering a coal-fired plant to shut down; banning the manufacture of polychlorinated biphenyls (PCBs)
	Phased-in restriction	Requiring all new city buses to run on a clean fuel and requiring existing buses to meet the standard by a future date
	Technology mandate	Ordering a coal-fired plant to install a scrubber; requiring cars to have catalytic converters
	Performance-based standard	Requiring a manufacturer's fleet of passenger cars to have an average fuel economy of 27.5 miles per gallon or better
Market-based	Taxes	Imposing a fee for every ton of carbon a company releases; charging for the use of plastic bags at grocery stores
	Tradable quotas	Allocating allowances for companies to emit specified quantities of SO_2 and letting these allowances be bought and sold
	Environmentally-motivated subsidies	Tax credits for wind and solar energy generation; direct payments for biodiversity conservation
Information disclosure	Education Campaigns	Raising a community's level of awareness with respect to the best environmental practices for stormwater management
	Eco-labeling	Requiring appliances to carry labels with energy efficiency information; certifying timber products that come from forestry operations that meet specified environmental standards
	Reporting	Requiring a manufacturing facility to report annually on its release of toxic chemicals

Table 4
Comparisons across policy options for phasing out copper-based antifouling paints.

Evaluation criteria	Immediate ban	Marina-by-marina ban	Market-based approaches (*e.g.* tax, tradable permits)	Two-part ban (new boats immediately; existing boats at future date)
Feasible	No	Yes	Yes	Yes
Minimizes costs to boat owners at the time they convert	n/a	No	Yes	Yes
Minimizes costs to boat owners at times they do not convert	n/a	Yes	No	Yes

The cost of a policy that directly increases the price of copper hull repainting would be borne by boaters. One potential drawback is that the price of copper would increase for *all* boat owners who are reapplying copper-based paints, as opposed to *only* affecting those for whom a small change in prices would induce a switch to nontoxics (*i.e.*, those who are close to needing their hull stripped). Additionally, an administrative burden will be placed on the government agency collecting the tax, but the additional revenue generated by this policy will go directly to this government.[15]

5.1.2. Tradable copper permits

An alternative to a user fee on copper is a system of tradable copper quotas that limit copper use during specified time periods. If the total copper quota is set below the level that would otherwise be demanded, boatyards will raise the price of applying copper until demand for copper-based hull coatings again equals supply. A binding copper quota therefore works in the same way as a user fee on copper and the overall cost would, again, be borne by boat owners.

Allowing boatyards to trade initial copper quotas among themselves allows for adjustment to individual supply and demand shocks. This increase in market efficiency generally benefits both firms and consumers. It is also possible to vary copper quotas over time to phase out copper use on a smooth schedule, even in the presence of price or demand uncertainty.[16]

The effects of a tradable permit program on parties other than boat owners will depend upon the initial allocation mechanism. Common ways to allocate quotas include auctioning them off to firms and distributing the quotas to firms free of charge in proportion to their current copper usage. If auctioned off, the revenue generated by the program goes to the government whereas a free distribution system, or "grandfathered" quota scheme, essentially would result in a transfer of revenue from taxpayers to the boatyards.

5.2. Command-and-control measures

5.2.1. Marina-by-marina ban

Once the boatyard capacity constraint is recognized and an immediate copper ban is understood to be infeasible, an obvious approach is to consider a sequential marina-by-marina ban that allows enough time for the phase out. Under this policy, the ordering with which boats are converted from copper to noxtoxic paint is essentially arbitrary from a cost perspective.[17] Rather than selecting boaters with the lowest conversion costs at each point in time, as would a market-based measure, this policy has the usual failing of a command-and-control approach, namely that the policy's inherent inflexibility would result in a higher cost of pollution abatement. Essentially, each boater would be selected to switch to a nontoxic paint at a random point in his or her hull maintenance schedule, resulting in an increase in lifetime hull maintenance costs that could range from being quite low, if the required conversion happens to coincide with a hull stripping that was already needed (or soon-to-be needed), to being quite high, if the hull was recently stripped and/or has a fresh coat of copper-based paint. A clear disadvantage of this approach is that it would result in higher overall costs to boat owners.

This cost disadvantage is likely to be exacerbated by economic incentives for boaters to relocate. The first marina to be regulated would be at a competitive disadvantage and boaters not wishing to

15 We do not consider issues related to how this revenue might be spent but the usual assumptions in the pollution control literature is that it would be spent in such away as to maximum the aggregate utility of the relevant population.

16 A successful example of this tool was the use of marketable permits for lead in gasoline that declined in quantity over time to zero.

17 This of course assumes that boats are not sorted into marinas by age in any significant way. This assumption is supported both intuitively and empirically with our observations in San Diego Bay.

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convert early may seek to leave for marinas not yet subject to the ban. This process would continue until all marinas in a basin were subject to the ban. A marina-by-marina phase out therefore would create economic costs for the first marinas to be regulated; it would also put considerable pressure on marinas to take at least a partial role in monitoring copper use, which is not in their self interest.

One advantage of this command-and-control approach over the market-based measures is that boaters who are not in regulated marinas at any given time are unaffected, since the price of copper would not be directly affected. The administrative burden, however, can be expected to be more severe to the regulatory agency (or marina) enforcing the program, since any mandated ban is likely to be effective only with strict monitoring and enforcement. Unlike with a copper user fee or auctioned copper permits, no revenue would be raised that could help offset these administrative costs.

5.2.2. A Two-part copper ban

Another regulatory option is to require all brand new boats to be painted with a nontoxic hull coating and to set a prohibition of copper (again, either on its application or on its presence on a boat's hull) far enough out in the future such that boatyard conversion capacity is not an issue. Any policy that sets a future date at which a ban will be enforced would work by essentially increasing the value of boats already converted to nontoxic hulls; since the cost of converting a hull to a nontoxic coating will need to be incurred by all boaters before the phase out deadline, the boats that have already been converted would be worth more on the resale market.

To minimize costs to boat owners, we've seen that the first boats induced to convert should be new boats and boats in need of a stripping. Coupled with the fact that a lifetime cost comparison of new hulls favors nontoxic paints, a least-cost policy should require that all new boats be painted with nontoxic coatings. Announcing a future date by which copper will be prohibited can then allow enough time for feasible implementation of the phase out and, moreover, would induce the least-cost boat owners to switch at each point in time, as each boater chooses his or her own optimal time to convert before the ban is imposed. This policy essentially mimics market-based policies by allowing for the flexibility of achieving the least-cost abatement schedule in terms of which boaters convert at which times. By allowing each boater to choose his or her own optimal time to convert before the ban is enforced, the least-cost group of boaters is induced to convert at every point time.

If the policy were allowed a long enough time horizon, these two groups of boats (new boats and boats in need of being stripped) could be the only groups of boats the policy would ever need to target, and 100% abatement could be achieved once every boat with a copper-painted hull in the population either needed to be stripped or was permanently retired. To phase out copper in a shorter time horizon, a cost-minimizing policy should target boats that will need to be stripped soon as the next group of boaters to convert, and so on until enough boats are targeted in each period to achieve 100% abatement in the desired amount of time. To choose the appropriate timeframe in which to achieve 100% conversion, the policymaker needs to weigh the costs and benefits of allowing a longer time horizon for the phase out against the benefits of achieving abatement sooner, within the constraint of the minimum feasible time horizon due to boatyard capacity.[18]

Table 5
Average cost to individual boat owners of alternate policy options to achieve 100% abatement in 15 years.

	Cost per boat (net present value, discounted at 5%)
Marina-by-marina ban	$2454
Market-based incentive approaches (e.g. tax, tradable permits)	$2351
Two-part ban (new boats immediately; existing boats at future date)	$346

In addition to minimizing costs to boat owners, the two-part ban approach has the advantage of not affecting boat owners who are not converting in any given period. The primary administrative burden would, again, be monitoring and enforcement of the ban, which would likely be less than for a marina-by-marina policy as it would involve only new boats and a one-time inspection of marinas at the time of the ban.[19]

Table 4 summarizes key features of this section's policy comparisons. What stands out here is that the feasible marina-by-marina command-and-control policy and the two standard economic incentive approaches are each bad on one criterion but they are different ones. The command-and-control policy does not minimize costs to converting boats but also does not impose costs on non-converting boats. The two economic incentive policies do the reverse; they minimize costs for converting boat owners but they also impose additional costs on non-converting boat owners. The two-part ban minimizes costs for converting boat owners *and* does not impose additional costs on non-converting boat owners, thus making it the preferred policy approach.

Table 5 presents the average cost to an individual boat owner in San Diego Bay of each policy option for achieving 100% abatement in 15 years. As discussed in Section 4, costs to boat owners are calculated as changes in hull maintenance costs over each boat's remaining lifetime, including the one-time conversion cost of switching to nontoxic hulls, assuming that boaters choose the optimal time to convert under each policy. Details of our cost calculations are provided in the online Appendix. As seen in Table 5, the two-part ban is considerably less expensive than the other options because it allows them to convert at the optimal times and does not impose costs during time periods when boaters do not convert.

6. Concluding remarks

Copper pollution from antifouling paints is affecting coastal water quality throughout the world in areas where there are high concentrations of recreational boats. Regulatory approaches to the problem will continue to evolve as governments become increasingly aware of copper concentrations in their waters and as viable alternative nontoxic coatings continue to be developed.

Policies used to address the copper pollution problem need to be focused on specific local populations of boat owners and need to selectively target certain boat owners at specific points in time to minimize the overall cost of the policy, which boat owners generally will bear. In San Diego Bay, requiring new boats to use nontoxic coatings and announcing that copper paints will be banned on existing boats in 15 years would accomplish the objective of a low-cost and administratively feasible phase out policy. To achieve a complete phase out of copper in a shorter time period, marketable copper permits that decline in value could be

[18] Rigorously addressing this tradeoff requires weighing marginal social costs and benefits to achieve the socially efficient outcome. The cost efficiency framework adopted in this paper allows us to recognize efficiency gains through means of implementation in a given time horizon.

[19] Both a marina-by-marina policy and a complete ban at a future date will involve some type of monitoring program for "used" boats coming from outside of San Diego Bay.

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used in combination with this two-part ban to ensure that the program would be kept on track.

It is our hope that lessons learned designing a policy for use in San Diego Bay can be useful to regulators addressing this pollution problem in other marine areas where potential savings from implementing the two-part ban are likely to be large. The conceptual framework presented here is also likely to be useful to other pollution control problems involving replacement of consumer durable goods when an environmentally harmful alternative is available. As such, we hope that a two-part ban be considered as a viable policy option for other instances where it is desirable to phase out adverse environmental impacts associated with long-lived products.

Appendix. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jenvman.2008.12.016.

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