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An empirical study of environmental policy and technology adoption : phasing out toxic antifouling paints on recreational boats

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An Empirical Study of Environmental Policy and Technology Adoption: Phasing out Toxic Antifouling Paints on Recreational Boats

A dissertation submitted in partial satisfaction of the
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in

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by

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2007

The dissertation of Maria Damon is approved, and it is acceptable in quality and form for publication on microfilm:

Chair

University of California, San Diego

2007

To my grandparents
Marne and Joan Obernauer
and
in memory of my grandmother
Helen Damon

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Chapter 1, “Conceptual Issues in Designing a Policy To Phase Out Metal-Based Antifouling Paints on Recreational Boats”, is co-authored with Richard T. Carson, Jamie A. Gonzalez, and Leigh T. Johnson.

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ABSTRACT OF THE DISSERTATION

An Empirical Study of Environmental Policy and Technology Adoption: Phasing out Toxic Antifouling Paints on Recreational Boats

by

Maria Damon
Doctor of Philosophy in Economics

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Professor Richard T. Carson, Chair

In marine areas throughout the world, copper-based hull coatings are used on recreational boats to kill algae and barnacles. Unfortunately, copper, a registered fungicide, harms other marine organisms and violates government concentration standards when there is a sizeable number of recreational boats moored in close proximity. An immediate nationwide ban of copper would cost over one billion dollars. Designing more efficient policies for phasing out copper requires an understanding of copper and non-toxic hull coatings as a dynamic capital replacement problem, an understanding of the behavior of utility-maximizing consumers, and how these two factors interact with possible pollution control instruments. Once the dynamic nature of the policy problem is established, heterogeneity in capital vintage and heterogeneity in consumer willingness-to-pay for environmental properties become key determinants of the overall cost of alternate policy instruments. This dissertation consists of three papers that analyze these types of heterogeneity in a dynamic context and explore their implications for the optimal design of pollution control policies.

The first chapter introduces the policy problem and puts forth a conceptual framework for thinking about how to design and evaluate alternative policies to transition to non-toxic boat hulls. Many of the issues raised are broadly applicable to environmental problems where the solution involves a large-scale replacement of durable consumer goods.

The second chapter analyzes the preferences of utility-maximizing boat owners in order to accurately evaluate policy options. I implemented a choice experiment with recreational boaters in San Diego Bay to build an econometric model of paint choice, and estimate willingness-to-pay for marginal changes in paint attributes and discount rates implicit in respondents' tradeoffs over time. I also consider how choice behavior would change with altered expectations of future policies. Using my results, I discuss a fifteen-year plan to phase out toxic paints in San Diego Bay at no cost.

The third and final chapter presents evidence that consumer preferences toward environmental attributes can be highly heterogeneous, and can strongly influence the time-path of pollution abatement. Prior studies tend either to ignore the speed of compliance/adoption by conducting static analysis or ignore heterogeneity by taking a representative agent approach; even models that condition on individual-level covariates are generally plagued by the fact that unobservable characteristics can drive the behavior of interest. Using data from my choice experiment, I estimate the distribution of environmental preferences. This heterogeneity will cause initial abatement to occur more quickly than would be expected without it, but the ultimate target will be achieved more slowly than in a homogeneous population. The greater the heterogeneity, the more this effect is exacerbated. Failure to understand and account for heterogeneity will prevent policymakers from achieving targets in desired time frames. I discuss implications of this finding, coupled with results from my first two chapters, for the optimal design of pollution control policies.

1

Conceptual Issues in Designing a Policy To Phase Out Metal-Based Antifouling Paints on Recreational Boats

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 coral, 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 non-toxic boat hulls. Many of the issues raised are broadly applicable to environmental problems where the solution involves a large scale replacement of durable consumer goods.

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[0] An earlier version of this paper was presented at the Second World Congress of Environmental and Resource Economists. All remaining errors are my own.

1.1 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 the copper pollution problem is posing 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 made a determination that dissolved copper in some boat basins has reached levels that are toxic to some species, and that bottom paints on recreational boats are the primary source of this copper. (U.S. Environmental Protection Agency 2002) As a result they are required to take regulatory action to reduce copper levels in San Diego by reducing the copper contamination coming from recreational boats. While San Diego is the main focus of regulatory action in California, the California Water Resources Control Board is also looking at copper pollution at points further up the California coast line starting at Oceanside Harbor in San Diego County, Newport Bay in Orange County, Marina Del Rey in Los Angeles County, and ending at Santa Barbara's harbor.[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 and environmental problems associated with such paints have long been recognized. Indeed, the current generation of copper-based paints

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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, Bushong, Jr., L.W., Lenkevich and Pinkey (1988), Trocine and Trefry (1993), and Stasch and Lynch (1999) for further discussion.

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 face 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 particular areas. (College voor de Toelating van Bestrijdingsmiddelen 2004, Danish Environmental Protection Agency 2003) Several European countries are now closely monitoring their levels of dissolved copper in boat basins, and antifouling paints applied in the United Kingdom, Sweden, Netherlands, Belgium, Finland, and Austria must be registered under current pesticide laws. (International Coatings Ltd. 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 that would induce this conversion. This paper addresses these issues in the context of designing and evaluating policies to transition to nontoxic bottom coatings and companion cleaning strategies 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 boats are required to convert to non-toxic paints one marina at a time; a tax on the use of copper; marketable copper quotas; 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.

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

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 III discusses technologically viable alternatives to copper-based antifouling paints. Section IV 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 V discusses the four policy alternatives we considered and proposes recommendations for policy design stemming from our experience analyzing policy options for use in San Diego Bay. Section VI provides some concluding remarks.

1.2 Regulatory Background

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 particular pollutants to order to attain water quality objectives. The TMDL are intended to be set so that once a pollutant's discharges have been reduced, water quality standards should be achieved.

Dissolved copper concentrations are elevated in many locations throughout San Diego Bay, especially in the southern reaches of the San Diego Bay and enclosed yacht basins. (Katz 1988, Valkirs, Davidson, Kear, Fransham, Zirino and Grovhoug 1994, VanderWeele 1996) Numerous studies have indicated that these concentrations exceed the water quality criteria of 3.1 parts per billion (ppb) dissolved copper set federal and state regulatory standards. (U.S. Environmental Protection Agency 2000) As early as 1980, dissolved copper concentrations in the 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 1990's 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 that evaluated dissolved copper levels throughout the Bay found over half of the samples exceeded the water quality criteria of 3.1 ppb. (Johnson, Grovhoug and Valkirs 1988)

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.[2] 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, MacInnes, Nelson, Greig and Yevich 1984, Coglianese and Martin 1984, Gould, Thompson, Buckley, Rusanowsky and Sennefelder 1988, Lee and Xu 1984, Lussier, Gentile and J. 1985, MacDonald, Shields and Zimmer-Faust 1988, Martin, Osborn, Billig and Glickstein 1981, Stromgren and Nielsen 1991)

According to studies done to help the California Water Resource Control Board (CARWQCB) set a TMDL, elevated levels of dissolved copper in San Diego Bay are due in large part to copper-based antifouling paints on boats, particularly in areas where recreational boats are densely located. The largest of these areas is the Shelter Island Yacht Basin which holds over 2,200 recreational boats and 99% of the dissolved copper in this basin is thought to come from antifouling paints. (CARWQCB, 2003).

The high concentrations of copper in these marine areas stems from the technological nature of antifouling paints on boats that are kept there. Recreational boats typically spend most time at their slips, where the antifouling paints continuously emit copper that may accumulate 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, Diehl and Valkirs 2003) The other major source of copper release is underwater hull cleaning with the scrubbing of copper-containing paints releasing dissolved copper into the surrounding water. The to-

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[2] 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 Total Maximum Daily Load for Dissolved Copper in the Shelter Island Yacht Basin (2003) for further discussion.

tal 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.[3] Switching to nontoxic hull coatings would reduce copper loading from both passive leaching and underwater hull cleaning.

1.3 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. The general strategy combines a nontoxic hull coating and a "companion strategy" such as cleaning the hull frequently, storing the boat out of water, or surrounding it with a slip liner. The number of specific solutions has increased substantially in recent years. Although many nontoxic hull coatings currently are available, they are new to the market and most consumers generally know very little about them. (Carson, Damon, Johnson and Miller 2002) This is unlikely to change as long as copper-based hull coatings are less expensive and not required by regulators. However, under threat of future regulation and the possibility of developing a niche market for the most environmentally sensitive boaters, most of the major marine paint companies have begun to extensively study biocide-free paints. (Kettlewell 2000)

Understanding certain technological features of antifouling strategies is necessary for policymakers to understand costs of using 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 coating are more durable and last longer than a copper-based paint because the hull paint does leaches off the

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[3] Professional underwater hull cleaners in San Diego are extremely sensitive to the San Diego Bay's copper pollution problem, and employ Best Management Practices in attempts of minimizing copper emissions.

boat over time. Costs of purchasing nontoxic coatings, preparing the hull, and applying the coating are presently higher than for copper-based paint, although this may change over time. As more paint companies develop and market nontoxic coatings, and as boat repair and maintenance companies learn appropriate application procedures and cleaning protocols, the costs of using these paints are likely to fall.

Currently available nontoxic bottom coatings may be silicone-based, epoxy-based, water-based, or polymer-based. Epoxy coatings are currently the most widely used type of nontoxic bottom coating; they tend to be highly durable, and require frequent cleaning. 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.[4] In contrast, most San Diego area boat owners reapply copper-based bottom paint every two to three years.

Silicone hull coatings provide another nontoxic alternative to copper-based paints and sometimes are used on racing boats as they can provide a small increase in speed. Silicon paints are sometimes called “fouling release” coatings, because fouling organisms slide off the hull when a boat exceeds a certain speed. Field tests have found that the critical speed for fouling release varies for different silicone coatings and for different organisms, though 20 knots is often cited. (Swain, Kavanagh, Kovach and Quinn 2001) Although many pleasure craft seldom or never operate at this speed, the slippery nature of these coatings also allows for fouling growth to be wiped off easily. Hull cleaners recommend especially frequent cleaning of silicone coatings since later stages of fouling growth can penetrate these coatings and become more firmly established on the hull. Due to the slippery nature of silicone, boats with these coatings require special handling at boatyards and silicone-based paints are less resistant to damage than epoxy based paints.

One of the major problems facing a regulatory agency in making a decision involving a transition to a new less polluting technology is that there will be substantial uncertainty concerning the properties of that technology. Much of the

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[4] One San Diego area sailboat that received a “test” epoxy coating more than nine years ago is reported to still be in good condition.

available information will come from the manufacturers of that technology, who simultaneously do not have a great deal of real world experience with the technology because it is new and have an incentive to over-emphasize its desirable properties and under-emphasize its disadvantages. The installers of the technology will have even less real world experience with the new technology and, because the new technology will involve depreciating the value of their capital investment, 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. As such it is important to recognize that there may be substantial gains from having the government or universities do some work on providing independent information concerning the properties of the new technology.[5]

Having an independent source of information can also help the regulatory process from being derailed by claims that there is too much uncertainty while at the same time being able 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 will provide much useful information for implementation of regulations on a large geographic scale and will by itself tend to foster further research and development by manufactures. One of the most interesting questions with regard to non-toxic paints is whether their cost will fall substantially as production is ramped up.

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[5] In the particular case we examine, the University of California's Sea Grant Extension Program in San Diego County has conducted a demonstration to provide preliminary information on nontoxic antifouling strategies. The project tracked the performance of three silicone and three epoxy-based coatings on six vessels in San Diego Bay from 2002 to 2007. This project established a reporting protocol to obtain data from underwater hull cleaners who documented fouling growth, cleaning tools, diver effort, and coating condition each time the vessels were cleaned. This protocol could be used in other locations where factors such a temperature that can influence the growth of algae and barnacles may be different than San Diego. From our perspective, the most notably result is that the epoxy coatings withstood intensive cleaning and showed promise of extended service life in excess of the estimate used in our analysis.

1.4 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.

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 in current dissolved copper coming from recreational boats 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 that could induce a complete phase-out of copper.[6]

We considered the design of a pollution control policy with respect to three main criteria:

1) Feasibility

2) Cost to recreational boat owners

3) The burden placed on other relevant parties (i.e. boatyards, hull cleaners, marinas, the Port District and the State of California)

A policy is considered strictly better than another policy if it is superior to that policy on all three of these dimensions.[7] More specifically, after narrowing our

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

[7] Otherwise, different stakeholders may place different weights on these criteria, and hence judge different policies preferable.

analysis to policies that can feasibly be implemented, policies that have lower costs and place lower burdens on other relevant parties were preferred.

Once a policy's objectives and evaluation criteria are established, policymakers can choose among a menu of policy instruments to that 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 primary policy options we considered for use phasing out copper in San Diego Bay, according to these criteria.

1.4.1 Feasibility and the Constraint of Boatyard Capacity

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

As discussed, antifouling paints are designed such that the copper slowly leaches off of a boat's hull to act as a preventative biocide. Because the toxic element is constantly leaching out of the paint, boaters with copper-based hull paints need to reapply them relatively often, approximately every 2-3 years at San Diego Bay.[8] Each repainting requires a boat to be hauled out of the water and is usually performed at a local boatyard. In addition, because new coats of the paint generally are applied directly on top of the old coats, old paint accumulates and new coats become increasingly difficult to apply. After about 6 repaintings, a boat's hull usually needs to be stripped entirely clean of the old paint in order to begin applying new coats again. Essentially, a clean hull is a new capital asset which depreciates over time, until it is fully depreciated and 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. Table 1.1 summarizes average maintenance properties of copper-based antifouling paints and non-toxic epoxy hull coatings.

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

Table 1.1: Standard Maintenance Cost Properties of Copper-Based and Epoxy Coatings

Property	Copper-Based Paints	Epoxy Hull Coatings
Application Frequency	Every 2-3 years	Every 7-8 years
Application Cost (per application)	$30 per foot	$40 per foot
Cleaning Frequency	14 times per year	22 times per year
Cleaning Cost (per application)	$1 per foot	$1 per foot
Stripping Frequency	Every 6th re-painting	Every 6th re-painting
Stripping Cost	$120 per foot	$120 per foot

Nontoxic coatings cannot be applied directly on top of copper-based paints; a hull with any amount of copper paint accumulation thus needs to be stripped in order to be converted to a nontoxic coating. In addition to the considerable cost of application, this particular feature of nontoxic coatings makes a very quick paint conversion of an entire population of boats infeasible due to the limited boatyard capacity. Boatyards routinely perform paint jobs and stripping jobs, and in San Diego Bay, boatyards serve a stable population of boats and are operating at close to full capacity. Stripping and repainting a boat takes more time than simply repainting a boat, so an immediate conversion of all 7,000 boats in San Diego Bay would place a demand that currently could not be met by boatyards.

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 specific case. The fact that boats need to be stored on location, where space is limited, and the need for paints to dry adequately, 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 actually implies less maintenance work in the long run since nontoxic coatings generally do not need to be reapplied as often as copper-based paints (as their efficacy does not depend on biocide leaching from the coating). Boatyards consequently have a strong incentive against large capital expenditures that would substantially increase long-term hull maintenance capacity.

The minimum time horizon for any policy to phase out copper is thus determined by boatyard capacity. This capacity constraint prevents immediate conversion of the current fleet of recreational boats in San Diego Bays; 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, and this additional capacity can be used for conversions over time. By speaking to boatyards and deriving a simple dynamic model of conversion capacity, Carson et al. (2002) determined that the quickest possible time horizon in which the objective of a 66% reduction in copper discharge could be achieved (after large scale commercial application is viable) is five years. The minimum time horizon necessary to achieve a complete phase-out in San Diego Bay is seven years.

1.4.2 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.

An economically rational boat owner should consider the present discounted value of hull maintenance over a boat's lifetime when making hull paint decisions. Even if he or she plans to sell the boat before it is permanently retired, the resale value of a boat in an efficient market will depend on features of the boat such as its current paint type and the ensuing maintenance costs, and boaters should make cost calculations over the expected remaining service life of a boat. Evidence from surveys of boat owners in San Diego empirically demonstrates that this is indeed true for this population of boaters.[9]

To formally model the boat owner's cost minimization problem, we let $C(t; l, c_f, c_c) = \sum_{i=1}^{E*c_f} \delta\left(t - i/c_f\right) * c_c * l$ represent the stream 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 number of times per year that it must be cleaned, l_i is the length in feet of individual i's boat, and $\delta(\cdot)$ is the Dirac delta function, with the property that $\int_{-\infty}^{\infty} \delta(x) * f(x)\, dx = f(0)$.[10] Similarly define $P(t; l, p_f, p_c) = \sum_{i=1}^{E*p_f} \delta\left(t - i/p_f\right) * p_c * l$ as the recurring cost of painting the boat and $S(t; l, s_f, s_c) = \sum_{i=1}^{E*s_f} \delta\left(t - i/s_f\right) * s_c * l$ as the cost of stripping the boat. An individual cost-minimizing boat owner therefore chooses T, the time to switch from a copper-based paint to a non-toxic hull coating (denoted with superscripts 0 and 1, respectively), to solve:

$$\begin{aligned} \min_T \int_a^T & \left(C\left(t; l, c_f^0, c_c^0\right) + P\left(t; l, p_f^0, p_c^0\right) + S\left(t; l, s_f^0, s_c^0\right)\right) * e^{-r(t-a)}\, dt \\ + \quad & \int_T^E \left(C\left(t; l, c_f^1, c_c^1\right) + P\left(t; l, p_f^1, p_c^1\right) + S\left(t; l, s_f^1, s_c^1\right)\right) * e^{-r(t-a)}\, dt \end{aligned} \tag{1.1}$$

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

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

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[9] The survey of San Diego boaters was conducted by the authors in order to understand how boat owners choose between different hull paint options. The methodology and results of this survey are discussed in Carson et al. (2002).

[10] The Dirac delta function is used here to represent discrete costs incurred in a continuous time framework. It is sometimes referred to as the "unit impulse function"; essentially, the Dirac delta is the limit of a standard normal distribution as its variance approaches zero. It returns an impulse with a mass of 1 when its argument is 0 and returns 0 for all other arguments. For further discussion, see Bracewell (1999) and Papoulis (1984)

the higher initial painting cost and the higher hull cleaning costs over the course of the life of the nontoxic hull coating.

As discussed, there is an additional cost that is highly significant when comparing costs across paint types: the cost of stripping old accumulated paint. A boat that is always repainted with copper hull paint must be stripped periodically (after roughly 6 repaintings), and the owner of a boat with copper hull paint who wishes to switch to a nontoxic coating must also strip all of the old copper paint from the hull. Stripping costs tend to be much larger than the painting costs (e.g. $150 per foot of boat length for stripping old paint and applying new paint versus $30 per foot of boat length for applying traditional copper paint on a 40-foot boat), so a comparison of total lifetime costs depends critically on whether the boat has to incur an additional stripping cost in order to apply the nontoxic hull coating.

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 may 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, each time it is repainted. A hull that needs stripping can be thought of as a fully depreciated hull. A policymaker’s understanding of this intuition is crucial when thinking about the lowest-cost way to design a policy, and we return to this point when discussing various 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. Different people may view policies with the same costs but occurring in different time periods differently, due to the discount rate they perceive to face with respect to hull maintenance decisions. Survey evidence found that boat owners in San Diego Bay trade off hull maintenance costs over time at a 5% discount rate, on average. (Carson et al. 2002)

Total maintenance costs for a new 40-foot boat in San Diego Bay, as a function of time horizon, are shown in Figure 1.1.[11] This figure shows that using copper-based paint is less expensive in initial years, but this cost advantage falls as one considers 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 profile of copper paints and nontoxic coatings is fairly small. It should also be noted that the cost of non-toxic paints is likely to fall as their scale of production increases and the labor and equipment costs of application fall due to increased experience applying these paints.

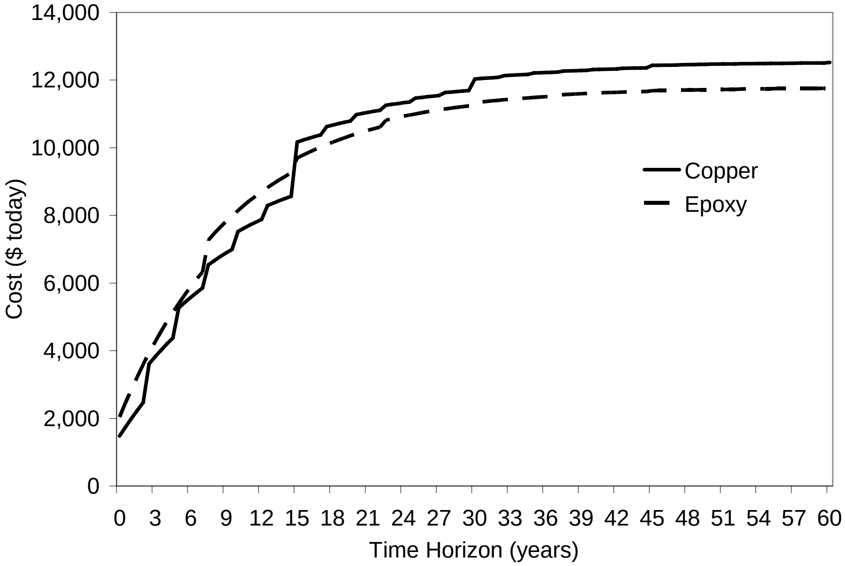

Figure 1.1: The Total Lifetime Cost of Maintenance for a New Boat

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[11] Baseline cost assumptions are summarized in Table 1.1; additionally, boats are assumed to be retired at 30 years of age. All assumptions come from conversations with San Diego boatyards, marinas, and recreational boaters. See Carson et al. (2002) for further discussion.

1.4.3 Burden on Other Parties

In addition to the economic costs borne by 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.

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

a) ensuring that only non-toxic hull coatings are applied to new boats,

b) ensuring that only non-toxic hull coatings are on boats on 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,

d) ensuring that a tax is collected on copper hull coatings 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 non-toxic hull paints. It is also clear that, for hull cleaners, special training and, likely, special equipment, will be needed to clean non-toxic 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. However, such training and equipment requirements are likely to impose substantial “upfront” expenditures on hull cleaners. We do not rigorously assess this issue further in our analysis.

The most obvious financial costs not accruing to individual boat owners is the change in revenue to boatyards and hull cleaners, which are also discussed in the following section. Marinas and mooring locations also bear financial costs under one policy option we considered (banning copper marina-by-marina), as discussed in the following section.

1.5 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.

As non-toxic 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 considerable uncertainty with respect to the application of non-toxic alternatives, and demonstration projects can exhibit the feasibility of undertaking certain actions or using particular technologies to achieve an efficient, large-scale commercial application of the new technology.[12] Boater education projects are also necessary, primarily to inform boaters that the copper hull paints they use cause pollution problems and to inform them the long-term cost implications of copper versus non-toxic hull paint options. These educational efforts can be coupled with any policy instrument used to phase out copper, but are likely to have a larger impact when used with market-based programs because they can alter the incentives of individuals by making them better-informed. We focus the remainder of this section 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, or a two-part regulatory phase-out - could be used to meet the policy's objectives.

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[12] Such a demonstration project was undertaken in conjunction with our project in San Diego Bay.

1.5.1 Command and Control Ban, Marina-by-Marina

Once the boatyard capacity constraint is recognized and an immediate copper ban is understood to be infeasible, a regulatory agency could modify the command-and-control approach to allow enough time for the phase-out by mandating a prohibition of copper (either on its application or on its presence on a boat's hull) one marina at a time, over seven years, such that a 100% elimination of copper is achieved in the necessary time frame. Indeed, it might be expected that many regulatory agencies would deem this the obvious approach to this type of time constraint.

Under this policy, the ordering with which boats are converted from copper to non-toxic paint is essentially arbitrary from a cost perspective.[13] Rather than selecting the least-cost boaters to convert, as would a market-based measure, this policy has the usual failing of a command-and-control approach, $i.e.$ that the policy's inherent inflexibility would result in a higher cost of abatement. Essentially, boaters would be selected to convert their boats to non-toxic paints at a random point in their hull maintenance schedule, resulting in an increase in the lifetime cost of hull maintenance 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 exorbitantly high, if the hull was recently stripped and/or has a fresh coat of copper-based paint. Clearly, a disadvantage of this approach is that it will necessarily result in higher overall costs to boat owners.

A marina-by-marina ban also could be expected to impact the marinas' business directly. If boats with copper hulls can move from marinas with an early imposed ban to marinas with a later ban, this policy is likely to create economic costs or profits for the marinas accordingly.

One advantage of this command-and-control approach over the market-based measures is that boaters who are not required to convert their hull at any given time are unaffected, since the price of copper would not be directly affected. (Of course, as the population of boaters converts, altered demand for copper paint could be expected to impact its price, but this impact can be expected to be roughly

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[13] 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.

consistent across all of the policies that we compare here.) The administrative burden, however, can be expected to be more severe to the regulatory agency enforcing the program, since a mandated ban will likely only be effective with strict monitoring and enforcement. Also, unlike with a copper tax or auctioned copper permits, no revenue will be raised that can help offset these administrative costs.

1.5.2 Market-based Measures

User fee on Copper

The price of copper hull paints can be directly increased by the imposition of a copper tax. As the price of applying copper-based paints increases relative to non-toxic alternatives, boaters will have an incentive either to switch to a non-toxic alternative or to reduce the amount of copper that leaches off the boat 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, given the application of the same amount of copper initially. 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 the targeted boaters will choose a non-toxic alternative.

An advantage of this approach is that it "selects" as volunteers the boat owners that are close 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). The cost comparisons described in Section 4 highlight the fact that that there are two types of boats for which an additional costly stripping need not be incurred in order to convert to a nontoxic coating: new boats and boats that need to be stripped before any other paint can be applied. Clearly, any least-cost policy should begin by targeting these boats. Coupled with the fact that a policy cannot feasibly impose immediate conversion, and thus some ordering of conversions must take place, a policymaker can substantially lower the cost of the policy by targeting these boaters first. An appropriately-set user fee on copper can accomplish this cleanly 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 non-toxic paints the next time their boat is stripped.

The cost of a policy that directly increases the price of copper hull repainting will be borne by boaters. One potential drawback of this approach is that the price of copper would increase for all boat owners who are re-applying 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 that collects the tax, but the additional revenue generated by this policy will, of course, go directly to this agency.

Tradable Copper Permits

An alternative to a user fee on copper is to set up a system of tradable copper quotas that limit copper use during specified time periods. If the 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 thus works in the same way as a user fee on copper, and the overall cost will, 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 and, as such, a desirable feature of this system is that it an be used to phase-out copper use on a smooth schedule, even in the presence of price or demand uncertainty.[14]

The effects of a tradable permit program on parties other than boat owners will depend on the initial allocation mechanism. Common ways to allocate quotas include auctioning them off to firms and distributing the quotas free of charge to

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[14] A successful example of this tool was the use of marketable permits for lead in gasoline that declined in quantity over time to zero. See Kerr and Newell (2003) for further discussion.

firms 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.

1.5.3 A Two-Part Copper Ban

Another regulatory option is to require all new boats to be painted with a non-toxic 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.[15] 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 non-toxic hulls; since the cost of converting a hull to a non-toxic coating will need to be incurred by all boats before the phase-out deadline, the boats that have already been converted will be worth more on the resale market.

To minimize the cost to boat owners, we’ve seen that the first boats induced to convert should be all new boats and all boats in need of a stripping. Coupled with the fact that a lifetime cost comparison of new hulls favors nontoxic paints, any 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 would induce the least cost boat owners to switch first, as each boater chooses his or her own optimal time to convert before the ban is imposed. This policy essentially mimics the market-based policies by allowing for the flexibility of achieving the least-cost abatement, in terms of which boaters will convert at which times.

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 ever needs 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 is permanently retired. To phase out copper in a shorter time horizon, a cost-minimizing policy should target boats that will need to be stripped very soon as the

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[15] Theoretical properties of this approach are examined in more detail in Chapter 2 of this dissertation.

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 the 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.[16] The two-part ban approach will induce each boater to choose his or her own optimal time to convert before the ban is enforce and, as such, the least-cost group of boaters are induced to convert at any given time.

In addition to minimizing costs to boat owners, this policy also has the advantage of not affecting boat owners who choose not to convert in any given period through a direct increase in copper prices. The primary administrative burden will, again, be monitoring and enforcement of the ban. The magnitude of this burden may be smaller than that of the marina-by-marina ban, as more of the abatement is coming from new boats with the two-part ban approach and, as such, fewer existing boats will require inspection.

Table 1.2 summarizes key features of the policy comparisons presented in this section.

1.5.4 Specific Insights for San Diego Bay

A revealing aspect of our study in San Diego Bay is that a two-part ban approach, whereby new boats are required to use non-toxic coatings and copper use is prohibited on existing boats after a certain date, would be exceptionally easy to implement in this market. This result comes from two findings of the surveys conducted by Carson et al. (2002). The first is that the population of boaters in San Diego is willing to pay a considerable premium for the nontoxic property of coatings; on average, this premium is $800 for the nontoxic property alone, holding other properties (cost and frequency of paint application, cleaning, etc.)

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[16] To rigorously address this tradeoff would require the usual economist's weighing of marginal social costs and benefits in order to achieve the socially efficient outcome. The cost efficiency framework adopted here allows us to recognize efficiency gains through means of implementation in a given time horizon.

Table 1.2: Comparisons Across Feasible Policy Options for Phasing Out Copper-Based Antifouling Paints

Evaluation Criteria	**Marina-by-Marina Ban**	**Market-Based Approaches** (e.g. tax, tradeable permits)	**Two-Part Ban** (new boats immediately; existing boats at future date)
Minimizes overall cost to boat owners	No	Yes	Yes
Impacts boat owners not converting to non-toxic paints	No	Yes	No

equal.[17] This willingness-to-pay turns out to be greater than the cost differential between nontoxic coatings and copper paints (which had favored copper) over the remaining lifetime of a boat that is being stripped today. Therefore, once the environmental concern among boaters in San Diego is taken into account, and once boaters are well educated as to the costs and properties of nontoxic coatings, boaters who are stripping their depreciated copper-painted hull will choose to apply nontoxic coatings on their own, without any additional economic incentive provided by a policy (including knowledge of a future ban).

The second survey finding that supports this notion is that announcing a future ban on copper paint would significantly affect the choice of paint type that a boat owner currently makes. This second finding suggests that the resale value of boats would indeed reflect the increased cost of using copper paint induced by a future ban. Therefore, even boaters with less-than-average concern for the environment will switch at the “right” time, as long as these boaters are well-informed.

In light of the ease of implementation and low cost of such a policy, a reasonable policy recommendation for use in San Diego Bay is as follows: Announce that copper paints will be banned in fifteen years, require new boats to be coated

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[17] The second chapter of this dissertation provides a more detailed and technical discussion of these findings.

with nontoxic coatings, and educate boaters and boatyards as to the cost and properties of newly available nontoxic coatings. The cost borne by boat owners will, again, be equivalent to the change in hull maintenance costs resulting from a switch to nontoxics, and the cost and administrative burden would basically be no more than the cost of the education campaign.

1.6 Concluding Remarks

Copper pollution from antifouling paints is affecting coastal water quality all over 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 the 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 various points in time in order to minimize the cost of the policy, which boat owners will generally bear. In San Diego Bay, requiring that new boats use only nontoxic coatings and announcing that copper paints will be banned on existing boats in fifteen years would accomplish a complete phase-out of copper at close to no cost and in an administratively feasible way. To achieve a complete phase-out in a shorter period of time, marketable copper permits that decline in value could be 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 while designing such a policy for use in San Diego Bay can be useful to regulators addressing this pollution problem in other marine areas.

Chapter 1, “Conceptual Issues in Designing a Policy To Phase Out Metal-Based Antifouling Paints on Recreational Boats”, is co-authored with Richard T. Carson, Jamie A. Gonzalez, and Leigh T. Johnson.

2

Environmental and Time Preferences of Recreational Boaters: Evidence from a Choice Experiment

Abstract

Comparing alternate policies for reducing pollution requires accurate predictions of the behavior of affected agents. If a policy targets consumers, one needs to understand the behavior of a utility maximizing individual rather than a profit maximizing firm. In addition to cost minimization, an individual's utility function may depend on non-market values such as environmental preferences. This paper shows that modelling individual utility functions can allow policymakers to achieve efficiency gains by better estimating the costs of different policy instruments. The heart of the paper is a case study drawn from experience evaluating alternate policies to phase out the toxic element of boat paints in San Diego Bay. We implement a choice experiment with San Diego boaters and build an econometric model of boat owner paint choice in which we estimate individual willingness-to-pay for marginal changes in paint attributes. Using the estimation results we identify the least-cost policies that can achieve 100% abatement over various time

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[0] Earlier versions of this paper were presented at the Annual Conference of the European Association of Environmental and Resource Economists in Budapest, Hungary and the Seventh Occasional Conference on Environmental Economics in Santa Barbara, California. All remaining errors are my own.

horizons and compare their costs to the costs of policies that would have been estimated had the consumer's decision been modelled as simple cost minimization without regard to other utility parameters in the boater population. Using the results from our choice experiment we devise a fifteen year plan to phase out copper use in San Diego Bay at no cost.

2.1 Introduction

Environmental policies function by inducing firms or individuals to change their current behavior. The change can be either explicitly forced, as with command and control policy instruments, or encouraged through changes in relative prices, as with market-based instruments. Within these two classes there exist a menu of policy instruments, each of which can be customized to particular policy contexts. Any comparison across these alternate policies, and ultimately the design of an optimal policy, begins with an accurate prediction of behavior under each policy. The choice of policy design will then depend on the objective of policy makers, be it cost efficiency, fairness in the distribution of costs, political feasibility, or most likely some combination thereof. (Sterner 2003)

Economic discussions of policy instruments are often centered around policies aimed at industrial firms. This is especially true of empirical analysis, given that most market-based instruments that have been employed in the real world have been aimed at industry, such as the phasedown of lead in gasoline that took place in the United States in the 1980's and the SO_2 allowance trading program initiated under the Clean Air Act amendments of 1990. Kerr and Newell (2003) document the effect of the lead phasedown on the technology adoption decision of petroleum refineries, providing some of the first empirical evidence of the dynamic effects of environmental regulation. Similarly, Keohane (2002) models firms' choices of abatement technique under various policies and empirically tests his predictions with data from SO_2 regulation of coal-fired electric power plants.[1]

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[1] Other than these two studies, there is very little empirical work that looks at the relative dynamic effects of market based pollution control policies on the players which the policies target. Nelson, Tietenberg and Donihue (1993) examine firm decisions regarding the rate of capital turnover under differential environmental regulations of the electric power industry. A similar literature addresses the effect of changes in energy prices on consumer decisions with regard to

In these contexts one can understand firm behavior by modelling the profit function and assuming (quite reasonably) that firms are profit maximizers. Economic analysis of pollution control policies increasingly uses this framework, especially as issues related to technological change are increasingly permeating discussions of the dynamic efficiency of environmental policies. (For a thorough review of this literature, see Jaffe, Newell and Stavins (2002).) However, as approaches to environmental protection increasingly rely on public concern and voluntary participation, understanding consumer preferences toward environmental products is increasingly essential to designing efficient and effective policies.

If a policy is instead to target consumers or firms that are highly sensitive to consumer demand, the setting may not be as straightforward. In this case, accurate policy cost estimates requires an understanding of the behavior of utility maximizing individuals rather than profit maximizing firms. While profit maximization (or cost minimization) can of course be expected to enter into individuals' utility functions, this may not be the entire story. An individual may have environmental preferences irrespective of cost, or may make tradeoffs over time at discount rates which differ from the interest rate prevailing in credit markets.

Analysis of consumer capital replacement problems have of course cropped up in other areas of economics. Many studies have examined consumer behavior with regard to energy efficiency, beginning with Hausman (1979), who suggested that individuals use an average discount rate of 20% when deciding whether to install room air conditioners. Since then, many others have presented similar findings, $i.e.$ that consumer technology adoption decisions are more sensitive to up-front cost considerations than to longer-term operating expenses.[2] However, such studies tend not to model (or generally account for) optimal capital replacement schedules and, moreover, can often be limited by the fact that unobservable factors such as environmental preferences may be important drivers of the choice behavior of interest.

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energy efficient technologies, but the pollution control literature seems to have focused exclusively on firm behavior. The energy efficiency literature is discussed in more detail below.

[2] For example, Jaffe and Stavins (1995) found that a change in the adoption cost of energy-efficiency technologies in new home construction was three times as effective in encouraging adoption as an equivalent change in energy prices. Hassett and Metcalf (1995) found an even larger discrepancy.

This paper presents evidence that accurately modelling individual behavior can allow a policymaker to achieve sizeable efficiency gains by better estimating the costs of alternative policy instruments. First, we develop a theoretical framework for estimating the cost of a policy. Section 2.2 presents this framework and demonstrates that individual preferences can map to an optimal policy structure that may not have been identified having modelled individuals solely as profit maximizers.

The heart of the paper is a case study that demonstrates this result, drawn from experience designing a policy to phase out the toxic element of boat paints in San Diego Bay. In marine areas throughout the world where recreational boats are densely located, the copper concentrations in the water are in excess of government standards. The pollution is coming from the paints which boaters apply to their hulls in order to prevent marine organisms from attaching to their boats. This problem provides a rich example of a policy context in which individual consumers need to be targeted, but where an approach in which individuals are modelled solely as cost minimizers will lead to incorrect policy cost estimates and ultimately to the wrong choice of policy.

Our policy cost estimates are developed in two stages. First, we implemented a choice experiment, described in Section 2.3. We build and econometric model of boat owner choice in which we can determine an individual's willingness to pay for marginal changes in paint attributes. Three key parameters were of particular interest: the relative willingness to pay for non-toxic paints vs. copper-based paints, the discount rate individual boaters use when making tradeoffs over time, and whether or not boaters take an economically rational lifetime cost perspective when making complicated cost calculations. We also consider the way in which choice behavior would change with altered expectations of future policies.

In the second stage, we use the estimation results to calculate the cost of achieving 100% abatement over various time horizons. Section 2.5 develops the specific framework used to derive policy cost estimates for this problem and presents our estimates. We estimate the costs of policies for completing the phaseout over various time horizons, ranging from immediate abatement to fifteen years, both accounting for and not accounting for the population's willingness to pay for environmental paint properties. The policy cost estimates are presented at the end of Section 2.3.

One particularly interesting feature of this case study is that, for a time horizon of fifteen years, the optimal policy turns out to have no social cost; moreover, abatement will happen voluntarily with very little policy structure. A fifteen year policy is thus attractive along many possible criteria of the policy maker, not only cost efficiency. Understanding the ease of implementation of this policy may induce policy makers in other regions facing the same policy problems (i.e. marine areas throughout the world) to adopt a similar policy, given that the cost is so low and the implementation so easy. Presuming that the goal of the policy was identified in order to achieve a more efficient level of pollution to society, identifying the ease of implementation could lead to even larger efficiency gains due to these political economy effects.[3] This additional efficiency gain is not addressed in this paper, but it is important to note that the sheer identification of worthwhile policies that would happen voluntarily is another reason to understand the choice behavior of the polluting individual in particular policy contexts.

Section 3.4 concludes with an attempt to characterize the type of policy problem found in San Diego Bay in a general form, in hopes that other policy problems can benefit from these findings.

2.2 Theoretical Framework

Consider an individual utility maximizing consumer deciding whether or not to adopt a new technology, and if so, choosing the optimal time of adoption. To model this consumer's decision under various policy scenarios, we develop the model of technology adoption used by Kerr and Newell (2003) which considers a profit maximizing firm's decision. Instead of a profit function, the agent here maximizes a utility function which depends on individual-specific utility parame-

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[3] To rigorously address the potential efficiency gains of these political economy effects would require a calculation of marginal social costs and benefits in order to understand whether any of these policies lead to the socially efficient outcome. The cost efficiency framework which is prevalent in the instrument choice literature allows us to recognize efficiency *gains* through means of implementation, but we do not ask which policy *goal* would provide incentives for a *fully* efficient outcome.

ters.[4]

We first define $\mathbf{K}_{it}$ to represent the units of capital owned by individual *i* at time *t* that he or she has the option of replacing with a newer technology. $\mathbf{K}_{it}^{\mathrm{O}}$ and $\mathbf{K}_{it}^{\mathrm{N}}$ denote the old and new types of capital, respectively. By imposing the constraint that the total capital owned by any agent in any given time is one unit (Equation (2.3) below), we restrict our attention to agents directly affected by the policy that targets this type of capital and assume that no consumer will chose to discontinue his or her personal use of the capital (whether by exiting an industry or exiting a leisure activity such as boating) because of the regulation.

Next we impose the hedonic assumption that individuals derive utility from the attributes of $\mathbf{K}_{it}$ and define $\mathbf{Z}_{it}$ to be a matrix of characteristics of each individual's capital at time *t*. In the context of a policy to phase out an old polluting technology, the capital characteristics prior to adoption of the new technology, denoted $\mathbf{Z}_{it}^{\mathrm{O}}$, include a polluting element, while the post-adoption capital, with attributes $\mathbf{Z}_{it}^{\mathrm{N}}$, is non-polluting. For example, if a recreational boater is deciding whether to switch from an old polluting antifouling paint to a new non-toxic paint, $\mathbf{Z}_{it}$ represents the characteristics of the individual's boat such as its age, size, and properties of its paint such as its cost of maintenance and environmental properties. $\mathbf{Z}_{it}^{\mathrm{O}}$ includes a polluting paint property while $\mathbf{Z}_{it}^{\mathrm{N}}$ includes a non-toxic paint property.

In addition to $\mathbf{Z}_{it}$, two other factors will affect the price of capital in our model. If the consumer faces regulation which is designed to induce a switch to the new technology, then the relative prices of the old and new technologies will be altered. We model a policy here as a time horizon in which the old polluting technology will be phased out, and we let R represent the length of this time horizon.[5] By not allowing R to change over time, we assume that the time horizon is known at the onset of the policy and does not change. Lastly, a "learning-by-doing" effect for

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[4] For this framework to be directly relevant to estimating the cost of an environmental policy, we need to assume that technology replacement is the only way in which the polluters will choose to abate. This is realistic for the policy problem of toxic boat paints since the only two ways to stop leaching copper into the water are to switch the type of paint or to stop boating. The cost of conversion to a non-toxic paint is unlikely to be so high as to force a boater to sell his or her boat. In general, it seems reasonable to assume that programs aimed at consumers attempt to be as non-distortionary as possible, so this assumption will rarely be binding.

[5] Any market-based instrument which is employed the achieve the phase-out will change the relative prices identically, so our model is agnostic about the specific form of the policy.

the new technology could also influence the price differential between alternative types of capital, and we can expect this effect to be particularly significant if a new environmental regulation creates a large-scale demand for a young product. The prices therefore depend on the extent to which other individuals in the population have already adopted the new technology, which we will denote as D_t.

Letting $\mathbf{P}_t^{\mathrm{K}}(\mathbf{Z}_{it}, D_t, R)$ represent the price of this capital over time, $\mathbf{X}_{it}$ represent all other consumption, and $\mathbf{P}_t^{\mathrm{X}}$ represent the price of all other consumption, we can model the individual consumer's technology adoption decision as choosing the time of adoption T to maximize her indirect utility:

$$\max_T \int_0^T U\left(\mathbf{Z}_{it}^{\mathrm{O}}, \mathbf{X}_{it}\right) e^{-rt} dt + \int_T^\infty U\left(\mathbf{Z}_{it}^{\mathrm{N}}, \mathbf{X}_{it}\right) e^{-rt} dt \tag{2.1}$$

$$s.t. \quad \mathbf{Y}_{it} + \mathbf{P}_t^{\mathrm{K}}\left(\mathbf{Z}_{it}^{\mathrm{O}}, D_t^O, R\right) \mathbf{K}_{it}^{\mathrm{O}} + \mathbf{P}_t^{\mathrm{K}}\left(\mathbf{Z}_{it}^{\mathrm{N}}, D_t^N, R\right) \mathbf{K}_{it}^{\mathrm{N}} = \mathbf{P}_t^{\mathrm{X}} \mathbf{X}_{it} \tag{2.2}$$

$$\mathbf{K}_{it}^{\mathrm{O}} + \mathbf{K}_{it}^{\mathrm{N}} = 1 \tag{2.3}$$

$$T <= R \tag{2.4}$$

where $\mathbf{Y}_{it}$ is income and r is the discount rate.

Normalizing the price of the representative good (setting $\mathbf{P}_t^{\mathrm{X}}$=1) and substituting constraints (2.2) and (2.3) into Equation (2.1), we can see explicitly that $\mathbf{Z}_{it}$ affects the agent's intertemporal problem both directly and through the price of capital:

$$\begin{aligned} \max_T \int_0^T & U\left(\left[\mathbf{Y_t} + \mathbf{P}_t^{\mathrm{K}}\left(\mathbf{Z}_{it}^{\mathrm{O}}, D_t, R\right)\right], \mathbf{Z}_{it}^{\mathrm{O}}\right) e^{-rt} dt \\ + \int_T^\infty & U\left(\left[\mathbf{Y_t} + \mathbf{P}_t^{\mathrm{K}}\left(\mathbf{Z}_{it}^{\mathrm{N}}, D_t, R\right)\right], \mathbf{Z}_{it}^{\mathrm{N}}\right) e^{-rt} dt \end{aligned} \tag{2.5}$$

In order to predict the T at which each individual will choose to convert, it is useful to simplify this dynamic optimization problem by imposing an arbitrage condition. Namely, we assume that an individual will adopt the new technology at the first time T where the investment provides a higher lifetime utility than not adopting the technology. The consumer's problem becomes choosing the first time T at which

$$V\left(\left[\mathbf{Y}_T + \mathbf{P}_T^{\mathrm{K}}\left(\mathbf{Z}_{iT}, D_T, R\right)\right], \mathbf{Z}_{iT}\right) \geq 0 \tag{2.6}$$

where $V(\cdot) = U\left(\mathbf{Z}_{iT}^{\mathrm{O}}\right) - U\left(\mathbf{Z}_{iT}^{\mathrm{N}}\right)$ represents the net utility gain from adopting the new technology at time T. As long as preferences are not time-inconsistent, the arbitrage condition is a sufficient condition and we can solve the consumer's problem using equation (2). Simply stated, in any given time period an individual will make the technology choice which leads to a higher lifetime utility. The overall cost of a policy that imposes a switch within the time horizon R is then the total lifetime cost of switching to this new technology, summed across all individuals, where each individual switches at the time within R that maximizes his or her lifetime utility.

In practice, a policymaker wishing to predict an agent's choice of T can model equation (2.6) for the targeted population. To do so, it is necessary to understand the agents' utility functions as well as the relationship between observable technological characteristics and the price of capital. An informed policy maker can understand the distribution of key parameters in each of these functions over the targeted population. In the following sections we examine a specific policy problem, the phaseout of toxic antifouling paints on recreational boats, and build a model of the consumer's technology adoption decision in order to better predict the actual effect of alternate policies on this decision. We therefore obtain more accurate estimates of overall policy cost, and in doing so we hope to demonstrate that a more accurate prediction of behavior can lead to the design of a more efficient policy.

2.3 Empirical Study: San Diego Bay

2.3.1 The Policy Problem

In many marine areas where recreational boats are densely located, concentrations of copper are being found to be in excess of government standards. The pollution is due to copper-based antifouling paints that boaters use to prevent organisms such as barnacles and algae from attaching to the bottoms of their boats. The attachment of organisms to a boat's hull has many undesirable effects on the boat's performance, including an increase in corrosion and drag, a reduction in safety and maneuverability, and decreased fuel efficiency. Antifouling paints function by slowly releasing copper into the water surrounding the hull, in order to act as a preventative biocide, and unfortunately the copper is harmful to these and other organisms in the marine environment at high concentrations. Copper is currently the most widely used biocide in antifouling paints.

San Diego Bay is one of the first marine areas to be targeted by regulatory agencies addressing the copper pollution problem. The California Regional Water Quality Control Board, San Diego Region has listed 50 acres in Shelter Island Yacht Basin in north San Diego Bay on the 1998 Clean Water Act Section 303(d) list as impaired for dissolved copper. (California Water Quality Control Board, San Diego Region 2001) This led to a study conducted under a legislative mandate to the California Resources Agency's Department of Boating and Waterways to investigate various policy instruments which could be used to induce recreational boat owners to switch from copper-based hull coatings to non-toxic alternatives. (Carson et al. 2002)

Non-toxic alternatives to metal-based hull coatings exist, but they currently are not widely available and are infrequently used. Interest is growing in these paints because of their environmental properties, greater durability, and because some of the coatings being developed appear to increase boat speed and decrease fuel usage. Further development of non-toxic hull coatings is likely to continue and may be accelerated as areas such as San Diego become aware of a growing copper contamination problem and start to adopt policy measures to deal with them.

By nature, non-toxic paints have different economic properties than copper-based paints, stemming from the fact that they do not function by releasing a biocide. For example, they need to be applied less often, but cleaned more often. Importantly, non-toxic hulls need to be stripped much less often than copper-based hulls; as the biocide leaches out of the copper paints, they need to be reapplied quite frequently (approximately every 2-3 years), and the build-up of old paint makes it increasingly difficult to apply new coats. After approximately 7 or 8 repaintings, all of the old paint must be stripped from the hull so that new paint can be applied. This process is expensive, as the boat must be hauled completely out of the water to be stripped clean, and the ability to repaint a boat's hull with copper paint multiple times before having to strip the old paint off acts like a capital asset that depreciates over time. Also importantly, non-toxic paints cannot be applied on top of copper-based paints, so a boat owner must retire this asset to convert a hull from copper-based paint to a non-toxic one. These fundamental features of different paint alternatives create a dynamic capital replacement problem that must be understood and accounted for when predicting the choice behavior of boaters and, consequently, when considering policies to induce conversion to non-toxic paints.

2.3.2 Econometric Framework

The choice experiment's main objective was to understand aspects of boat owner behavior that will allow us to predict their choice of paint technology under alternate policies. We therefore build an econometric choice model that allows us to answer the following four questions:

1) What is the relative willingness to pay for non-toxic paints vs. copper-based paints?
2) How do individual boaters make cost tradeoffs over time?
3) Do boaters take an economically rational lifetime cost perspective when making complicated cost calculations?
4) How would their choice behavior change with altered expectations of future policies?

We adopt the standard Random Utility Model (RUM) framework of McFadden (1973) in which each individual in the boater population faces a finite number of paint alternatives and chooses an alternative that maximizes his or her utility. We assume that the survey data collected were generated by the repeated drawing of an individual at random from the population, where we observed a vector s of each individual's attributes, the set A of alternatives available to the individual, and the individual's favorite choice x from the set A. Note that x is a vector of attributes which defines the chosen alternative.

Individual i's indirect utility from choosing paint j takes an additive form:

$$U_{ij} = V_{ij} + \varepsilon_{ij} \tag{2.7}$$

We interpret V_{ij} to be a representative component of utility, common to all individuals (containing the subscript i because the levels of attributes can and do vary across individuals, and because the parameters will be allowed to vary across individuals as discussed below), while ε_{ij} is an individual-specific component of utility, specific to the drawn individual i. We assume that the systematic component of utility can be written as a linear function of paint attributes

$$V_{ij} = \sum_{k=1}^{K} \beta_{ijk} x_{ijk} \tag{2.8}$$

where the β's are utility parameters, the x's are attribute levels, and K is the total number of attributes entering the utility function. Note that the β's contain the subscript i; in the most general specification, the utility parameters are not necessarily assumed to be constant across individuals.

In the RUM framework, we can model the boat owner's decision as a draw from a multinomial distribution with a certain selection probability, depending on the assumptions placed on individual choice behavior. This dissertation presents the results from two estimation procedures for the representative component of utility, each corresponding to different assumptions on individual choice behavior. The conditional logit model is the simplest and places the strongest assumptions on behavior, and the mixed logit (or random parameters logit) model relaxes some of these assumptions and allows for unobserved components among individuals. Results from the conditional logit specification are presented in this section, and the mixed logit estimation is discussed in the following chapter.

2.3.3 The Data

The choice experiment data was collected by surveying one hundred and eighty-seven recreational boat owners in San Diego Bay. Participants were drawn from the population of 7,342 boats kept at marina and mooring locations in the Bay. The sample of boaters contacted were drawn from a stratified random sample of boats, where stratification was done by area within the bay, based upon similarity of location and travel considerations. Table 2.1presents a summary of the sampling plan.

Table 2.1: Summary of Sampling Plan

Strata (Area)	**Percentage of Boats**	**Location Selected/ Number of Boats Sampled**
Chula Vista	12.6%	Chula Vista Marina/ 25
Coronado	10.2%	Coronado Yacht Club/ 20
Downtown /	36.8%	Cabrillo Marina/ 25
Harbor Island		Harbor Island West/ 25
		Sun Road Resort Marina/ 25
Shelter Island	32.9%	Half Moon Anchorage/ 22
		San Diego Yacht Club/ 22
		Shelter Pointe Marina/ 22
Moorings	7.5%	Laurel Street Mooring/ 15
Total	100.0%	200 Boats Sampled

Marinas were selected with a corresponding number of boat owners to be surveyed at that location. The specific slip numbers of boaters to be contacted at each marina were drawn randomly using marina maps in order to avoid a selection bias toward types of boats that may be clustered in one area of a given marina (e.g. if larger boats are all located toward one end of the docks). This was done using a simple method in which every k^{th} slip/mooring number was chosen where k is the number of completed interviews needed divided by the number of occupied slips/mooring at the given location. When k was not an integer we rounded down to the nearest integer.[6]

The surveys questioned boaters about their knowledge and preferences regarding copper hull paints and non-toxic alternatives.[7] We also collected a number of sample characteristics (age, income, etc.), and asked respondents about their boat's characteristics, their personal boating and boat maintenance habits, and their current knowledge of and preferences for various antifouling paints. Participants were then asked to complete twelve choice tables in which they selected their favorite and least favorite paint out of sets of four, where each paint was a different vector of the following five paint attributes: paint type, hull preparation cost, paint application cost, painting frequency, and hull cleaning frequency. The choices present in each table were generated by an orthogonal main-effects experimental design, as discussed in the following section.

Our survey also made use of a split sample design whereby half of those surveyed were given the following statement before the series of choice questions: "It is very likely that ten years from now all recreational boats in San Diego Bay will be required to be painted with a non-toxic paint." The other half of the sample was not given this statement.

Boat owners in our sample were mostly male, at and average age of 53, and generally well educated with upper-middle class income levels. 93% of the sample owned one boat in San Diego Bay with 7% owning two or more. The mean boat length was 36 feet with a range of 20 feet to 114 feet in length. Eighty percent of the boats were between 25 and 45 feet in length. Fifty-eight percent of the boats were sailboats. The average age of a boat was 20 years with the oldest boat being built in 1930 and the newest boat being built in 2001. Eighty percent of the boats were built between 1969 and 1997. The average number of years the boat had been owned was 6 years.

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[6] Predicting a survey response rate of 50%, we selected a sample of twice the size of the number of completed interviews desired. Hence we drew every k^{th} slip/mooring number twice, using two different initial randomly chosen starting points between the 1st and the k^{th} slip/mooring number. The two lists of boaters (generated from the two different starting points) were kept separately, and the second list was not contacted until all of the names on the first list were exhausted. This was also done to avoid a possible slip location effect within a given marina. Furthermore, a random starting point was used when taking names from the second list of boaters. Surveys were conducted both by mail and in person until approximately a 50% response rate was achieved and a total of 187 valid surveys were obtained.

[7] The survey instrument is presented in Appendix A.1.

Most of our sample reported using a copper based hull paint, although 5% of those surveyed reported using epoxy. (Epoxy appears to be the most widely used non-toxic alternative, and exhibits the standard properties of a non-toxic coating, discussed above.) The average boat was repainted every two and a half years and 16% of the boaters had at some time had their boats hauled out of the water for maintenance between paintings.

One part of the survey asked respondents to rank from one to five the importance of various factors when choosing between hull paints. The responses showed that some boaters are willing to switch to nontoxic paints even if they are substantially more expensive than copper (as supported by my choice experiment, discussed below). Other boaters appeared to be roughly indifferent between nontoxic paints and copper-based paints at similar prices and performance characteristics, while others even seemed to favor copper paint even if it is more costly than non-toxic hull coatings.

Most boaters (58%) did not know that the Regional Water Quality Control Board had found that there was a pollution problem involving copper in San Diego Bay. Of those that did know this, most were aware that the Regional Water Quality Control Board had found that recreational boats were the source of the problem. However, many of these boaters were unaware that copper was toxic to marine organisms, and substantially less than half of the respondents were aware that the Regional Water Quality Control Board was legally required to reduce the copper pollution to ensure that water quality standards were no longer violated in San Diego Bay. Taken together, these findings suggests that, while there is a group of reasonably well-informed boaters, the majority of boaters are not. One particularly telling figure for policy makers is that 76% of the boaters interviewed were not familiar with any specific non-toxic bottom paints.

2.3.4 Experimental Design

The context of the copper pollution problem is a perfect candidate for analysis by stated preference (SP) techniques. First off, non-toxic antifouling paints are a new product with a virtually non-existent current market, eliminating the possibility of obtaining substantial revealed preference (RP) data. Moreover, potential regulation could create a considerable new market for these paints, so whatever RP data may exist is likely of little interest to the current question faced by policy makers. Secondly, SP methods can get at the willingness-to-pay for specific paint qualities without worrying about the collinearity between attributes. For example, we can look separately at the weighting of paint application frequency and the weighting of paint type in the consumer's utility function, while this may not be possible with RP methods because these two attributes can essentially never be separated. SP methods can estimate these attribute-specific effects reliably, and allow us to concentrate only on the specific attributes of interest. (See Louviere, Hensher and Swait (2000) for a complete discussion of the advantages of stated preference data in specific contexts.)

In general, SP data is generated by a systematic experimental design in which the attributes and their levels are pre-defined without measurement error and are varied to create choice alternatives. The experiment in this study creates paint choice alternatives with five distinct attributes: paint type, one-time hull preparation cost, paint application cost, painting frequency, and hull cleaning frequency, each with four distinct levels. Table 2.2 presents the attributes and their respective levels that were varied across choice alternatives.[8]

An orthogonal main effects design was used to generate choice tables in my surveys. As such, only the main effect of an attribute can be estimated and tested.[9]

2.4 Estimation

I first estimate a standard conditional logit model, which assumes the elements of ε_{ij} are independent and identically distributed draws from the Type 1 extreme

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[8] The fifth attribute, cleaning frequency, is perfectly collinear with the first attribute, paint type, in all choice sets. Cleaning frequency takes a value of 12 times yearly for all high copper alternatives and 18 times yearly for the other three paint types. This can be viewed as an explicit specification of a technology constraint, as the required cleaning frequency is an important characteristic of paint type which, as discussed above, cannot be separated from its environmental properties. The cleaning frequency attribute makes this technology constraint explicitly clear to the respondent, and I discuss its implications for the interpretation of the model's coefficient when presenting my results, below.

[9] For the model to be well-specified, this type of experimental design implicitly assumes that there are no interaction effects between the different attributes. This assumption is standard, and has little impact on practical predictions of choice behavior. See Louviere et al. (2000) for a discussion of main effects designs.

Table 2.2: Attributes and Attribute Levels

Paint Type	**Hull Conversion Cost**	**Paint Application Cost**	**Paint Application Frequency**	**Hull Cleaning Frequency**
High Copper	$0	$1,500	2 years	12 times (yearly)
Low Copper	$1,000	$2,000	3 years	18 times (yearly)
Epoxy	$2,000	$2,500	4 years	
Silicone	$3,000	$3,000	6 years	

value distribution. (McFadden 1973) The independence assumption creates a simple and powerful model, allowing choice probabilities to be evaluated analytically, but at the expense of embodying several well-known restrictions on choice behavior, including the troublesome Independence of Irrelevant Alternatives (IIA) property. (McFadden 1981, Train 2003) Also, by assuming that that the estimated utility parameters are homogeneous across all choice situations, the model does not allow for random variation in preferences. These issues are addressed in the following chapter, where I estimate the more general mixed logit specification. In this section, I examine the conditional logit model with a simple functional form that includes only paint attributes and also with a form which includes interaction terms between attributes and individual characteristics. I then use my estimation results to gain an overall picture of choice behavior among San Diego Boaters in order to more accurately estimate the cost of alternate policies.

The variables used in the estimations are summarized in Table 2.3. Each observation is a paint alternative in a choice set and is defined by a vector of attributes. The dummy variable fav denotes whether or not an observation is chosen as a favorite paint and serves as my dependent variable.

Results: Simplest Model

Table 2.4 presents the estimation results for the initial conditional logit model, where I estimate a utility parameter for each attribute and one for each attribute-

Table 2.3: Summary of Estimation Variables

Variable	**Description**
fav	Limited dependent variable signifying choice
$highcu$	Dummy variable for high copper paint type
$lowcu$	Dummy variable for low copper paint type
$epoxy$	Dummy variable for epoxy paint type
$silic$	Dummy variable for high copper paint type
$concost$	One time hull conversion cost attribute
$appcost$	Paint application cost attribute Must be paid each time the paint is reapplied.
$pfreq$	Frequency with which the paint must be applied
$nontoxic$	Dummy for non-toxic paint type
$totcost$	"Total cost" attribute. (= $concost$ plus $appcost$)
$income$	Index of boater income ranging 1-9. (1=\$25,000 or less, 5=\$100,001-125,000, 9=\$200,001 or more)
$educ$	Index of boater education ranging 1-6. (1=high school grad or less, 2 = some college, 3 = associates degree 4=B.A., 5 = graduate degree (M.A., Ph.D.) 6 = prof. degree (J.D., MBA)
$educ1 - educ5$	Dummy variables for education categories 1 through 5
$noninc$	Interaction term between $nontoxic$ and $income$
$noneduc$	Interaction term between $nontoxic$ and $educ$
$costinc$	Interaction term between $totcost$ and $income$
$costeduc$	Interaction term between $totcost$ and $educ$
$pfreqinc$	Interaction term between $pfreq$ and $income$
$pfrqeduc$	Interaction term between $pfreq$ and $educ$

level dummy in the case of the qualitative attribute, paint type. Note that $highcu$ is the omitted paint type dummy and therefore high copper paint serves as the baseline when interpreting the paint type parameters.

Looking at these first estimates, the only attribute that appears not to be significant is the $lowcu$ dummy. This suggests that boaters did not distinguish between high-copper and low-copper types when selecting paints. A likelihood ratio test confirms this result.[10] Considering that the survey did not provide much information that distinguished between these two types, this result is not surprising.[11] I

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[10] The likelihood ratio test statistic for this test is 0.07.

[11] In practice, low-copper paints do not release less copper than high-copper paints; they just

Table 2.4: Conditional Logit Parameter Estimates: Initial Estimates

Variable	Coefficient	Standard Error	z	P $> \|z\|$
$lowcu$	0.024818	0.136560	0.182	0.8558
$epoxy$	0.601462	0.137711	4.368	0.0000
$silic$	0.623348	0.132883	4.691	0.0000
$concost$	-0.000737	0.000034	-21.831	0.0000
$appcost$	-0.000788	0.000061	-12.843	0.0000
$pfreq$	0.540666	0.022281	24.266	0.0000

Log likelihood = -1548.503

also tested whether respondents differentiated between epoxy and silicone paint types when choosing a favorite paint and, again, found that they do not ($i.e.$ estimation with a dummy variable for "nontoxic" is equivalent to estimation with the two separate dummies for epoxy and silicone).[12] This suggests that the environmental property of the two non-toxic paints is the significant element factoring into the average boater's decision, and also is unsurprising since very few boaters are familiar with specific non-toxic paints and the survey tells the respondent little else about the differences between these two types.

A final likelihood ratio test confirms that I cannot reject the hypothesis that respondents do not treat hull conversion costs and paint application costs differently in a significant way.[13] I therefore estimate the model using a variable for "paint cost" (denoted $pcost$), which is the sum of the two cost attributes, $concost$ and $appcost$. This result supports the notion that respondents are behaving rationally, since it essentially demonstrates that two different cost attributes are treated equivalently, regardless of how the dollars are being spent.[14]

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need to be re-applied more often.

[12] The likelihood ratio test statistic for this test is 0.06.

[13] The likelihood ratio test statistic for this test is 1.09.

[14] It should be noted that, because paint application frequency is included as a separate attribute, the paint application cost attribute captures only the *magnitude* of the cost, which is why the application cost attribute should be treated identically to the hull conversion cost attribute by rational respondents.

With these insights into the average boater's utility function, I re-estimate the parameters of interest with the simplest form for ease of interpretation. The updated conditional logit parameter estimates are presented in Table 2.5.

Table 2.5: Conditional Logit Parameter Estimates: Revised Model

Variable	Coefficient	Standard Error	z	P $> \lvert z \rvert$
$nontoxic$	0.596251	0.076367	7.808	0.0000
$pcost$	-0.000745	0.000032	-23.300	0.0000
$pfreq$	0.544622	0.021907	24.861	0.0000

Log likelihood = -1548.945

An average boater's relative willingness to pay for marginal trade-offs between different attributes can be inferred by looking at the ratio of the attributes' coefficients. The results show that the average boater is willing to pay \$800 more for non-toxic paint than for copper-based paint, controlling for other attributes.[15]

Also, the average boater is willing to pay \$734 in order to delay painting her boat for one year. This figure is close to the cost that an average boater pays for hull paint, and the difference can be used to infer the discount rate with which he or she trades off costs over time. In my sample of boat owners, the average boater's discount rate is approximately 5%. Derivation of this rate is presented in Appendix A.2. This rate is quite reasonable and is likely consistent with rate of return being earned by respondents on other investments at the time of my survey, given the average income level of my sample. Furthermore, since this estimate was not achieved by asking directly but instead was deduced from their choice behavior, it suggests that respondents are behaving rationally in their decisions regarding cost are highly capable of calculating and comparing costs across alternatives and over time.

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[15] It should be noted that, by capturing the willingness-to-pay for the reduced cost of needing to clean the hull less often, inclusion of the cleaning frequency coefficient may cause the inferred willingness-to-pay the nontoxic paint property to be underestimated.

Results: Interactions with Individual Characteristics

It is, of course, reasonable to believe that specific characteristics of individual boaters could affect the relative utility gained from certain paint attributes. For example, wealthier boaters could potentially be less sensitive to the cost of a paint. To examine the individual-specific effects within the framework of the conditional logit model we include in the regression interaction terms between individual characteristics and paint attributes.

First we examine the above mentioned question - whether income affects the disutility a boater gets from paint cost - by including the interaction term $costinc$. Table 2.6 presents the results of this regression. (Refer to Table 2.3 for descriptions of all the variables, including the interaction terms.) Surprisingly, the coefficient was of the opposite sign than one might initially expect. Boaters with a higher income have a greater disutility of cost than lower income boaters, although the coefficient is significant at the 10% level but not at the 5% level.

Table 2.6: Conditional Logit Estimation with Cost & Income Interactions

Variable	Coefficient	Standard Error	z	P $> \|z\|$
$nontoxic$	0.656171	0.081752	8.026	0.0000
$totcost$	-0.000616	0.000077	-7.987	0.0000
$pfreq$	0.546880	0.023459	23.312	0.0000
$cost * inc$	-0.000024	0.000013	-1.838	0.0661

Log likelihood = -1356.303

We next considered whether education was the driving factor of this result by adding the interaction variable $costeduc$ to the previous regression. The estimates are shown in Table 2.6. These results show that education indeed explains the income effect that we saw before. The $costinc$ interaction is no longer significant while $costeduc$ is negative and highly significant.

A similar analysis was used to examine the interactions between the nontoxic and paint frequency attributes and the income and education individual characteristics. The regressions showed that $noneduc$ is highly significant whereas $noninc$

Table 2.7: Conditional Logit with Cost & Income and Cost & Educ Interactions

Variable	Coefficient	Standard Error	z	P $> \|z\|$
$nontoxic$	0.661473	0.081874	8.079	0.0000
$totcost$	-0.000370	0.000114	-3.245	0.0012
$pfreq$	0.548635	0.023522	23.324	0.0000
$cost * inc$	-0.000011	0.000014	-0.804	0.4212
$cost * educ$	-0.000063	0.000022	-2.875	0.0040

Log likelihood = -1352.136

is now not significant, and neither $pfreqinc$ nor $pfrqeduc$ were significant. We also find evidence that the relationship between educational attainment interactions and paint choice is highly nonlinear, so we estimate the model with interaction terms between $nontoxic$ and dummies for each education category, where category 6 (professional degree) is the omitted category. Table 2.8 presents the results of this regression.

Table 2.8: Conditional Logit Estimation with Education Interactions

Variable	Coefficient	Standard Error	z	P $> \|z\|$
$nontoxic$	1.230069	0.217679	5.651	0.0000
$pcost$	-0.000752	0.000032	-23.365	0.0000
$pfreq$	0.549841	0.022113	24.865	0.0000
$nontoxic * Educ1$	-0.433133	0.457763	-0.946	0.3440
$nontoxic * Educ2$	-0.910256	0.275093	-3.309	0.0009
$nontoxic * Educ3$	0.752254	0.424511	1.772	0.0764
$nontoxic * Educ4$	-0.813061	0.251204	-3.237	0.0012
$nontoxic * Educ5$	-0.771264	0.261559	-2.949	0.0032

Log likelihood = -1533.465

Educational attainment appears to be a strong predictor of environmental preferences. The relationship clearly is nonlinear, with individuals with a professional degree (education level 6, which is the baseline level in the estimation shown in Table 2.8) or an Associate's degree (which includes teaching certificates and nursing degrees) placing the highest premium on non-toxic paints.

Effect of an Expected Future Copper Ban

Lastly, we turn to the third question that the choice experiment set out to answer: how boaters' choice behavior would change with altered expectations of future policies. As discussed above, half of each version of the surveys included a statement that copper paints will likely be banned in ten years, while the other half of the surveys did not include this clause.

The inclusion of this clause had a significant effect on the respondents' paint choices, providing a powerful result from a policy perspective. Since a split-sample design was used, the effect of this clause does not need to be analyzed under a specific model specification. We therefore restrict our attention to the sub-sample of high copper paint alternatives and ask whether the statement made a copper choice significantly more likely to be chosen. Using a simple t-test of the difference between two means, we find that respondents who did not have the statement in their surveys were on average 26% more likely to select a copper paint as the paint that they would choose when they next have their boat repainted. As it is likely that the information in this statement could have been easily inferred by some respondents from earlier information in the survey ($e.g.$ questions about the legal requirement of the Regional Water Quality Control Board to reduce copper pollution), the statement's true impact may be underestimated here.

2.5 Policy Cost Estimation

From the results of our estimation, we know some key features of the boater population in San Diego Bay. The average boater is willing to pay $800 more for a non-toxic paint than for a copper paint, other attributes being held equal. This willingness-to-pay is not uniform across boaters, and one predictor for the distribution is the distribution of educational attainment across the population.

We also know that, when choosing a paint, the average boater trades off costs over time with a rational lifetime-cost perspective and with a discount rate of approximately 5%. Lastly, we know that paint choices are affected by altered expectations of future policies. In this section, we look at the effect of these findings when estimating the costs of policies to achieve copper abatement.

The cost of the optimal (from a cost efficiency standpoint) policy to achieve abatement in a given time horizon can be calculated as the sum of the total lifetime cost of converting to non-toxic paint.[16] The upfront conversion cost and the additional costs of maintaining non-toxic paints, over the costs of maintaining copper-based paints, must be summed over all boaters, assuming that each boat owner chooses the optimal time to convert. The relevant time horizon for these costs is the remaining lifetime of each boat, regardless of whether or not the boater will own her boat until its expiration, because any change in the lifetime maintenance cost of a boat will be reflected in the boat's resale value.

When choosing the optimal time for conversion, each boater will consider gains from minimizing the maintenance cost over the remaining lifetime of the boat and gains from desirable paint properties. The gains from desirable paint properties can be realized both through one's own direct utility and through the resale value of one's boat; thus, with a perfect resale market, every boat owner will account for the population's willingness to pay for the non-toxic paint property. One can model a boat owner as wanting to maximize a utility function which, as we saw in Section 2.2, depends on the resale value of his or her boat and on his or her personal willingness to pay for other boat characteristics, where the only control variable is paint type.

The resale value of a boat that is bought or sold in the population of boaters in San Diego Bay can be modelled using the results of our choice experiment. Invoking the same assumption from Section 2.3, that cost and willingness to pay for environmental properties are additively separable in a boater's utility function, we can model the resale value ($\mathbf{P}_t^{\mathrm{K}}$ from Section 2.2) of a boat as:

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[16] Whether this cost is borne by the boat owners themselves, a government subsidizing the conversion, or any other group of agents, is, of course, irrelevant when calculating the overall cost of the policy.

$$\mathbf{P}_t^{\mathrm{K}} = V_0\left(\frac{1}{1+\theta}\right) - Cost(\mathbf{Z}_{it}) + WTP(\mathbf{Z}_{it}) \tag{2.9}$$

where $\mathbf{Z}_{it}$ here refers only to antifouling paint characteristics, V_0 represents the components of a boat's gross value which cannot be affected by changing antifouling paints, and V_0 depreciates at rate θ. Boaters can affect the $Cost(\mathbf{Z}_{it})$ and $WTP(\mathbf{Z}_{it})$ components of a boat's resale value with their paint decision.

In estimating policy costs, one could think about three different models of policy costs, each with an increasing degree of accuracy. In the first, all boaters in the population are modelled solely as cost minimizers. In the second, boaters are modelled as resale value maximizers (controlling for boat characteristics which are unaffected by paint type) and the average willingness to pay for environmental paint properties in the population is accounted for in the resale value calculation. In the third, boaters are modelled as utility maximizers where they trade off resale value gains with their own utility gains achieved by their choice of paint. Another way to look at this third type of model is to think of a perfect resale market in which the heterogeneity in willingness-to-pay across boaters is fully accounted for. Chapter 3 of this dissertation addresses individual-level preference heterogeneity and its policy implications.

In this section, we estimate the cost of the optimal policy in the first two types of models. We can then calculate the difference in the cost of a copper phase-out when we account for the overall willingness to pay for environmental properties in the population, as it affects the value of each boater's capital, and we consider the efficiency gains achieved by including the effect of the overall WTP on the resale value of each boat.

2.5.1 The Epoxy-Copper Lifetime Cost Differential

Whatever his or her objective function, a boat owner will consider the difference in this function, summed over the boat's remaining lifetime, between copper paint and nontoxic paint. We consider epoxy paint as our baseline nontoxic paint (with baseline cost assumptions given in the discussion below) because it is currently the most widely used nontoxic paint and its cost and maintenance properties are similar to many other nontoxic paints.

In this section, we model the epoxy-copper lifetime cost differential for two objective functions, simple cost minimization and resale-value maximization, in order to demonstrate the increased accuracy in policy cost estimates achieved by accounting for the population's overall WTP. Comparisons between the resulting policy cost estimates are presented at the end of the section, in Table 2.9.

Individuals as Simple Cost Minimizers

We model total maintenance cost as consisting of the same three maintenance costs that appeared in the survey's choice tables: painting cost, cleaning cost, and stripping cost (or "one-time hull preparation cost" as described in the surveys). Surveys of boatyards revealed that these are the primary components of paint-related costs faced by a typical boat owner and provided us with baseline assumptions regarding the levels of these costs and the average frequencies with which they need to be incurred. Our baseline cost assumptions are as follows, where epoxy paint is used as our standard non-toxic paint: Hulls with copper-based paints need to be repainted every 2.5 years at a cost of $30 per square foot for a standard painting job. Non-toxic paints need to be applied every 7.5 years and costs $40 per square foot to apply. Hull cleaning costs $1 per square foot and must occur 14 times a year for copper hulls and 22 times a year for non-toxic hulls. A hull must be stripped after every 6th repainting at a cost of $150 per foot of a boat's length. All boats are retired at 30 years of age.

The nature of the stripping cost provides important intuition with regard to policy design. A hull that is painted with copper paint will accumulate a build-up of old paint because the biocide leaches out of the paint and therefore new paint must be applied relatively often. The new paint is typically applied on top of the old paint until there is too much accumulation to effectively apply more new paint. At this point, usually after about 6 re-paintings, all of the old paint needs to be stripped off of the hull in order to apply more paint. Essentially, the lack of copper paint accumulation on a boat's hull is a depreciating capital asset. Nontoxic paints must be applied to a clean (stripped) hull, making the decision to switch paint types a dynamic capital replacement problem in which the boat owner must choose when to replace depreciating capital.

To formally model these costs, let $C(t; l, c_f, c_c) = \sum_{i=1}^{E*c_f} \delta\left(t - i/c_f\right) * c_c * l$, where c_c is the cost of cleaning the boat which occurs with a frequency c_f, and where $\delta(\cdot)$ is the Dirac delta function, with the property that $\int_{-\infty}^{\infty} \delta(x) * f(x)\, dx = f(0)$, a is the age of the boat today, and l is the length of the boat.[17] Similarly define $P(t; l, p_f, p_c) = \sum_{i=1}^{E*p_f} \delta\left(t - i/p_f\right) * p_c * l$ as the recurring cost of painting the boat and $S(t; l, s_f, s_c) = \sum_{i=1}^{E*s_f} \delta\left(t - i/s_f\right) * s_c * l$ as the cost of stripping the boat. The individual cost-minimizing boat owner therefore chooses T, the time to switch to non-toxic paint, to solve:

$$\begin{aligned}\min_T \int_a^T & \left(C\left(t; l, c_f^0, c_c^0\right) + P\left(t; l, p_f^0, p_c^0\right) + S\left(t; l, s_f^0, s_c^0\right)\right) * e^{-r(t-a)}\, dt \\ & + \int_T^E \left(C\left(t; l, c_f^1, c_c^1\right) + P\left(t; l, p_f^1, p_c^1\right) + S\left(t; l, s_f^1, s_c^1\right)\right) * e^{-r(t-a)}\, dt \qquad (2.10)\end{aligned}$$

Substituting the baseline cost assumptions (given above) into equation (2.10), we can simulate the objective function that each boat owner calculates when deciding which paint to apply. Figure 2.1 plots, for each paint type, the total remaining lifetime cost of maintenance as a function of boat age.

The copper curve is simply the present discounted value of the cost of hull maintenance if the boat owner continues to choose copper-based paint for the remainder of the boat's life. The epoxy curve plots the present value of the cost of choosing to convert the boat's hull to epoxy paint today, and to continue to choose epoxy paint for the remainder of the boat's life. Each boat owner compares these two costs and chooses the lower one. For example, a boat owner with a new boat (age 0) faces a cost differential which favors epoxy paint because he does not need to strip the boat today in order to apply epoxy. At all other boat ages, the cost of choosing to convert to epoxy paint will include the one-time cost of stripping the old copper paint off the boat's hull today. It is this factor that drives the dramatic differences in the cost of conversion across various aged boats. Boats that need to

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[17] The Dirac delta function is used here to represent discrete costs incurred in a continuous time framework. Basically, this function is the limit of a standard normal distribution as its variance shrinks to zero. It returns an impulse with mass 1 when its argument is 0 and returns 0 for all other arguments.

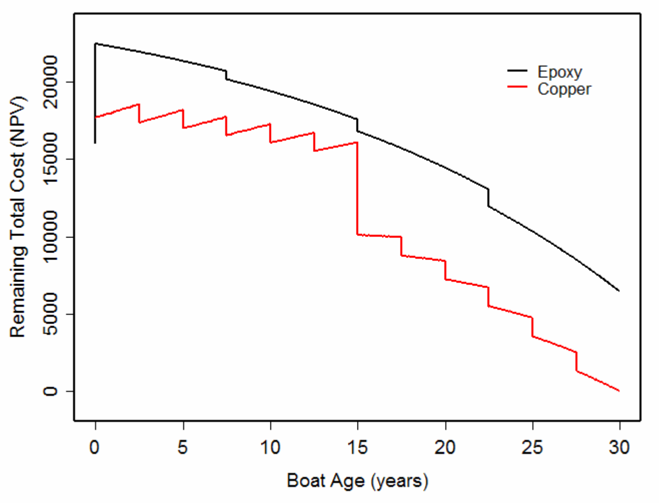

Figure 2.1: Lifetime Future Costs of Maintenance for Copper-Based and Epoxy Paints (NPV)

strip their hull anyway in order to reapply copper paints will face a more favorable cost differential toward epoxy paint. On the other hand, an individual with a 15 year old boat that has just stripped the boat's hull and reapplied copper paint will face a cost differential that favors copper by over $7,000.

Figure 2.2 plots the difference between these two curves. Essentially, this figure plots the total lifetime cost of conversion to epoxy paint as a function of boat age if the boater were to choose to convert today. From this figure, we can see clearly the significant effect of capital depreciation on the overall cost of converting to non-toxic paints. New assets (one-day old boats and just-stripped boats) face cost differentials which are quite favorable to copper paints, while fully depreciated assets (new boats and boats that are about to strip the hull today) face the cost differentials which are relatively more favorable to non-toxic paints. The smaller fluctuations in the differential result from different application properties of the two paint types. For example, each time a boat has just applied copper paint the cost of conversion spikes upward, and each time a boat passes an age at which it will require one fewer epoxy applications over its lifetime, the cost of conversion drops (*i.e.* at age seven and a half, a converting boat will suddenly require two epoxy paint re-applications over its lifetime, as opposed to a seven year old

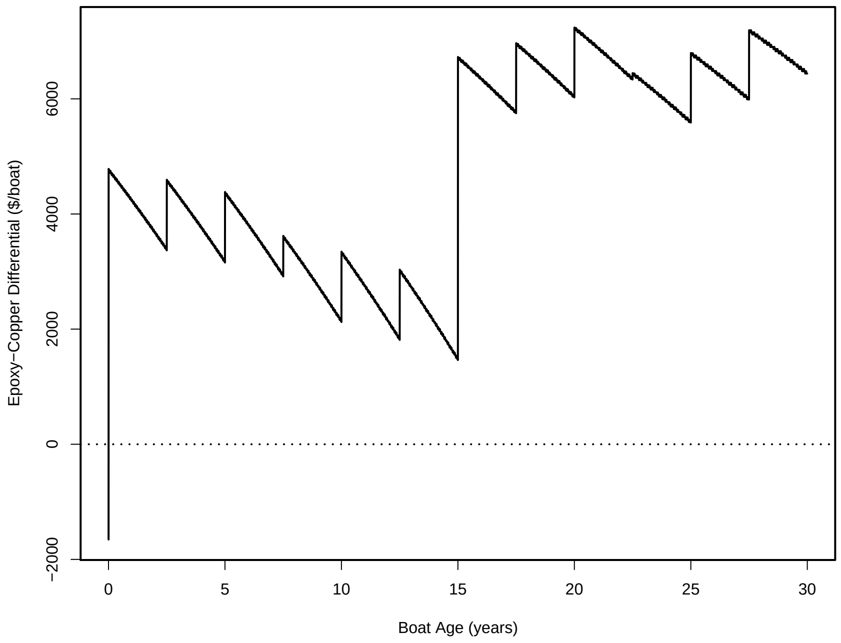

Figure 2.2: Lifetime Total Cost Differential Between Epoxy and Copper-Based Paints (Not Accounting for WTP)

boat which will require four.)

The total cost of a policy that induces all boat owners to convert to epoxy paint will equal the sum of the conversion costs across all boat owners, given that they each choose the optimal time to convert. (Equivalently, the policy cost can be thought of as equalling the sum over all consumers' solution functions). For example, if the conversion must occur immediately, this cost is equal to the integral of the cost differential curve in Figure 2.2. This policy would cost approximately $33.9 million for a population of 7,000 boats of uniform age distribution. Similarly, if the conversion can occur over multiple time periods, the policy cost is equal to the area under the cost-differential curve over all consumers who convert to non-toxic paint in each period, summed over all time periods of the policy. It is important to note that new boats face a cost differential that favors epoxy without any government intervention (stemming from the fact that they have not already invested in a copper asset). Since a rational and fully informed owner of a brand new boat should choose epoxy to minimize costs in the absence of government intervention, we do not include the surplus received by these boaters in our policy cost calculations. However, an information campaign coupled with any government policy would help these owners of new boats to achieve these gains.

In San Diego Bay example, the policy maker's problem is to design a policy to induce a 100% phase-out of copper over a specified time horizon while minimizing the the overall cost of the policy. The intuition needed to solve the policymaker's problem can be seen in Figure 2.2. A least-cost policy that achieves abatement in fifteen years is one which reverses the cost differential for the fifteen-year old boats (the ones with the lowest differential) but does not affect the cost differential of boats at other ages by enough to change affect the paint choice decisions at these points in a boat's lifespan. For example, a market-based policy such as a copper tax that reverses the cost differential by approximately $1,500 would induce every boat to convert when it reaches age fifteen. New boats will apply epoxy paint at the start of their lives and, since boats retire at age 30, boats that are older than fifteen years old at the onset of the policy will be retired by the end of the policy's fifteen year time horizon. All remaining boats will have non-toxic hulls by the end of the policy's term. We calculate the cost of this fifteen-year old policy to be approximately $2.4 million for a population of 7,000 boats of uniform age distribution.

The costs of policies with other time horizons can be derived in the same way, by determining when each boater would choose to convert if she knew she would need to have a non-toxic hull by the end of the given time horizon, calculating the epoxy-copper cost differential to each boater if they she chooses this optimal conversion time, and summing the cost differential across all boaters. Any optimal market-based policy would function by offsetting the cost differential just enough such that boaters will choose to convert when optimal, essentially targeting the right boaters to convert at the right time. Similarly, the cost of a policy that achieves abatement immediately would simply equal the integral under the epoxy-copper differential function in Figure 2.2. Policy costs for various time horizons are presented in Table 2.9.

Individuals as Resale Value Maximizers

As we know, the policy cost estimations in the previous section are not entirely accurate because boaters are not solely cost minimizers. The willingness to pay for environmental properties will alter the value of every individual's capital, regardless of the owner's personal environmental preferences, and will thereby alter the choice behavior of boaters. This section demonstrates the effect on policy costs of accounting for this willingness-to-pay in the boater population.

Modelling a boat's resale value as an additive function of cost and WTP for nontoxicity, we shift the cost differential curve in Figure 2.2 down by the average WTP for the non-toxic paint property in order to derive the lifetime differential between the resale values of copper and epoxy paints (on an otherwise identical boat). It should be noted that the curve does not shift uniformly. Because the average boater is willing to pay $800 more for a nontoxic paint, we assume that boaters are willing to pay, on average, $800 for seven and a half years of the non-toxic paint property, since 7.5 years is the average lifetime of a non-toxic epoxy paint. Therefore, the longer the remaining life of a boat, the more the resale value of boats with epoxy will shift upward. Figure 2.3 shows the lifetime costs of each paint type, offset by the average willingness to pay for its environmental properties. Figure 2.4 plots the differential between these two values.

One interesting policy implication can be seen in Figures 2.3 and 2.4. Once the $800 average WTP is accounted for, owners of fifteen year old boats face a cost differential which favors epoxy paint without any government intervention. If boat owners are fully informed and epoxy paints were widely available, owners of new boats *and* owners of fifteen-year-old boats would be likely to voluntarily choose nontoxic paints. 100% abatement of copper would then happen on its own over fifteen years, at no cost to the government agency and with no overall utility loss to the population of boaters. Since we know from our choice experiment that current decisions by boat owners are affected by altered expectations of future policies, the conversion can be spurred by the announcement that copper paint will be banned fifteen years into the future.[18]

Table 2.9 presents the policy cost estimates for various time horizons, both

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[18] Chapter 1 of this dissertation discusses this result in more depth.

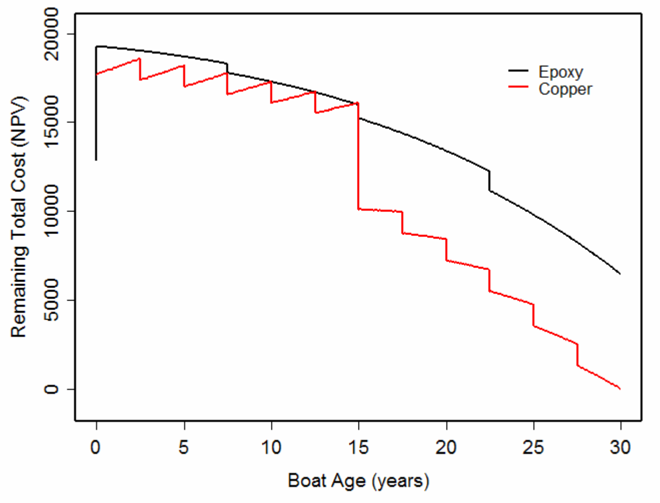

Figure 2.3: Lifetime Future Costs of Maintenance for Copper-Based and Epoxy Paints (NPV), Offset by WTP for Non-Toxic Paint

accounting for and not accounting for the population's average WTP for the non-toxic paint property.

Table 2.9: Policy Cost Estimations (Millions of $)

Horizon	No WTP	WTP=$800
Immediate	33.9	22.7
1 Year	27.3	17.6
2 Year	23.2	14.5
5 Year	13.9	8.5
10 Year	5.8	2.6
15 Year	2.4	0.0

2.6 Conclusion

When designing a policy to induce agents to adopt a non-polluting behavior such as the adoption of a cleaner technology, a policymaker can accurately achieve

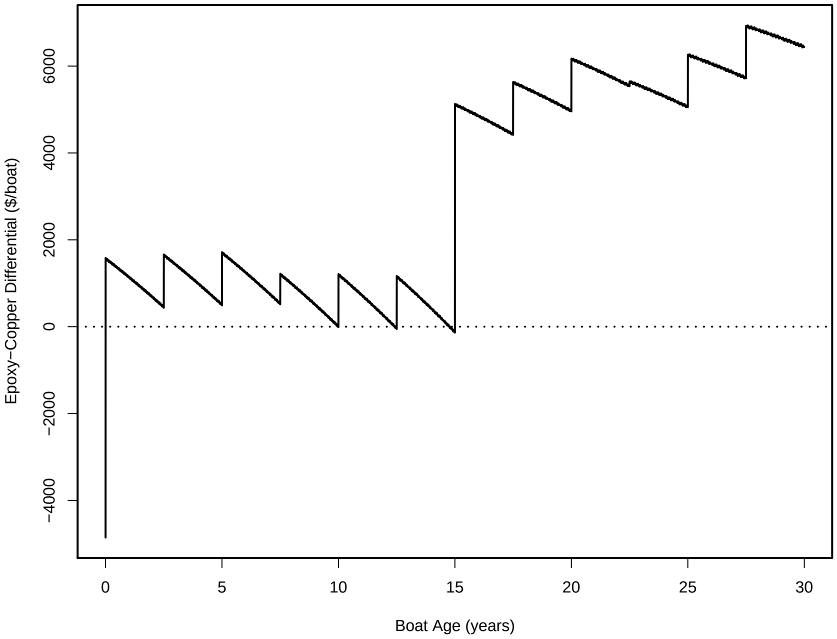

Figure 2.4: Lifetime Total Cost Differential Between Epoxy and Copper-Based Paints, Offset by WTP for Non-Toxic Paint

a least-cost policy only with an accurate model of agents' response to the policy. Since individual agents are utility maximizers with utility functions that depend on non-market values as well as financial costs, policymakers can benefit from studies, such as a choice experiment or contingent valuation analysis, that estimate the willingness to pay for non-market values in the target populations. As we have demonstrated with our analysis policy options to phase out copper-based antifouling paints in San Diego Bay, accounting for boat owners' willingness-to-pay for environmental paint properties can allow us to reduce the policy's cost by $2.4 million for a fifteen-year abatement policy, or by $11.2 million for an immediate abatement policy, in a population of 7,000 boats.

Because we accounted only for the effect of a population's overall willingness-to-pay for environmental properties, and did not consider explicitly the distribution of preferences within the population, this chapter's analysis is incomplete. The following chapter investigates the distribution of preferences in our sample and, specifically, analyzes the effect of preference heterogeneity on choice behavior, and thus on the time path of abatement under pollution control policies.

3

The Role of Heterogeneity in Driving the Speed of Pollution Abatement

Abstract

This paper presents evidence that consumer preferences toward environmental attributes can be highly heterogeneous, and the distribution of tastes drives the time path of abatement under policies that target individuals. Prior studies tend either to ignore the speed of compliance/adoption by conducting static analyses or ignore heterogeneity by taking a representative agent approach; even models that condition on covariates at the individual level can be plagued by the fact that unobservable characteristics often are the primary drivers of the choice behavior of interest. Using the results of a choice experiment with recreational boaters in San Diego, I find that individuals vary greatly with respect to their environmental preferences. I demonstrate that, in the case of a policy to phase out toxic antifouling paints on recreational boats, this heterogeneity across boaters will cause initial abatement to occur more quickly but the ultimate target to be achieved more slowly than in a homogeneous population, and the greater the variance the more this effect is exacerbated. Not understanding and accounting for this heterogeneity

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[0] I am tremendously grateful to Richard T. Carson, Eli Berman, Joshua Graff Zivin, Dale Squires, Tom Corringham, Roger Gordon, and the Environment and Resource Group at UCSD for valuable comments and suggestions. The National Science Foundation and the Center for Marine Biodiversity and Conservation at the Scripps Institute of Oceanography provided generous support for this research. An earlier version of this paper was presented at the Third World Congress of Environmental and Resource Economists in Kyoto. All remaining errors are my own.

will prevent a policymaker from achieving targets in desired timeframes. I also discuss implications of this finding for the optimal design of pollution control policies that target consumers.

3.1 Introduction

Environmental policies often aim to induce agents to adopt new technologies, to upgrade or replace old capital earlier than they would otherwise, and/or to change their behavior in ways that result in altered dynamic costs, such as through participation in voluntary programs. This paper demonstrates that, in all of these cases, individual-level heterogeneity can cause initial abatement to occur more quickly but an ultimate emissions target to be achieved more slowly than in a homogeneous population.

An extensive literature investigates determinants of pollution abatement decisions and, in particular, the adoption of abatement technologies under environmental policies. Much of this work is theoretical and models the overall incentive effects of alternate policy instruments. (See Baumol and Oates (1988), Milliman and Prince (1989), and Jung, Krutilla and Boyd (1996) for prominent examples.) This research often aims to determine cost advantages of particular instruments in particular contexts, and economists generally accept that price-based instruments such as taxes and tradeable pollution quotas minimize the aggregate cost of achieving given levels of abatement, at least in a theoretical, first-best setting.[1]

In more recent work, Newell and Stavins (2003) point out that, despite this recognition, little is known about the precise nature of this prospective cost savings. While it is accepted that the cost advantages of market-based approaches come from gains in trade stemming from abatement cost heterogeneity, there is a dearth of studies that examine the relationship between the nature and/or magnitude of this heterogeneity and the potential cost savings. Similarly, other potentially important effects of individual-level heterogeneity, such as its impact on the time-path of abatement under various policies, also remain largely unexplored, along with the implications of such impacts.

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[1] Weitzman (1974) and Mendelsohn (1986) are important and widely-cited studies in this area.

This paper presents an empirical study in which individual consumers are targeted by policymakers, and individual choice behavior must be understood to achieve abatement targets in desired time-frames. I find evidence that consumer preferences toward environmental attributes are highly heterogeneous, and the distribution of tastes drives the time path of abatement under policies that target individuals or firms that are highly sensitive to consumer demand.

Some theoretical studies have analyzed the impact of consumer preference heterogeneity on the relative economic efficiency of the price system (Weitzman 1977, Suen 1990), but they do not address the dynamic aspects of technology adoption. Research that does analyze the dynamic efficiency of environmental policies is, again, largely theoretical, and focuses broadly on the effects of alternate policies on overall incentives for technological change, as opposed to explicit models of adoption and/or other forms of compliance under particular environmental policies.[2]

A related empirical literature examines abatement decisions in the context of participation in voluntary programs. These studies often look at factors influencing participation in programs such as EPA's Green Lights (DeCanio and Watkins 1998) and Climate Challenge (Welch, Mazur and Bretschneider 2000) programs, but prior research in this area tends not to consider the dynamic aspect of agents' adoption decisions.[3] Moreover, these studies have focused largely on policies aimed at industry, investigating characteristics of firms that drive technology adoption decisions, voluntary agreements between firms and regulators, etc. (One prominent exception is Alberini, Harrington and McConnell (1995), which looks at voluntary vehicle retirement programs and models the participation decision as a function both of overall costs and individual-level characteristics.) Meanwhile, positive publicity is a strong incentive for firms to abate (Mazurek 1998), and firms with high proximity to consumers, $i.e.$ firms producing final goods, with high advertising expenditures, and/or with highly visible pollution, are more likely to participate in voluntary programs (Videras and Alberini 2000, Khanna and Da-

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[2] For a thorough review of the literature on technological change under environmental policies, see Jaffe et al. (2002).

[3] In another study, Arora and Cason (1996) find that a firm's size and magnitude of toxic release both positively affect its likelihood of participation in EPA's 33/50 program.

mon 1999). Such findings make it clear that consumer preferences are important not only for designing policies that must specifically target consumers, but also can be highly relevant to firms' participation decisions.

Lastly, even studies that do analyze the impact of individual-level heterogeneity on abatement decisions by conditioning on characteristics at the individual level often still are plagued by the fact that unobservable factors can affect the choice behavior of interest. The importance of heterogeneity in these unobservables in driving the time-path of technology adoption has yet to be explored in the literature.

My analysis finds that the degree of a population's heterogeneity - both in abatement costs and in consumer preferences (both observable and unobservable) - can, in fact, be an important driver of the time-path of abatement. I illustrate this finding by extending the simulation developed in Chapter 2, which modelled the dynamic capital replacement decisions of recreational boat owners targeted by a phase-out of copper-based antifouling paints in San Diego Bay.

First, I relax the assumption of homogeneous preferences and examine the time path of copper abatement under various distributional assumptions on individual willingness-to-pay (WTP) for environmental properties. Section 3.2.3 presents the theoretical framework for my simulation and the effect of an increased variance in this distribution on the time-path of copper abatement. I then use my choice experiment data to model explicitly the distribution of WTP for the nontoxic paint property in my sample, using a mixed logit model specification. Results of this estimation and its implications are presented in Section 3.3. Section 3.4 combines the results from this more realistic simulation with key findings from Chapter 2 to consider implications for designing pollution control policies.

3.2 The Effect of Individual-Level Heterogeneity

3.2.1 Theoretical Framework

To model the dynamic capital replacement decision, I break down the value of an individual's asset into two components: the total discounted lifetime cost of owning/maintaining the asset and the total discounted lifetime (monetized) utility. Both of these components depend on the asset's attributes, $\mathbf{Z}_{it}$, and I define $Cost_i(\mathbf{Z}_{it})$ and $WTP_i(\mathbf{Z}_{it})$ to represent the cost and utility functions, respectively.

Note that both the characteristics of the capital and the functions themselves can vary across individuals, $i.e.$ individuals may differ in the way they value certain attributes or in the way they trade off costs over time.

In each period t, individual j chooses capital **Z** to maximize the overall resale value of his or her asset:

$$\max_{Z_{jt}}[WTP_i(\mathbf{Z}_{jt}) - Cost(\mathbf{Z}_{jt})] \tag{3.1}$$

where i denotes the buyer, j denotes the seller, and in the absence of a resale market, $i = j$.

When agents are deciding whether and/or when to adopt a new technology, $\mathbf{Z}_{it}$ can take two general forms, "old" and "new", which I denote with superscripts **0** and **1**, respectively. In my simplified model, the variation across i within these two classes stems only from the differing age of capital across individuals in any given period t. Individuals deciding between these types of capital care only about the relative values, $i.e.$ the lifetime maintenance cost differential and the difference in willingness-to-pay for the vectors of attributes, $\mathbf{Z^0}$ and $\mathbf{Z^1}$.

It should be noted that the WTP function is an additive function of the willingness-to-pay for each attribute in the vector $\mathbf{Z}_i$. I define the relative willingness-to-pay function, $WTP'(z)$, to return the premium that an individual is willing to pay for a single attribute, relative to that attribute's value in the old (baseline) technology, $\mathbf{Z^0}_i$. (The value of $WTP'(\cdot)$ can, of course, be negative if an agent prefers the old attribute.)

Assuming that individuals do not switch back to the old technology once they have converted to the new one,[4] agents convert in the first period at which the total lifetime cost differential favors the new technology, or when:

$$Cost(\mathbf{Z}_i^1) - Cost(\mathbf{Z}_i^0) - \sum_q WTP_i'(Z_{iq}^1) \leq 0 \tag{3.2}$$

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[4] This assumption is realistic in many policy contexts and is not necessarily binding, such as when adoption/compliance costs are non-increasing and convex.

where Z_{iq} represents the q^{th} value in the vector of attributes, $\mathbf{Z_i}$.

3.2.2 Simulation of San Diego Boaters

Recalling the policy cost simulation from Chapter 1, we know the difference in the total value function (the left-hand side of Equation 3.2) for boats of every age. Any policy aiming to induce a conversion to the new technology will employ measures to change relative prices such that Equation 3.2 favors the new technology for the appropriate number of individuals over the policy's time horizon, in order to achieve the desired target.[5] The time path of abatement can then be modelled by plotting the number of agents that convert in each period.

In the San Diego policy problem, boat owners will consider the difference in total lifetime utility, over their boats' remaining lifetimes, between copper paint and nontoxic paint. They make this calculation in each time period, and will convert their hull from a copper-based paint to a non-toxic paint if and when Equation 3.2 holds.

Taking cost assumptions from surveys of San Diego boatyards and knowledge of choice behavior from the results of my choice experiment, I simulate the painting decisions in the population of 7,000 boats of uniform age distribution, under alternate policies to phase out copper paints over specified time horizons. As discussed in Chapter 1, the nature of the stripping cost is important with regard to understanding a boater's dynamic decision-making, because the lack of copper paint accumulation on a boat's hull is a depreciating capital asset. New boats (which do not yet have any hull paint applied) and boats with hulls that currently need to be stripped will therefore be the most favorable to a switch to non-toxic paints.

Figure 3.1 provides a snap-shot of the average boater's dynamic capital replacement problem, by plotting the left-hand side of Equation 3.2 as a function of boat age. Epoxy paint is used as the baseline non-toxic paint in my simulation, because it is currently the most widely used non-toxic and has standard properties. Boat owners convert their hulls to epoxy paint when their boats reach an age at

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[5] While a market-based instrument would manipulate prices directly, a command-and-control approach would do so essentially by setting the price of the toxic agent to infinity at the time it is

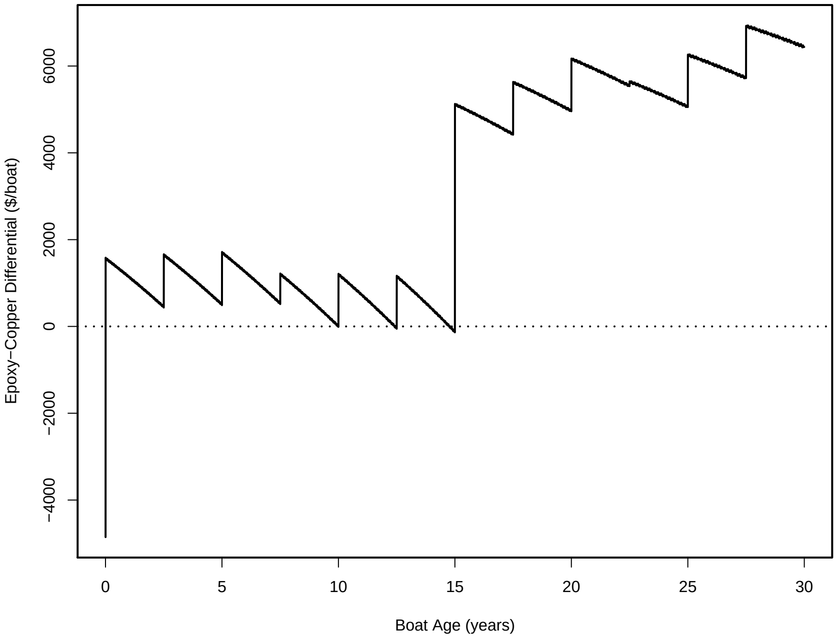

Figure 3.1: Lifetime Total Cost Differential Between Epoxy and Copper-Based Paints

which the lifetime-cost differential dips below zero, which in this scenario occurs at age 0 and age 15. (Also, it is assumed that, at age 30, boats are retired; this assumption also comes from boatyard surveys and is conservative.)

3.2.3 The Importance of Heterogeneity

If boaters had homogeneous preferences (or every boater were willing to pay the average of $800 for the nontoxic paint property), Figure 3.1 would tell us everything we needed to predict each boater's paint choice in each period, and a histogram showing how many hulls are converted to non-toxic paint in each period displays the time-path of abatement under a policy of a given time horizon. For a 15-year policy to induce a 100% phase-out of copper, this time path is plotted in Figure 3.2.

However, when the willingness-to-pay varies randomly in the population, some

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banned.

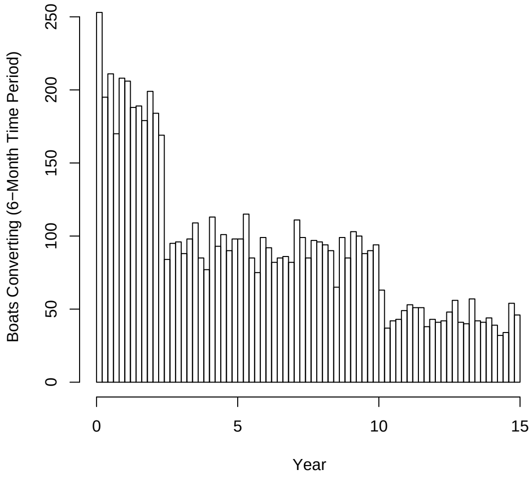

Figure 3.2: Time-path of Copper Pollution Abatement - Uniform WTP (15-yr Policy)

boaters would convert earlier and others would convert later than in Figure 3.2. To demonstrate the effects of heterogeneity on copper abatement over time, I plot the time path of abatement under different distributional assumptions (again, under a policy that imposes a 100% copper phase-out over 15 years). Assuming a normal distribution around a mean of $800, Figure 3.3 plots the time-path of abatement if the variance is 200 and Figure 3.4 assumes a variance of 400.

We can see from these figures that even introducing a relatively small degree of heterogeneity causes abatement to "spread out" quite dramatically, $i.e.$ more individuals convert in early periods but the pollution is more persistent in later periods than in a uniform population, and the greater the WTP distribution's variance, the more this effect is exacerbated. (Note the change in scale of the y-axis between these three plots.) Also, it is important to highlight the fact that these figures plot conversion under a policy that imposes a phase-out in a set (15-year) time frame; if abatement were plotted in the absence of an enforced ban date, the pollution would clearly be even more persistent over time as the variance of WTP increased.

Intuitively, this rather dramatic effect of heterogeneity stems from the threshold-

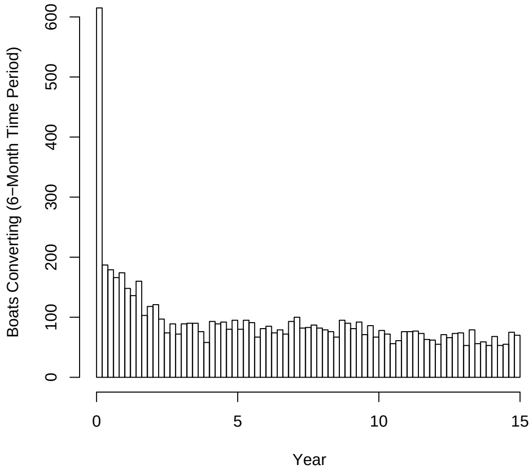

Figure 3.3: Time-path of Copper Pollution Abatement - σ(WTP)=200 (15-yr Policy)

nature of the decision faced by individuals choosing when and if to replace old, depreciating capital with a new type of capital; they convert in the first period that their lifetime-utility differentials favor the new technology, and more individuals cross this threshold in initial periods as the variance of willingness-to-pay increases. A resale market will further intensify this effect by essentially allowing buyers who especially favor the new technology to convert even earlier than the point when it would have been optimal to replace their old capital, while sellers with particularly low taste for the new technology can benefit from the consumer surplus generated by the buyers' preferences for it.

3.3 Estimation

In Chapter 2, we estimated the utility parameters of paint attributes in a representative boater's utility function using a conditional logit model specification, which assumes that utility parameters are the same across all individuals. We examined this model with a simple functional form that included only paint attributes and also with a form that included interaction terms between attributes

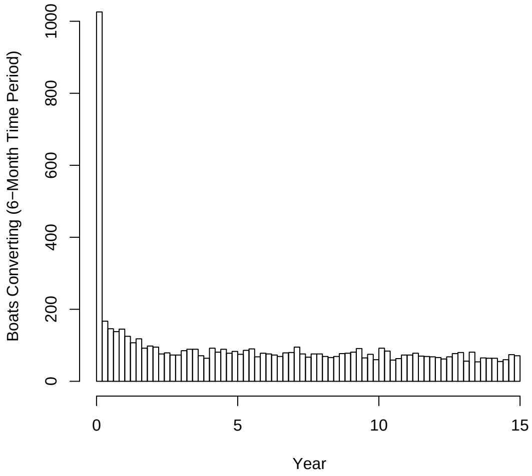

Figure 3.4: Time-path of Copper Abatement - σ(WTP)=400 (15-yr Policy)

and individual characteristics. We found that, on average, boaters are willing to pay $800 more for a non-toxic paint than for a copper paint, other attributes being held equal.

In this section, I relax the two primary assumptions (independence of irrelevant alternatives and constant utility parameters across individuals) and estimate my model with a more general mixed logit specification. (McFadden and Train 2000)

Mixed Logit Model

One part of our survey asked respondents to rank from one to five the importance of various factors of paint choice. The responses show that some boaters are willing to switch to nontoxic paints even if they are substantially more expensive than copper (as supported by the conditional logit estimation). On the other hand, some boaters appeared to be roughly indifferent between nontoxic and copper-based hull coatings at similar prices and performance characteristics, while others even seemed to favor copper coatings even if they are more costly than non-toxic ones.

Seeing evidence in survey responses and in the conditional logit estimation that individual effects influence boater paint choice, coupled with the finding, discussed in Section 3.2.3 that the second moment of the willingness-to-pay distribution is a key driver of the speed of abatement, a model specification that explicitly allows utility parameters to vary across individuals clearly is desirable. The mixed logit (or random parameters logit) model relaxes the independence assumption by allowing for common unobserved components among individuals and allowing utility parameters to vary across individuals. (Train 1997) For descriptions of this model in cross-sectional and panel data settings, see Brownstone and Train (1999) and Revelt and Train (1998), respectively.[6] I therefore estimate my model with a mixed logit specification to build a richer picture of paint choice in the heterogeneous population of boaters.

Specifying the price coefficient to be non-random, I allow the other attributes' parameters to vary randomly across individuals. I employ this specification because the implied WTP distributions are realistic and easy to interpret; if the price coefficient is constant, the willingness to pay for each of the other attributes takes same distribution as that attribute's coefficient.[7] I estimated the model assuming normal, lognormal, and uniform distributions for both the nontoxic and the painting frequency attributes (as well as combinations thereof), and find that a normal distribution on each provides the best fit. Moreover, parameter estimates are largely robust to the distributional assumption, and in all cases the variance/spread of the $nontoxic$ coefficient is very high. Table 3.1 presents the results of this specification.

The results reveal a similar picture to the conditional logit estimation. Both the mean WTP for the nontoxic property and the mean WTP to delay painting for one year are somewhat higher, at \$845 and \$777 respectively. And, indeed, we can see strong evidence that environmental preferences are highly heterogeneous, as the

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[6] Furthermore, McFadden and Train (2000) established that mixed logit models with normally distributed coefficients can approximate, as closely as one desires, a multinomial probit model (which allows ε_{ij} to follow a multivariate normal distribution, and is hence an obvious way to relax the independence assumption).

[7] Specifying the price coefficient to be non-random is a standard practice in these types of models; see, for example, Revelt and Train (1998) and Hensher, Shore and Train (2005). Specifying the price coefficient to vary randomly as well as the other attributes' coefficients would imply unreasonable willingness-to-pay distributions.

Table 3.1: Mixed Logit Estimation: Normally Distributed WTP

Variable	Coefficient	Standard Error	b/St.Er.	$P > \|z\|$
Parameter Estimates:				
$nontoxic$	0.772448	0.123078	6.276	0.0000
$pcost$	-0.000914	0.000054	-16.851	0.0000
$pfreq$	0.710050	0.050333	14.107	0.0000
Derived standard deviations of parameter distributions:				
$nontoxic$	1.8414	0.3229	5.7030	0.0000
$pcost$	0.0000	..........(Fixed Parameter)..........		
$pfreq$	0.4741	0.0823	5.7610	0.0000

Log likelihood = -1533.176

derived standard deviation of the $nontoxic$ coefficient is over twice the estimated coefficient value.

Next, I parameterize the mixed logit model with demographic variables to better understand what is driving the willingness to pay distribution for nontoxic paints. I find that educational attainment is one variable that absorbs some of the heterogeneity that was not adequately accounted for by the simple RPL model. (Income also works reasonably well, but I report the education specification here because many respondents failed to report their income, resulting in a large number of missing values for this variable. Interactions between the non-toxic property and indicators of knowledge about hull paints also are significant, but do not explain heterogeneity as well as the education interactions and are not significant once education is included in the model.) Table 3.2 presents the results of the mixed logit specification including interactions between education level and the nontoxic attribute. We can see that education explains some, but not all, of the heterogeneity in boaters' willingness-to-pay for the non-toxic property.

Figure 3.5 displays the willingness-to-pay distribution for the non-toxic paint property among San Diego boaters, and shows that educational attainment accounts for a component of this variation. Clearly, there is still a significant unex-

Table 3.2: Mixed Logit Estimation with Education Interactions

Variable	Coefficient	Standard Error	b/St.Er.	P $> \|z\|$
Parameter Estimates:				
$nontoxic$	1.771037	0.357198	4.958	0.0000
$pcost$	-0.000932	0.000055	-17.055	0.0000
$pfreq$	0.728609	0.051309	14.200	0.0000
$nontoxic * Educ1$	-0.647702	0.707221	-0.916	0.3598
$nontoxic * Educ2$	-1.463265	0.433054	-3.379	0.0007
$nontoxic * Educ3$	1.040063	0.630993	1.648	0.0993
$nontoxic * Educ4$	-1.256134	0.394981	-3.180	0.0015
$nontoxic * Educ5$	-1.186836	0.408921	-2.902	0.0037
Derived standard deviations of parameter distributions:				
$nontoxic$	1.693222	0.324957	5.211	0.0000
$pfreq$	0.490796	0.081254	6.040	0.0000

Log likelihood = -1518.579

plained stochastic component as well.

3.3.1 Implications for the Timepath of Abatement

Our estimation results show that the variation of willingness-to-pay for non-toxic paints is quite high in the population of San Diego recreational boaters. As such, its effect on the timepath of copper abatement is even more dramatic than the histograms presented in section 3.2.3. Figure 3.6 plots abatement over time in the population of San Diego recreational boaters, under a 15-year phase-out of copper.

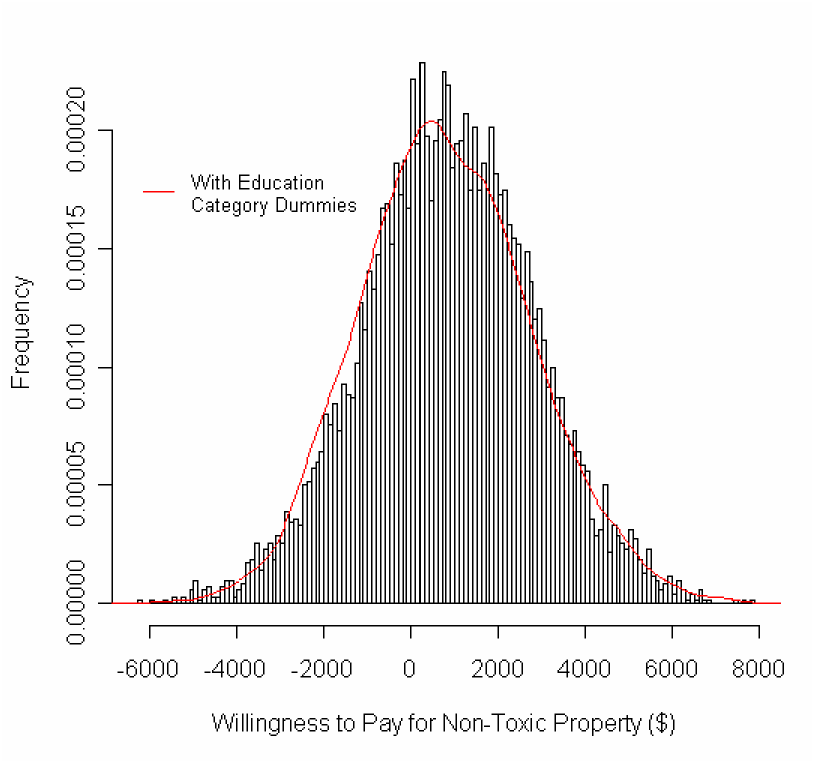


Figure 3.5: Distribution of Willingness-to-Pay for the Non-Toxic Paint Property

3.4 Conclusion

Taken together, the results of the choice experiment and simulation presented in this paper and in Chapter 2 of this dissertation can provide a policymaker with key insights for designing a policy that would induce boaters to switch to non-toxic paints.

First off, setting a date for a future ban is a powerful policy tool, as seen by the effect of the copper-ban clause in half of the surveys. An education campaign and increased availability of viable non-toxic paint alternatives will induce a voluntary switch from many boaters, especially in initial periods, as many boaters who strongly favor non-toxic properties will convert early-on. However, voluntary measures alone are unlikely to phase out copper-based paints entirely, as seen from the high variance of the utility parameter for the nontoxic paint attribute, and the resulting persistence of copper pollution over time. For a complete phase-out

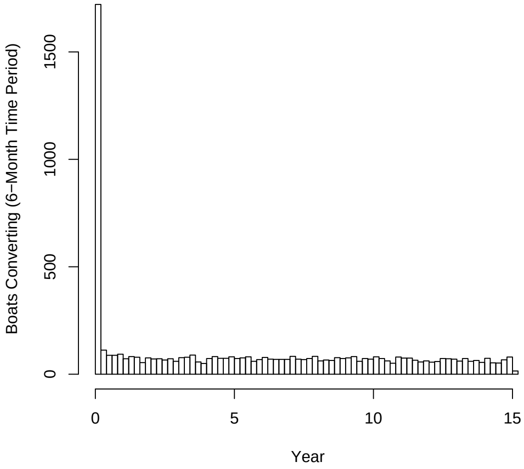


Figure 3.6: Timepath of Copper Pollution Abatement - San Diego Bay (15-yr Policy)

of copper, market-based measures would need to be employed which recognize that some boaters are far less willing than others to switch to non-toxic paints. Interestingly, when cast in a dynamic context with heterogeneous distributions of capital depreciation and/or preferences, the introduction of phase-out date appears, in fact, to function as an incentive approach, in terms of inducing agents to convert at optimal times.

These lessons can be applied to any policy that targets consumers (or firms that are particularly sensitive to consumer demand), and may provide especially valuable insight when considering environmental programs that rely on voluntary participation.

A

Appendix - Chapter 2

A.1 Survey Instrument

An exact replication of our survey instrument is presented in Figures A.1 through A.13.

A.2 Derivation of the Implied Discount Rate

Inferring the discount rate implicitly used by respondents when selecting paints is straightforward. The conditional logit model estimates boat owner utility as a function of the nontoxic paint property, cost, and painting frequency:

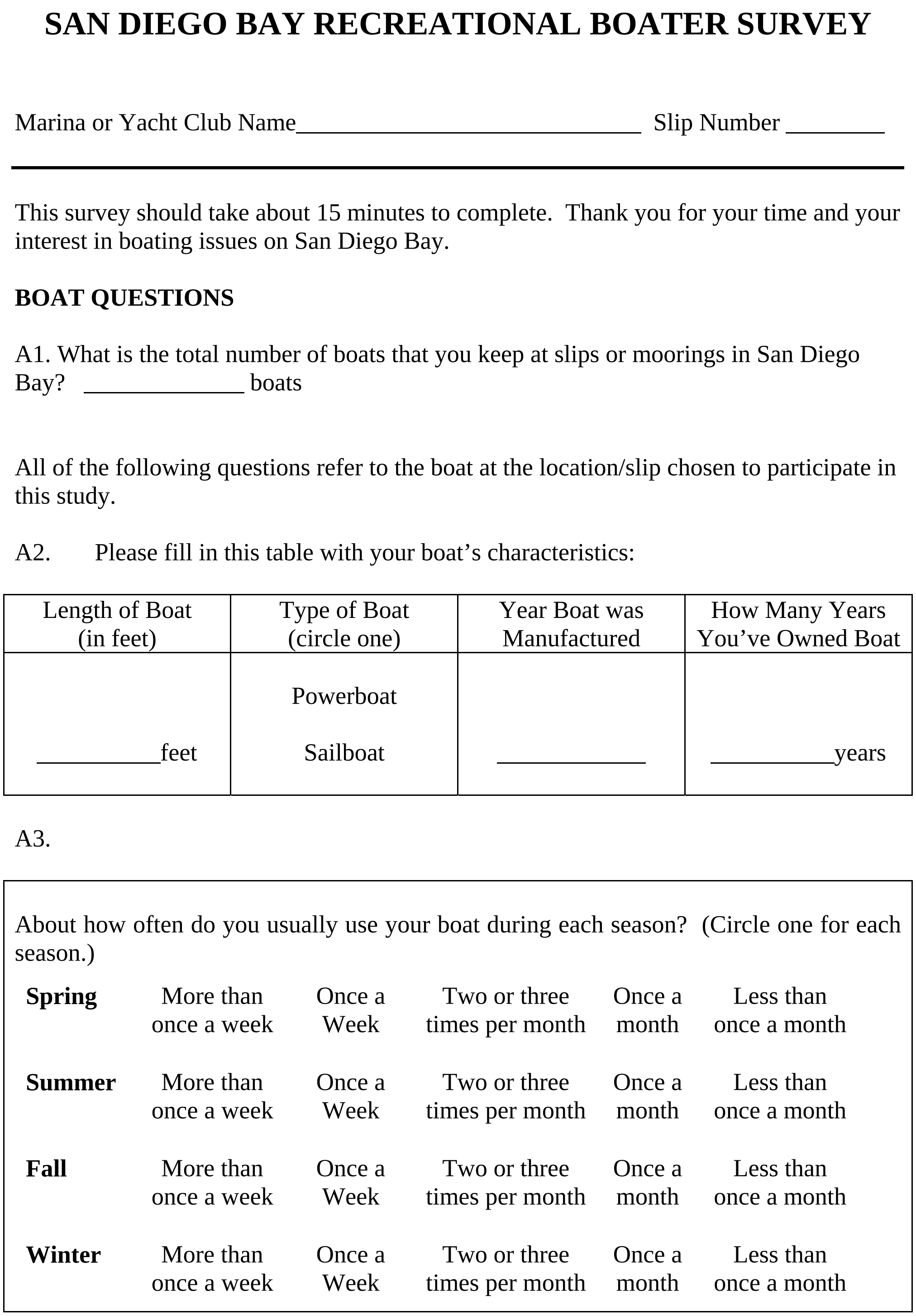
$$U_i(\mathbf{x_{ij}}) = \alpha + \beta_1 * nontoxic + \beta_2 * pcost + \beta_3 * pfreq + \varepsilon_{ij} \tag{A.1}$$

As discussed, the ratio $-\beta_3/\beta_2$ can be interpreted as the willingness-to-pay (WTP) of the average boater to delay the painting cost by one year. My estimation results yield an approximate WTP to delay painting of $734.

The actual current annual cost of keeping a hull painted was calculated with cost figures from a survey of San Diego boatyards, and the average boat length and average frequency of paint reapplication within our sample of boats. In reality, boat owners in our sample pay an average of $772 per year for painting costs.

The willingness to pay to delay paying this amount was then used to calculate the implicit discount rate of respondents choosing between paints, as follows:

$$\begin{aligned} r &= (\text{True Paint Cost})/(\text{WTP to Delay Painting}) - 1 \\ &= (772/734) - 1 = 5.2\% \end{aligned} \tag{A.2}$$



SAN DIEGO BAY RECREATIONAL BOATER SURVEY

Marina or Yacht Club Name____________________________ Slip Number ________

This survey should take about 15 minutes to complete. Thank you for your time and your interest in boating issues on San Diego Bay.

BOAT QUESTIONS

A1. What is the total number of boats that you keep at slips or moorings in San Diego Bay? _____________ boats

All of the following questions refer to the boat at the location/slip chosen to participate in this study.

A2. Please fill in this table with your boat's characteristics:

Length of Boat (in feet)	Type of Boat (circle one)	Year Boat was Manufactured	How Many Years You've Owned Boat
__________feet	Powerboat Sailboat	_____________	__________years

A3.

About how often do you usually use your boat during each season? (Circle one for each season.)

Spring	More than once a week	Once a Week	Two or three times per month	Once a month	Less than once a month
Summer	More than once a week	Once a Week	Two or three times per month	Once a month	Less than once a month
Fall	More than once a week	Once a Week	Two or three times per month	Once a month	Less than once a month
Winter	More than once a week	Once a Week	Two or three times per month	Once a month	Less than once a month

Figure A.1: Survey Instrument: Page 1

A4. What is the main use of your boat? (Please circle one, and explain if other.)

Cruising Racing Daysailing Other (specify) __________

A5. What type of antifouling system are you currently using on your boat?

A6. In each of the following seasons, about how many weeks go by between cleanings of your boat's hull?

Summer: ________weeks between hull cleanings

Fall: ________weeks between hull cleanings

Winter: ________weeks between hull cleanings

Spring: ________weeks between hull cleanings

A7. How many months go by between times that you apply bottom paint?

________ months between bottom paint application

A8a. Is it necessary to haul out your boat for any maintenance between the times that you replace the bottom paint? YES NO

A8b. If yes, what type of maintenance did you have done the last time your boat was hauled out but the bottom paint was not replaced?

Figure A.2: Survey Instrument: Page 2

ARE YOU AWARE THAT:

A9. The California Regional Water Quality Control Board for San Diego has found that there is a pollution problem involving copper in San Diego Bay? YES NO

IF YES, are you aware that:

A10. The California Regional Water Quality Control Board for San Diego has found that copper-based hull coatings on recreational boats contribute over 90% of the copper pollution? YES NO

A11. Copper coming off boats is toxic to marine organisms (other than those attaching to the hulls of boats), such as crabs, mussels, and sea urchins?
YES NO

A12. The California Regional Water Quality Control Board for San Diego is legally required to reduce copper pollution so that water quality standards are no longer violated in San Diego Bay? YES NO

IF NO, then please read the following:

A13. The California Regional Water Quality Control Board for San Diego has found that copper-based hull coatings on recreational boats contribute over 90% of the copper pollution and that copper is toxic to marine organisms (other than those attaching to the hulls of boats), such as crabs, mussels, and sea urchins. The California Regional Water Quality Control Board for San Diego is legally required to reduce copper pollution so that water quality standards are no longer violated in San Diego Bay.

Figure A.3: Survey Instrument: Page 3

The rest of this survey deals with possible ways to reduce the amount of copper pollution coming from recreational boats in San Diego Bay.

A14. Are you familiar with any specific non-toxic bottom paints? YES NO

IF YES, which ones ____.

On a scale from 1 to 5 with 1 being not important, 2 being slightly important, 3 being somewhat important, 4 being very important and 5 being extremely important how would you rate the following factors in deciding whether to switch from a copper-based bottom paint to a nontoxic bottom paint?

		not important	slightly important	somewhat important	very important	extremely important
A18a.	Old copper paint is expensive to remove	1	2	3	4	5
A18b.	Non-toxic paint lasts longer	1	2	3	4	5
A18c.	Hull would need to be cleaned more often	1	2	3	4	5
A18d.	Would help make San Diego Bay cleaner	1	2	3	4	5
A18e.	Recommendation by boatyard	1	2	3	4	5
A18f.	Recommendation by underwater hull cleaner	1	2	3	4	5
A18g.	Boat would be easier to resell	1	2	3	4	5
A18h.	Required by marina/yacht club/mooring co.	1	2	3	4	5
A18i.	Required by law	1	2	3	4	5

Figure A.4: Survey Instrument: Page 4

B. BOTTOM PAINT CHOICE QUESTIONS

I am going to ask you several questions where you get to pick both your favorite and least favorite options for what bottom paint is applied to your boat the next time it is needed. First, I need to define some basic concepts that will help you compare the options.

DIFFERENT TYPES OF PAINT:

HIGH-COPPER: A toxic paint. (Cuprous oxide levels range from 40-76%.)
LOW-COPPER: A much less toxic paint. (Cuprous oxide levels range from 15-40%.)
EPOXY: A non-toxic paint. (Hard, durable bottom paint that can be scrubbed hard.)
SILICONE: A non-toxic paint. (Rubbery, slick surface. Fouling slides off easily.)

It is very likely that ten years from now all recreational boats in San Diego Bay will be required to be painted with a non-toxic paint.

ANTIFOULING COSTS:

There are four main costs of keeping your hull from becoming fouled:

(a) the cost of preparing your hull for painting,
(b) the cost of applying the bottom paint once the hull is prepared,
(c) how often the boat's hull needs new bottom paint, and
(d) how often your hull needs to be cleaned.

HULL PREPARATION COST:

There is often a one-time hull preparation cost if a new brand of bottom paint is applied. These costs vary depending on the formulation of the new paint and the similarity of the new paint to the one currently on the boat. Costs tend to be high if all existing paint must be removed and negligible when it is possible to paint over the existing bottom paint.

PAINT APPLICATION COST:

The different paints can have quite different application costs due to a variety of factors. Some of these relate to how long the bottom paint lasts or to the hull preparation cost.

PAINTING FREQUENCY:

Typically boats with high copper bottom paints have needed to be repainted once every 2 to 3 years. Proposed formulations of these paints and other types of bottom paint can extend the need to repaint to 4 to 6 years.

HULL CLEANING COST:

Boats with high-copper bottom paints usually need their hulls cleaned about 12 times per year. Boats with other types of bottom paint need to be cleaned about 18 times per year.

Figure A.5: Survey Instrument: Page 5

In each of the following questions, costs are given for four different available bottom paints that are labeled A, B, C, and D. These costs are for a 40-foot boat with an 11-foot beam. If your boat is smaller, your cost for the different options would be proportionately less and if your boat is larger, your costs would be proportionately more.

Please indicate at the bottom of each box your most preferred choice (in #1) and your least preferred choice (in #2) from among the four options offered (A-D).

B1.

Bottom Paints Available for Your Boat

	A	**B**	**C**	**D**
Features of Bottom Paint	**Low-Copper**	**Epoxy (Non-Copper)**	**Silicone (Non-Copper)**	**High-Copper**
One-time hull preparation cost	$1,000	$2,000	$3,000	$0
Bottom paint application cost	$2,500	$3,000	$1,500	$2,000
How often you must repaint hull	Every 6 years	Every 4 years	Every 3 years	Every 2 years
How often you must clean hull	18 times (yearly)	18 times (yearly)	18 times (yearly)	12 times (yearly)
1. Which of the options do you like most? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐
2. Which of the options do you like least? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐

B2.

Bottom Paints Available for Your Boat

	A	**B**	**C**	**D**
Features of Bottom Paint	**Low-Copper**	**Epoxy (Non-Copper)**	**Silicone (Non-Copper)**	**High-Copper**
One-time hull preparation cost	$2,000	$3,000	$0	$1,000
Bottom paint application cost	$1,500	$2,000	$2,500	$3,000
How often you must repaint hull	Every 4 years	Every 3 years	Every 2 years	Every 6 years
How often you must clean hull	18 times (yearly)	18 times (yearly)	18 times (yearly)	12 times (yearly)
1. Which of the options do you like most? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐
2. Which of the options do you like least? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐

Figure A.6: Survey Instrument: Page 6

B3. **Bottom Paints Available for Your Boat**

	A	**B**	**C**	**D**
Features of Bottom Paint	**Low-Copper**	**Epoxy (Non-Copper)**	**Silicone (Non-Copper)**	**High-Copper**
One-time hull preparation cost	$3,000	$0	$1,000	$2,000
Bottom paint application cost	$2,000	$2,500	$3,000	$1,500
How often you must repaint hull	Every 2 years	Every 6 years	Every 4 years	Every 3 years
How often you must clean hull	18 times (yearly)	18 times (yearly)	18 times (yearly)	12 times (yearly)
1. Which of the options do you like most? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐
2. Which of the options do you like least? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐

B4. **Bottom Paints Available for Your Boat**

	A	**B**	**C**	**D**
Features of Bottom Paint	**Low-Copper**	**Epoxy (Non-Copper)**	**Silicone (Non-Copper)**	**High-Copper**
One-time hull preparation cost	$0	$1,000	$2,000	$3,000
Bottom paint application cost	$3,000	$1,500	$2,000	$2,500
How often you must repaint hull	Every 3 years	Every 2 years	Every 6 years	Every 4 years
How often you must clean hull	18 times (yearly)	18 times (yearly)	18 times (yearly)	12 times (yearly)
1. Which of the options do you like most? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐
2. Which of the options do you like least? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐

Figure A.7: Survey Instrument: Page 7

B5.

Bottom Paints Available for Your Boat

	A	**B**	**C**	**D**
Features of Bottom Paint	**Low-Copper**	**Epoxy (Non-Copper)**	**Silicone (Non-Copper)**	**Low-Copper**
One-time hull preparation cost	$1,000	$2,000	$3,000	$2,000
Bottom paint application cost	$2,500	$3,000	$1,500	$2,000
How often you must repaint hull	Every 6 years	Every 4 years	Every 3 years	Every 6 years
How often you must clean hull	18 times (yearly)	18 times (yearly)	18 times (yearly)	18 times (yearly)
1. Which of the options do you like most? (✓ only one box)	A. ☐	B. ☐	C. ☐	D. ☐
2. Which of the options do you like least? (✓ only one box)	A. ☐	B. ☐	C. ☐	D. ☐

B6.

Bottom Paints Available for Your Boat

	A	**B**	**C**	**D**
Features of Bottom Paint	**Low-Copper**	**Epoxy (Non-Copper)**	**Silicone (Non-Copper)**	**Low-Copper**
One-time hull preparation cost	$2,000	$3,000	$0	$1,000
Bottom paint application cost	$1,500	$2,000	$2,500	$2,500
How often you must repaint hull	Every 4 years	Every 3 years	Every 2 years	Every 6 years
How often you must clean hull	18 times (yearly)	18 times (yearly)	18 times (yearly)	18 times (yearly)
1. Which of the options do you like most? (✓ only one box)	A. ☐	B. ☐	C. ☐	D. ☐
2. Which of the options do you like least? (✓ only one box)	A. ☐	B. ☐	C. ☐	D. ☐

Figure A.8: Survey Instrument: Page 8

B7.

Bottom Paints Available for Your Boat

	A	B	C	D
Features of Bottom Paint	**Low-Copper**	**Epoxy (Non-Copper)**	**Silicone (Non-Copper)**	**Low-Copper**
One-time hull preparation cost	$3,000	$0	$1,000	$2,000
Bottom paint application cost	$2,000	$2,500	$3,000	$1,500
How often you must repaint hull	Every 2 years	Every 6 years	Every 4 years	Every 4 years
How often you must clean hull	18 times (yearly)	18 times (yearly)	18 times (yearly)	18 times (yearly)
1. Which of the options do you like most? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐
2. Which of the options do you like least? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐

B8.

Bottom Paints Available for Your Boat

	A	B	C	D
Features of Bottom Paint	**Low-Copper**	**Epoxy (Non-Copper)**	**Silicone (Non-Copper)**	**Low-Copper**
One-time hull preparation cost	$0	$1,000	$2,000	$3,000
Bottom paint application cost	$3,000	$1,500	$2,000	$2,000
How often you must repaint hull	Every 3 years	Every 2 years	Every 6 years	Every 2 years
How often you must clean hull	18 times (yearly)	18 times (yearly)	18 times (yearly)	18 times (yearly)
1. Which of the options do you like most? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐
2. Which of the options do you like least? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐

Figure A.9: Survey Instrument: Page 9

B9. **Bottom Paints Available for Your Boat**

	A	B	C	D
Features of Bottom Paint	**Silicone (Non-Copper)**	**Epoxy (Non-Copper)**	**Silicone (Non-Copper)**	**Epoxy (Non-Copper)**
One-time hull preparation cost	$0	$2,000	$3,000	$3,000
Bottom paint application cost	$3,000	$3,000	$1,500	$2,500
How often you must repaint hull	Every 3 years	Every 4 years	Every 3 years	Every 4 years
How often you must clean hull	18 times (yearly)	18 times (yearly)	18 times (yearly)	18 times (yearly)
1. Which of the options do you like most? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐
2. Which of the options do you like least? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐

B10. **Bottom Paints Available for Your Boat**

	A	B	C	D
Features of Bottom Paint	**Silicone (Non-Copper)**	**Epoxy (Non-Copper)**	**Silicone (Non-Copper)**	**Epoxy (Non-Copper)**
One-time hull preparation cost	$3,000	$3,000	$0	$2,000
Bottom paint application cost	$1,500	$2,000	$2,500	$3,000
How often you must repaint hull	Every 3 years	Every 3 years	Every 2 years	Every 4 years
How often you must clean hull	18 times (yearly)	18 times (yearly)	18 times (yearly)	18 times (yearly)
1. Which of the options do you like most? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐
2. Which of the options do you like least? (✓ <u>only one</u> box)	A. ☐	B. ☐	C. ☐	D. ☐

Figure A.10: Survey Instrument: Page 10

B11.

Bottom Paints Available for Your Boat

	A	**B**	**C**	**D**
Features of Bottom Paint	**Silicone (Non-Copper)**	**Epoxy (Non-Copper)**	**Silicone (Non-Copper)**	**Epoxy (Non-Copper)**
One-time hull preparation cost	$0	$0	$1,000	$3,000
Bottom paint application cost	$2,500	$2,500	$3,000	$2,000
How often you must repaint hull	Every 2 years	Every 6 years	Every 4 years	Every 3 years
How often you must clean hull	18 times (yearly)	18 times (yearly)	18 times (yearly)	18 times (yearly)
1. Which of the options do you like most? (✓ only one box)	A. ☐	B. ☐	C. ☐	D. ☐
2. Which of the options do you like least? (✓ only one box)	A. ☐	B. ☐	C. ☐	D. ☐

B12.

Bottom Paints Available for Your Boat

	A	**B**	**C**	**D**
Features of Bottom Paint	**Silicone (Non-Copper)**	**Epoxy (Non-Copper)**	**Silicone (Non-Copper)**	**Epoxy (Non-Copper)**
One-time hull preparation cost	$1,000	$1,000	$2,000	$0
Bottom paint application cost	$3,000	$1,500	$2,000	$2,500
How often you must repaint hull	Every 4 years	Every 2 years	Every 6 years	Every 6 years
How often you must clean hull	18 times (yearly)	18 times (yearly)	18 times (yearly)	18 times (yearly)
1. Which of the options do you like most? (✓ only one box)	A. ☐	B. ☐	C. ☐	D. ☐
2. Which of the options do you like least? (✓ only one box)	A. ☐	B. ☐	C. ☐	D. ☐

Figure A.11: Survey Instrument: Page 11

C. Interest in Sea Grant Extension Demonstration Project Questions

C1. Are you interested in using or learning more about nontoxic bottom paints?

YES NO

C2. Would you like to receive a Sea Grant Extension Program brochure on nontoxic paints and other alternative antifouling methods? YES NO

The Sea Grant Extension Program will be conducting a field demonstration of nontoxic bottom paints on boats in the Shelter Island yacht basin during the next year. Would you be interested in:

C3a. In attending a field day for this demonstration? YES NO

C3b. In receiving more information about our project? YES NO

D. Boater Characteristic Questions

D1. How many years have you owned any boat kept at a slip or mooring in San Diego Bay? _____________years.

D2. Do you read any boating magazines or newspapers on a regular basis?
YES NO

D3. Do you ever get any information on boating from the Internet? YES NO

D4. What is your gender: FEMALE MALE

D5. What is your age? ______

D6. What is your highest level of education?

Some High School or less
High School graduate
Some College
Associates degree
Bachelors degree
Masters degree
Ph.D. degree
Professional Degree (J.D. or M.D.)

D7. Which of the following broad categories best describes your total household income from all sources in 2001?: (Circle One)

$25,000 or less
$25,001-$50,000
$50,001-$75,000
$75,001-$100,000
$100,001-$125,000
$125,001-$150,000
$150,001-$175,000
$175,001-$200,000
$200,001 or more

D8. What is your zip code? ________________

Figure A.12: Survey Instrument: Page 12

OPTIONAL

Providing your contact information is entirely optional. If you are interested, the Sea Grant Extension Program would like to have your contact information so that we can:

-Send you the brochure, field day announcement and other project information.
-Contact you in about a year and a half to assess the effectiveness of our program.

All information will be compiled and reported as overall results. Individual information will not be released. If you have a particularly interesting comment, you may provide it in the space below, and we will ask your permission if we would like to quote it.

Your Name: ____________________________________

Address: ____
____

Phone: ____

And

Email address: ______________________________________
(put none, if none)

Comments:

Please return your survey in the enclosed self-adressed stamped envelope, to:

Leigh T. Johnson, Marine Advisor
Sea Grant Extension Program
University of California
5555 Overland Avenue, Building 4
San Diego, CA 92123-1200

Figure A.13: Survey Instrument: Page 13

Bibliography

Alberini, Anna, Winston Harrington, and Virginia McConnell, "Determinants of Participation in Accelerated Vehicle-Retirement Programs," *The RAND Journal of Economics*, Spring 1995, *26* (1), 93–112.

Arora, Seema and Timothy N. Cason, "Why do Firms Volunteer to Exceed Environmental Regulations? Understanding Participation in EPA's 33/50 Program," *Land Economics*, November 1996, *72* (4), 413–432.

Baumol, W.J. and W.E. Oates, *The Theory of Environmental Policy*, Cambridge, MA: Cambridge University Press, 1988.

Bracewell, R., *The Fourier Transform and Its Applications, 3rd ed.*, New York: McGraw-Hill, 1999.

Brownstone, David and Kenneth Train, "Forecasting new product penetration with flexible substitution patterns," *Journal of Econometrics*, 1999, *89* (1), 109–129.

Calabrese, A., J.R. MacInnes, D.A. Nelson, R.A. Greig, and P.P. Yevich, "Effects of Long-Term Exposure to Silver or Copper on Growth, Bioaccumulation and Histopathology in the Blue Mussel Mytilus edulis," *Marine Environmental Research*, 1984, *11*, 253–274.

California Water Quality Control Board, San Diego Region, "Draft Technical TMDL for Dissolved Copper: Shelter Island Yacht Basin," Technical Report April 2001.

Carson, Richard T., Maria Damon, Leigh T. Johnson, and Jamie Miller, "Transitioning to Non-Metal Antifouling Paints On Marine Recreational Boats in San Diego Bay," November 2002. Report Submitted to the California Department of Boating and Waterways.

Coglianese, M.P. and M. Martin, "Individual and Interactive Effects of Environmental Stress on the Embryonic Development of the Pacific Oyster, Crassostrea gigas," *Marine Environmental Research*, 1984, *5*, 13–27.

College voor de Toelating van Bestrijdingsmiddelen, "Pesticides Database Online," 2004. http://www.ctb-wageningen.nl/.

Danish Environmental Protection Agency, "Statutory Order on Biocidal Antifouling Paint," 2003. Ministry of the Environment.

DeCanio, Stephen J. and William E. Watkins, "Investment in Energy Efficiency: Do the Characteristics of Firms Matter?," *The Review of Economics and Statistics*, 1998, *80* (1), 95–107.

Gould, E., R.J. Thompson, L.J. Buckley, D. Rusanowsky, and G.R. Sennefelder, "Uptake and Effects of Copper and Cadmium on the Gonad of the Scallop Placopecten magellanicus: Concurrent Metal Exposure," *Marine Biology*, 1988, *97*, 217–223.

Hall, W.S., S.J. Bushong, Hall Jr., L.W., M.J. Lenkevich, and A.E. Pinkey, "Monitoring Dissolved Copper Concentrations in Chesapeake Bay," *Environmental Monitoring and Assessment*, 1988, *11*, 33–42.

Hassett, Kevin A. and Gilbert E. Metcalf, "Energy Tax Credits and Residential Conservation Investment: Evidence from Panel Data," *Journal of Public Economics*, 1995, *57*, 201–217.

Hausman, Jerry A., "Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables," *The Bell Journal of Economics*, Spring 1979, *10* (1), 33–54.

Hensher, David, Nina Shore, and Kenneth Train, "Households' Willingness to Pay for Water Service Attributes," *Environmental and Resource Economics*, 2005, *32*, 509–531.

International Coatings Ltd., "Antifoulings: The Legislative Position by Country," 2004.
http://www.yachtpaint.com/superyacht/sy/pdf/antifouling_legislation.pdf.

Jaffe, Adam B. and Robert N. Stavins, "Dynamic Incentives of Environmental Regulations: The Effects of Alternative Policy Instruments on Technology Diffusion," *Journal of Environmental Economics and Management*, 1995, *29*, S43–S63.

____**, Richard G. Newell, and Robert N. Stavins**, "Environmental Policy and Technological Change," *Environmental and Resource Economics*, June 2002, *22* (1-2), 41–69.

Johnson, H.D., J.G. Grovhoug, and A.O. Valkirs, "Copper Loading to U.S. Navy Harbors: Norfolk, VA; Pearl Harbor, HI; and San Diego, CA," Technical Report 3052, Space and Naval Systems Center, San Diego, CA 1988.

Jung, Chulho, Kerry Krutilla, and Roy Boyd, "Incentives for Advanced Pollution Abatement Technology at the Industry Level: An Evaluation of Policy Alternatives," *Journal of Environmental Economics and Management*, 1996, *30*, 95–111.

Katz, C., “Seawater Polynuclear Aromatic Hydrocarbons and Copper in San Diego Bay,” Technical Report 1768, Space and Naval Systems Center, San Diego, CA 1988.

Keohane, Nathaniel O., “Environmental Policy and the Choice of Abatement Technique: Evidence from Coal-Fired Power Plants,” 2002. Working Paper.

Kerr, Suzi and Richard G. Newell, “Policy-Induced Technology Adoption: Evidence from the U.S. Lead Phasedown,” *The Journal of Industrial Economics*, September 2003, *51* (3), 317–343.

Kettlewell, J.J., “Marine Paint Marketers Change the Pitch,” 2000. http://www.boating-industry.com.

Khanna, Madhu and Lisa Damon, “EPA’s Voluntary 33/50 Program: Impact on Toxic Releases and Economic Performance of Firms,” *Journal of Environmental Economics and Management*, January 1999, *37* (1), 1–25.

Krett Lane, S.M., “Productivity and Diversity of Phytoplankton in Relation to Copper Levels in San Diego Bay,” Technical Report 533, Naval Ocean Systems Center 1980.

Lee, H.H. and C.H. Xu, “Effects of Metals on Sea Urchin Development: A Rapid Bioassay,” *Marine Pollution Bulletin*, 1984, *15*, 18–21.

Louviere, Jordan J., David A. Hensher, and Joffre D. Swait, *Stated Choice Methods: Analysis and Application*, Cambridge: Cambridge University Press, 2000.

Lussier, S.M., J.H. Gentile, and Walker J., “Acute and Chronic Effects of Heavy Metals and Cyanide on Mysidopsis bahia (Crustacea: Mysidacea),” *Aquatic Toxicology*, 1985, *7*, 25–35.

MacDonald, J.M., .JD. Shields, and R.K. Zimmer-Faust, “Acute toxicities of eleven metals to early life-history stages of the yellow crab Cancer anthonyi,” *Marine Biology*, 1988, *98*, 201–207.

Martin, M., K.E. Osborn, P. Billig, and N. Glickstein, “Toxicities of Ten Metals to Crassostrea gigas and Mytilus edulis Embryos and Cancer magister Larvae,” *Marine Pollution Bulletin*, 1981, *12*, 305.

Mazurek, Janice, “The Use of Voluntary Agreements in the United States: An Initial Survey,” Technical Report ENV/EPOC/GEEI(98)27/FINAL, Organization for Economic Cooperation and Development December 1998.

McFadden, Daniel, *Frontiers in Econometrics*, New York: Academic Press, 1973.

——— , *Structural Analysis of Discrete Data with Econometric Applications,*, Cambridge: MIT Press, 1981.

——— **and Kenneth Train**, "Mixed MNL models for discrete response," *Journal of Applied Econometrics*, 2000, *15* (5), 447–470.

McPherson, T.N. and G.B. Peters, "The Effects of Copper-Based Antifouling Paints on Water Quality in Recreational Boat Marinas in San Diego and Mission Bays," Technical Report 533, California Regional Water Quality Control Board, San Diego CA 1995.

Mendelsohn, Robert, "Regulating heterogeneous emissions," *Journal of Environmental Economics and Management*, December 1986, *13*, 301–312.

Milliman, S.R. and R. Prince, "Firms incentives to promote technological change in pollution controle," *Journal of Environmental Economics and Management*, 1989, *17*, 247265.

Nelson, Randy A., Tom Tietenberg, and Michael R. Donihue, "Differential Environmental Regulation: Effects of Electric Utility Capital Turnover and Emissions," *Review of Economics and Statistics*, May 1993, *75* (2), 368–373.

Newell, Richard G. and Robert N. Stavins, "Cost Heterogeneity and the Potential Savings from Market-Based Policies," *Journal of Regulatory Economics*, 2003, *23* (1), 43–59.

Papoulis, A., *Probability, Random Variables, and Stochastic Processes*, 2nd ed., New York: McGraw-Hill, 1984.

PRC Environmental Management, Inc., "Report of Copper Loading to San Diego Bay, California," 1997. Prepared for California Regional Water Quality Control Board, San Diego Region and the San Diego Bay Interagency Water Quality Panel.

Revelt, David and Kenneth Train, "Mixed logit with repeated choices: Households' choices of appliance efficiency level," *Review of Economics and Statistics*, 1998, *80*, 647–657.

Schiff, K., D. Diehl, and A. Valkirs, "Copper Emissions from Antifouling Paint on Recreational Vessels," Technical Report 405, Southern California Coastal Water Research Project, Westminster, CA 2003.

Stasch, P. and D. Lynch, "Ship Shape," 1999. Single Industry Campaign: Summary Report, Publication No. 99-16. Washington State Department of Ecology, Water Quality Program.

Sterner, Thomas, *Policy Instruments for Environmental and Natural Resource Management*, Washington, DC: Resources for the Future, 2003.

Stromgren, T. and M.V. Nielsen, “Spawning Frequency, Growth, and Mortality of Mytilus edulis Larvae, Exposed to Copper and Diesel Oil,” *Aquatic Toxicology*, 1991, *21*, 171–180.

Suen, Wing, “Statistical Models of Consumer Behavior with Heterogeneous Values and Constraints,” *Economic Inquiry*, 1990, *28* (1), 79–98.

Swain, G., C. Kavanagh, B. Kovach, and R. Quinn, “The Antifouling Performance of Non-Toxic Silicone Fouling Release Coatings,” in “Proceedings of Symposium on Prevention of Pollution from Ships and Shipyards” Miami 2001.

Train, Kenneth, “Recreation Demand Models with Taste Differences Over People,” *Land Economics*, 1997, *74* (2), 230–239.

Train, Kenneth E., *Discrete Choice Methods with Simulation*, Cambridge: Cambridge University Press, 2003.

Trocine, R.P. and J.H. Trefry, “Toxic Substances Survey for the Indian River Lagoon System,” 1993. Florida Institute of Technology, Melbourne, FL.

U.S. Environmental Protection Agency, “Establishment of Numeric Criteria for Priority Toxic Pollutants for the State of California Rule, 40 CFR Part 131, Water Quality Standards,” May 2000. Federal Register.

——, “Total Maximum Daily Loads for Toxic Pollutants, San Diego Creek and Newport Bay, CA,” 2002. U.S. EPA Region 9, San Francisco, CA.

Valkirs, A.O., B.M. Davidson, L.L. Kear, R.L. Fransham, A.R. Zirino, and J.G. Grovhoug, “Environmental Effects from In-Water Hull Cleaning of Ablative Copper Antifouling Coatings,” Technical Report 2662, Naval Command, Control and Ocean Surveillance Center, RDT&E Division, San Diego, CA 1994.

VanderWeele, D.A., “The Effects of Copper Pollution on the Bivalve, Mytilus edulis and the Amphipod, Grandidierella japonica in the Shelter Island Yacht Basin, San Diego Bay, California,” Master’s thesis, San Diego State University 1996.

Videras, Julio and Anna Alberini, “The Appeal of Voluntary Environmental Programs: Which Firms Participate and Why?,” *Contemporary Economic Policy*, October 2000, *18* (4), 449–461.

Weitzman, Martin, “Prices vs. Quantities,” *Review of Economic Studies*, October 1974, *61* (4), 477–491.

Weitzman, Martin L., “Is the Price System or Rationing More Effective in Getting a Commodity to Those Who Need It Most?,” *Bell Journal of Economics*, 1977, *8* (2), 517–524.

Welch, Eric W., Allan Mazur, and Stuart Bretschneider, “Voluntary Behavior by Electric Utilities: Levels of Adoption and Contribution of the Climate Challenge Program to the Reduction of Carbon Dioxide,” *Journal of Policy Analysis and Management*, July 2000, *19* (3), 407–425.