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*39 ECOSYSTEM SERVICE TRADEOFF ANALYSIS: QUANTIFYING THE COST OF A LEGAL REGIME

As decision makers in the United States transition toward more holistic management of living and nonliving marine resources, they must confront the inevitable tradeoffs that flow from choosing one suite of ecological and economic benefits over another. The U.S. National Ocean Policy appreciates this reality, and provides for a Coastal and Marine Spatial Planning (CMSP) approach to managing marine resources in U.S. waters. But while CMSP inherently recognizes the tradeoffs that inhere in ecosystem-based natural resource management, the preferred mechanism by which those tradeoffs will be evaluated remains unclear.

This article focuses on one emerging tool that can enable prospective evaluation of the tradeoffs inherent in natural resource decision-making processes like CMSP: ecosystem service tradeoff analysis. We demonstrate the potential of this tool through an evaluation of the ecological and economic tradeoffs flowing from the institution of Territorial Use Rights in Fisheries (TURFs) in the southern California red sea urchin fishery. While ecosystem service tradeoff analysis does not reveal to policy makers the “best” solution to resource allocation decisions--that determination is a societal value judgment--it can illuminate the potential costs and benefits of an extant or proposed law, regulation, or policy in a clear, transparent way. This, in turn, enables more effective communication of decision-making rationales to the public and can provide a catalyst for policy overhaul. In sum, ecosystem service tradeoff analysis represents one of the most powerful tools available to facilitate the transition to CMSP and comprehensive, ecosystem-based natural resource management.

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*41 INTRODUCTION

On July 19, 2010, in response to the final recommendations of the Interagency Ocean Policy Task Force and in furtherance of a new National Ocean Policy, President Obama issued an Executive Order on the *Stewardship of the Ocean, Our Coasts, and the Great Lakes*.[1] The President issued this Executive Order in response to a growing recognition of our nation's long history of marine resource overexploitation and marine system degradation.[2] From overfishing and habitat destruction,[3] to ocean acidification[4] and land ***42** based pollution,[5] our oceans face an unprecedented onslaught of anthropogenic stressors. Governance and institutional failures,[6] competition for scarce ocean resources, and disagreement among stakeholders over how ocean resources should (or should not) be used exacerbate these challenges.[7]

To address these challenges, the Executive Order provides for a Coastal and Marine Spatial Planning (CMSP) approach to managing marine resources in U.S. waters.[8] CMSP is "a comprehensive,[9] adaptive, integrated,[10] ecosystem-based,[11] and transparent spatial ***43** planning process, based on sound science, for analyzing current and anticipated uses of ocean, coastal, and Great Lakes areas."[12] CMSP allows decision makers[13] to consider how multiple users of marine resources[14] interact with each other across ocean space, and represents a scaling-up of ocean resource management from the traditional, single-sector approach to holistic, ecosystem-based management.[15] As such, it reflects society's growing ***44** recognition of and appreciation for the ecological and economic benefits that intact and functioning ecosystems can provide.[16]

Through a CMSP forum, practitioners and stakeholders from across the disciplinary and interest group spectrum can come together to jointly inform holistic ocean resource management.[17] CMSP provides a way for decision makers to "identif[y] areas most suitable for various types or classes of activities in order to reduce conflicts among uses, reduce environmental impacts, facilitate compatible uses, and preserve critical ecosystem services to meet economic, environmental, security, and social objectives."[18] A CMSP approach respects the fact that different activities--and the environmental impacts flowing from those activities--occur at different spatial and temporal scales, and incorporates such considerations into the decision-making process.[19] Through its focus on siting and its ***45** recognition of competing uses, CMSP necessitates and facilitates an "evaluat[ion of] the tradeoffs associated with proposed alternative human uses" across ocean space.[20]

Evaluating such tradeoffs is a critical and unavoidable part of the natural resource decision-making process,[21] albeit one that has often been done on an ad hoc basis.[22] CMSP provides decision makers with the opportunity to tackle tradeoffs head-on, a proactive, deliberative approach that has the potential to reduce stakeholder conflict in the long run. Various tools are emerging that can enable prospective evaluation of the tradeoffs inherent in natural resource decision-making processes like CMSP.[23] One such tool is ecosystem ***46** service tradeoff analysis.[24] Ecosystem service tradeoff analysis is grounded in economics and decision theory,[25] and traditionally has been used in the ecological and economic disciplines.[26] Tradeoff analysis has not received as much attention in the law and policy literatures, but holds great potential for informing the discourse in those fora as well.[27]

***47** The purpose of this article is twofold: first, to show how ecosystem[28] service tradeoff analysis can quantify[29] the effects of alternative resource management[30] regimes, and second, to consider the policy implications of such assessment.[31] For demonstration ***48** purposes, we develop a tradeoff analysis model that considers ecological and economic tradeoffs flowing from the institution of Territorial Use Rights in Fisheries (TURFs) in the southern California red sea urchin (*Strongylocentrotus franciscanus*) fishery. This article is not meant to be prescriptive; it does not seek to identify TURFs as the "best" fishery management option for the red sea urchin fishery.[32] Rather, this article aims to show how one tool, ecosystem service tradeoff analysis, can be used to clearly illustrate the extent to which the contours of a given law, policy, or management strategy impede, facilitate, or are neutral to the provision of a given ecosystem service. In other words, tradeoff analysis can serve as an effective tool for evaluating different regulatory schemes. While ecologists and economists have been aware of this tool's potential for some time,[33] this article seeks to bring this tool to a new audience: policy makers and legal scholars. Practitioners and stakeholders from across the political sphere and disciplinary spectrum will be engaged in the CMSP process, and ecosystem service tradeoff analysis--to the extent it becomes a well-known and well-used tool--can communicate relevant information to this multidisciplinary audience in a straightforward and mutually understandable manner.[34]

***49** This Article begins with a general overview of fishery management in the United States: its history, and the trend toward property rights-based approaches like TURFs. It then describes ecosystem services (what they are) and ecosystem service tradeoff analysis (what it is and the process it encompasses). A discussion of the particular model developed for this article follows,[35] along with some recommendations on how tradeoff analysis might be used in natural resource decision-making processes.

I. GENERAL BACKGROUND

A. Why TURFs?

United States fisheries managers historically have relied upon a combination of techniques to manage marine fisheries. These techniques include restrictions on season length, gear type, fishing grounds (e.g., spatial restrictions and area closures), the number of fishermen allowed to fish, and the total allowable catch (TAC).[36] In fisheries with a "hard ***50** TAC," the fishery is closed once the TAC has been harvested for a given species in a given fishing season.[37] A fishery's impending closure often leads fishermen to embark upon a "race to fish," as each fisherman strives to catch as many fish as possible before the season ends.[38] This race to fish is not only unsafe for the fishermen, who may defy hazardous weather conditions to take part in the derby,[39] it can also lead to overcapacity in fishing fleets (i.e., overcapitalization)[40] and overexploitation of wild fish stocks.[41] The race to fish, in concert ***51** with overcapitalization and subsidization, can lead to the commercial extinction[42] of fish stocks and staggering economic waste.[43] One of the keys to halting the race to fish and its deleterious consequences is to develop fishery management techniques that provide fishermen with the incentive to harvest in a more sustainable manner.

To this end, many scientists, economists, and fishery managers are now recommending the incorporation of property rights into the fishery management framework.[44] "Limited access privilege programs" (LAPPs), also known as "catch shares," comprise one class of property rights-based management techniques that holds promise for ***52** sustainable fisheries management.[45] Under a catch share system, an individual fisherman or group of fishermen[46] is guaranteed exclusive access[47] to some portion of the catch.[48] The allure of catch shares is that they provide fishermen with a more encompassing harvesting right than do traditional fishery management techniques.[49] By vesting fishermen with an exclusive, secure interest in some fraction of the fishery resource, catch shares reduce the need for fishermen to race to fish or engage in activities harmful to fish stocks and fish habitat.[50] Consequently, catch shares should, per economic theory, cultivate in fishermen a vested interest in the future health of the fishery and encourage stewardship behavior.[51]

***53** Globally, the most commonly used catch share is the individual fishing quota (IFQ).[52] Under an IFQ program, an individual fisherman or group of fishermen is guaranteed a specified percentage of the seasonal TAC for a given species.[53] IFQs currently are used in a number of U.S. fisheries,[54] including the Alaskan halibut and sablefish longline fishery,[55] the Gulf of Mexico red snapper fishery,[56] the South Atlantic wreckfish fishery,[57] and the Mid-Atlantic surf clam and quahog fishery.[58] To date, empirical evidence on the performance of IFQs supports the theoretical predictions of the sustainability value of catch shares.[59] According to a recent comprehensive survey of 11,135 fisheries, "the fraction of ***54** [IFQ]-managed fisheries that were collapsed ... was about half that of non-[IFQ] fisheries[.]"[60]

This Article focuses on TURFs, a spatially based catch share that has not been used extensively in the United States in the past,[61] but has the potential for expanded use in wild capture fisheries. TURFs have been used successfully in other countries,[62] and find support in U.S. fishery policy pronouncements including the National Oceanic and Atmospheric Administration's *Catch Share Policy*.[63] In a TURF system, a fisherman (or group of fishermen)[64] is provided with exclusive harvesting rights for a particular species (or suite of species) on the seafloor[65] of and/or in the water column[66] overlying[67] a delimited spatial ***55** area.[68] Along with other property rights-based approaches to fishery management, TURFs are designed to promote long-term resource stewardship. In TURF systems, where individuals, communities, or cooperatives retain durable, exclusive harvesting privileges to areas of ocean space, fishermen should "have a strong incentive to manage their TURFs for long-term profitability, which typically involves ... sustainable harvests in perpetuity."[69] Yet whether or not sustainable harvest incentives inhere depends--to a perhaps underappreciated extent--on the specific and nuanced contours of a particular fishery ***56** management policy.[70] Ecosystem service tradeoff analysis can illuminate how expected outcomes might change depending on the specific structure of the regulatory or management regime.

B. Why Ecosystem Services?

The notion of "ecosystem services" has come into the policy making fore in recent years.[71] Simply speaking, ecosystem services are "the *benefits people obtain* from ecosystems."[72] More broadly, ecosystem services are

> the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life. They maintain biodiversity and the production of ecosystem goods, such as seafood, forage timber, biomass fuels, natural fiber, and many pharmaceuticals, industrial products, and their precursors."[73]

As these definitions suggest, ecosystem services more explicitly account for and reflect a human dimension than do other ecological criteria.[74] For example, a marine ecosystem's ***57** ability to provide seafood is an ecosystem service that has implications for food security and fishermen's livelihoods. Likewise, the ability of a wetland to buffer a coastal community from storm surges and flooding has a direct impact on the health, safety, and welfare of the community's residents. This focused link between ecosystem health and human society reinforces the critical role that institutions, law, and policy play in environmental protection efforts,[75] and has led to calls for policy makers to "examine opportunities for using ecosystem service values in decision making[.]"[76]

To date, however, much of the discourse regarding ecosystem services remains theoretical.[77] Nevertheless, interest in ecosystem service-based decision making continues to grow, and

> ***58** [m]ajor players, from conservation groups to multinational corporations, are waking up to the idea that a focus on [ecosystem] services can enhance conservation and earn a competitive return on investment. Governments at the local, national and international levels are increasingly aware of the potential for an explicit focus on conserving ecosystem services and creating service markets. As never before, academic researchers face both the daunting responsibility and refreshing opportunity to examine how to move the theory of service market creation to practice.[78]

Moving toward an ecosystem service-based policy framework will require "[r]adical transformations ... to move from conceptual frameworks and theory to practical integration of ecosystem services into decision making, in a way that is credible, replicable, scalable, and sustainable."[79] Such a transition undoubtedly will be challenging, particularly because many ecosystem services are not easily quantified in monetary terms, nor are they explicitly accounted for through existing law and policy.[80] The emergence of CMSP, with its comprehensive, ecosystem-based approach to marine resource management, offers an opportunity for more intentional consideration of ecosystem services in decision making processes. Ecosystem service tradeoff analysis is one tool that can be used in CMSP and other venues to help move ecosystem service-based decision making from theory into reality.

C. Ecosystem Service Tradeoff Analysis: in General

Ecosystem service tradeoff analysis has the potential to fill an important information gap, providing decision makers with a clear picture of the tradeoffs that flow ***59** from a given natural resource management strategy.[81] Without an ability to ascertain and evaluate such tradeoffs, decision makers may adopt a policy that, while furthering the provision of one ecosystem service, actually--and perhaps unexpectedly--hinders provision of another.[82] Intuition cannot always serve as a reliable guide in determining how a given policy will affect the distribution of ecosystem services across space and time. Parsing out just how Policy A might affect the provision of ecosystem services X and Y requires a more formal, multidisciplinary analysis.[83]

Decision making is all the more complex because policy makers oftentimes are not versed in all the disciplines relevant to an informed analysis. In many cases, scientists end up "playing policy analysts ... leading inquiry about the linkages between scientific insights and the design of institutions for managing [those] systems."[84] Unfortunately, just as policy ***60** makers often are not fluent in the language of science, scientists often are not fluent in the language of policy.[85] Tradeoff analysis can serve as a useful translation device, facilitating information flow between social and natural scientists and policy makers. A primary strength of this tool is that it can convey complex information in a clear, understandable manner,[86] and provide "a framework for thinking about ecosystem services across their ecological, geographic, economic, social, and legal dimensions [.]"[87] Armed with the knowledge gleaned from tradeoff analysis, policy makers can engage in a more informed, transparent decision making process.[88]

Tradeoff analysis allows decision makers to identify situations where tradeoffs among ecosystem services are unavoidable, as well as situations where win-win outcomes are ***61** possible.[89] It can also identify inefficient management options--situations where the provision of at least one ecosystem service can be increased at no cost to another.[90] The ready availability of this type of information will be invaluable as the United States moves toward spatial planning in the marine realm, illuminating the tradeoff bargains that will be struck as society allocates uses across ocean space.[91]

D. Ecosystem Service Tradeoff Analysis: the Process

Ecosystem service tradeoff analysis graphically depicts the expected tradeoffs between any two (or more) ecosystem services of interest.[92] *See* Figure 1. While empirical data can be used to inform the tradeoff analysis, such data is not required;[93] neither is a ***62** common metric (e.g., dollars) a prerequisite for comparison.[94] This flexibility allows for direct comparison between socio-economic and ecological outputs of interest,[95] making it particularly useful for policy evaluation. Of course, the more accurately the points on the curve can be plotted, the more useful the tradeoff analysis will be as a policy-making tool.[96]

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Figure 1. This figure depicts tradeoffs between two ecosystem services of interest. The outer boundary of the curve, or efficiency frontier, is a representation of the most efficient possible combinations of the analyzed ecosystem services given a fixed budget and specified legal, policy, regulatory, or management regime. All points falling inside the frontier are inefficient.

***63** A tradeoff analysis plot's axes correspond to the ecosystem services of interest, and the plotted coordinate pair points represent the outcome obtained from a given natural resource management strategy. The curve's outer boundary is called an efficiency frontier; it represents the most efficient possible combinations of the analyzed ecosystem services given a fixed budget and specified law, policy, or management regime.[97] The curve's shape represents how many units of *Ecosystem Service 1* must be sacrificed to gain one additional unit of *Ecosystem Service 2* (and vice versa).[98] While the efficiency frontier oftentimes is convex, it can have any number of possible shapes depending on the interaction between the ecosystem services of interest.[99] With convex curves, it is often possible to significantly increase the production of one ecosystem service without exacting much of a cost on the ***64** other.[100] For example, in Figure 1, we can move from point A to point B on the curve, substantially increasing provision of *Ecosystem Service 1* without exacting much of a cost on *Ecosystem Service 2*.

Points that fall along the efficiency frontier are all economically efficient. Exactly which point along the curve represents the "best" point (i.e., the "best" tradeoff among ecosystem services) is a societal value judgment.[101] Arriving at this societal judgment presents its own set of problems,[102] as consensus often is difficult to reach and societal value judgments tend to shift over time.[103] Political pressures and processes introduce additional layers of complexity.[104]

***65** Despite these difficulties--and in many ways because of them--the information flowing from ecosystem service tradeoff analysis can provide valuable guidance to policy makers. For example, it would never be "best" to set a policy resulting in a point inside the efficiency frontier, such as point C in Figure 1. All points falling inside the frontier are inefficient; for those points, the provision of at least one ecosystem service can be improved at no cost to the other(s).[105] In Figure 1, it is possible to move from point C vertically to point B on the efficiency frontier, substantially increasing the provision of *Ecosystem Service 2* while providing the same amount of *Ecosystem Service 1*. It is likewise possible to move horizontally from point C to point D on the efficiency frontier, substantially increasing provision of *Ecosystem Service 1* while retaining the same amount of *Ecosystem Service 2*. Unfortunately, existing policies have led to inefficient outcomes in numerous, real-world resource management contexts.[106] Ecosystem service tradeoff analysis can help identify such regulatory bottlenecks to efficiency, illustrate how ecosystem service outcomes can be ***66** improved, and reduce stakeholder conflict by making at least one user group better off (and no group worse off).[107]

In addition to highlighting inefficient outcomes, ecosystem service tradeoff analysis can also identify how a change in policy might effect a more fundamental change to the efficiency frontier. In some cases, a law may shift the frontier or change its shape entirely. For example, if an appropriation bill increases the relevant budget, it may be possible to simultaneously increase the provision of two competing ecosystem services.[108] *See* Figure 2. Lant *et al.* report on this type of outward shift in the agricultural sector with the introduction of a Conservation Reserve Program.[109] By paying farmers to replace farming with conservation practices on wetlands, riparian buffer zones, and highly erodible areas, this Program simultaneously increased both farmers' profits and soil conservation.[110] Conversely, decreasing a program budget might shift the frontier inwards or--in the extreme case where a program budget is zeroed out--eliminate an entire frontier. For example, on May 10, 2012, the U.S. House of Representatives passed appropriation legislation that would prohibit the ***67** funding of new catch share programs in a subset of federal fisheries.[111] If enacted, this legislation would effectively eliminate consideration of any and all efficiency frontiers made possible by catch share management for the affected fisheries.[112]

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Figure 2. This figure shows how certain laws or policies, such as a law that increases a program budget, might shift the efficiency frontier outwards, making it possible to increase the provision of the ecosystem services of interest. Conversely, some policies might shift an efficiency frontier inwards, decreasing the provision of the ecosystem services of interest.

***68** In other (less extreme) situations, instituting a new policy might simply eliminate certain points along a given efficiency frontier. For example, consider a case where the citizens of State Z are concerned about the tradeoff between the ecosystem services of fish biomass and fishery profit. To accommodate these concerns, the legislature of State Z passes a law requiring the maintenance of at least 30% of a fish stock's biomass. Whereas prior to the law's enactment, any of the points along the efficiency frontier would have been possible (assuming no other constraint came into play), the state's new law would eliminate all points to the left of 30% biomass. *See* Figure 3. Interestingly, maintaining 30% biomass, while perhaps significant from a conservation perspective, would actually have very little impact on total fishery profit. Tradeoff analysis is a powerful tool for decision makers because it can clearly show how different laws, policies, or management strategies might affect the provision of ecosystem services. The remainder of the Article seeks to demonstrate this potential through an analysis of the ecosystem service tradeoffs flowing from various permutations on fishery management policy in California state waters.

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***69 Figure 3.** This figure represents possible tradeoffs between the ecosystem services of fish biomass and fishery profit in the waters off of State Z. The vertical line at 30% biomass represents the "cutoff point" for a law that requires conservation of 30% biomass; upon enactment of such a law, all points in the shaded area to the left of that line (where less than 30% biomass would be maintained) are off the table. At the same time, maintaining 30% of the stock's biomass has very little impact on fishery profit, as represented by the vertical blue arrow along the *y*-axis.

E. Ecosystem Service Tradeoff Analysis: the Model Fishery

Wild fisheries, such as the southern California red sea urchin fishery, provide a host of ecosystem services to human beings.[113] Fisheries provide food,[114] a means of livelihood,[115] ***70** and opportunities for recreation.[116] They contribute to regional food webs, helping maintain ecosystem structure and function.[117] To individuals and populations, fish stocks provide countless opportunities for education and research.[118] They also provide what is known as pure "existence value," the value people derive from simply knowing that these fish exist.[119] Both ecosystem services considered in the following red sea urchin model, fish biomass and fishery profit, are important to society and receive attention in state and federal law. For example, the federal Magnuson-Stevens Fishery Conservation and Management Act ("MSA")[120] seeks to balance these dual objectives, providing that:

> management measures shall, consistent with the conservation requirements of this Act (including the prevention of overfishing and rebuilding of overfished stocks), take into account the importance of fishery resources to fishing communities by utilizing economic and social data ... in order to (A) provide for the sustained participation of such communities, and (B) to the extent practicable, minimize adverse economic impacts on

such communities.[121]

The California Fish and Game Code likewise recognizes the importance of both ecosystem services, requiring fishery management plans to both end overfishing and rebuild ***71** stocks,[122] as well as account for economic and social considerations.[123] Tradeoff analysis can help decision makers assess how well current management is performing with respect to these ecosystem service objectives, and evaluate how other management approaches might compare. To demonstrate this potential, the following tradeoff analysis explores how fishery management policy affects ecosystem service outcomes in the red sea urchin fishery in southern California.

Established approximately forty years ago, the commercial red sea urchin fishery is a relatively new fishery in southern California.[124] The fishery has become quite valuable over the past two decades, its rise driven largely by the Japanese export market.[125] Increased fishing pressure and several life history characteristics of the red sea urchin have acted in concert to affect urchin population status in southern California. Reproductive behavior is one life history characteristic of particular import. Sea urchins, like many marine invertebrates, reproduce via external fertilization.[126] Female urchins can spawn[127] several ***72** million eggs into the ocean environment at a time;[128] however, the probability of a successful fertilization event declines as urchin densities decrease.[129] If fishing (or some other pressure) reduces urchin densities below two urchins per square meter, fertilization success is known to be poor.[130] When fertilization does occur, urchin larvae disperse on ocean currents for forty to sixty days before settling.[131] This means that urchins produced in one region may settle in another; this "spillover" effect has implications for fishery management, as discussed in more detail below.

Under the current fishery management regime, divers harvest urchins in nearshore waters.[132] Fishery effort is regulated by several mechanisms, including seasonal closures, a minimum size limit, a restricted access program with a moratorium on the issuance of new permits, and an effort reduction scheme that mandates the retirement of ten permits for each new entrant into the fishery.[133] The California Department of Fish and Game, which oversees urchin fishery management, has found these regulations to be largely ineffective in reducing overall fishery effort;[134] it considers the southern California red sea urchin fishery ***73** to be fully exploited, and in some cases, overfished.[135] The Department has encouraged the investigation of "equitable, practicable and enforceable methods for reducing fishing capacity" to ensure the future viability of the urchin fishery.[136] TURFs represent one such method, and could prove effective for several reasons. First, adult urchins are relatively sedentary and prefer nearshore habitats, making them amenable to spatial management.[137] Second, a property rights-based management regime like TURFs can incentivize sustainable harvesting practices, thus accounting for the link between urchin density (insofar as low densities result from overfishing) and reproductive success. Finally, a properly designed TURF management framework can incorporate and account for the effects of larval dispersal on fishermen's behavior.[138] The following model explores the notion of a red sea urchin TURF management regime in more detail, specifically considering how TURF policy might affect ecosystem service outcomes. Readers interested in a detailed description of the modeling methodology are directed to Appendix A, *available at* http://www.ajelp.com/wp-content/uploads/Carden.Appendix.pdf.

II. RESULTS: TRADEOFFS IN THE URCHIN FISHERY

Broadly speaking, this analysis compares four scenarios: a baseline scenario, where a fleet of non-cooperative, individual fishermen compete for catch ("fleet model"); two ***74** permutations on a TURF policy, where exclusive spatial access rights are granted to fishermen; and "optimal" management. "Optimal" management is defined as the scenario that optimizes the spatial pattern of fishing effort in order to maximize fishery profit; this result is what one would expect under sole ownership or full cooperation in the fishery.[139] The word "optimal" is not to be confused with "best," however. What is "best" from a societal value perspective may be entirely different than the "optimal" solution from an *economic* standpoint.

The two TURF policies considered in this model include one with revenue sharing and one without revenue sharing. Revenue sharing provides a mechanism by which fishermen can potentially increase revenues while conserving the harvested resource; the reasons for this are discussed in more detail below. Before proceeding further, it is necessary to clarify a potential point of confusion: the use of fishery *profit* as the relevant ecosystem service, versus the use of *revenue* sharing in the TURF Policies. Profit and revenue are related concepts, but they are not interchangeable. Profits, by definition, equal revenues minus costs.[140] If costs exceed revenues, profits are negative and fishing becomes a losing enterprise. At the end of the day, it is a fisherman's profits that determine whether or not it makes economic sense for him to stay in the fishery. Thus, the *ecosystem service* of interest in ***75** the following model is fishery *profit*. However, the TURF policies considered in the model below consider the effects of *revenue* sharing (not profit sharing) on ecosystem service outcomes. Revenue sharing was chosen because it is, in some respects, a more realistic scenario than profit sharing. A fisherman's revenues (i.e., ex vessel receipts at the port of landing) can be readily quantified, collected, and redistributed. Quantifying and fairly apportioning costs (e.g., maintenance, fuel, gear, labor)--which would be required to conduct profit sharing (recalling that profit is a function of revenue minus cost)--is more challenging, and cost sharing also requires a greater level of buy-in from the affected fishermen. At the same time, the effects of revenue sharing may have different behavioral implications than profit sharing; this difference is discussed *infra* Part III.

Ecosystem service tradeoff analysis enables us to see, at a glance, how four different management strategies affect the focal ecosystem services in this analysis: sea urchin biomass and fishery profit. In Figure 4, the *x*-axis depicts urchin biomass, and the *y*-axis represents fishery profit. The blue square represents the maximum possible fishery profit under the optimal management strategy (i.e., the result expected under management by a sole owner or with full cooperation). Again, this "optimal" management strategy does not necessarily represent the "best" strategy from a societal standpoint, but rather the optimal strategy from an economic standpoint. The other management strategies' economic outcomes are scaled relative to this value (which represents 100%).

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***76 Figure 4.** This figure depicts the tradeoffs between red sea urchin biomass and fishery profit under several management regimes: optimal spatial management (blue square), a fleet model (black line), and TURF management with varying degrees of revenue sharing (green circle and line). Inter-TURF revenue sharing under the TURF policy ranges from 0% (TURF Policy 1) to 100%. Depending on the percentage of revenue sharing required under TURF Policy 2 (>0%-100%), any point along the green line could be obtained.

The black line in Figure 4 represents the tradeoffs between urchin biomass and fishery profit under the baseline situation with varying fishing effort levels. If total allowable fishing effort is set at zero (i.e., fishing is banned), the ecosystem service of urchin biomass is maximized (i.e., 100% of total possible biomass) but profits are zero. As total allowable fishing effort increases, biomass remaining in the ocean decreases and fishery profits increase until the point where 53% of total possible urchin biomass remains. At this point, ***77** represented by the red triangle, the fleet is able to obtain 88% of the maximum profit possible under the optimal harvest strategy, although biomass remaining in the ocean is slightly lower than under the optimal strategy. Additional fishing beyond this point reduces urchin biomass and fishery profit as costs begin to exceed revenue.[141]

The two TURF Policies are represented by the dotted green line. *See* Figure 4. The percentage figures along that line indicate the percent of revenue sharing among fishermen. When TURF Policy 1 (no revenue sharing) is implemented, the green circular point obtains. At this point, total profit to the fishery falls below both the optimal management strategy's maximum economic return and the fleet model's maximum possible economic return. Biomass conservation is considerably lower at this point[142] than under optimal management,[143] and is also lower than biomass conserved at the fleet model's maximum profit point.[144]

If the TURF Policy is modified to mandate revenue sharing (i.e., if TURF Policy 2 is implemented), the tradeoffs change. With increasing levels of revenue sharing, profits increase to the point denoted by the yellow star.[145] At this point, biomass conservation is ***78** approximately equal to[146] biomass conservation at the fleet model's profit-maximizing harvest level, and total profits are higher than the fleet model (though both biomass conservation and profits still fall below those obtained by the optimal management strategy). Revenue sharing beyond this point leads to lower profits and less fishing.

III. DISCUSSION

As decision makers and natural resource managers seek to promote the sustainable use of living marine resources, policy options abound. Yet even a well-intentioned policy or management strategy can lead to unanticipated results if it is not crafted carefully. Tradeoff analysis can highlight how various ecosystem services stand to fare under different policy or management regimes. Take, for example, the sea urchin case presented in this article. Given that society values both fish biomass and fishery profit, which management option leads to the most socially desirable results? While the particular balance point is a societal value judgment, ecosystem service tradeoff analysis can paint a picture of the universe of options and can help policy makers determine (1) where current management falls along (or within) the efficiency frontier of a given management strategy, and (2) what policies might increase (or decrease) net societal welfare.

The model presented in this article compares how ecosystem service outcomes differ for several fishery management options for the southern California red sea urchin fishery. The optimal spatial management strategy, by definition, maximizes the ecosystem ***79** service of fishery profit. Of the four management strategies, the optimal strategy also results in the highest biomass level for the profit-maximizing point.[147] To achieve this economically optimal result, decision makers would have to enable either sole ownership of the urchin fishery (unlikely, for political, equitable, and legal reasons)[148] or its equivalent (*e.g.*, full cooperation via a fishery cooperative). Cooperatives have been formed for a subset of fisheries in the United States, and one theoretically could be instituted for the southern California red urchin fishery - either on its own or in conjunction with a TURF regime. Cooperation could be achieved by other means as well, such as fishing by a tight-knit community, or fishing in a situation where the extent of larval dispersal is uncertain. Of the management options considered, implementing such cooperative strategies would result in delivery of the greatest overall ""ecosystem service package," i.e., the greatest combination of the ecosystem services of fishery profit and fish biomass.

The baseline management regime for the red sea urchin fishery in southern California, if optimally managed,[149] provides for 88% of the maximum profit possible under the optimal spatial harvest strategy,[150] and biomass conservation that is almost equivalent to that under the optimal strategy. Points to the right of the red triangle along the efficiency ***80** frontier perform increasingly better from a conservation perspective, and increasingly worse from a profit standpoint. Decision makers would never want to mandate a fishing effort level that pushes biomass to the left of the red triangle because for each such point, an equivalent profit level could be attained while preserving more biomass.[151]

Now that we can see graphically how the baseline situation fares, we can consider whether policy makers might want to upset the status quo and facilitate TURF management. And, more importantly, we can consider *how* they should structure TURF management so as to enhance overall ecosystem service provision. As noted above, if a TURF regime was implemented in conjunction with a fishery cooperative, effectively unitizing ownership of the resource,[152] it should be possible to achieve the economically optimal result. If cooperative management is not socially or politically desirable, TURF management with individual tenure could still be instituted in a variety of ways, including the two variations on TURF policy considered herein.

TURF Policy 1, which permits TURFs generally but does not allow revenue sharing, should never be chosen by policy makers over the status quo.[153] While it is true that TURF Policy 1 (green circle) results in higher profits than baseline management for an equivalent level of harvest, this profit level and the biomass remaining are both lower than that ***81** obtained under an optimally managed fleet (red triangle). This result is not ideal from either a profit or a conservation standpoint, and it is difficult to conceive of a circumstance where society would seek to attain this outcome. Given that rights-based approaches to fishery management like TURFs are supposed to incentivize stewardship behavior, why does this result ensue? It is likely that each TURF-holder is overharvesting within his own TURF.[154] Because TURFs are connected by larval dispersal (i.e., because fish larvae drift or disperse from one TURF to another), a TURF-holder is not able to capture or internalize all the benefits or positive externalities[155] of his stewardship behavior.[156] The "spillover" of larvae thus leads fishermen to overharvest the resource.[157]

The introduction of revenue sharing[158] in TURF Policy 2 counters this overexploitation tendency to a certain point. As revenue sharing increases, fishermen are able to obtain up to 96% of the profits obtainable under optimal spatial management and retain a biomass level that--while slightly lower than the optimal strategy--is approximately equivalent to that attained at baseline management's profit-maximizing point. With revenue sharing, spillover of fish from one TURF to another no longer represents an unmitigated loss. Instead, some of the value of that fugitive resource will be recovered in future years via ***82** the revenue-sharing mechanism. Consequently, a TURF-holder can increase his profits while harvesting less than he would in a non-revenue-sharing world.[159]

At the same time, even a revenue-sharing TURF Policy never quite reaches the maximum possible profit level (i.e., the blue square). This is because the revenue-sharing arrangement does not account for all of the economic factors affecting the fishermen's decision-making processes (e.g., costs); the fishermen are still acting to further their individual interest, and thus cannot reap all the financial benefits that would flow from genuine cooperation. Another indication of the fishermen's fundamentally selfish behavior is that, as revenue sharing exceeds the 55% level, fishermen begin to fish less because fishing becomes increasingly unprofitable. If fishermen are required to share most or all of their revenues, but at the same time are forced to internalize all of their own costs, they will begin to harvest less biomass than they might otherwise seek in order to keep costs down. In the extreme case (i.e., 100% revenue sharing), it becomes unprofitable for a TURF-holder to fish at all. One way to address this particular shortcoming would be to mandate *profit* sharing, which would require cost sharing as well as revenue sharing.[160] It seems reasonable to conclude that a profit-sharing TURF Policy frontier would approach, and perhaps even terminate at, the profit-maximizing point (blue square). However, we cannot say this for certain until we run the profit-sharing option through the tradeoff analysis model.

***83** Actually running policy options through a tradeoff analysis model can provide decision makers with valuable insights that might not otherwise be obvious. As this article has made clear, ecosystem service outcomes are not always intuitive. For example, a decision maker who believes wholeheartedly in catch share management might not have expected TURF Policy 1 to actually reduce both fish biomass and fishery profit outcomes as compared to an optimally managed fleet. Likewise, those in the United States House of Representatives who are pushing for an effective moratorium on new catch share systems might be surprised to find that both fishery profit and fish populations fare better under certain TURF management regimes than under the status quo. But therein lies the true value and tremendous potential of ecosystem service tradeoff analysis as a policy-making tool. By providing decision makers with a clear and straightforward picture of the tradeoffs flowing from different management strategies, ecosystem service tradeoff analysis can enable more informed, transparent decision-making processes.

While ecosystem service tradeoff analysis holds much potential, and while the example presented in this article provides some interesting results, it is important to note the limitations of the model system presented herein. The urchin analysis presented in this article looked at one fishery in one region; results for other fisheries or other regions might differ.[161] In addition, per existing federal and state legislative mandates, harvest levels must ***84** not constitute overfishing.[162] This model did not expressly evaluate where along the biomass continuum the overfishing tipping point occurs. A point along the efficiency frontier that might otherwise appear to provide a good package of ecosystem services might not be viable if the corresponding harvest level results in overfishing. Further, this model only looked at two ecosystem services; it did not consider other societally relevant ecosystem service effects (e.g., habitat protection) that might flow from the implementation of any of these management strategies,[163] although ecosystem service tradeoff analysis is capable of delivering multidimensional models.[164] Thus, while ecosystem service tradeoff analysis has great potential to help inform natural resource decision-making processes like CMSP, the models must be carefully designed for their intended purpose and their limitations must be recognized.

CONCLUSION

In the ecosystem services literature, authors have asked many pertinent and pointed questions, such as: "how might we use laws to protect ecosystem services?"[165] "Do ***85** environmental and resource management laws help or hinder efforts to make ecosystem service provision an integral part of a landscape [or seascape] conservation plan?"[166] "[H]ow do we get from the economics and the science to the law?"[167] The goal of this article has been to show that ecosystem service tradeoff analysis is a workable and useful tool that can help answer these types of questions, integrate science and economics into policy and law, and shed light on the ways in which policy changes might affect the provision of ecosystem services. Tradeoff analysis does not reveal to policy makers the "best" solution to resource allocation decisions. That determination is, and always will be, a societal value judgment. Tradeoff analysis can, however, illuminate the potential costs and benefits of a proposed law, regulation, or policy. It can show, in a clear and understandable manner, what tradeoffs exist between various ecosystem services of interest under different policies, whether current management regimes are inefficient, and whether and where it is possible to "expand the pie" and reduce stakeholder conflict by tweaking the regulatory regime.[168]

The analysis presented in this article demonstrates that even within a broad policy regime (e.g., fishery management), nuances in how a policy is crafted (e.g., TURFs with ***86** revenue sharing versus without) can have a large impact on ecosystem service outcomes. Tradeoff analysis can highlight, in a straightforward and direct manner, how the nuances of a proposed policy can affect the interplay among ecosystem services of interest - sometimes in counterintuitive ways. For example, in the red urchin fishery model described herein, simply instituting TURF management instead of a fleet model did not, in and of itself, enhance net societal benefits (as might be expected given the widespread perception that catch shares promote sustainable fisheries). Instead, it was the requirement that TURF-holders share a limited percentage of their revenues that enhanced ecosystem service outcomes.[169] Requiring profit sharing might increase the overall package of societal benefits even more; exploring other policy avenues such as profit sharing would be an interesting and worthwhile future endeavor. In every analysis, the more policy options considered, the more informed the ultimate decision.

By facilitating a more informed dialogue, tradeoff analysis can “take the discussion of ecosystem services out of the ‘easy frame of mind’ and push it to the next level, at which serious and detailed law and policy implementation frameworks can be designed, tested, and implemented.”[170] This approach has extraordinary potential for use by policy makers, legal scholars and practitioners, natural resource managers, and advocacy organizations above and beyond its traditional use by ecologists and economists. Tradeoff analysis can highlight how societally valuable ecosystem services fare under different institutional, regulatory, and legal regimes. The clear, transparent process that undergirds tradeoff analysis thus enables more ***87** effective communication of resource decision making rationales (ecological, economic, and social) to affected stakeholders and to the public at large.[171]

By clearly depicting how ecosystem service tradeoffs manifest under different regulatory or management regimes, tradeoff analysis can serve as a catalyst for policy overhaul. Unless and until the costs of the regulatory status quo can be clearly identified, it is easy for decision makers to either succumb to inertia and become complacent, or punt on potentially controversial policy changes.[172] CMSP provides a platform for decision makers to effect real change in marine resource management, and ecosystem service tradeoff analysis is a tool that can be used in that planning process to facilitate and encourage more informed decision making.[173] What’s more, resource management agencies already collect and have access to much of the data needed to perform such analyses. In sum, ecosystem service tradeoff analysis represents one of the most powerful tools we have to facilitate the transition to CMSP and comprehensive, ecosystem-based natural resource management.

APPENDIX A

MODEL METHODOLOGY

The baseline management policy for California’s red sea urchin fishery is a fleet model. Under a fleet model, a fishery operates across its geographic domain (in this case, the waters along the southern California coastline, including coastlines of the eight Channel Islands) as a non-cooperative collection of fishermen. The fishery is regulated in the aggregate by an exogenously determined[1] total allowable fishing effort, F; in theory, F could be controlled by a variety of mechanisms, such as limiting the number of fishermen, days fished, and/or total allowable catch.[2] In the model, the total allowable fishing effort, F, is distributed across I fishable “patches” in the geographic domain:

<<equation>>

Each year, the fleet spatially allocates fishing effort across these patches so that the average profit to the fleet (profit per unit effort) is uniform across ocean space.[3] To better understand how effort is distributed across ocean space, the geographic domain is divided into 135 discrete coastal patches of equal size (~5 km in length and ~20 km^2 in area).[4] Catch in a patch is positively proportional to fishing effort and the biomass of legally harvestable urchins in that patch. Revenue is calculated as the biomass of catch multiplied by market price per unit biomass ($0.80/lb);[5] profit is revenue less cost. Cost of harvest increases with effort at a rate, whose value is chosen such that continued fishing will bring the urchin stock to a “break-even” population density. The “break-even” population density is the density where the marginal cost of exerting an additional unit of fishing effort equals the marginal revenue gained from that unit of effort, resulting in marginal profit per unit effort of zero.[6] Beyond that point, it is no longer profitable to continue fishing in that year. For purposes of this paper, the break-even population density is set at 10% of the average unfished population density for the geographic region.[7]

To enhance ecological accuracy, the fleet model just described is integrated into a spatially-explicit simulation model of red sea urchin population and fishery dynamics within and among the 135 coastal patches. The population model keeps track of the number of urchins of each age class in each patch, as well as the length, L, and weight (biomass), W, of those urchins in accordance with the von Bertalanffy growth and allometric weight-at-length functions:[8]

<<equation>>

$W={}_{a}L^{b}$

where t is age in years, $L\infty$ is the asymptotic urchin length (*i.e.*, diameter of red sea urchin tests),[9] k is the test growth rate, t_0 relates to the size at first settlement, and a and b determine the multiplicative and exponential effect of urchin length on urchin biomass. Parameters[10] for the red sea urchin population model are presented in Table 1 (below).[11]

	L_∞(cm)	11
	K (y^{-1})	0.22
Growth	t_0(y)	0
	c_1 (cm,kg)	6.76E-04
	c_2	2.68
	Age at maturity (y)	4
Life history	Age first fished (y)	8
	Maximum age (y)	20
	Natural mortality rate (y^{-1})	0.08
Habitat	Substrate	Hard
	Depth range (m)	(0-100)
Larval dispersal	Pelagic larval duration (d)	49
	Spawning season	December-March

Table 1. The values for red sea urchin life history traits presented in this table were used as parameter values in the population model described herein.[12]

Year-to-year urchin survival and transference to the next size class depends on both the natural mortality rate, which applies uniformly across the entire population and across all urchin age classes, and the fishing mortality rate, which is equal to patch-specific fishing effort, F_i, and applies only to legally-harvestable urchin age classes.[13] In patch i, the number of urchins of age j at the end of the year, N_{i,j_end}, is a function of the population of urchins age $j-1$ at the beginning of the year and of the total (*i.e.*, natural plus fishing) mortality in the patch:

<<equation>>

Patch-specific fishing effort, F_i, equals zero for all age classes j that are not legal to harvest. For each legally harvestable age class, the patch-specific biomass loss due to mortality is equal to one minus the above equation. Of this mortality loss, the amount attributable to the fishery (as opposed to natural mortality) is proportional to the relative rate of fishing versus natural mortality in that patch, F_i /(F_i +). At the maximum age limit for this urchin species, natural mortality is 100%.

In addition to the total mortality rate, another factor that influences patch biomass is reproductive rate. As described in Part

II.E.1, *supra*, urchin reproduction is a function of spawning behavior. Sexually mature urchins spawn into the pelagic environment[14] at a rate proportional to their weight. Thus, reproductive capacity increases exponentially with age,[15] and total larval production in a patch is proportional to the total biomass of reproductive-aged urchins in that patch.

In the case of the red sea urchin, larvae disperse via ocean currents for one to two months before settling onto the seafloor. Larval dispersal is simulated using a Regional Ocean Model System (ROMS) model[16] that takes into account the timing of larval release (*i.e.*, urchin spawning season), the length of the pelagic larval dispersal period, and the geography and oceanography of the region.[17] The ROMS model is run offline[18] using seven years (1996-2002) of available data on oceanographic circulation patterns in southern California. Results from the seven years are averaged, and the output is arranged into a matrix that shows the mean probabilities of dispersal between all pairwise patches in the region. This matrix is called a dispersal kernel, and is used in the population model to estimate how larvae are likely to move from spawning sites to settling patches.

Once larvae settle to the seafloor and mature into the one year-old age class, they are deemed to have "recruited" to the area. The number of settling urchins that ultimately recruit to a patch is regulated by a local "density dependent process" that occurs between settlement and recruitment. "Density dependence" refers to the fact that each patch can support a limited number (*i.e.*, a particular density) of urchins due to resource availability. Once a patch gets too crowded, various pressures start acting upon the urchins to reduce the population to a supportable size. The number of settling larvae that ultimately recruit depends on the density of larval settlers relative to the amount of suitable habitat in the patch. Suitable habitat for red sea urchins includes hard-substrate, such as rocky reefs, that provide food and shelter sufficient for urchin growth and survival. *See* Table 1. For purposes of this analysis, the amount of suitable habitat in each patch is determined from maps developed by the California Department of Fish and Game for the Marine Life Protection Act.[19]

Mathematically, the relationship between the number of settling larvae arriving in patch *i*, S_i, and the number of age one urchins recruiting in the patch, N_{i1}, follows a Beverton-Holt function[20] with parameters, representing the maximum recruit survival rate, and $_i$, which regulates the maximum number of recruits ($R_{\max}$) possible in that patch:

<<equation>>

where

<<equation>>

H_i represents the area of suitable urchin habitat within patch *I*. The values of parameters and $R_{\max}$ are not known directly; rather, they are "free parameters" that are chosen or "tuned" so that two conditions are met. First, in a world without fishing, the survival rate of larvae in a patch with a low settlement density (*i.e.*, S_i 0) must be set at some fraction of maximum larval survival. That maximum larval survival rate is specified by the compensation ratio[21] for the species. Second, the unfished urchin biomass must match a target unfished biomass.[22] While the baseline unfished biomass for red sea urchins in southern California is not well known,[23] previous studies have found model results to be insensitive to the value chosen when they are scaled to unfished biomass.[24]

After modeling the expected urchin biomass/fishery profit tradeoffs under the baseline scenario (*i.e.*, the fleet model) using the above information, the model was modified to simulate expected tradeoffs under two variations of a TURF regime. In both TURF management models, each of the 135 discrete patches in the geographic domain represents one TURF. Each TURF is leased in perpetuity[25] to one individual fisherman,[26] and each fisherman is permitted to "choose" his own fishing effort level.[27]

TURF Model #1 does not mandate (or allow) revenue sharing[28] among TURF-holders.[29] This model assumes that each TURF leaseholder chooses an effort level that maximizes long-term profits in his own TURF, given effort levels in the other TURFs and the state of the system (*i.e.*, regional urchin population dynamics).[30] Fishing effort levels in other TURFs matter because, although the fishers in the different TURFs do not interact directly with each other, the urchins within the different TURFs are connected via larval dispersal.[31] Thus, fishing effort in one TURF indirectly affects population dynamics (and thus fishery profit) in other TURFs. Given a fisherman's knowledge that he will lose urchins from his TURF via larval dispersal (*i.e.*, "spillover"), he will tend to overharvest the resource.[32] In the end, even though a fisherman has secured his own TURF fishing ground, he is still, to some degree, competing with other fishermen. This is where game theory comes into play.

The connectivity of TURFs via larval dispersal leads to the emergence of a strategic game among fishermen. Each player in the game seeks to maximize his private gain, given full knowledge of, but no

influence over, the actions of the other players (*i.e.*, fishermen) with whom he interacts. This type of game converges at a "Nash equilibrium,"[33] where, by definition, each player's effort level is optimal[34] given the other players' effort levels.[35] The Nash equilibrium is determined through a process called fixed-point iteration.[36] In this fixed-point iteration, the effort levels of all but one TURF-holder are fixed. That one TURF-holder chooses the effort level that maximizes his long-term profit. This process is replicated for each TURF (in random order) until all TURF-holders have the opportunity to "choose" an effort level.[37] This iterative process is repeated in its entirety (each time using a new random order of TURFs) until TURF effort levels are unchanged by subsequent iterations. At this point, every TURF-holder has chosen the best effort level he can, given the decisions of the other TURF-holders. To verify that the final effort levels represent the true solution to the Nash equilibrium (*i.e.*, to verify "convergence"), the iterative process described above is repeated using various different initial effort levels and different TURF iteration orders.

TURF Model #2 changes the game by requiring a specified level of revenue sharing among TURF-holders. Under TURF Model #2, a given percentage of each fisherman's revenues (ranging from >0%-100%) is allocated to a common pool; this pool is divided evenly among all fishermen at the end of the season. Because each fisherman benefits from the common pool, and because that benefit depends on the combined value of all TURFs in the system, the revenue-sharing mechanism instills in each fisherman a concern for the value of other fishermen's TURFs.

To identify how well each management scenario fares as compared with the optimal economic case scenario, the set of patch-specific fishing effort levels that maximizes total profit to the fishery was identified.[38] As noted above, this "optimal" strategy does not necessarily correlate with the "best" management option from a societal value perspective. Rather, results from this optimal scenario provide an economic benchmark against which the fleet model and TURF model results can be compared. In all of the management policies examined, the population and fishery results presented are based on equilibrium model conditions.[39] Urchin biomass and fishery profit outcomes are scaled relative to maximum levels at 100%.

Footnotes

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[1] *See generally* Interagency Ocean Pol'y Task Force, White House Council on Envtl. Quality, Final Recommendations of the Interagency Ocean Policy Task Force (2010); Nat'l Ocean Council, National Ocean Policy (2010), *available at* http://www.whitehouse.gov/administration/eop/oceans/policy (last visited Nov. 26, 2010) [hereinafter *Interagency Ocean Policy Task Force Report*]; Stewardship of the Ocean, Our Coasts, and the Great Lakes, Exec. Order No. 13,547, 75 Fed. Reg. 43,023 (July 19, 2010), *available at* http:// www.whitehouse.gov/the-press-office/executive-order-stewardship-ocean-our-coasts-and-great-lakes (last visited Nov. 26, 2010), 75 Fed. Reg. 43023, 43023 (July 22, 2010), *available at* http:// edocket.access.gpo.gov/2010/pdf/2010-18169.pdf (last visited Nov. 26, 2010) ("establish[ing] a national policy to ensure the protection, maintenance, and restoration of the health of ocean, coastal, and Great Lakes ecosystems and resources, enhance the sustainability of ocean and coastal economies, preserve our maritime heritage, support sustainable uses and access, provide for adaptive management to enhance our understanding of and capacity to

respond to climate change and ocean acidification, and coordinate with our national security and foreign policy interests") [hereinafter E.O. 13547].

[2] *See generally id. See also* Oran R. Young et al., *Solving the Crisis in Ocean Governance: Place-Based Management of Marine Ecosystems*, 49 ENVT. SCIENCE & POL'Y FOR SUSTAINABLE SOLUTIONS 20, 22 (2010) (noting "a growing awareness [of] the escalating crisis is marine ecosystems--from biodiversity losses to marine pollution and warming waters"); Mary Turnipseed et al., *Legal Bedrock for Rebuilding America's Ocean Ecosystems*, 324 SCIENCE 183 (2009) ("[w]ith new leadership in place in Washington, U.S. ocean policy is poised for a long-overdue transformation.").

[3] *See generally* Boris Worm et al., *Rebuilding Global Fisheries*, 325 SCIENCE 578 (2009) (discussing overfishing problem); *See also* James A. Bohnsack & Jerald S. Ault, *Management Strategies to Conserve Marine Biodiversity*, 9 OCEANOGRAPHY 73 (1996) (discussing overfishing and habitat destruction).

[4] *See generally* Scott C. Doney et al., *Ocean Acidification: The Other CO2 Problem*, 1 ANN. REV. MARINE SCI. 169 (2009); James C. Orr et al., *Anthropogenic Ocean Acidification Over the Twenty-First Century and Its Impact on Calcifying Organisms*, 437 NATURE 681 (2005).

[5] *See, e.g.*, Robert J. Diaz & Rutger Rosenberg, *Spreading Dead Zones and Consequences for Marine Ecosystems*, 321 SCIENCE 926 (2008) (discussing eutrophication and dead zones in marine ecosystems resulting from fertilizer runoff and fossil fuel burning); Nat'l Oceanic & Atmospheric Admin., *Marine Debris* (2011), *available at* http://marinedebris.noaa.gov/info/plastic.html (discussing plastic pollution).

[6] Young et al., *supra* note 2, at 22 ("[t]here is a growing awareness that the escalating crisis is marine ecosystems - from biodiversity losses to marine pollution and warming waters - is in large part a failure of governance. Problems arise from fragmentation in the governance systems used to manage specific human uses of marine resources, together with spatial and temporal mismatches between biophysical systems and the rights, rules, and decision making processes created to manage human interactions with these systems."); Larry Crowder & Elliot Norse, *Essential Ecological Insights for Marine Ecosystem-Based Management and Marine Spatial Planning*, 32 MARINE POL'Y 772 (2008).

[7] *See, e.g.*, Christopher Costello et al., *Can Catch Shares Prevent Fisheries Collapse?*, 321 SCIENCE 1678 (2008) (discussing competition for scarce fishery resources); Crowder & Norse, *supra* note 6 (discussing the need to manage competing human uses and conservation across ocean space).

[8] Exec. Order. No. 13547, 75 Fed. Reg. 43023 at 43024, 43026 (2010). In the United States, federal waters extend from three nautical miles (three marine leagues in the Gulf of Mexico) to 200 nautical miles from shore. U.S. COMM'N ON OCEAN POL'Y, AN OCEAN BLUEPRINT FOR THE 21ST CENTURY 98 (2004), *available at* http://www.oceancommission.gov; Submerged Lands Act, 43 U.S.C. § 1301(b) (2002). Some states have begun implementing CMSP in state waters. *See, e.g.*, MASSACHUSETTS OCEAN MGM'T PLAN (2009), *available at* http:// www.mass.gov/ (last visited Nov. 26, 2010). State waters extend from the high tide line to three nautical miles (three marine leagues in the Gulf of Mexico) offshore. 43 U.S.C. § 1301(b); CAL. PUB. RES. CODE § 36108.

[9] The comprehensive nature of CMSP differentiates it from traditional, single-sector natural resource management. *See* Sarah E. Lester et al., Ecosystem Service Trade-Off Analysis 6 (2010) (unpublished manuscript, on file with author) ("[m]anagement in the oceans ... tends to be particularly fragmented, with limited governance or institutional frameworks for spatial management and coordinated management across sectors.").

[10] *See* J.B. RUHL ET AL., THE LAW AND POLICY OF ECOSYSTEM SERVICES 284 (2007), *citing* MILLENNIUM ECOSYSTEM ASSESSMENT, ECOSYSTEMS AND HUMAN WELL-BEING: SYNTHESISSS 94 (2005) [hereinafter MEA SYNTHESIS] (calling for the "[d]evelopment of institutional frameworks that promote a shift from highly sectoral resource management approaches to more integrated approaches"); Christopher L. Lant et al., *Using GIS-Based Ecological-Economic Modeling to Evaluate Policies Affecting Agricultural Watersheds*, 55 ECOLOGICAL ECON. 467, 481 (2005) (describing the importance of integrated, cross-sectoral policy in an agricultural context).

[11] *See* Gretchen C. Daily & Pamela A. Matson, *Ecosystem Services: From Theory to Implementation*, 105 PROC. NAT'L ACAD. SCI. 9455 (2008) (conservation advances like ecosystem-based management focus on "ecology, economics, and institutions, and their integration"); Lant et al., *supra* note 10, at 468 (ecosystem-based management should allow "society [to] make greater investments in natural capital to ensure greater delivery of ecosystem services in the present and the future").

[12] INTERAGENCY OCEAN POLICY TASK FORCE REPORT, *supra* note 1, at 41.

[13] In this article, the term "decision makers" encompasses those individuals and groups with the power to make decisions affecting natural resource management, including (but not limited to) lawmakers, policy makers, natural resource managers, and the public (via public processes). The term is context-dependent, and could include one or a combination of these groups depending on the circumstances.

[14] Users include, for example, fishermen, oil and gas exploration and production companies, renewable energy developers, and marine mammal ecotourism outfits. CMSP's ecosystem-based focus allows for an express consideration of the interactions among these stakeholders' uses. *See* Lester et al., *supra* note 9, at 4 (Ecosystem based management "recognizes the need to account for the cumulative impacts of human activities and the connections and feedbacks within and among the social and ecological components of the system, in contrast to management approaches that focus on a single species, sector, or human activity.").

[15] CMSP seeks to "align economic forces with conservation, and ... explicitly link human and environmental well-being." Daily & Matson, *supra* note 11, at 9455. *See also* Per Olsson et al., *Navigating the Transition to Ecosystem-Based Management of the Great Barrier Reef, Australia*, 105 PROC. NAT'L ACAD. SCI. 9489, 9489 (2008) ("ecosystem-based management of marine resources ... address[es] the mismatch between social systems and ecosystem dynamics"); *id.* at 9489 (calling attention to the "urgent need to identify strategies that have enabled transitions in management from a conventional focus on a single resource or habitat to large-scale ecosystem-based management"). The shift to ecosystem-based CMSP parallels a similar trend in terrestrial resource management. *See, e.g.,* Lant et al., *supra* note 10, at 468 ("the scale of management ... is increasingly at the landscape and watershed scale"); RUHL ET AL., *supra* note 10, at 249 (discussing the development of a """"fully integrated decision-making framework for natural resources").

[16] *See* Lant et al., *supra* note 10, at 468 ("Ecosystem services ... are increasingly recognized as essential to society and of great economic value.").

[17] *See* Olsson et al., *supra* note 15, at 9489 (stating that historically, "[d]ifferent disciplines have studied pieces of the puzzle, for example, organizational and institutional aspects, but have rarely analyzed broader social-ecological dynamics"); Stephen R. Carpenter et al., *Science for Managing Ecosystem Services: Beyond the Millennium Ecosystem Assessment*, 106 PROC. NAT'L ACAD. SCI. 1305, 1305 (2009) (stating that in the field of sustainability science, "[r]esearch topics transcend the issues of traditional academic disciplines and focus instead on complex interactions of people and nature" and that "demand from the policy community for this information is expanding").

[18] INTERAGENCY OCEAN POLICY TASK FORCE REPORT, *supra* note 1, at 41. *See also* Sara Curran et al., *Interactions Between Coastal and Marine Ecosystems and Human Population Systems: Perspectives on How Consumption Mediates this Interaction,* 31 AMBIO 264 (2002) ("Besides providing ecosystem services, coastal ecosystems as sites for human economic development put in sharp relief competing human demands for multiple, and not always compatible, uses."); Stephen Polasky et al., *Where to Put Things? Spatial Land Management to Sustain Biodiversity and Economic Returns*, 141 BIOLOGICAL CONSERVATION 1505, 1506 (2008) ("By thinking carefully about the pattern, extent, and intensity of human activities across the landscape, it may be possible to achieve important biodiversity conservation objectives while also generating reasonable economic returns.").

[19] *See, e.g.,* Heather Tallis et al., *An Ecosystem Services Framework to Support Both Practical Conservation and Economic Development*, 105 PROC. NAT'L ACAD. SCI. 9457, 9464 (2008) ("Different ecosystem services will respond on different temporal and spatial scales, and efforts to track interactions will have to anticipate these different scales."); RUHL ET AL., *supra* note 10, at 260 ("Models employed for purposes of decision making about natural capital and ecosystem services must be

integrated between resource and human systems and between spatial and temporal scales."); *id.* at 48 ("Scales of study implicate [ ] not only ecosystem scales but also social, political, and economic scales ... [T]he adoption of a particular scale for articulation of ecosystem service values dictates the type of problems likely to be identified and addressed, the range of policy options that can be considered, and the distribution of ecosystem services among the population").

[20] INTERAGENCY OCEAN POLICY TASK FORCE REPORT, *supra* note 1, at 43. *See also* Polasky et al., *supra* note 18, at 1507 (referring to "tradeoffs between biodiversity conservation and economic returns"). Note that "[s]ome of the tradeoff challenges of ecosystem services policy formulation will be mooted or amplified depending on [sector-specific] legal constraints[.]" J.B. Ruhl, *Ecosystem Services and Federal Public Lands: Start-Up Policy Questions and Research Needs,* 20 DUKE ENVTL. L. & POL'Y F. 275, 285 (2010).

[21] *See* RUHL ET AL., *supra* note 10, at 10 (noting that in the ecosystem services context, "[t]rade-offs are inevitable"); *id.* at 34 ("Managing for one ecosystem service ... has inevitable tradeoff impacts for other ecosystem services" and that "the ecology of ecosystem services must focus on trade-offs and synergies of many kinds and scales"); Lester et al., *supra* note 9, at 5 ("[S]ociety must make decisions about trade-offs among ecosystem services.").

[22] *See* Trevor A. Branch et al., *Fleet Dynamics and Fishermen Behavior: Lessons for Fisheries Managers*, 63 CAN. J. FISHERIES & AQUATIC SCI. 1647, 1648 (2006) ("There are few formal discussions of the tradeoffs needed between different objectives in fisheries management."); Lester et al., *supra* note 9, at 3 (noting that "[c]urrently such trade-offs are made implicitly or with little forethought[,]" and citing the need to "develop[ ] rigorous yet practical approaches for balancing the costs and benefits of diverse human uses of ecosystems"); Polasky et al., *supra* note 18, at 1521 ("There are few prior examples of multi-species conservation planning that integrate a formal mathematical basis with principles of decision theory.").

[23] Carpenter et al., *supra* note 17, at 1308 ("Making these tradeoffs explicit is a core function of ecosystem assessments. Economic analysis is often used to quantify tradeoffs.").

[24] *See generally* Crow White et al., *Ecosystem Service Tradeoff Analysis Reveals the Value of Marine Spatial Planning for Multiple Ocean Uses*, 109 PROC. NAT'L ACAD. SCI. 4696 (2012). Tradeoff analysis can show, in a relatively simple manner, how natural resource use "decisions produce important economic and ecological outputs[.]" Lant et al., *supra* note 10, at 471. Another tool used in this type of analysis is "spatial decision support systems" (SDSS). *See generally id.*; *id.* at 472-73 ("SDSS's [sic] can aid watershed planning activities by estimating the effects of different alternative policies on economic performance and ecosystem services produced by the watershed."). The Natural Capital Project also "seeks to develop tools that capture the value of ecosystem services in decision-making, further integrate the consideration of ecosystem services in the policy process, and demonstrate how this can and should be done in practice." J.B. Ruhl & James Salzman, *The Law and Policy Beginnings of Ecosystem Services*, 22 J. LAND USE & ENVTL. L. 157, 163 (2007). Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) "consists of a suite of models that use [land-use/land-cover (LU/LC)] patterns to estimate levels and economic values of ecosystem services, biodiversity conservation, and the market value of commodities provided by the landscape." Erik Nelson et al., *Modeling Multiple Ecosystem Services, Biodiversity Conservation, Commodity Production, and Tradeoffs at Landscape Scales*, 7 FRONTIERS IN ECOLOGY & ENV'T 4, 5 (2009). *See also* Tallis et al., *supra* note 19, at 9462 fig. 4 caption ("Tradeoff flowers' depict[ ] alternative scenarios for ecotourism projects aimed at biodiversity protection and economic growth.").

[25] Lester et al., *supra* note 9, at 3 (describing ecosystem service tradeoff analysis as "a conceptual framework, building on decision theory and economics, [that] explicitly examine[s] real and perceived trade-offs among multiple ecosystem services").

[26] *See generally* White et al., *supra* note 24. *See also* Polasky et al., *supra* note 18, at 1506 (using a model for the Willamette Valley, Oregon, that "integrate[s] spatially explicit biological and economic models to analyze the consequences of alternative land-use decisions for both biodiversity conservation and economic objectives"); Erik Nelson et al., *Efficiency of Incentives to Jointly Increase Carbon Sequestration and Species Conservation on a Landscape*, 105 PROC. NAT'L ACAD. SCI. 9471, 9474 (2008) ("combin[ing] a model that predicts land-use decisions by multiple private landowners with models that predict the consequences of these decisions on the provision of an ecosystem service and on biodiversity conservation"); James Salzman, *A Field of Green? The Past and Future of Ecosystem Services*, 21 J. LAND USE & ENVTL. L. 133, 147 (2006) (commenting on "a significant increase in scientific research examining the relationship between biodiversity, on the one hand, and the relative intensity and nature of land use, on the other"). For examples of papers looking at conservation tradeoffs in the forestry context, *see, e.g.*, David E. Calkin et al., *Developing a Production Possibility Set of Wildlife Species Persistence and Timber Harvest Value*, 32 CAN. J.

FOREST RESEARCH 1329 (2002); Darek J. Nalle et al., *Modeling Joint Production of Wildlife and Timber*, 48 J. ENVTL. ECON. & MGMT. 997 (2004); Mark E. Lichtenstein & Claire A. Montgomery, *Biodiversity and Timber in the Coast Range of Oregon: Inside the Production Possibility Frontier*, 79 LAND ECON. 56 (2003). *See also* RUHL ET AL., *supra* note 10, at 24 (“Researchers in both fields [(i.e., ecology and economics)] ... have begun to bridge the gap, to fill in the very large hole of knowledge surrounding how *ecologically* important ecosystem attributes are *economically* valuable services to humans.”) (emphasis in original).

[27] As J.B. Ruhl has recognized, it is “important for law to work closely with economics, ecology, geography, and other relevant disciplines ... to understand where they had taken the theoretical research and practical applications ... [and] ensure that those disciplines in turn appreciate the nature and limits of legal institutions and instruments.” RUHL ET AL., *supra* note 10, at x. *Id.* at 83 (commenting that “[i]t is essential ... that economists team with ecologists to inform society of the marginal value of ecosystem services”); Tallis et al., *supra* note 19, at 9463-64 (citing the need for “[t]he natural science, social science, and practitioner communities jointly ... to establish a standard set of measures and approaches for quantifying and monitoring ecosystem service levels and values”).

[28] RUHL ET AL., *supra* note 10, at 9 (“The component [of the ecosystem service discussion] that is least developed in the literature on ecosystem services is *the law*, particularly as it relates to property rights and governance institutions.”) (emphasis in original); Carpenter et al., *supra* note 17, at 1305 (noting the need to identify “new possibilities for measuring and projecting the effects of policy choices and human actions on the structure and processes of ecosystems, the services they provide, and human well-being”). In other words, tradeoff analysis can be used in settings where “scientific inquiry and practical application are commingled” to “synthesize what [is] known about sustainability science in policy-relevant ways.” *Id. See also id.* at 1309 (referring to the “problem-solving aspects of social-ecological research”).

[29] Carpenter et al., *supra* note 17, at 1309 (Tradeoff analysis seeks “to quantify and determine the value of services, insofar as possible”).

[30] In this article, the Authors use the terms law, regulation, policy, and management strategy rather loosely and interchangeably, albeit with an acceptance and understanding of the technical differences between these instruments and the bodies by which the instruments are made (e.g., federal and state legislatures, local governmental bodies, administrative agencies, courts). They are all meant to refer to instruments that permit, prescribe, or encourage a particular course of action in the natural resources realm.

[31] *See* RUHL ET AL., *supra* note 10, at 258 (stating that “[t]he purpose of building an integrated model ... is to evaluate different policy options” and that “[a] reliable integrated model ... would allow [decision makers] to evaluate how implementing these options or combinations thereof would affect the relevant resource and human systems”); Carpenter et al., *supra* note 17, at 1307 (“Explicit models of coupled social-ecological systems are essential for research, synthesis, and projection of the consequences of management actions”). In so doing, tradeoff analysis can “begin to organize an analysis of how attributes of (*i*) a resource system (e.g., fishery ...), (*ii*) the resource units generated by that system (e.g., fish ...), (*iii*) the users of that system, and (*iv*) the governance system jointly affect and are indirectly affected by interactions and resulting outcomes achieved at a particular time and place.” Elinor Ostrom, *A Diagnostic Approach for Going Beyond Panaceas*, 104 PROC. NAT’L ACAD. SCI. 15181, 15182 (2007). *See also id.* (stating that such “““framework[s may] also enable [...] one to organize how these attributes may affect and be affected by the larger socioeconomic, political, and ecological settings in which they are embedded, as well as smaller ones”).

[32] Indeed, there is unlikely to be one policy panacea for sustainable fisheries management. *See* Ostrom, *supra* note 31, at 15181 (“call[ing] attention to perverse and extensive uses of policy panaceas in misguided efforts to make social-ecological systems (SESs), also called human-environment systems, sustainable over time”); Carpenter et al., *supra* note 17, at 1311 (“[E]vidence suggests that success and failure are context-specific and that no policy or practice is a panacea.”).

[33] *See, e.g.,* sources cited *supra* note 26.

[34] *See* Lester et al., *supra* note 9, at 8 (stating that ecosystem service tradeoff analysis is a “means for evaluating and making more informed management decisions about real and perceived trade-offs among ecosystem services”); *id.* at 11 (“[T]he shape of the frontier can inform what the optimal management solution(s) is likely to be, narrowing the scope of potential policy decisions available.”); RUHL ET AL., *supra* note 10, at 259 (“[T]o the extent that improved ... information mean[s] that natural capital and

ecosystem service values are more fully integrated into our market economy, overall social welfare cannot help but rise, as resource owners and resource users would make more informed decisions about what is the most economically efficient investment when the values of natural capital and ecosystem services are included"); Nelson et al., *supra* note 26, at 9475 ("[P]resenting decision-makers with tradeoffs among ends provides information regarding the opportunity cost of achieving particular environmental goods and, hence, a measure of the minimum value that those environmental goods must possess for a particular policy to achieve a net gain in social welfare.").

[35] In the ecological and economic sciences, "models are used to clarify spatial boundaries of systems, units of analysis, time horizons, inputs and drivers, key components of the system and their relationships, and outputs." Carpenter et al., *supra* note 17, at 1307. Models can compare "the degree of change in each indicator relative to the reference case (no action taken) ... for one or more levels of intervention." R.J. SCHOLES & G.P. VON MALTITZ, QUANTIFYING TRADEOFFS BETWEEN SUSTAINABLE LAND MANAGEMENT, GLOBAL ENVIRONMENTAL CONCERNS AND LOCAL SOCIO-ECONOMIC IMPACTS 16 (2006).

[36] Katrina M. Wyman, *The Property Rights Challenge in Marine Fisheries*, 50 ARIZ. L. REV. 511, 516-17 (2008). *See also* Worm et al., *supra* note 3 (discussing the use of various fishing management techniques); J.R. Beddington et al., *Current Problems in the Management of Marine Fisheries*, 316 SCIENCE 1713, 1713-14 (2007); Branch et al., *supra* note 22, at 1653-56; Ray Hilborn et al., *Institutions, Incentives and the Future of Fisheries*, 360 PHIL. TRANSACTIONS ROYAL SOC'Y SERIES B 47 (2005) (discussing different fishery management strategies and their successes and failures). *See also* Ragnar Arnason, *Theoretical and Practical Fishery Management, in* MANAGING FISHERY RESOURCES, WORLD BANK DISC. PAPERS 217, at 3-10 (E.A. Loyayza ed., 1994), *available at* http://innri.unuftp.is/fppreadings/arnason_r_1994-b.pdf; Jonathan M. Karpoff, *Suboptimal Controls in Common Resource Management*, 95 J. POL. ECON. 179 (1987) (discussing season closure and capital constraints).

[37] The National Oceanic and Atmospheric Administration (NOAA) defines the TAC as "the total regulated catch from a stock in a given time period, usually a year." NOAA NORTHEAST FISHERIES SCI. CTR., STATUS OF FISHERY RESOURCES OFF THE NORTHEASTERN US-INTRODUCTION, http:// www.nefsc.noaa.gov/sos/intro/. TACs that, when reached, result in the closure of a fishery are called "hard TACs." *See, e.g.,* 50 C.F.R. § 648.87(b)(vi) (stating that for Fisheries of the Northeastern United States, "[o]nce a hard TAC allocated to a Sector is projected to be exceeded, Sector operations will be terminated for the remainder of the fishing year"); 50 C.F.R. § 679.20(d)(2) (setting hard TACs for Gulf of Alaska and Bering Sea/Aleutian Island commercial groundfish fisheries).

[38] Costello et al., *supra* note 7, at 1679. *See also* PAMELA B. BAKER ET AL., MANAGING THE GULF OF MEXICO COMMERCIAL RED SNAPPER FISHERY 11 (1998), *available at* http://cleartheair.edf.org/documents/550_RedSnapper.PDF ("Under derby conditions, [...] fishers are encouraged to harvest fish as quickly as possible to maximize their share of the quota before it is filled and the season closed.").

[39] *See* Press Release, U.S. Dep't of Labor, Bureau of Labor Statistics, National Census of Fatal Occupational Injuries in 2009 - Preliminary Results (Aug. 19, 2010) (finding that fishers and other fishery workers had the highest fatal work injury rate in 2009); ENVTL. DEF. FUND, FISHING SAFETY FACT SHEET (citing the above census and stating that the "'race for fish' created a negative trend in safety as captains became more willing to risk crew safety by fishing in adverse weather and water conditions in order to maximize catches during limited days at sea") (on file with Author); David R. Griffith, *The Ecological Implications of Individual Fishing Quotas and Harvest Cooperatives*, 6 FRONTIERS IN ECOLOGY & ENV'T 191, 191-92 (2008) (discussing safety implications of the race to fish).

[40] Overcapitalization occurs when "harvesting capacity [...] increase [s] beyond that which will be required to take the TAC." Dominique Gréboval & Gordon Munro, *Overcapitalization and Excess Capacity in World Fisheries: Underlying Economics and Methods of Control, in* MANAGING FISHING CAPACITY: SELECTED PAPERS ON UNDERLYING CONCEPTS AND ISSUES, FAO FISHERIES TECHNICAL PAPER 386 (Dominique Gréboval ed., 1999), *available at* http:// www.fao.org/DOCREP/003/X2250E/x2250e03.htm.

[41] *See* Costello et al., *supra* note 7, at 1679 ("This race can lead to poor stewardship and lobbying for ever-larger harvest quotas, creating a spiral of reduced stocks, excessive harvests, and eventual collapse.").

[42] Commercial extinction occurs when "it is no longer economically viable to harvest" a species or stock. MICHAEL L. MCKINNEY & ROBERT M. SCHOCH, ENVIRONMENTAL SCIENCE SYSTEMS AND SOLUTIONS 323 (3d ed. 2003). Overfishing can also lead to ecological extinction, when "overfished populations no longer interact significantly with other species in the community." Jeremy B.C. Jackson et al., *Historical Overfishing and the Recent Collapse of Coastal Ecosystems*, 293 SCIENCE 629 (2001).

[43] Branch et al., *supra* note 22, at 1648 (citing F.T. Christy, *Economic Waste in Fisheries: Impediments to Change and Conditions for Improvement, in* AM. FISHERIES SOC'Y SYMP., GLOBAL TRENDS: FISHERIES MANAGEMENT (E.K. Pikitch et al. eds., 1997)) (estimating waste of $2.9 billion annually).

[44] Wyman, *supra* note 36, at 527 ("[Economists] have tended to prescribe private property rights for wild fisheries, such as territorial use rights, or proxies for private rights, such as cooperatives or [individual transferable quotas (ITQs)]."); Shankar Aswani, *Customary Sea Tenure in Oceania as a Case of Rights-Based Fishery Management: Does it Work?*, 15 REV. IN FISH BIOLOGY & FISHERIES 285, 286 (2005) (same); Gail Osherenko, *New Discourses on Ocean Governance: Understanding Property Rights and the Public Trust*, 21 J. ENVTL. L. & LITIG. 317, 325 (2006) (same); *see* Rod Fujita & Kate Bonzon, *Rights-Based Fisheries Management: an Environmentalist Perspective*, 15 REV. IN FISH BIOLOGY & FISHERIES 309 (2005) (discussing the intersection between rights-based fisheries management and incentive structures); Christopher J. Costello & Daniel Kaffine, *Natural Resource Use with Limited Tenure Property Rights*, 55 J. ENVTL. ECON. & MGMT. 20, 20 (2008) ("The ability of property rights to help correct resource overexploitation is increasingly being appreciated in policy circles."); *id.* at 22 (discussing how secure property rights promote investment); *But see* Amy Sinden, *The Tragedy of the Commons and the Myth of a Private Property Solution*, 78 U. COLO. L. REV. 533, 538 (2007) ("It is only under a very limited and idealized set of circumstances that the delineation of property rights and/or the creation of markets can actually solve the tragedy ...").

[45] *See* Costello et al., *supra* note 7 at 1679 ("[C]atch shares ... can be manifest as individual (and tradable) harvest quotas, cooperatives, or exclusive spatial harvest rights; the idea is to provide - to fishermen, communities, or cooperatives - a secure asset, which confers stewardship incentives."); 16 U.S.C. § 1853a (the Magnuson-Stevens Fishery Conservation and Management Act's ("MSA") LAPP provision).

[46] *See generally* Branch et al., *supra* note 22, at 1656-59 (Group allocations typically go to cooperatives or communities).

[47] *See* RUHL ET AL., *supra* note 10, at 64 (commenting that rights-based or market-based resource allocation programs "work [...] best when the goods and services being traded are [...] 'excludable"' so that "sellers can control their distribution and deny access").

[48] *See, e.g.*, 16 U.S.C. § 1802(16)(A) (2007). *See also* Branch et al., *supra* note 22, at 1657.

[49] Costello et al., *supra* note 7, at 1679 (stating that catch shares "work by allocating a dedicated share of the scientifically determined total catch to fishermen, communities, or cooperatives. This provides a stewardship incentive; as the fishery is better managed, the value of the shares increases").

[50] *See* Trevor A. Branch, *How Do Individual Transferable Quotas Affect Marine Ecosystems?*, 10 FISH & FISHERIES 39, 50-52 (2009) (discussing effects of IFQs on habitat, and noting that in the "Aitutaki trochus fishery[,] ... the reef was damaged during the competitive race for the TAC, and this halted under ITQs"); DONALD R. LEAL ET AL., THE ECOLOGICAL ROLE OF IFQS IN U.S. FISHERIES: A GUIDE FOR FEDERAL POLICY MAKERS 8 (2005), http://ifqsforfisheries.org/pdf/pr_ ifq_ecology.pdf ("Another crucial ecological role for IFQs is in reducing fleet excesses and their environmental impacts[,]" including habitat damage.). Wyman, *supra* note 36, at 527 ("[P]roperty rights should reduce the need fishers currently have to race for the fish[.] [...] Fishers with property rights such as territorial use rights or individual transferable quotas also might become more focused on conserving fish stocks and less likely to pressure regulators to increase total allowable catches because fishers will internalize the benefits of improved stewardship").

[51] Per economic theory, providing fishermen with a more encompassing property interest in the fishery should eliminate the race to fish and foster stewardship behavior, because "fishing participants [...] stand to directly suffer the consequences of

overexploitation and directly benefit from maintaining high stock sizes of exploited populations." Timothy E. Essington, *Ecological Indicators Display Reduced Variation in North American Catch Share Fisheries*, 107 PROC. NAT'L ACAD. SCI. 754, 754 (2010). Christopher Costello & Daniel T. Kaffine, *Marine Protected Areas in Spatial Property-Rights Fisheries*, 54 AUSTL. J. AGRIC. & RESOURCE ECON. 321, 321-22 (2009) (The "appropriate assignment of rights internalizes externalities and facilitates stewardship, leading to sustainability through a profit motive.").

[52] Ragnar Arnason, *Iceland's ITQ System Creates New Wealth*, 1 ELEC. J. SUSTAINABLE DEV. 35, 35 (2008), *available at* http:// www.ejsd.org/public/journal_article/9 (last visited Dec. 14, 2009) ("There are several possible types of private property rights in fisheries, of which individual transferable quotas (ITQs) are the most common."); Kevin J. Lynch, Student Article, *Application of the Public Trust Doctrine to Modern Fishery Management Regimes*, 15 N.Y.U. ENVTL. L.J. 285, 304 (2007).

[53] *See, e.g.,* Magnuson-Stevens Fishery Conservation and Management Act (MSA), 16 U.S.C. § 1802(26)(A)-(B) (2007).

[54] IFQ programs in federal waters are sanctioned by the LAPP provision of the MSA, and generally have been upheld by the courts.

[55] NOAA FISHERIES SERVICE, ALASKA IFQ HALIBUT AND SABLEFISH PROGRAM (November 2009), http://www.nmfs.noaa.gov/sfa/domes_fish/catchshare/docs/ak_ halibut_sablefish.pdf.

[56] NOAA FISHERIES SERVICE, GULF OF MEXICO RED SNAPPER IFQ (November 2009), http://www.nmfs.noaa.gov/sfa/domes_fish/catchshare/docs/gom_ redsnapper.pdf.

[57] NOAA FISHERIES SERVICE, WRECKFISH ITQ PROGRAM (November 2009), http://www.nmfs.noaa.gov/sfa/domes_fish/catchshare/docs/wreckfish.pdf.

[58] NOAA FISHERIES SERVICE, SURF CLAM AND OCEAN QUAHOG ITQ (November 2009), http://www.nmfs.noaa.gov/sfa/domes_fish/catchshare/docs/surfclam_ oceanquahog.pdf.

[59] *See generally* Costello et al., *supra* note 7. *See also* Carpenter et al., *supra* note 17, at 1310 ("[F]isheries with property rights systems such as tradeable catch shares are less prone to collapse than open-access fisheries."); CAL. FISH & GAME COMM'N, *Miscellaneous Provisions - Restricted Access to Commercial Fisheries* (1999), http:// www.fgc.ca.gov/policy/p4misc.aspx (last visited May 13, 2012) ("The first 15 years of experience with individual quota management has shown that they end the race for fish and provide incentives to fishermen to change their business to maximize revenues and minimize costs.").

[60] Costello et al., *supra* note 7, at 1678, 1680. A "collapsed" fishery is one that has experienced more than a 90% decline from baseline abundance. *See* Boris Worm et al., *Impacts of Biodiversity Loss on Ocean Ecosystem Services*, 314 SCIENCE 787, 788 (2006).

[61] *But see* HAW. REV. STAT. § 188-22.6 (2009) (establishing community-based subsistence fishing areas in Hawaii, where harvest rights are assigned to Native Hawaiian communities for spatially delineated marine areas). These spatially-defined fishing grounds fall within the broader TURF rubric.

[62] *See, e.g.,* Juan Carlos Castilla, *Fisheries in Chile: Small Pelagics, Management, Rights, and Sea Zoning*, 86 BULL. MARINE SCI. 221, 230 (2010) (since fishery reforms including TURFs were implemented in Chile, "the 'race for fish' appears to have been counteracted"); Costello & Kaffine, *supra* note 44, at 30-31 (finding that in Mexico, spiny lobsters have been managed quite sustainably since the inception of a TURF system in 1936.).

[63] DEP'T OF COMMERCE, NAT'L OCEANIC & ATMOSPHERIC ADMIN., CATCH SHARE POLICY (2010), *available at* http://www.nmfs.noaa.gov/sfa/domes_ fish/catchshare/docs/noaa_cs_policy.pdf (including TURFs in the definition of catch shares). TURFs-*qua*-TURFs have not yet been brought before U.S. courts. LexisNexis Academic searches in the combined U.S. Federal and State case law database for ("territorial use rights in fisheries" OR "territorial user right fisheries") and ("territorial

use*” and fish*) produced no relevant results (search run April 20, 2012).

[64] *See* Wyman, *supra* note 36, at 517-18 (“[I]n Japan, fishing cooperatives--not individuals--have TURF rights to fish in ‘specific territories extending as far as five and a half miles seaward.’”) (internal citation omitted).

[65] In other words, a fisherman could receive harvesting rights for a sedentary species on a defined area of ocean floor, like a garden plot in a community garden.

[66] For species that live not on the ocean floor but in the water column, the water overlying a particular, defined area of ocean floor could constitute the area in which the fisherman could harvest.

[67] Because of logistical difficulties and jurisdictional issues, TURFs generally are thought to be most useful for nearshore, sedentary species that do not routinely migrate out of the TURF boundary. Castilla, *supra* note 62, at 229 (“Fisheries ... for benthic species, showing spatially explicit population structure ..., have been rightly argued to be more appropriate for these management approaches than fisheries for pelagic mobile species.”) (citations omitted). *See also* Omar Defeo & Juan Carlos Castilla, *More Than One Bag for the World Fishery Crisis and Keys for Co-Management Successes in Selected Artisanal Latin American Shellfisheries*, 15 REVS. FISH BIOLOGY & FISHERIES 265, 269 (2005) (same); Lynch, *supra* note 53, at 305 (same); Wyman, *supra* note 36, at 517 (same); Sinden, *supra* note 44, at 600 (same). *But see* José P. Cancino et al., *TURFs and ITQs: Collective vs. Individual Decision Making*, 22 MARINE RESOURCE ECON. 391, 394-95 (2007) (while Chilean TURFs focus on the relatively sedentary *loco*, sea urchin, and limpets, in Japan, Fisheries Cooperative Association jurisdictions encompass both sedentary and moderately mobile species).

[68] *See* Christopher Costello & Daniel T. Kaffine, *Marine Protected Areas in Spatial Property-Rights Fisheries*, 54 AUSTL. J. AGRIC. & RESOURCE ECON. 321 (defining TURFs as a property rights-based approach to fisheries management that “allocate[s] units of space to private firms, cooperatives, or fishermen”); Wyman, *supra* note 37, at 517 (“[TURFs] give fishers ownership of the stock of the fish in designated areas.”); Lynch, *supra* note 52, at 305 (noting that “[i]n addition to rights of access and withdrawal, TURFs generally give the holders the right to exclude others from their section of the ocean”). To be clear, the term “TURF” as used in this article refers to a subset of the universe of spatial harvesting privileges. It could be argued that the waters under a given state’s jurisdiction (or even the entire United States Exclusive Economic Zone) constitute a TURF insofar as those waters represent a spatially-delineated area with restricted fishing access. What the Authors are referring to as a TURF, however, occurs on a smaller scale (e.g., the southern California red sea urchin fishery). Personal communication with Dr. Christopher Costello, Professor of Environmental and Resource Economics, Bren School of Environmental Science and Management, University of California, Santa Barbara, in Santa Barbara, Cal. (Sept. 27, 2010).

[69] Costello & Kaffine, *supra* note 68, at 322.

[70] *See* RUHL ET AL., *supra* note 10, at 278-79 (“[U]nder the right conditions economists find tradable permits and other market-based programs have been shown to provide effective rationing of access to common-pool resources[,]” but “market-based systems are only as effective as their design permits.”).

[71] *See, e.g.*, Ruhl & Salzman, *supra* note 24, at 161 (“If one focuses on legal scholarship as a proxy, from 1990 through 1996 there were only 17 articles containing the term ‘ecosystem services.’ During the following seven years, from 1997-2003, over ten times that number of law review articles referred to ecosystem services.

[72] MILLENNIUM ECOSYSTEM ASSESSMENT, ECOSYSTEMS AND HUMAN WELL-BEING: A FRAMEWORK FOR ASSESSMENT 49 (2005) [hereinafter MEA FRAMEWORK] (emphasis added). *See also id.* at 55, *citing* Robert Costanza et al., *The Value of the World’s Ecosystem Services and Natural Capital*, 387 NATURE 253, 253 (1997) (“Ecosystem goods (such as food) and services (such as waste assimilation) represent the *benefits human populations derive*, directly or indirectly, from ecosystem functions.”) (emphasis added).

[73] MEA FRAMEWORK, *supra* note 72, at 54, *citing* Gretchen C. Daily, *Introduction: What Are Ecosystem Services?, in*

NATURE'S SERVICES: SOCIETAL DEPENDENCE ON NATURAL ECOSYSTEMS 3 (Gretchen Daily ed. 1997) (emphasis added).

[74] *See* Ruhl, *supra* note 20, at 278 ("[T]he concept of ecosystem services is anthropogenic in focus--it is about delivering economic value to humans.").

[75] *See* A. Dan Tarlock, *Ecosystem Services in the Klamath Basin: Battlefield Casualties or the Future?*, 22 J. LAND USE & ENVT'L L. 207, 217 (2007) ("[E]nvironmental protection remains relentlessly anthropocentric."); Carpenter et al., *supra* note 17, at 1306 (stating that the Millennium Ecosystem Assessment "made a thorough effort to assess the effects of policies on ecosystem services and human well-being").

[76] RUHL ET AL., *supra* note 10, at ix. *See also* Ruhl, *supra* note 20, at 276 (noting the need for the federal government to "begin to consider as a policy matter how it might manage the flow of ecosystem services on and off of its landholdings").

[77] *See* RUHL ET AL., *supra* note 10, at 8 ("The United Nations Millennium Ecosystem Assessment project (2005) has moved the dialogue beyond academic discourse to concerted policy analysis. Yet proposals to date are largely conceptual in scope."); Salzman, *supra* note 71, at 875
("[I]t is fair to say that we have achieved a good understanding of the theoretical issues concerning ecosystem service provision. There is also a growing literature, though largely anecdotal, that describes some of the practical issues concerning ecosystem service provision. The problem is that theory and practice often have not been effectively joined so that one meaningfully informs the other.");
Tarlock, *supra* note 75, at 217 (noting that "[t]he problem has been to apply these diverse rationales from concept to the working landscape"). *See also* RUHL ET AL., *supra* note 10, at 168 (providing the "rather bleak message - that none of the institutions usually relied on to facilitate sustainable resource allocation [(i.e., property rights, regulation, social norms)] has worked effectively toward that end with respect to natural capital and ecosystem services").

[78] Salzman, *supra* note 26, at 151.

[79] Daily & Matson, *supra* note 11, at 9456.

[80] *See* RUHL ET AL., *supra* note 10, at 6 ("Yet ecosystem service values derived directly from nature show up practically nowhere in our economy as it is structured, and much less so in the law supporting that structure ...." While "[t]he concept of ecosystem services is not new, ... it is sufficiently recent that it is yet to be fully developed into coherent policy terms, and surely not yet into hard law to be applied.").

[81] *See* SCHOLES & MALTITZ, *supra* note 35, at 11 ("us[ing] the term "'tradeoffs' to describe the relationship between the outcome of interventions undertaken in one sphere of environmental management, and the outcomes in another sphere [...] are an example of project externalities"); RUHL ET AL., *supra* note 10, at 258 ("There exist not only "ecological trade-offs ... within and between ecosystems as a consequence of decisions about how to manage a service regime at a particular place and time[,]" but also "trade-offs and transitions inherent in every policy option relevant to every other policy option.").

[82] *See, e.g.*, Nelson et al., *supra* note 26, at 9474 ("We found some cases in which a policy directed toward one goal actually reduced the ability to attain the other goal .... If programs that pay for ecosystem services are not designed carefully, they may yield minimal gains in services of interest and may well result in harm to other services or biodiversity conservation.").

[83] Such comparison is crucial, as "[l]aw and policy depend on other disciplines to inform effective decisions about the appropriate institutions and instruments to use[.]" RUHL ET AL., *supra* note 10, at 13. *See also* Carpenter et al., *supra* note 17, at 1308 ("Quantification of tradeoffs among ecosystem services and their interactions with human well-being are among the most pressing areas for research."); Olsson et al., *supra* note 15, at 9489 ("The burgeoning literature on ecosystem-based management offers few empirically based insights into social-ecological strategies that make transitions to such management possible.").

[84] Christopher Costello & Stephen Polasky, *Optimal Harvesting of Stochastic Spatial Resources*, 56 J. ENVTL. ECON. & MGMT. 1, 3 (2008). *See also* H. Scott Gordon, *The Economic Theory of a Common Property Resource: the Fishery*, 62 J. POL. ECON. 124, 124 (1954) ("Owing to the lack of theoretical economic research, biologists have been forced to extend the scope of their own thought into the economic sphere and in some cases have penetrated quite deeply, despite the lack of the analytical tools of economic theory.").

[85] *See, e.g.,* Ruhl & Salzman, *supra* note 24, at 158, *citing* NATURE'S SERVICES: SOCIETAL DEPENDENCE ON NATURAL ECOSYSTEMS xv (Gretchen C. Daily ed. 1997) (noting the "failure of the scientific community to ... effectively convey the necessary information to the public"); Olsson et al., *supra* note 15, at 9493 (discussing "the need to coordinate scientist interactions with each other, the public, and politicians").

[86] In this role, tradeoff analysis can provide "a framework for assessing the connections between ecosystem services and economic development on a project-by-project basis and suggest indicators and metrics that could increase the likelihood of win-win outcomes." Tallis et al., *supra* note 19, at 9458. *See also* RUHL ET AL., *supra* note 10, at 274 (noting the importance of "manag[ing] or distribut[ing] ... information in a way that [is] useful to policy development").

[87] RUHL ET AL., *supra* note 10, at 8. *See also id.*

[88] Nelson et al., *supra* note 24, at 10 (highlighting the importance of "[t]he kinds of analyses ... [that] make transparent the tradeoffs between ecosystem services, biodiversity conservation, and market returns, and [emphasizing] that transparency ... is desirable in engaging stakeholders and decision makers"); RUHL ET AL., *supra* note 10, at 281 ("[Q]uestions of institutional design focus primarily on ... how to design regulatory institutions that are effective at implementing the regulatory instruments but also exhibit the key attributes of legitimacy - transparency, accountability, and efficiency.") (internal citations omitted).

[89] *See* SCHOLES & MALTITZ, *supra* note 35, at 11 ("Not all 'tradeoffs' are negative in the sense that the outcomes in another sphere are necessarily negatively correlated with outcomes in the intended spheres.

[90] Lester et al., *supra* note 9, at 3 (noting that ecosystem service tradeoff analysis "can reveal inferior management options"); Nelson et al., *supra* note 26, at 9474 (in the terrestrial context, certain "policies that pay private landowners to restore land to natural cover increase the provision of an ecosystem service and biodiversity conservation; however, these increases are less than what is feasible for a given budget, as shown by the efficiency frontier. It is possible that more sophisticated policies ... may be able to close the gap vis-à-vis the efficiency frontier.").

[91] *See* RUHL ET AL., *supra* note 10, at 58 (decision makers will have to "address resource allocation issues that will inevitably arise given the inherent trade-offs among different ecosystem services and, more generally, between ecosystem services and other benefits of technology and natural capital").

[92] *See* Lester et al., *supra* note 9, at 9. *See also* Robin Kundis Craig, *Valuing Coastal and Ocean Ecosystem Services: The Paradox of Scarcity for Marine Resources Commodities and the Potential Role of Lifestyle Value Competition*, 22 J. LAND USE & ENVTL. L. 355, 384 (2007) ("In contrast to natural resources commodities, the effects of demand for natural resource amenities can occupy many points on a continuum between consumptive/destructive use and non-consumptive/observational use."). This tool is not limited to comparing two ecosystem services, as in this article; it can assess tradeoffs among a suite of ecosystem services through multi-dimensional models.

[93] Lester et al., *supra* note 9, at 5 ("[V]aluation is not required to formally evaluate tradeoffs among management alternatives."); *id.* at 9 (the efficiency frontier can be crafted "using empirical data, quantitative models or conceptual models, depending on data and model availability"). This characteristic of ecosystem service tradeoff analysis is important because "whether we know [ecosystem services'] precise economic value or not, ... society has to choose how to allocate natural resources[.]" RUHL ET AL., *supra* note 10, at 31.

[94] Lester et al., *supra* note 9, at 9 ("[S]ervices do not need to be quantified in common metrics within a given analysis."); *id.* ("[T]he

only requirement is that the service can be quantified, whether in dollars or another metric ...."); *But see* Tarlock, *supra* note 76, at 217 ("It is ... harder to argue against a policy with dollar values attached.").

[95] *See* Lant et al., *supra* note 10, at 470 (noting the importance of identifying the "interaction between socioeconomic and biophysical processes").

[96] *See* Lester et al., *supra* note 9, at 14 ("[O]ur ability to distinguish among these different types of interactions depends on our level of certainty regarding the location of individual points or, in other words, our ability to predict how much of the services of interest will be realized under different management options.").

[97] Polasky et al., *supra* note 18, at 1506 ("The efficiency frontier illustrates what can be achieved in terms of biological and economic objectives by carefully arranging the spatial allocation of activities across the landscape. The efficiency frontier also demonstrates the degree of inefficiency of other land-use patterns not on [the] frontier."); *id.* ("An efficient land-use pattern is one that generates the maximum biological score for a given economic score (and vice versa)."). *See also* Lant et al., *supra* note 10, at 478 (describing the production possibility frontier (PPF), i.e., efficiency frontier, as "represent[ing] a set of social choices involving trade-offs among multiple objectives, with each choice manifested as a landscape"); Nelson et al., *supra* note 26, at 9472 ("Efficient outcomes occur when it is not possible to increase one desired objective without simultaneously decreasing another desired objective ... We summarize the set of efficient outcomes, with efficiency frontiers that show the maximum feasible combinations of multiple outputs that can be generated by the landscape.").

[98] *See* Carpenter et al., *supra* note 17, at 1309 ("Economic analysis of tradeoffs employs the marginal value, or the value of a small increment or decrement of that service from its current supply."); Salzman, *supra* note 26, at 134 (discussing marginal change); Nelson et al., *supra* note 26, at 9472 ("Starting from an efficient land-use pattern, an increase in the production on one objective requires a decrease in the level of the other." In their study, "[t]radeoffs were found between carbon sequestration and species conservation on efficiency frontiers in the Willamette Basin as indicated by the negative slope of each efficiency frontier.").

[99] Lant et al., *supra* note 10, at 478 ("In theory, the PPF should ... be convex, but where various economic and ecological goals are neutral or complementary, it can be linear or even concave" and "it is frequently the case that adjacent points along the PPF produce substantially different land-use patterns due to nuances in the effects of spatial pattern on ecosystem service production."); Carpenter et al., *supra* note 17, at 1309 ("An important piece of qualitative information is the shape of the curves relating various levels of activity and the corresponding levels of delivery for key services. From these, it is often possible to agree on certain thresholds that should not be exceeded.").

[100] *See* Nelson et al., *supra* note 26, at 9472 ("With the complex biophysical models, we find significant portions of the efficiency frontiers where one objective can be increased without significantly lowering the other."); Polasky et al., *supra* note 18, at 1520 ("[O]ther studies that have combined biological and economic models in terms of an efficiency frontier ... have generally found that a large portion of conservation benefits can be achieved at relatively low cost but that obtaining the final few increments of a conservation objective are extremely expensive.").

[101] *See* Nelson et al., *supra* note 24, at 10 (mentioning the ""crucial ... step" of "determin[ing] how much of this production is actually of value to people and where that value is captured"); RUHL ET AL., *supra* note 10, at 35 (raising the "question of which service to favor when enhancing one diminishes or enhances another"); *id.* at 209 ("[T]here can be trade-offs between ecosystem goods and ecosystem services, and society must choose what it wants from a set of possibilities."); Salzman, *supra* note 71, at 900 ("the very first question to consider is which service you care about ..."); Lester et al., *supra* note 9, at 10 ("The societal preference for one service compared with another will determine which point along the frontier maximizes social value of ecosystem services.").

[102] Daily & Matson, *supra* note 11, at 9456 (finding this challenge significant given "the social and political challenges associated with incorporating [our] understanding [of human-ecosystem interactions] into effective and enduring institutions, to manage, monitor, and provide incentives that accurately reflect the social values of ecosystem services to society").

[103] SCHOLES & MALTITZ, *supra* note 35, at 12 ("[S]ocietal preferences for one service over another change over time."); Craig, *supra* note 93, at 406 ("Regulation of marine ecosystems gives ample evidence of the difficulty of translating changing values

among the experts to in-the-legislature political will ...").

[104] *See, e.g.*, Craig, *supra* note 93, at 394 ("In the political realm, the paradox of single-commodity competition for marine resources is that, regardless of market perception of scarcity, such competition undermines any regulatory attempt to preserve the resource or the supporting ecosystem because there is insufficient economic - and hence political - opposition to the continuation of that use.").

[105] Lester et al., *supra* note 9, at 10 ("Points interior of the efficiency frontier are inefficient--at least one service [can be] increased, at no cost to other services."); Lant et al., *supra* note 10, at 478 ("[I]n reality, many producers may not be producing on the [efficiency frontier] but at a point interior to it, making possible simultaneous improvements in both gross margin and environmental benefits.").

[106] *See*, *e.g.*, Polasky et al., *supra* note 18, at 1514 fig. 2 (2008) (showing estimated biodiversity/economic return outcomes falling well below the efficiency frontier in the Willamette Valley, Oregon); RUHL ET AL., *supra* note 10, at 209 ("[C]urrent land use patterns may be suboptimal, inside rather than on the [efficiency frontier], and so we may be able to improve multiple goals at the same time by closely examining these patterns.").

[107] RUHL ET AL., *supra* note 10, at 211 (suboptimal points relative to an efficiency frontier "can ... inform us of what is possible, that we can do better and by how much"); Lester et al., *supra* note 9, at 11 ("Such knowledge ... has the potential to eliminate some conflicts among user groups, as it allows clearly inferior management decisions to be objectively eliminated."); *id.* at 24 (Ecosystem service tradeoff analysis "reveals suboptimal management decisions" and has "the potential for eliminating conflicts among user groups when a service or multiple services could be maintained or even increased without a cost to other services.").

[108] *See* Nelson et al., *supra* note 26, at 9472 (referring to "[t]he shifting-out of the efficiency frontiers with increased conservation budget").

[109] Lant et al., *supra* note 10, at 477 fig. 6; *id.* at 477 ("Introducing the [Conservation Reserve Program] ... expands the [efficiency frontier] outward, allowing higher levels of both objectives [(i.e., farm income and reduced soil erosion)] to be reached.").

[110] Lant et al., *supra* note 10, at 469, 477.

[111] Making Appropriations for the Departments of Commerce and Justice, Science, and Related Agencies for the Fiscal Year Ending September 30, 2013, and for Other Purposes, H.R. 5326 § 543, 112th Cong. (2012) ("None of the funds made available by this Act may be used to develop, approve, or implement a new limited access privilege program (as that term is used in section 303A of the Magnuson-Stevens Fishery Conservation and Management Act) ... for any fishery under the jurisdiction of the South Atlantic, Mid-Atlantic, New England, or Gulf of Mexico Fishery Management Council"). The current Senate version does not contain this restriction. *See* Making Appropriations for the Departments of Commerce and Justice, Science, and Related Agencies for the Fiscal Year Ending September 30, 2013, and for Other Purposes, S. 2323, 112th Cong. (2012).

[112] For example, if California's red sea urchin fishery fell within the purview of this legislation, all of the points along the TURF frontier pictured in Figure 4, *infra*, would be eliminated from consideration. California's red sea urchin does not fall under the purview of this legislation, however; rather, the California Department of Fish and Game and California Fish and Game Commission oversee the red sea urchin fishery. *See generally* CAL. DEP'T OF FISH & GAME, ANNUAL STATUS OF THE FISHERIES REPORT (2003), http:// nrm.dfgca.gov/FileHandler.ashx?DocumentID=34394&inline=true [hereinafter CDF&G 2003 STATUS REPORT].

[113] The authors of the 2005 *Millennium Ecosystem Assessment* categorize ecosystem services into four categories: (1) provisioning services (e.g., food production), (2) regulating services (e.g., flood control), (3) cultural services (e.g., recreational and religious benefits), and (4) supporting services (e.g., nutrient cycling). MEA FRAMEWORK, *supra* note 72, at 49. An ecosystem service can fall into one or several of these categories. *id.* at 56 (recognizing that there can be considerable overlap between the categories).

[114] "The provisioning of ecological goods such as food ... depends both on the flow and the 'stock' of the good." MEA FRAMEWORK, *supra* note 72, at 63. Standing biomass represents the "stock" aspect of a provisioning ecosystem service. *See id.*

[115] MEA FRAMEWORK, *supra* note 72, at 63. The "flow" side of a fishery can be represented by profit, a reflection of the quantity of urchins caught and sold by fishermen. *See id.*

[116] Opportunities for recreation and ecotourism (e.g., SCUBA diving, recreational fishing) are examples of "cultural" ecosystem services. *See id*. at 59.

[117] *See* Charles H. Peterson & Jane Lubchenco, *Marine Ecosystem Services, in* NATURE'S SERVICES: SOCIETAL DEPENDENCE ON NATURAL ECOSYSTEMS 178 (Gretchen Daily ed. 1997) (noting that one important ecosystem service provided by fish stocks is "the biological food-web production process that results in making goods available for exploitation").

[118] Education and research opportunities are additional examples of cultural services. MEA FRAMEWORK, *supra* note 72, at 59.

[119] Existence value is another example of a cultural service. For an in-depth discussion of existence value, *see* David A. Dana, *Existence Value and Federal Preservation Regulation*, 28 HARV. ENVTL. L. REV. 343 (2004). *See also id.* at 348-49 ("When people value the existence of ... [a] resource intrinsically, then the destruction of the resource in and of itself harms them. That harm occurs even if the destruction of the resource never has and never will result in physical spillovers or losses in use.

[120] 16 U.S.C. §§ 1801-1884 (2007).

[121] 16 U.S.C. § 1851(a)(8) (2007).

[122] *See* CAL. FISH & GAME CODE § 7086(b) (providing that "[i]n the case of a fishery management plan for a fishery that has been determined to be overfished or in which overfishing is occurring, the fishery management plan shall contain measures to prevent, end, or otherwise appropriately address overfishing and to rebuild the fishery").

[123] CAL. FISH & GAME CODE § 7080(e) ([F]ishery management plans must also "summarize readily available information about the fishery including ... [e]conomic and social factors related to the fishery."); CAL. FISH & GAME CODE § 7083(b) ("If additional conservation and management measures are included in the plan, the department shall ... summarize anticipated effects of those measures on ... fishery participants ... and on coastal communities and businesses that rely on the fishery.").

[124] CDF&G 2003 STATUS REPORT, *supra* note 112, at 9-1.

[125] *Id.*

[126] *Id.* at 9-7.

[127] Spawning is the production and release of gametes into the environment for external fertilization. *See generally* Definition of Term: Spawning, FISHBASE GLOSSARY, http://www.fishbase.org/Glossary/Glossary.php?q=spawning&language=english&sc=is (last visited Aug. 19, 2013); a gamete is "[t]he sperm or unfertilized egg of animals that transmit the parental genetic information to offspring." Definition of Term: Gamete, FISHBASE GLOSSARY, http://www.fishbase.org/Glossary/Glossary.php?q=gamete&language=english&sc=is (last visited Aug. 19, 2013).

[128] CDF&G 2003 STATUS REPORT, *supra* note 112, at 9-7.

[129] *Id.*

[130] *Id.*

[131] CAL. DEP'T OF FISH & GAME, CALIFORNIA MARINE LIFE PROTECTION ACT INITIATIVE: METHODS USED TO EVALUATE DRAFT MARINE PROTECTED AREA PROPOSALS IN THE MLPA SOUTH COAST STUDY REGION (DRAFT): SECTION 8.0 - SPACING 2 (2009).

[132] In southern California, these waters primarily include those surrounding the Channel Islands off of Santa Barbara. CDF&G 2003 STATUS REPORT, *supra* note 112, at 9-1.

[133] *Id.* at 9-4.

[134] *Id.* at 9-4. Any effort reductions witnessed are more likely due to declining harvestable urchin populations and reduced market demand. *id.* The percentage of legally harvestable urchins decreased from 15% to 7% between 1985 and 1995. *id.* at 9-8.

[135] *Id.* at 9-9.

[136] *Id.* at 9-9, 9-10.

[137] *See* Wyman, *supra* note 36, at 517 (mentioning TURFs for inshore fisheries, and for sedentary fisheries); Castilla, *supra* note 62, at 229 (noting that "[f]isheries ... for benthic species, showing spatially explicit population structure ..., have been rightly argued to be more appropriate for these management approaches than fisheries for pelagic mobile species.").

[138] *See* Appendix A, notes 31-39, and accompanying text, *available at http://www.ajelp.com/wp-content/uploads/Carden.Appendix.pdf*. *See generally* Crow White & Christopher Costello, *Matching Spatial Property Rights Fisheries with Scales of Fish Dispersal*, 21 ECOLOGICAL APPLICATIONS 350 (2011).

[139] A sole owner "attempt[s] to maximize [the] present value [of a piece of property] by taking into account alternative future time streams of benefits and costs and selecting that one which he believes will maximize the present value of his privately-owned ... rights." Harold Demsetz, *Toward a Theory of Property Rights,* 57 AM. ECON. REV. 347, 355 (1967). In a situation characterized by full cooperation, individuals coordinate decision-making processes and act in the best interest of the unified group, mimicking the behavior of a sole owner. *See* Anthony Scott, *The Fishery: The Objectives of Sole Ownership*, 63 J. POL. ECON. 116, 116 (1955).

[140] Wil Schroter, *Startup Less No. 1: Revenue Minus Expenses Equals Profit*, HOUSTON BUS. J. (Mar. 18, 2007), http://www.bizjournals.com/houston/stories/2007/03/19/smallb5.html?page=all.

[141] The fleet model efficiency frontier, therefore, begins at the red triangle (the profit-maximizing fishing effort level for the baseline situation) and moves in a convex fashion down and to the right. This frontier terminates at the point where biomass equals 100% and fishery profit equals $0. The curve to the left of the red triangle is not, then, technically part of the fleet model efficiency frontier because for any of those points, an equivalent profit level could be obtained while retaining more urchin biomass (i.e., points to the left of the red triangle are not economically efficient).

[142] At this point, biomass is at 40%.

[143] Biomass conservation under optimal management is at 55%.

[144] Biomass conserved at the fleet model’s maximum profit point is at 53%.

[145] Peak profits under TURF Policy 2 occur at 55% revenue sharing.

[146] To two decimal places, biomass conservation at the profit-maximizing point under TURF Policy 2 is 53.23%, while at the fleet model’s profit-maximizing point, biomass conservation is 53.05%.

[147] Of the four policies, biomass conservation at the profit-maximizing point is highest under the optimal spatial management strategy. For the optimal spatial management strategy’s profit-maximizing point, biomass is at 55%. For the fleet model’s profit-maximizing point, biomass is at 53%. For TURF Policy 1, biomass is at 40%, and for TURF Policy 2’s profit-maximizing point, biomass is at 53%.

[148] One such legal restraint is the public trust doctrine. *See generally* Kristin N. Carden, *The Legal Viability of Territorial Use Rights in Fisheries (TURFs) in California*, 38 Ecology L.Q. 121, nn. 57-73 and accompanying text (2011).

[149] This is, if we do the very best we can (manage optimally) under the baseline strategy.

[150] In this article, the “optimal harvest strategy” is defined as the management strategy that maximizes profit. If you “optimally manage” the baseline regime, you can get 88% of the maximum profit obtained under the “““optimal harvest strategy.”

[151] *See* SCHOLES & MALTITZ, *supra* note 35, at 12 (In the land restoration context, “the objective ... is to increase the package of services, not just one.”).

[152] *See* Barton H. Thompson, Jr., *Essay: Tragically Difficult: The Obstacles to Governing the Commons*, 30 ENVTL. L. 241, 244 (2000) (“A related solution [to the tragedy of the commons] is to unitize the resource: organize a single operator to manage exploitation of the resource and divide any profits among the community of resource users or owners.”).

[153] While TURF Policy 1 would never be chosen as compared to an optimally-managed fleet model, it might be chosen over a fleet model that overharvests at a point to the left of the red triangle.

[154] *See also* Costello & Kaffine, *supra* note 51, at 20-21 (stating, with respect to similar model, that each TURF owner has a private incentive to over-harvest her own TURF. When choosing an optimal harvest, a TURF owner ignores the dispersal of larvae from her TURF into other spatially connected TURFs.).

[155] *See* RUHL ET AL., *supra* note 10, at 65 (defining an “externality [a]s any cost or benefit from the production or consumption of a good or service that is not borne or enjoyed by the producer or consumer but is borne or enjoyed by a third party”).

[156] Costello & Kaffine, *supra* note 7, at 32 (stating that local stewardship may be somewhat eroded when fish disperse from these spatially delineated patches).

[157] Whereas, if the fishery resource was completely contained within one’s TURF, one presumably would steward it more carefully. *See generally* discussion *supra* Part II.A.

[158] For more information on revenue sharing, see discussion *supra* Part III.

[159] *See* Costello & Kaffine, *supra* note 45, at 22 (finding that cooperation plays an important role in determining the efficacy of marine protected areas interspersed among TURFs).

[160] For a more in-depth discussion of profit sharing, *see* Daniel T. Kaffine & Christopher Costello, *Unitization of Spatially Connected Renewable Resources*, 11 BERKELEY ELEC. J. ECON. ANALYSIS & POL'Y art. 15, 2011, at 2-3, http://www.bepress.com/bejeap/vol11/iss1/art15.

[161] *See* Costello & Kaffine, *supra* note 51, at 1 (commenting that for their TURF/MPA model, "[s]pecies with other life history traits might affect our quantitative results, but are ... unlikely to affect the qualitative conclusions. Examining a multispecies fishery, in which TURF owners had exclusive rights to harvest multiple species in their TURFs, might affect results"). (This can be left in if necessary - CK)

[162] The California Fish and Game Code defines "overfishing" as "a rate or level of taking that the best available scientific information, and other relevant information that the commission or department possesses or receives, indicates is not sustainable or that jeopardizes the capacity of a marine fishery to produce the maximum sustainable yield on a continuing basis." CAL. FISH & GAME CODE § 98. Similarly, the MSA defines "overfishing" as "a rate or level of fishing mortality that jeopardizes the capacity of a fishery to produce the maximum sustainable yield on a continuing basis." 16 U.S.C. § 1802(34).

[163] Nor does this model track how other benefits might reveal themselves over the long-term. Costello et al., *supra* note 7, at 1680 (commenting that, in the context of ITQs, "there may be temporal benefits").

[164] *See supra* note 92.

[165] Salzman, *supra* note 24, at 137. A related question was posed by A. Dan Tarlock: "Does ecosystem service provision offer positive advantages ... compared to the current litigation-regulation strategies that are being followed?" Tarlock, *supra* note 75, at 217.

[166] Tarlock, *supra* note 75, at 217. For Tarlock's own insight on that question, *see id.* at 229 (stating that "Western natural resources law has a fundamental bias toward resource exploitation, and the legislative process has generally operated, at least until recently, to reinforce the expectation that there will be few limits on exploitation").

[167] Craig, *supra* note 92, at 362. *See also* RUHL ET AL., *supra* note 10, at 35, *citing* Margaret Palmer et al., *Ecology for a Crowded Planet*, 304 SCIENCE 1251, 1251 (2004) (asking "[h]ow do individual, corporate, and government decisions sustain or degrade ecosystem services?").

[168] As such, tradeoff analysis represents one way for "the policy and science communities [to] establish a capacity to create and implement policies for social-ecological systems, predict consequences, and evaluate outcomes." Carpenter et al., *supra* note 17, at 1311. *See also* RUHL ET AL., *supra* note 10, at 34 (commenting that "[i]ncreasingly, ... ecologists and economists [are] develop[ing] models for portraying ecosystem service delivery, models both of the ecosystem dynamics and of the services values, and over time they will surely build yet more robust models capable of improved description of cause and effect of different policy options").

[169] For a similar result, *see* Costello & Kaffine, *supra* note 51 (noting that in the mixed TURF/MPA context, it was the level of coordination among owners that drove economic and ecological performance of the fishery).

[170] RUHL ET AL., *supra* note 10, at 9.

[171] *See* Lester et al., *supra* note 9, at 3 (Natural resource "management will be much more effective and less controversial with a means for explicitly and transparently evaluating ... decisions" among resource uses.).

[172] *See, e.g.*, RUHL ET AL., *supra* note 11, at 85 ("Although a consensus is building that ecosystem services hold tremendous values that we should seek to understand and incorporate into decision making about the environment, regulatory frameworks and social

norms for efficiently managing ecosystem services have not materialized."). At the same time, "[i]nstitutional inertia can develop into a major transition within a fairly short period ... when a policy window of opportunity [is] effectively used." Olsson et al., *supra* note 15, at 9493. *See also id.* (describing how "shifts [in people's perceptions] are critical factors in altering the trajectory of natural resource management").

[173] "This research [thus] ... build[s] on existing disciplinary strengths, bridge[s] disciplines effectively, and create[s] new areas of knowledge that are needed to build resilient social-ecological systems." Carpenter et al., *supra* note 17, at 1311. *See also* Lester et al., *supra* note 9, at 25 (stating that "evaluating tradeoffs explicitly ha[s] the potential to dramatically advance how marine resource management is conducted. Managers and scientists need simple and transparent means for determining the trade-offs, or lack thereof, among key services and communicating these interactions to policy makers and stakeholders.").

[1] The total allowable catch would be set by the relevant government agency, *e.g.*, the California Department of Fish and Game (fisheries in California state waters) or NOAA's National Marine Fisheries Service (fisheries in federal waters).

[2] The effort (F) in the red sea urchin fishery is currently controlled by seasonal closures, a minimum size limit, a restricted access program with a moratorium on the issuance of new permits, and an effort reduction scheme that mandates the retirement of ten permits for each new entrant into the fishery. CAL. DEP'T OF FISH & GAME, CALIFORNIA MARINE LIFE PROTECTION ACT INITIATIVE: METHODS USED TO EVALUATE DRAFT MARINE PROTECTED AREA PROPOSALS IN THE MLPA SOUTH COAST STUDY REGION (DRAFT): SECTION 8.0--SPACING 9-4, 9-5 (2009).

[3] In other words, effort is distributed so that no individual fisherman in the fleet can improve his average profit by changing fishing locations during that year.

[4] For a graphic depicting this map, *see* S. Mitarai et al., *Quantifying Connectivity in the Coastal Ocean with Application to the Southern California Bight*, 114 J. GEOPHYSICAL RES. C10026, at 3 Fig. 1(a) (2009).

[5] Urchin price is driven by quality of the gonads ("uni"). MILLENNIUM ECOSYSTEM ASSESSMENT, ECOSYSTEMS AND HUMAN WELL-BEING: A FRAMEWORK FOR ASSESSMENT 9-1 (2005) [hereinafter MEA FRAMEWORK]. From 1998-2007, average annual sea urchin landings off of Santa Barbara, California, equaled 4,299,401 lbs, and annual average value was $3,451,281. This translates to an average of $0.80/lb. CAL. MARINE LIFE PROTECTION ACT INITIATIVE, DRAFT REGIONAL PROFILE OF THE MLPA SOUTH COAST STUDY REGION--APPENDIX III, at 5 (Sept. 15, 2008), www.dfg.ca.gov/mlpa/pdfs/scprofile/appendix3.pdf. We assume price is constant and use a zero discount rate. These assumptions should not qualitatively affect our primary conclusions. *See* Christopher Costello & Daniel T. Kaffine, *Marine Protected Areas in Spatial Property-Rights Fisheries*, 54 AUSTL. J. AGRIC. & RESOURCE ECON. 321, 339 (2009).

[6] In other words, short-term additional profit cannot be gained from additional effort fishing a patch whose population is at or below this density.

[7] Empirical evidence indicates that many fisheries in California and elsewhere can profitably harvest populations to <10-20% of the original stock level. *See* Massimiliano Cardinale & Henrik Svedäng, *Modelling Recruitment and Abundance of Atlantic Cod*, Gadus morhua, *in the Eastern Skagerrak-Kattegat (North Sea): Evidence of Severe Depletion Due to a Prolonged Period of High Fishing Pressure*, 69 FISHERIES RESEARCH 263, 280 (2004) (referring to logbook and trawl survey records documenting a 90% decline in cod abundance between 1982 and 1999); *id.* at 269, Table 1, and 270, Table 2 (showing abundance declines to less than 10% of original biomass); Romuald N. Lipcius & William T. Stockhausen, *Concurrent Decline of the Spawning Stock, Recruitment, Larval Abundance, and Size of the Blue Crab* Callinectes sapidus *in Chesapeake Bay*, 226 MARINE ECOLOGY PROGRESS SERIES 45, 55 (2002) (noting an 81% decline in the Chesapeake Bay blue crab spawning stock between 1992 and 2000); Jeremy B.C. Jackson et al., *Historical Overfishing and the Recent Collapse of Coastal Ecosystems*, 293 SCIENCE 629, 631-32 (2001) (discussing baseline versus current abundance for species including Atlantic cod off the Gulf of Maine and Georges, and abalone in California); Paul K. Dayton et al., *Sliding Baselines, Ghosts, and Reduced Expectations in Kelp Forest Communities*, 8 ECOLOGICAL APPLICATIONS 309, 316-18 (1998) (discussing dramatic declines in abundance and biomass in California waters of white seabass, yellowtail, abalone, sea urchins, and other species). Rarely is it profitable to harvest a stock to zero density. *See generally* Rögnvaldur Hannesson, *A Note on the "Stock Effect,"* 22 MARINE RESOURCE ECON. 69 (2007). Given the bounds established by these and similar studies, we set the break-even density equal to 10% of the average unfished

population density; this value is typical of other studies. *See, e.g.,* Crow White et al., *Ecosystem Service Tradeoff Analysis Reveals the Value of Marine Spatial Planning for Multiple Ocean Uses*, 109 PROC. NAT'L ACAD. SCI. 4696, Supporting Information Appendix at 14 (2012); Crow White et al., *The Value of Coordinated Management of Interacting Ecosystem Services,* 15 ECOLOGY LETTERS 509, 511-12 (2012); Andrew Rassweiller et al., *Marine Protected Areas and the Value of Spatially Optimized Fishery Management*, 109 PROC. NAT'L ACAD. SCI. *in press* (2012).

[8] Simply put, the von Bertalanffy growth function describes an organism's body length as a function of its age. *See generally* Ludwig von Bertalanffy, *Quantitative Laws in Metabolism and Growth*, 32 Q. REV. BIOLOGY 217 (1957). The weight at length function, in turn, considers organism weight as a function of its length. *See generally* Per Sparre & Siebren C. Venema, *Estimation of Growth Parameters, in* INTRODUCTION TO TROPICAL FISH STOCK ASSESSMENT, FAO FISHERIES TECHNICAL PAPER 306/1 REV. 2, at 47-116 (1998).

[9] A test is a shell. CAL. DEP'T OF FISH & GAME, ANNUAL STATUS OF THE FISHERIES REPORT, at 9-6 (2003), http://nrm.dfg.ca.gov/FileHandler.ashx? DocumentID=34394&inline=true [hereinafter CDF&G 2003 STATUS REPORT].

[10] Mathematical models incorporate quantities known parameters. Parameters can be defined as "'constants' which stand for inherent properties of nature[.]" Wikipedia, *Parameter*, http://en.wikipedia.org/wiki/Parameter #cite_note-1, *citing* YONATHAN BARD, RESPONSE OF PHYSICAL SYSTEMS 13 (1950).

[11] These parameter values are borrowed from a similar model of red sea urchins in southern California created to support implementation of California's Marine Life Protection Act (MLPA). *See generally* Rassweiler, *supra* note 7, and references cited therein; Marine Life Protection Act, CAL. FISH & GAME CODE §§ 2850-2863 (2009).

[12] *See generally* CAL. FISH & GAME CODE §§ 2850-2863 (2009); Andrew Rassweiller et al., *Marine Protected Areas and the Value of Spatially Optimized Fishery Management*, 109 PROC. NAT'L ACAD. SCI. *in press* (2012), and references therein.

[13] In southern California, the minimum legal size for red sea urchin harvest is 3.25 inches. CDF&G 2003 STATUS REPORT, *supra* note 9, at 9-10. This minimum size allows the urchins to spawn before they are harvested. BLUE OCEAN INSTITUTE, RED SEA URCHIN--CALIFORNIA, http:// www.blueocean.org/programs/seafood-view?spc_id=190.

[14] The pelagic environment is the open ocean environment. Merriam-Webster Online Dictionary, *Pelagic (adj),* www.merriam-webster.com/dictionary/pelagic.

[15] Reproductive capacity increases exponentially with age due to the von Bertalanffy growth and allometric weight-at-length functions. *See* note 8, *supra*, and accompanying text.

[16] Specifically, we used a Regional Ocean Modeling System (ROMS)-based Lagrangian particle-tracking model. *See generally* REG'L OCEAN MODELING SYS., http://www.myroms.org/. Particle-tracking models provide a means by which to estimate how larvae move through ocean space, *i.e.*, how they disperse. Tiffany C. Vance et al., *GeoFish--Visualization and Analysis of Particle Tracking Model Output for Fish and Shellfish Larvae*, ICES CM 2008/R:23, at 2 (2008), www.pmel.noaa.gov/foci/publications/2008/vanc0666.pdf. Lagrangian models attempt to account for small-scale turbulence. *Id.* For more information on this type of modeling process, *see generally* Rassweiler, *supra* note 7.

[17] *See generally* Mitarai et al., *supra* note 4; Changming Dong et al., *Circulation and Multiple-Scale Variability in the Southern California Bight*, 82 PROGRESS IN OCEANOGRAPHY 168 (2009); James E. Watson et al., *Realized and Potential Larval Connectivity in the Southern California Bight*, 401 MARINE ECOLOGY PROGRESS SERIES 31 (2010).

[18] In other words, the ROMS model was run beforehand, and the output stored for use in the fish population model. *See* GRAPHWALKER, RUNNING AN OFFLINE TEST, http://graphwalker.org/documentation/running-an-offline-test/ (stating that "[a]n offline test sequence, is a test sequence generated from a model, and stored to file for later use. The file is fed to a test execution tool, which later runs the test").

[19] These comprehensive maps depict all major seafloor habitat types occurring at less than 100 m depth (100 m is considered to be the maximum depth for red sea urchin habitat, see Table 1, *infra*). The maps are based on sonar data and aerial surveys of giant kelp (*Macrocystis pyrifera*), the latter of which serves as an indicator for the presence of hard substrate. *See generally* CAL. SEAFLOOR MAPPING PROJECT, *supra* note 7, *available at* http:// seafloor.csumb.edu/csmp/csmp.html.

[20] Generally speaking, a Beverton-Holt function describes "density-dependent survival from one life stage to the next." Darren W. Johnson, *Habitat Complexity Modifies Post-Settlement Mortality and Recruitment Dynamics of a Marine Fish*, 88 ECOLOGY 1716, Appendix A (2007).

[21] The compensation ratio is "the ratio of maximum larval survival at low densities to survival at carrying capacity." Crow White & Christopher Costello, *Matching Spatial Property Rights Fisheries with Scales of Fish Dispersal*, 21 ECOLOGICAL APPLICATIONS 350, 352 (2011).

[22] In this paper, the "target unfished biomass" refers to the dynamic equilibrium biomass one would expect in the defined geographic area in the absence of fishing.

[23] Thus, this value is not specified in Table 1, *infra*.

[24] Simply stated, the model results are insensitive to the chosen value because scaled results show proportional changes, which are not affected by the particular, absolute unfished biomass value chosen. *See, e.g.,* White et al., *supra* note 7, Supporting Information Appendix at 27; Rassweiler, *supra* note 7.

[25] Leases in perpetuity (as opposed to a shorter, fixed-term lease) best provide for long-term sustainability incentives in TURF leaseholders. *See generally* Christopher J. Costello & Daniel Kaffine, *Natural Resource Use with Limited Tenure Property Rights*, 55 J. ENVTL. ECON. & MGMT. 20, 20 (2008) (discussing the need to structure insecure rights, such as leases, to achieve "economically efficient resource use or desired stewardship incentives").

[26] In theory, TURFs could also be leased to groups of fishermen that coordinate fishing effort, or fishery cooperatives. For ease of discussion, however, this paper considers TURFs leased to individual fishermen.

[27] *See* Costello & Kaffine, *supra* note 25, at 21 (noting that in the abalone and spiny lobster fisheries in Mexico, "[b]eyond the assignment of the concession, the regulator plays no role in management of the resource--harvest decisions are made privately, without restriction, by the appropriator"). Whether an actual TURF-holder operating in the United States would be constrained by an exogenously-determined effort level or TAC is a policy decision, and may be influenced by other legal constraints. Under a functioning TURF system, fishermen ideally should be able to determine at least the proper *minimum* fishing level (if not the maximum) without government intervention. Usurping that authority could undermine the incentive structure of TURF management.

[28] Revenue sharing occurs when all the fishermen pool their revenues in a common fund, then divide the entire fund among the contributors according to an agreed-upon formula. *See* Daniel T. Kaffine & Christopher Costello, *Unitization of Spatially Connected Renewable Resources*, 11 BERKELEY ELEC. J. ECON. ANALYSIS & POL'Y art. 15, at 2-3 (2011), http:// www.bepress.com/bejeap/vol11/iss1/art15.

[29] I use the term "TURF-holder" rather than "TURF-owner" to reflect the fact that fishermen who have harvesting rights within a TURF function as leaseholders, rather than true owners of the resource. *See* Costello & Kaffine, *supra* note 25, at 20 (noting that "governing bodies are reluctant to relinquish complete control over public trust resources, and instead often grant to resource appropriators various forms of limited tenure with the probability of renewal").

[30] The term "population dynamics" refers to the changes in the size and age structure of a population over time. *See, e.g.*,

STANFORD UNIVERSITY, POPULATION DYNAMICS, http://www.stanford.edu/group/stanfordbirds/text/essays/Population_Dynamics.html (stating that "[t]he 'dynamics' of bird populations ... [are] the ways in which their numbers grow and shrink as time goes by").

[31] Larval dispersal is described by Gaines et al. as follows: "The great majority of invertebrates and nearly all fish produce young that are microscopic and grow by feeding in the plankton. Larvae can spend days, weeks, or months drifting, eating, and growing in the plankton, and commonly increase in size by an order of magnitude. The potential fitness benefits from being able to produce minute young that can forage on their own, however, have a key side effect--larvae are dispersed away from their natal site as they drift and feed." Steven D. Gaines et al., *Connecting Places: the Ecological Consequences of Dispersal in the Sea*, 20 OCEANOGRAPHY 90, 91 (2007). Because the size of each TURF is larger than the average home range size for a red sea urchin, we assume that adults do not disperse beyond a TURF boundary. *See* J. Wilson White et al., *Decision Analysis for Designing Marine Protected Areas for Multiple Species with Uncertain Fishery Status*, 20 ECOLOGICAL APPLICATIONS 1523, Appendix B (2010) (stating that "[n]o direct measurements of home range size have been made, ... so we estimated a value based on consistent observations that red sea urchins move very little after settlement (less than 10 m ...)") (internal citation omitted). The assumption that adults do not disperse out-of-TURF is common. *See, e.g.,* Costello & Kaffine, *supra* note 5, at 324 (assuming that "adults do not disperse out-of-TURF").

[32] Whereas, if the fishery resource was completely contained within his TURF, he presumably would steward it more carefully. *See generally* discussion *supra* Part II.A.

[33] "[A] Nash equilibrium is a set of strategies, one for each of the *n* players of a game, that has the property that each player's choice is his best response to the choices of the *n-1* other players." Charles A. Holt & Alvin E. Roth, *The Nash Equilibrium: A Perspective,* 101 PROC. NAT'L ACAD. SCI. 3999, 3999 (2004).

[34] In other words, "if all players announced their strategies simultaneously, nobody would want to reconsider." *Id.*

[35] Drew Fudenberg & Jean Tirole, *Perfect Bayesian Equilibrium and Sequential Equilibrium*, 53 J. ECON. THEORY 236, 240 (1991). For a more detailed description of a TURF fishery and the Nash equilibrium under a simplified fishery situation, *see generally* White & Costello, *supra* note 21.

[36] For more detail on fixed-point iteration, *see* White et al., *supra* note 7, at 512.

[37] The assumption that TURF-holders are determining their own harvest levels is key to the model outcome. If fishermen are instead required to meet an externally-imposed, TURF-specific TAC (as might be required per the strictures of antitrust law), and that TAC is set too high, overfishing may ensue regardless of the institution of a TURF regime instead of a fleet model.

[38] Under optimal management, total allowable fishing effort (*F*) is not exogenously regulated; instead, a strategic set of fishing effort levels across patches is chosen that maximizes total profit to the fishery.

[39] Equilibrium model conditions are steady state conditions that are expected over the long-term. *See* Frances R. Homans & James E. Wilen, *A Model of Regulated Open Access Resource Use*, 32 J. ENVTL. ECON. & MGMT. 1, 10 (1997) (stating that "[a] long run steady state is achieved when the biomass is in equilibrium").