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Title: Evaluating tradeoffs among ecosystem services to inform marine spatial planning

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Running Title: Ecosystem service tradeoffs

Abstract

A central challenge for natural resource management is developing rigorous yet practical approaches for balancing the costs and benefits of diverse human uses of ecosystems. Economic theory has a long history of evaluating tradeoffs in returns from different assets to identify optimal investment strategies. There has been recent progress applying this framework to the delivery of ecosystem services in land use planning. However, despite growing national and international interest in marine spatial planning, we lack parallel frameworks in the marine realm. This paper reviews an ecosystem service tradeoff analysis framework and provides a more comprehensive synthesis for how it can be applied to marine spatial planning and marine ecosystem-based management. A tradeoff analysis approach can reveal inferior management options, demonstrate the benefits of comprehensive planning for multiple, interacting services over managing single services, and identify ‘compatible’ services that provide win-win management options.

Keywords: economics; ecosystem based management; ecosystem services; efficiency frontier; marine spatial planning; tradeoff analysis.

1. Introduction

Given the scope and magnitude of the environmental challenges facing natural resource management, there is an increasing demand for more holistic, ecosystem-based approaches to management [1-4]. Ecosystem-based management (EBM) is a place-based approach that aims to achieve the long-term ecosystem health and functioning that in turn provide the ecosystem services on which people rely [4-8]. Marine spatial planning (MSP) is one type of planning process that offers a promising opportunity for more integrated management and has been gaining political momentum throughout the world [9, 10]. MSP identifies which areas of the ocean are appropriate for different uses or activities in order to reduce use conflicts and achieve ecological, economic and social objectives [11]. One central challenge for translating EBM and MSP tenets from concept to practice is developing rigorous and straightforward approaches for balancing diverse human uses of ecosystems [12]. This paper highlights tools from economic theory and multi-objective decision making for evaluating tradeoffs in the delivery of ecosystem services, with particular emphasis on how such an approach could transform ocean management.

Ecosystem services range from tangible to intangible (e.g., food production versus aesthetic value) and provide natural capital that is essential to human welfare [13]. The Millennium Ecosystem Assessment [1] brought ecosystem service concepts to the forefront, developing four widely used service categories: provisioning (e.g., of seafood, timber), regulating (e.g., of climate, floods, water quality), supporting (of other services, e.g., pollination for food production, nutrient cycling), and cultural (e.g., recreation, spiritual value). MSP attempts to allocate space to the full range of services provided by the oceans, presenting a significant challenge to natural resource managers. Services frequently are not independent of one another, but instead exhibit complex interactions that generate tradeoffs in the delivery of one service relative to the delivery of others [14-17]. In some cases, two services may be mutually exclusive in space (e.g., wave energy buoys may preclude commercial fishing and vice versa), while in other cases the tradeoff is less severe (e.g., fishing and recreational activities can often occur in the same locations, but fishing impacts might have a negative effect on some types of recreation). Because not all interacting services can be maximized simultaneously, society must make decisions about their relative preferences for different services, and, consequently, how this affects management decisions [15, 18-20]. Managers make these types of decisions on a regular basis, but often do so without explicit consideration of these tradeoffs [21].

Balancing the delivery of a range of services is particularly critical for coastal and ocean ecosystems, which face growing human populations, increasing associated impacts, and declining ecosystem services [22-24]. Marine systems offer a challenging and interesting opportunity for implementing MSP and specifically for examining tradeoffs among services. For one, service valuation in marine settings is complicated given the general absence of property rights and the related fact that many key services are not traded in markets (e.g., recreation, wildlife viewing, protection from shoreline erosion). Furthermore, the primary market service from the oceans – fisheries – often lacks property rights, has inappropriate incentives and frequently ineffective governance, and is managed using limited-quality stock assessments, which together promote unsustainable fishing [25, 26]. Management in the oceans also tends to be fragmented, with limited governance or institutional frameworks for spatial management and coordinated management across sectors [27, 28]. Lastly, marine systems host numerous emerging uses, such as wave energy and offshore aquaculture. These emerging uses will contribute to crowding among efforts to maximize the delivery of particular services, posing an ideal prospect for more integrated planning prior to their development. Such planning demands an explicit analysis of tradeoffs among services under different management scenarios.

The economics discipline has developed a rich "production theory" which concerns how firms optimally trade-off between different inputs to production [29]. This is similar to portfolio theory, which analyzes the tradeoff between variance (i.e. risk) and return of a collection of assets, whether financial stocks or fish stocks, so as to maximize return for a given level of risk [30-32]. In parallel, there is a long history within decision theory, including multi-criteria and multi-objective analyses, of developing tools for decision-making where there are numerous and often competing objectives [33]. Multi-criteria analysis has been applied to numerous marine applications [34-37] and there has been recent progress applying these ideas to managing ecosystem services [20, 38-41]. However, we lack a synthesis of how tradeoff analysis can used in an EBM or MSP approach. This paper: 1) highlights one framework for analyzing tradeoffs, including reviewing the types of tradeoffs possible in an ecosystem services context and examining how this framework can guide EBM, and 2) provides demonstrations of how ecosystem service tradeoff analysis can be applied to MSP using two stylized examples based on data.

2. Conceptual framework for ecosystem service tradeoff analysis

Production theory, a branch of microeconomics that deals with the production (as opposed to the consumption) side of the economy, was developed to examine marketed commodities [42]. While not a perfect parallel, this approach can also be applied to the production of ecosystem services, marketed or otherwise [43]. The guiding principle when applied to EBM is to ensure the sustainable and efficient delivery of multiple interacting services. The challenge in meeting this goal is that providing ecosystem services is “costly” in the sense that actions taken to deliver one service may inhibit or divert scarce resources away from actions that could have been taken to deliver other services. For example, if one is using marine protected areas to provide the ecosystem service of biodiversity preservation, the possible provision of fishery yield is reduced as a second service. The cost of lost provisions from one service due to use of another service depends on the strength and nature of their interaction. Not all services produce ‘costs’ to other services and this framework allows one to identify ‘compatible’ services as well. In short, the following analytical approach supports more informed management decisions about real and perceived tradeoffs among ecosystem services.

Production theory considers how different inputs produce different levels of outputs, typically expressed as production functions. When applied to ecosystem services, production functions are models that translate the structure and functioning of ecosystems into the provision of ecosystem services [40, 44, 45]. A production function approach has been used to value non-market ecosystem services that can be considered as inputs into the production of goods or services with market value (e.g., seagrass habitat as nursery grounds is an input into fisheries) [43, 46], but also applies to ecosystem services that are not readily connected to a marketed output. Importantly, there may be many potential ecosystem service outcomes that can arise from a given set of inputs. This provides a basis for examining which outcomes are optimal in terms of providing the combination of services that are important to society.

In cases with a small number of services or objectives, ecosystem service outcomes can be analyzed graphically to evaluate tradeoffs. In an EBM context, this involves some quantification of the ecosystem services produced across a broad range of potential management actions or spatial plans (e.g., all possible MPA siting options, all possible harvest regulations, etc.). This can be conducted using empirical data, quantitative models or conceptual models, depending on data and model availability, and ideally considers as many sets of management actions as possible. In such an analysis, the axes of the graph correspond with levels of ecosystem services and each point corresponds with the outcomes from a given set of management actions that are known or estimated to produce amounts of each service. After plotting all (or a large subset of) possible management options, the constraint envelope, or outer bound of all the points, is the "efficiency frontier" comprised of Pareto-efficient options (Box 1). This "ecosystem services" frontier depicts management options that provide for the optimal delivery of the two or more services [37, 47, 48]. Points interior to the frontier are suboptimal – at least one service could be increased, at no cost to other services.

Although this approach may seem simplistic, it provides two critical insights that can be used to guide EBM. First, the position of a point relative to the frontier can suggest improvements to current management practices. Regardless of the shape of the frontier or social preferences for specific services, all sets of management actions interior to the frontier represent suboptimal decisions. These are situations where an EBM approach can lead to societal benefits at no extra cost, and commonly a gain, for both services. Such knowledge therefore has the potential to eliminate some conflicts among user groups, as it allows clearly inferior management decisions to be objectively eliminated. Of particular interest are situations in which management options that are all interior to the frontier are being debated. In such cases of "false tradeoffs," these options may be unnecessarily pitted against each other, and tradeoff analysis could illustrate that additional management options exist that simultaneously remove the perceived tradeoff and produce a win-win outcome.

Second, the relationship between or among services also indicates whether coordinated management across services is necessary. In other words, the shape of the frontier can inform what the optimal management solution(s) is likely to be, narrowing the scope of potential policy options. Examining pairwise service interactions, important rules of thumb and insights emerge (Panel 1). There are likely other variants on these curves, but this set captures the most common (or at least the most expected) types of relationships. Furthermore, the societal preference for one service compared with another, represented by an indifference curve, will determine which point along the frontier maximizes social value of ecosystem services [42]. Knowing both the shape of the frontier and at least some approximation of the indifference curve allows managers to hone in on a single or small number of optimal management decisions (Fig. 1).

There are numerous examples in the terrestrial literature of applying ecosystem service tradeoff analysis to decision-making. As one example, Nalle et al. [49] examine a three dimensional tradeoff for timber production and conservation of two wildlife species using a spatially-explicit, dynamic model. They identify optimal land management decisions, the shortcomings of current management practices, and the nature of the tradeoff among the three goals. Polasky et al. [48] examine the tradeoff between biodiversity conservation (number of species) and economic return from different types of land use. This spatially explicit analysis demonstrates the potential for large improvements along both axes by altering current spatial patterns of land use and that optimal land management options fall along a concave frontier. As another example, Wossink and Swinton [50] examine tradeoffs between agriculture production and the provision of non-market services such as pollination. They theoretically explore the potential for non-monotonic concave frontiers, whereby, for example, crop output and pollination service can have a complimentary or competitive relationship over different levels of pollination output.

Production theory can also be used to examine service tradeoffs without employing graphical analysis. For example, Naidoo and Ricketts [51] conduct a cost-benefit analysis for forest conservation in Paraguay, examining the benefits in terms of five ecosystem services, relative to opportunity costs. Their approach compared maps of different spatial planning decisions, informing what spatial configurations of conservation measures yielded the highest benefits relative to costs. All of these examples illustrate how tradeoff analysis can be applied to natural resource management, but these in-depth case studies lack a more general framework. Panel 1 is intended to provide a synthesis of ecosystem service tradeoff theory that will enable more widespread adoption of the approach.

3. Ecosystem service tradeoff analysis for the oceans

As demonstrated thus far, the fundamental economic theory behind tradeoff analysis is well developed and applicable to any ecosystem type. However, marine systems offer a particularly challenging opportunity for examining tradeoffs among services. Oceans are facing an ever increasing number of human uses and threats, while also typically plagued by fragmented governance. However, MSP offers a promising opportunity for more integrated and ecosystem-based management of multiple services, provided there are the scientific approaches to support such integrated decision making. Two hypothetical case studies grounded in data are presented here, suggesting how tradeoff analysis can advance marine resource management. These examples are intended to catalyze future applications of tradeoff analysis within MSP processes.

3.1 Case study: fishery yield and biomass preservation

Fisheries over-exploitation is widely regarded as the primary cause of recently publicized fisheries collapses [23, 52]. One suggested approach for conserving fish stocks and marine biodiversity is to create no-take marine reserves [53-56]. Indeed, marine protected areas are typically one of the spatial designations identified in MSP and ocean zoning plans [57, 58]. Although marine reserves eliminate fishing within their boundaries, fisheries management outside the reserves can have significant effects on the performance of the reserve, and on the ultimate system-wide biomass. For example, for species with considerable adult movement or larval dispersal, small (or sparsely located) marine reserves may not protect stocks if fishing pressure is sufficiently high outside [59, 60]. Furthermore, although it is intuitive that fishery closures reduce profit from fishing, a less intuitive but powerful recent finding is that fisheries profits can be maintained or even enhanced, for some species, by the tactical siting of marine reserve networks that take advantage of adult spillover and larval export [61-65]. Thus, the size, proximity, and locations of marine reserves will interact in complex ways with fish growth, production, and dispersal, as well as with spatially-distinct fisheries exploitation, to influence two common management objectives: fish conservation and profitable fisheries.

To evaluate the tradeoff between biomass conservation (fish biomass remaining in the sea) and sustainable fishery profit, a spatially-heterogeneous model of fish production, dispersal, harvest, and profits is used, building on Costello and Polasky [62]. This model is illustrative, and is not intended to replicate any particular geographic region. However, to maintain some level of realism, it is loosely parameterized based on data from the central coast region of California. The model contains a set of 48 distinct patches, each with its own adult survival, larval production, and dispersal to other patches. Spatial heterogeneity enters in two ways. First, larval dispersal depends on ocean currents [66], which are non-uniform in the study system. Second, patch-level adult survival depends on local habitat. In this case, the model focuses on a species associated with kelp, e.g. kelp bass. In the model, higher kelp density in a patch leads to higher adult survival, and density dependence enters through a Beverton-Holt stock recruitment relationship [67]. The full suite of model parameters for each of the 48 patches is available from the authors upon request.

Spatial harvest interacts with abundance (assuming intracohort density-dependence) to affect fish production. Thus, any given spatial harvest strategy (e.g., constant patch-level harvest, heterogeneous harvest across space to maximize steady state profit, set harvest to 0 in some subset of patches to effectively designate these patches as marine reserves) gives rise to an equilibrium fish abundance (in each of N patches), and an equilibrium fishery profit. System-wide fishery profit is the sum of patch-level profit. Profit in a patch is price (scaled to 1) multiplied by harvest minus harvest cost, where harvest cost includes a small "stock effect," as in White et al. [61]. Data on kelp abundance, bottom type, and dispersal characteristics, obtained from the Marine Life Protection Act Initiative (http://marinemap.org/mlpa/), are overlaid on the model domain. The larval dispersal matrix is derived from a Regional Ocean Modeling System [68] oceanographic circulation model [69], assuming a pelagic larval duration of 26-36 days; larvae that reach patches with suitable habitat at the conclusion of the larval period recruit into the adult population. Adults are assumed to have a sufficiently small home range to be considered sessile.

The model was run simulating 300 harvest policies. Each simulated policy is generated by randomly designing a marine reserve network among the 48 patches and optimizing exploitation of the fishery outside that network. The objective to be maximized (by choosing spatial harvest outside the reserve) is the weighted sum of fishery profit and biomass, in steady state. The simulated harvest policies randomize the weights within this objective. Equilibrium profit is plotted against equilibrium fish biomass remaining in the sea, with any given harvest strategy representing a point on the tradeoff graph. All points are scaled relative to the maximum profit and maximum biomass, so the theoretical maximum joint production is (1,1). The frontier itself is calculated by optimizing the weighted objective specified above, but by leaving the marine reserve network unconstrained. The weights in the objective function are altered to trace out the frontier.

In this example, the frontier is concave (Fig. 2), indicating that it is possible to increase the delivery of one service substantially without a large cost for the other service, and that corner solutions would only be chosen if there exists extreme societal preference for one service over the other. Instead, management is likely to seek a combination of conservation and fishery profit services. The potential role of marine reserves in obtaining this combination of services can be explored by examining the percentage of the study area set aside in reserves (if any) for management actions that lie along the efficiency frontier. In this situation, all harvest policies along the efficiency frontier include a significant percent of the area set aside in marine reserves, suggesting that protected areas not only contribute to conservation but are also an important component of an economically profitable management scenario. Even the policy that maximizes profit without explicit regard for system biomass ("*" in Figure 2) contains 34% of the area in marine reserves. This result, if it holds more generally, has the potential to be quite powerful in minimizing disputes between conservation and fisheries interests and for implementing marine reserves as a key component of marine spatial plans.

3.2 Case study: wave energy, fishery yield and real estate value

Rising fuel costs and concerns about the negative impacts of climate change have led to an increased interest in renewable, zero-emissions energy sources [e.g., 70, 71]. As a result, wind, wave and tidal power harnessed from coastal areas are being widely considered and implemented around the world. However, in many cases we lack a thorough understanding of the ecological and environmental consequences of these new technologies, or how they may interact – positively or negatively – with other services [72-74]. This is true of wave energy, which is being actively considered for many coastal regions [75], including the Oregon coast in the US and Spain in Portugal in the EU [76, 77]. As an emerging service, wave energy offers the opportunity to apply the ecosystem service tradeoff analysis proactively, using it as a tool to inform the spatial siting of wave energy facilities in a manner that minimizes conflicts among multiple ocean uses.

In this case example, siting of wave energy conversion arrays is examined, considering tradeoffs between wave energy production and fishery profits and the value of the coastal viewshed. This analysis approximates wave energy siting for the coast of Oregon, and focuses on siting in the offshore dimension. While in reality, placement decisions will need to be made in a two-dimensional context, this cross-shore analysis provides a first approximation of some of the key service interactions. Specifically, wave energy devices are best anchored over sandy bottoms, which is also prime habitat and fishing grounds for Dungeness crab. Additionally, real estate value of coastal properties may be affected by the visual impact of wave energy devices. A simple model is used to examine the interactions among wave energy production, crab fishery profit, and impact to coastal real estate value from the altered viewscape, with respect to the offshore placement of a wave buoy array.

Design studies based on a single wave energy conversion (WEC) device generating 190 kW were used, suggesting that a target commercial wave power farm of 34 MW would require 180 WEC devices arranged in an array extending 2 km cross-shelf and 9 km alongshore [78]. This amounts to about 4 MW/km of coastline. The 34-MW wave power array generates 300,000 MW-hours per year. If wave energy can be produced and sold at a profit of $0.01/kW-hour, this would amount to $\$3\times10^6$ per year per array. Dividing by the alongshore length of the array yields about $\$3\times10^5$ per year per alongshore km. Wave energy conversion devices are not safe to deploy too close to shore where large winter waves could damage the devices and potentially uproot the array. Therefore, the assumption is made that WEC devices would not be placed shallower than the 30-m isobath (3 km offshore for a 1% bottom slope). The expense of larger mooring elements and longer electrical transmission lines diminishes the profitability of wave power generation as water depth increases offshore. Thus, it is assumed the highest profitability occurs in a water depth of 50 m [79], which for the typical inner-shelf bottom slope off Oregon of 1%, is found 5 km offshore. Profitability declines shoreward of this location, dropping to zero at 3 km and also declines toward the deep sea, dropping to zero at 10 km offshore (Fig. 3b; Table 1).

The annual revenue from the Oregon Dungeness crab fishery is $5-44 million per year (http://www.oregondungeness.org/fishery.shtml). Using the high value and dividing by the length of the Oregon coastline, about 440 km (admittedly an overestimate since about 10% of the Oregon shelf is rocky bottom, which is not exploited by the crab fishery), this is $\$1\times10^5$ per alongshore kilometer of coastline per year. The high value of the crab fishery was used to represent potential value of the fishery. While not needed for the tradeoff analysis, one can estimate the number of crab pots needed to realize this catch value. Using an estimate of $1.43 per crab, this amounts to 7.0×10^4 crabs per km per year. If it is assumed that during the fourmonth intensive crab fishing season, pots are turned around every 6 days and about 10 crabs are caught in each pot per soak, then the total crab catch would require about 350 pots per kilometer (i.e., 154,000 pots fished in Oregon waters), which is not an unrealistic number (http://www.oregondungeness.org/fishery.shtml). In order to estimate the impact of displacing the crab fishery for a WEC array, it is necessary to know the cross-shelf distribution of pots. It is assumed that pots are placed no closer than the 30-m isobath (3 km offshore) (an underestimate of how close to shore crabs are fished) and no deeper than the 90-m isobath (9 km offshore) and that the optimum crab fishing depth is at the 60-m isobath (6 km offshore) (Table 1) (http://www.oregondungeness.org/fishery.shtml). To estimate the impact on the crab fishery due to the presence of a wave energy installation, the loss of a 2-km cross-shelf swath – the width of the WEC array – is moved across the crab fishery profit curve from zero to 15 km offshore, resulting in the curve in Figure 3a.

To model the effect of a wave farm on coastal real estate values via its alteration of the viewscape, it is assumed that a wave buoy is approximately 6 meters in height and 4.5 meters in width (e.g., Finavera Renewables, AquaBuOY) and the height of an observer is 5 meters (height from a typical bluff). The wave buoy array is modeled as 9 km long perpendicular to the coast, with wave buoys evenly distributed across the 9 x 2 km array. In Oregon, the median value of a 1-acre cross-shore, 1-km along-shore parcel of coastal property (*c.* 15 acres along the coast), with a median distribution of one residence structure per acre, is $21,000,000 (using www.rwre.com, the median was calculated based on 33 coastal properties with ocean views that listed the asking price and acreage, November 2008). To make this property value comparable to the fishery and energy annualized values, the property value (with an intact view) was multiplied by a discount rate of 5% to get the future value of the view in $/km through infinite time (Table

1). Finally, given that there is somewhat equivocal evidence regarding the effect of offshore wind or wave farms on aesthetics and property values [80-82], it was assumed that annualized property values were decreased by the proportion of the horizon view that is impacted. This proportion is calculated using simple geometry, based on the height of the observer, the height and width of the energy facility, and the distance of the facility offshore (from zero to 15km offshore), taking into account the curvature of the earth and assuming that coastal properties have a 90 degree angle view of the ocean. Property values are reduced by 2% or less (Fig. 3c).

The analysis reduces to a cost-benefit analysis because all three services are modeled in the same units ($/km/year); the values of the three services are summed to determine the optimal offshore placement for a WEC array, where total value is maximized (Fig. 4a). In cases where services are not valued in common units, the frontier can be determined from multi-dimensional tradeoff analysis. In this example, the frontier is complex with multiple inflection points (Fig. 4b). Considering all three services, the optimal placement of a wave energy facility is at 4.95 km offshore. This is only slightly inshore from where it would be sited without considering the other services (5km). This can also be compared with the optimal siting considering wave energy and the crab fishery only (4.93 km) or wave energy and property value only (5.12 km). The value distribution of the crab fishery pushes the optimal placement of a wave facility closer to shore, while property value has the opposite effect.

Considering all three services, wave facility placement is minimally affected by the two other services because of the large dollar value of energy production relative to the other services and because of the opposing spatial effects of interactions with the other services. In some cases, as is shown here, tradeoff analysis may indicate that interactions that were presumed to be important are relatively insignificant, potentially ameliorating stakeholder conflicts. On the other hand, if other services had been examined or if these services had been valued in terms other than dollars, a different answer may have emerged.

4. Conclusions

This paper presents a straightforward, scientifically-based approach for quantitatively evaluating tradeoffs among multiple ecosystem services. Acknowledgement of such tradeoffs is not new – managers and ecologists have long recognized the complex interactions between different human uses of ecosystems. However, there is a tendency for decisions about tradeoffs to be made implicitly, which is often exacerbated by fragmented or single-sector management, whereby each service is managed independently. An ecosystem service tradeoff approach reveals when the single-sector approach is appropriate and when there is a need for a more integrated, ecosystem-based approach. It also reveals suboptimal management decisions, with 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. Finally, this framework can also be used to evaluate when the frontier is unobtainable due to regulatory or legal constraints and could even be used to guide institutional changes to ensure more equitable service delivery.

While the simplicity of the approach as presented here makes it an ideal starting point for evaluating tradeoffs among ecosystem services, implementing the approach in practice is not without challenges. It is difficult to accurately estimate indifference curves (and in particular, define what is meant by "societal preference"), develop production functions, and use appropriate ecosystem service metrics [83] given the diversity of human values, perceptions and preferences related to ocean uses. These challenges are not insurmountable, and added complexity will certainly be required to improve the applicability of this tool to real world management. For example, production functions and service interactions are not static over time. To consider temporal variability, efficiency frontiers can be assumed to have a dynamic path, rather than operating in steady state [e.g., 49], with management decisions taking frontier trajectories into account. Additionally, our ability to distinguish among different types of service interactions depends on our level of certainty regarding how much of the services will be realized under different management policies. If uncertainty is high and the error bars around each point are large, it may be difficult to distinguish among frontier shapes. However, alternative frontiers can be analyzed in order to consider uncertainty from inputs, from external drivers, and for the effect of management actions. Historical data and past management "experiments" and associated outcomes can be used to learn more about the system. Ironically, management failures of the past may even prove beneficial in the long-term because of their contribution to reducing uncertainty.

The framework presented here has the potential to advance how marine spatial planning is conducted. Managers and scientists need simple and transparent means for determining the tradeoffs, or lack thereof, among key services and communicating these interactions to policy makers and stakeholders. This approach can be readily communicated, developed using complex simulation models, empirical data, or a conceptual understanding of the system, applied in a range of systems and to a variety of services and service metrics, and can be nested within other marine management approaches [e.g., Integrated Ecosystem Assessments, 84]. Tradeoff analysis can also evaluate services that are not readily valued in monetary units, and can consider services measured in different units, allowing managers a quantitative approach for balancing services that otherwise would seem like apples and oranges. These attributes suggest that ecosystem service tradeoff analysis is likely to be a key ingredient in efforts to realize effective marine spatial planning in which we explicitly plan for existing and emerging ocean uses in a spatial context.

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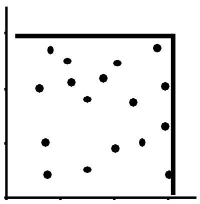
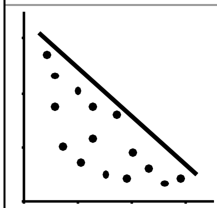
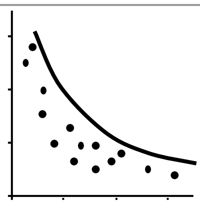
Box 1. Common types of ecosystem service interactions: insights gained from frontier shapes. Although the focus here is on pairs of services, management decisions will undoubtedly influence multiple services simultaneously. The logic for thinking about the frontier with multiple services, however, is the same, although it is difficult to visualize more dimensions.



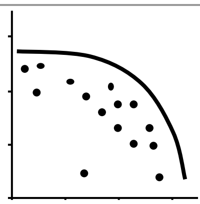
Non-interacting services: These services can be managed independently (e.g., two non-interacting fisheries species with non overlapping habitat requirements). The optimal management solution is at the vertex of the two lines. This type of relationship does not typically arise from traditional economic theory.



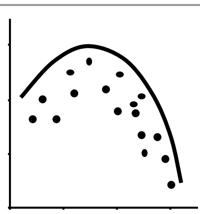
Direct tradeoff: A management decision that increases the provisioning of one service results in a proportional decrease of the other service, with no diminishing returns, and vice versa (e.g., zoning mutually exclusive uses of areas of the ocean). This is a common expectation of how services trade off with each other, although it is likely uncommon for most ecosystem services.



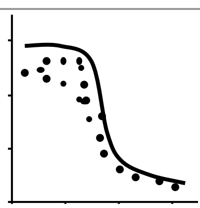
Convex tradeoff: Obtaining even a small increase in the provisioning of one service comes at a large cost for the other service. Scenarios near the middle of the frontier are optimal only when societal preferences for the two services are equal or nearly so. Asymmetrical preferences force management decisions toward "corner solutions" where the frontier asymptotes at one of the axes (Fig. 1). As a result, stakeholder conflicts are more likely because there is little middle ground for compromise.



Concave tradeoff: Although there is a tradeoff, there are scenarios that increase the delivery of one service substantially without a large cost to the other service (e.g., if MPAs produce significant spillover of targeted fish, they may provide conservation benefits with minimal cost to the fishery). Optimal management solutions for all types of concave curves occur between the horizontal and vertical tangents to the curve and corner solutions are unlikely because they would reflect an extreme societal preference for one service over the other. Management is likely to seek a combination of the two services (Fig. 1).



Non-monotonic concave tradeoff: There are some levels of one service for which there are two potential outcomes for the other service. There may be a synergism in the system (e.g., as the yield of a predator species increases, the yield of its prey can also increase because it is released from natural predation). It is sub-optimal to make a decision to the left of the peak of the curve, even in cases where the service on the y axis is valued infinitely more than the service on the x axis.



Backwards S tradeoff: Over some range of one service, it can be increased at no cost to the other service. However, after a threshold it becomes very costly to increase that service in terms of the other. This could result from the placement of ocean wind farms and a fishery. If the wind turbines exclude fishing or alter habitat, they could impose costs on the fishery. The costs could initially be small if they are placed in locations with strong winds and poor fishing grounds. Once these "low cost" sites are filled, however, obtaining more wind energy will come at great expense to the fishery.

Table 1: Functions used to model the three services in the wave energy case study.

Service	Functions
Wave energy profit (WE)	WE = 0 for x < 3 km, WE = $\$3\times10^5$sin[π(x-3km)/4km] for x >= 3 km and x < 5 km, WE = $\$3\times10^5$cos[π (x-5km)/10km] for x >= 3 km and x < 5 km, WE = 0 for x >= 10 km.
Crab fishery profit (CF)	CF = 0 for x < 3 km, CF = $ sin[π (x-3km)/6km] for x >= 3 and x < 9, CF = 0 for x >= 9 km.
Viewscape value (VS)	VS = $ 2.1×10^7 * δ; δ = discount rate = 0.05

Figure Legends

Figure 1

Two hypothetical ecosystem service frontier shapes (blue), shown with different possible indifference curves (red). An indifference curve is a representation of bundles of services for which one has equal preference. Higher indifference curves represent higher levels of total value or utility, but all points on a single curve are equally preferred. Indifference curves are down-sloping and typically convex, because the per-unit value of goods or services generally increases as that good or service becomes scarcer. The highest indifference curve that touches the frontier (yellow star) represents the optimal delivery given the preferences captured by the indifference curves. In the case of a concave frontier, knowing the indifference curve has relatively little impact on the optimal management solution; both panels A and B result in a combination of both services. In contrast, for the case of a convex frontier, most indifference curves result in one service being maximized at the extreme expense of the other service (panels C, D), and therefore it is more informative in this case to have a good estimate of the indifference curve.

Figure 2

Tradeoffs between system-wide biomass (horizontal axis) and system-wide profit (vertical axis) for a harvested, spatially-explicit meta-population. Fishery management is composed of patch-specific harvest levels, including the possibility of marine reserves in some patches. The solid line indicates the ecosystem service frontier and points represent (biomass, profit) combinations from 300 randomly designed marine reserve networks, with the percent of the area set aside in marine reserves indicated by the color and size of the point. The pure profit maximizing solution involves 34% closure and is shown by the asterisk (*).

Figure 3

The value of wave energy (B), the values of the crab fishery (A) and coastal property (C) as modified by the placement of a wave energy facility, with respect to the offshore placement of a wave energy facility.

Figure 4

The combined value of wave energy, crab fishery profit, and coastal property with respect to the offshore placement of a wave energy facility (A) and the tradeoff curve for this three service interaction (B). Each point on the graph refers to an offshore placement distance(s) of the wave energy facility and the star represents the optimal solution, where the tradeoff curve has a slope of -1 (all services tradeoff equally in marginal value) and the maximum total value is achieved when the wave farm is sited 4.95km from shore.

Figure 1

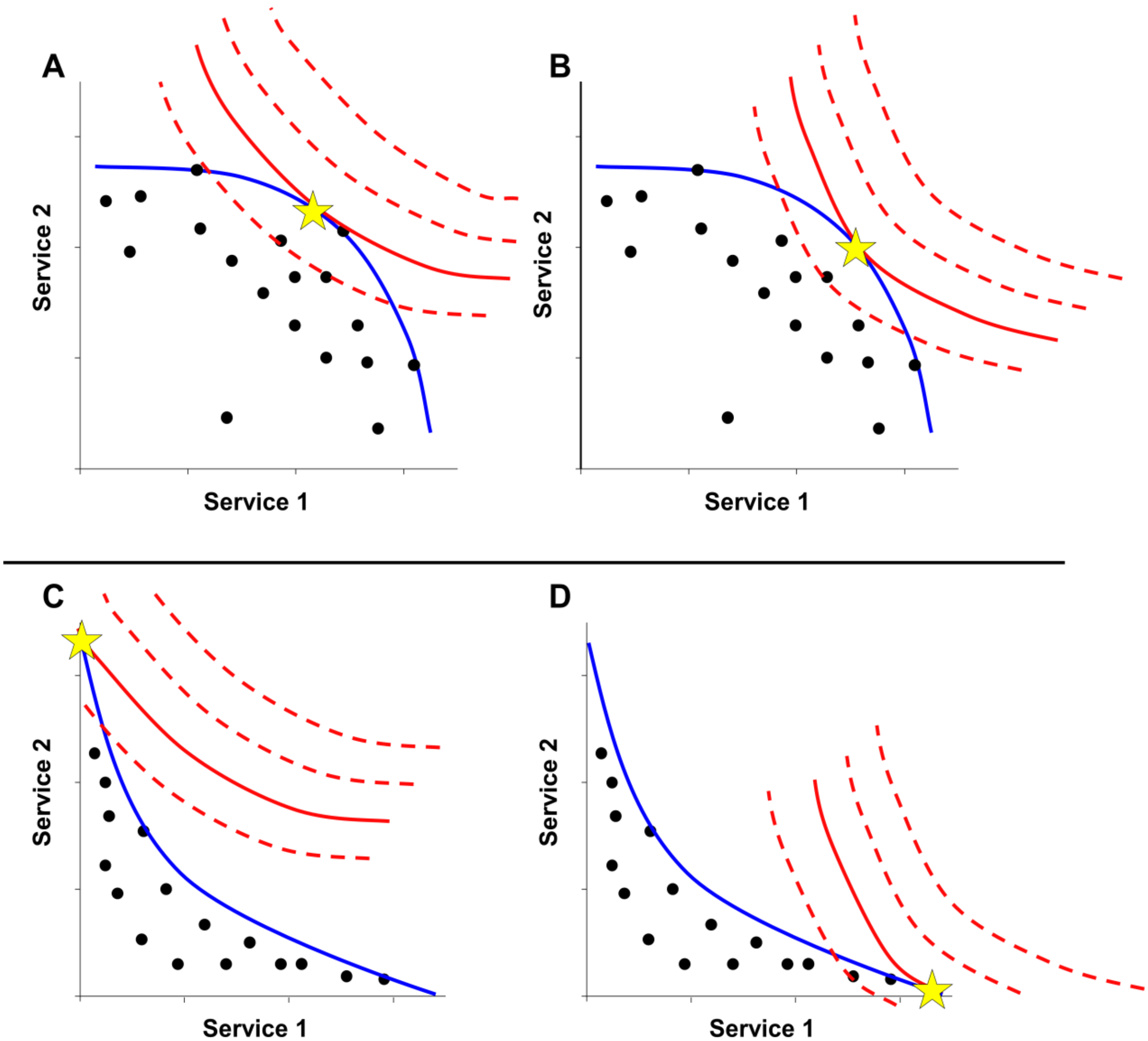

A
Service 2
Service 1
B
Service 2
Service 1
C
Service 2
Service 1
D
Service 2
Service 1

Figure 2

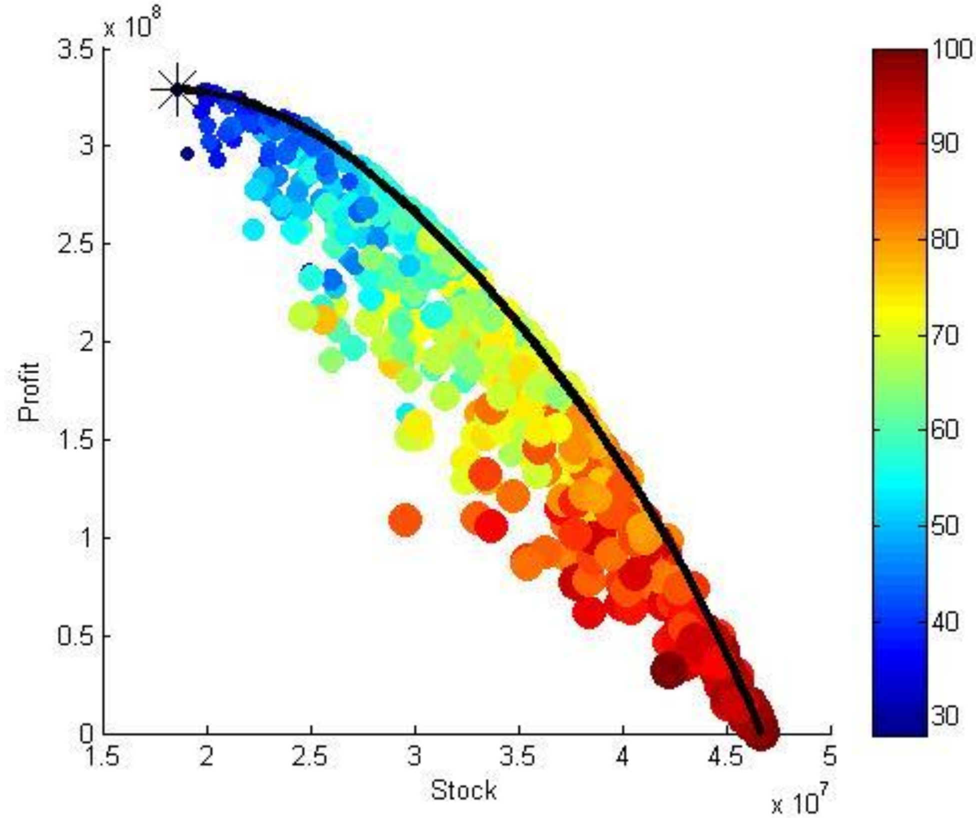

x 10^8
3.5
3
2.5
2
1.5
1
0.5
0
Profit
1.5
2
2.5
3
3.5
4
4.5
5
Stock
x 10^7
100
90
80
70
60
50
40
30

Figure 3

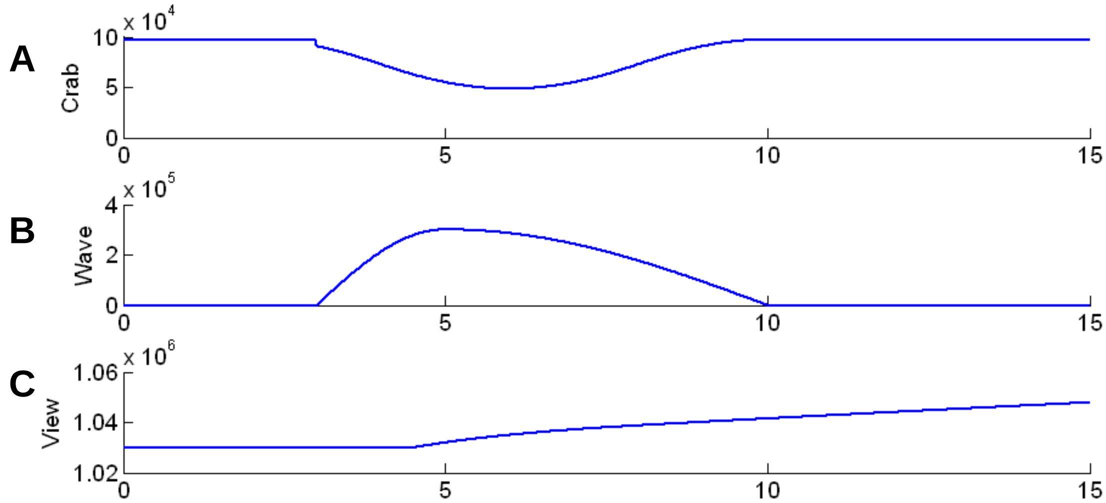
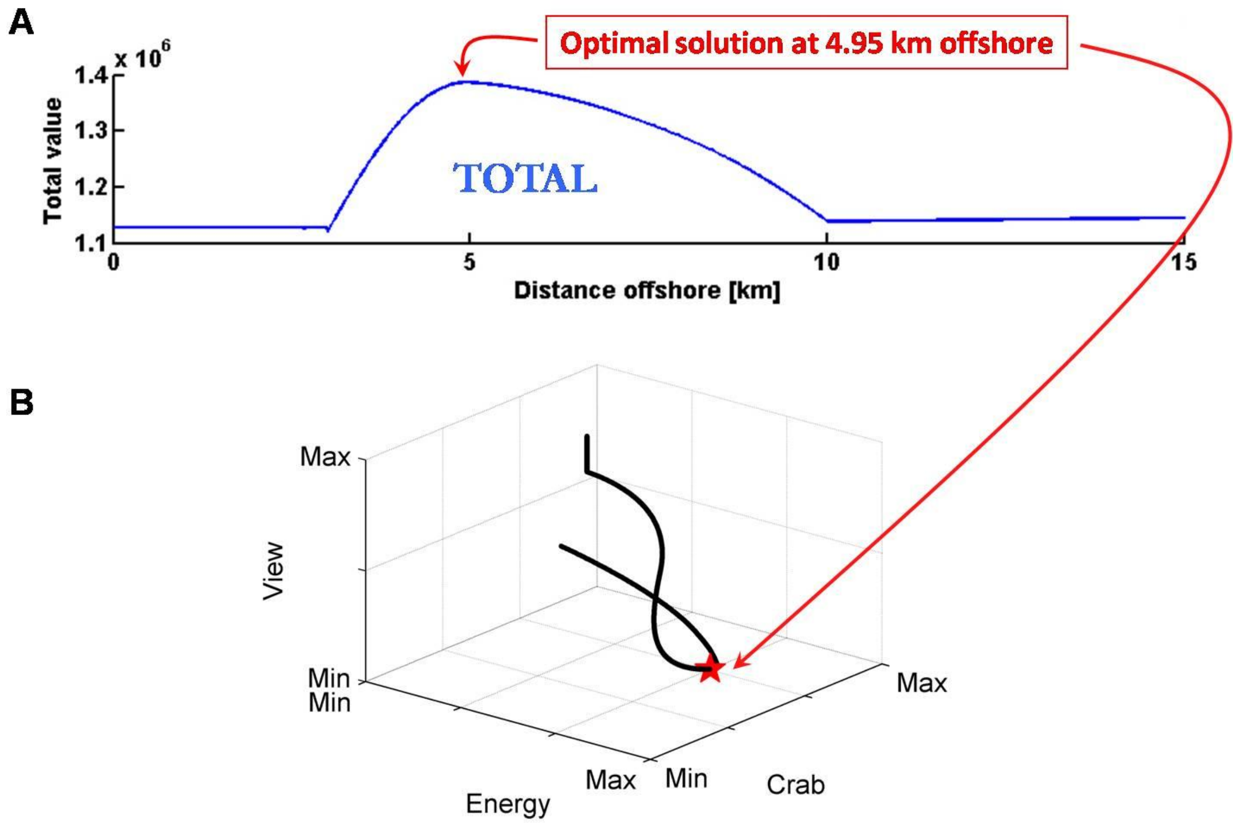

A
x 10^4
10
5
0
Crab
0
5
10
15
B
x 10^5
4
2
0
Wave
0
5
10
15
C
x 10^6
1.06
1.04
1.02
View
0
5
10
15

Figure 4


A
Optimal solution at 4.95 km offshore
x 10^6
1.4
1.3
1.2
1.1
Total value
TOTAL
0
5
10
15
Distance offshore [km]
B
Max
View
Min
Min
Energy
Max
Min
Crab
Max