Estuaries and Coasts
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Managing Bay and Estuarine Ecosystems for Multiple Services

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Abstract Managers are moving from a model of managing individual sectors, human activities, or ecosystem services to an ecosystem-based management (EBM) approach which attempts to balance the range of services provided by ecosystems. Applying EBM is often difficult due to inherent tradeoffs in managing for different services. This challenge particularly holds for estuarine systems, which have been heavily altered in most regions and are often subject to intense management interventions. Estuarine managers can often choose among a range of management tactics to enhance a particular service; although some management actions will result in strong tradeoffs, others may enhance multiple services simultaneously. Management of estuarine ecosystems could be improved by distinguishing between optimal management actions for enhancing multiple services and those that have severe tradeoffs. This requires a framework that evaluates tradeoff scenarios and identifies management actions likely to benefit multiple services. We created a management action-services matrix as a first step towards assessing tradeoffs and providing managers with a

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decision support tool. We found that management actions that restored or enhanced natural vegetation (e.g., salt marsh and mangroves) and some shellfish (particularly oysters and oyster reef habitat) benefited multiple services. In contrast, management actions such as desalination, salt pond creation, sand mining, and large container shipping had large net negative effects on several of the other services considered in the matrix. Our framework provides resource managers a simple way to inform EBM decisions and can also be used as a first step in more sophisticated approaches that model service delivery.

Keywords Ecosystem-based management · Ecosystem services · Estuary · Bay · Tradeoff analysis · Ecosystem function · Marine spatial planning · Decision support tool

Introduction

Estuaries and bays are among the most highly altered and degraded ecosystems, yet humans depend on the health of estuarine ecosystems for a variety of services (MEA 2005). Estuaries provide food, regulate water quality, protect against coastline damage and flooding by storms, provide recreational opportunities, and aesthetic and spiritual value (Costanza et al. 1997). Estuaries and bays also facilitate the transport of goods and associated services and are emerging as an important source for tidal energy. In addition, estuaries serve as a nursery habitat for many economically important coastal species (MEA 2005; Engle 2011). Production of many of these services is declining in many estuarine systems (MEA 2005; Lotze et al. 2006; Barbier et al. 2011); while at the same time, the demand for services provided by estuaries and bays is expected to increase substantially (Kennish 2002).

Traditionally, management of bays and estuaries has focused mostly on single sector outcomes (e.g., improved water quality and single species recovery) and restoration of natural ecosystems to their historic composition of species. Now, ecologists and managers are increasingly focused on the restoration of ecosystem function, rather than restoration of species per se, recognizing that some services are still provided with a novel species composition (Lenihan and Peterson 1998; Ewel and Putz 2004; Schlaepfer et al. 2011).

Shifting the management focus to the maintenance and restoration of ecosystem function is not without its challenges. First, there are different regulatory agencies and stakeholders involved in management decisions, often with competing mandates or objectives. For example, in the USA, separate agencies are tasked with managing fisheries (e.g., National Oceanic and Atmospheric Administration (NOAA)), water quality (e.g., Environmental Protection Agency (EPA)), and energy production (e.g., Department of Energy). The directive of one agency (or the targets of one stakeholder group) may be at odds with that of another. Therefore, management of estuaries is often siloed by individual sectors or services, without an explicit consideration of the functioning of the ecosystem as a whole.

The second, and potentially more problematic challenge, is that services are not independent of one another and there are often inherent tradeoffs in implementing management actions designed to enhance a single service (Barbier et al. 2008; Bennett et al. 2009; Koch et al. 2009). Moreover, economic activities valued by society are often at odds with maintaining or promoting ecosystem services provided by estuaries. Therefore, rather than managing for individual ecosystem services or economic activities alone, managers need to: (a) consider a suite of ecosystem services and economic activities in bays and estuaries and (b) predict how they will respond to different management options. This can involve complex decisions to determine socially desirable outcomes given that it may not be possible to maximize the delivery of all services (Tallis et al. 2008; Barbier 2009; Bennett et al. 2009; Nelson et al. 2009). There are also situations where services (including economic activities) are either positively correlated with one another or show a synergistic relationship (see Bennett et al. 2009; Table 1), providing an opportunity to impart numerous benefits. However, these types of interactions, whether positive or negative, are often missing from natural resource management plans (Lenihan and Peterson 1998). This may stem in part from the tendency for management agencies to focus on a single service but is also likely a result of the paucity of simple and practical yet rigorous approaches for assessing service tradeoffs.

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Table 1 Management action/service matrix

MS	#	Service	Management Action	HS	DV	RC	CY	CM	BP	NBP	PP	TR	FP	SS	NC	CP	BD
Cultural	1	Aesthetic, Historical and Spiritual Value	Viewshed protection	+	+/-	+/-	0	0	+/-	-	-	0/-	0/-	0/-	+	+	+/0
	2	Aesthetic, Historical and Spiritual Value	Site protection (e.g. archeological)	+	-	+/-	0	0	0/-	-	-	-	0/-	0/-	+	+/0	+/0
	3	Aesthetic, Historical and Spiritual Value	Species protection	+	-	+/-	0	0	+/-	0/-	0/-	0/-	+/-	+/-	+/-	+/-	+
	4	Area for Development	Siting, development (e.g. malls, parking lots, buildings)	-	+	+/-	-	-	-	+/-	+/-	+/-	+/-	+/-	0/-	-	-
	5	Recreation	Habitat restoration/creation	+	-	+	+	+	+	-	-	0/-	+/-	+	+	+	+
	6	Recreation	Habitat protection	+	-	+	+	+	+	-	-	0/-	+/-	+/-	+	+	+
	7	Recreation	Coastal access (e.g. trails, parking)	+	+	+	0	0	+/-	0/-	0/-	0	0/-	+/-	0/-	-	-
	8	Recreation	Beach nourishment	+/-	+	+	0	-	0	0	0	0	+	+	-	-	-
	9	Recreation	Installation of piers/ramps (for boating)	-	+	+	0	0/-	+	0	0	+	0/-	+/-	-	-	-
	10	Recreation	Dredging/channelization	-	+	+/-	+/-	-	+/-	+	+	+	+	-	-	-	-
	11	Recreation	Stock enhancement for recreational fisheries	+	+	+	+	0	+	0	0	0	0	0	+/-	+/-	+/-
Climate Regulation	12	Climate Regulation	Habitat protection - emergent vegetation (mangrove, marsh)	+	-	+/-	+	+	+	-	0/-	-	+	+	+	+	+
	13	Climate Regulation	Enhance/create emergent vegetation (e.g. mangrove, saltmarsh)	+	-	+/-	+	+	+	-	0/-	-	+	+	+	+	+
	14	Climate Regulation	Shoreside power (cold ironing)	0	0	0	0	+	0	0	0	0	0	0	0	0	0
	15	Climate Regulation	Restrict motorcraft use	+	0	+/-	0	+	0	0	0	0	0	0	0	0	+
	16	Climate Regulation	Fuel efficiency standards	+	0	+/-	0	+	0	0	0	0	0	0	0	0	+
Provisioning	17	Biotic (e.g. food)	Habitat restoration/creation	+	-	+	+	+	+	-	-	-	+	+	+	+	+
	18	Biotic (e.g. food)	Habitat protection	+	-	+/-	+	+	+	-	-	-	+	+/-	+	+	+
	19	Biotic (e.g. food)	Installation of piers/ramps	-	+	+	0	0/-	+	0	0	+	0/-	+/-	-	-	-
	20	Biotic (e.g. food)	Dredging/channelization	-	+	+/-	+/-	-	+/-	+	+	+	+	-	-	-	-
	21	Biotic (e.g. food)	Open diversion gates	+	-	+	+	+	+/-	0	0	0	+	0	+/-	+/-	+/-
	22	Biotic (e.g. food)	Stock enhancement	+	+	+	?	0	+/-	0	0	-	+	+	+	0	+/-
	23	Biotic (e.g. food)	Increase aquaculture development	-	+	-	+	?	+/-	-	0	-	0	0	+/-	0	-
	24	Biotic (e.g. food)	Non-native introductions (for the purposes of food)	-	0	+	+	0	+	0	0	0	0	+	+/-	0	-
	25	Biotic (e.g. food)	Treatment of sewage and discharge to increase aq. food production	+	+	0	+	0	+	0	0	0	0	0	+	+	+
	26	Biotic (e.g. food)	Fishery regulation	+	+	+	+	0	+	0	0	0	0	+	+	+	+
	27	Non-biotic (e.g. fresh water, salt, sand)	Desalination	-	+	-	-	-	-	+	-	0	0	0	-	-	-
	28	Non-biotic (e.g. fresh water, salt, sand)	Salt pond creation	-	0	-	-	0	-	+	0	0	-	0	0	-	-
	29	Non-biotic (e.g. fresh water, salt, sand)	Sand mining	-	+	-	-	-	-	+	0	+	-	0	-	-	-
	30	Physical (energy)	Provide tidal power	+/-	+	0	0	+	-	0	+	0/-	0	0	0	0	?
	31	Physical (energy)	Provide cooling source	-	+	+/-	+/0	+	-	+/0	+	0	0	0	-	0/-	-
	32	Transportation (shipping and ports)	Installation of piers/ramps	-	+	+/-	0	0/-	+	0	0	+	0/-	+/-	-	-	-
	33	Transportation (shipping and ports)	Dredging/channelization (for the maintenance of shipping)	-	+	+/-	+/-	-	+/-	+	+	+	+	-	-	-	-
	34	Transportation (shipping and ports)	Allowing large container shipping	+/-	+/-	-	0	-	-	0	0	+	0	0	-	-	-
Storm Protection	35	Flood Protection	Water storage: Manage water entry into estuary (e.g. flood gates, sewage)	0	-	+/-	+/-	0	0	0/-	0	0/-	+	+	-	-	-
	36	Flood Protection	Dredging/channelization	-	+	+	+/-	-	-	+	+	+	+	+/-	-	0	-
	37	Flood Protection	Creating levees	+/-	+	+	-	-	-	+	+	+	+/-	+/-	-	+/0	-
	38	Flood Protection	Implementing development regulations (buffers and zoning)	+	+	+	+	+	+	-	-	0	+	+	+	+	+
	39	Flood Protection	Implement managed retreat (realignment)	+	+/-	+/-	+	+	0	0	-	0	+	0	0	0/-	+
	40	Flood Protection	Open diversion gates	0	+	+	+	0	+/-	-	0/-	0	+	0	+/-	+/0	+/-
	41	Flood Protection	Invasive removal (e.g. mitten crab, nutria)	+/-	+	+	0	-	+/-	+	+	+	+	+	0	+	+

One framework for ecosystem service tradeoff analysis borrows from economic theory and multiobjective decision making (White et al. 2012; Lester et al. 2013). This type of analysis focuses on modeling or measuring the ecosystem service outcomes of different management approaches. Results can then be visualized on a multidimensional graph where axes correspond to services of interest and each point on the graph indicates the service outcome of a particular management option (Fig. 1). The outer bound of all the possible points is the “efficiency frontier” composed of

Table 1 (continued)

MS	#	Service	Management Action	HS	DV	RC	CY	CM	BP	NBP	PP	TR	FP	SS	NC	CP	BD
Storm Protection	42	Flood Protection	Estuary/wetland conservation/restoration/creation	+	+/-	+/-	+	+	+	+/-	+/-	-	+	+	+	+	+
	43	Shoreline Stability	Enhance/create emergent vegetation (e.g. mangrove, saltmarsh)	+	-	+/-	+	+	+	-	0/-	-	+	+	+	+	+
	44	Shoreline Stability	Enhance/create seagrass	+	-	+	+	+	+	-	+/-	0/-	+	+	+	+	+
	45	Shoreline Stability	Enhance/create barrier islands	+	+	+	+	?	+	-	+/-	-	+	+	+	+/0	+
	46	Shoreline Stability	Install revetment/riprap/ breakwater/bulkhead	-	+	+	+/-	+/-	+/-	+	+	+	+	+/-	-	0	-
	47	Shoreline Stability	Beach nourishment	+	+	+	0	-	0	0	0	0	+	+	-	0	-
	48	Shoreline Stability	Implement managed retreat (realignment)	+	+/-	+/-	+	+	0	0	-	+/-	+	+	0	-	+
	49	Shoreline Stability	Creating/maintaining cobble beach	+	+	+	0	-	0	0	0	0	+	+	0	0	+
	50	Shoreline Stability	Creating/maintaining sill/salt marsh vegetation	+	-	+	+	+	+	0	0	+/-	+	+	+	+/-	+
Water Quality	51	Nutrient Capture & Cycling	Treatment of wastewater prior to discharge	+	+	+	+	+/-	+/0	0	0	0	+/-	0/-	+	+	+
	52	Nutrient Capture & Cycling	Enhance/create emergent vegetation (e.g. mangrove, saltmarsh)	+	-	+/-	+	+	+	-	0/-	-	+	+	+	+	+
	53	Nutrient Capture & Cycling	Restore and enhance shellfish (filtration; e.g. oysters)	+	+	+	+	0	+	0/-	0	-	0	+/0	+	+	+/-
	54	Nutrient Capture & Cycling	Aerate (i.e. DO maintenance)	0	+	+	+	-	+	0	0	0	0	0	+	?	+
	55	Nutrient Capture & Cycling	Create bioswale/retention ponds	+	+	+	+	+	+	0	0	0	+	+/0	+	+	+
	56	Nutrient Capture & Cycling	Water disposal: direct untreated water into estuary	-	+/-	-	?	0	-	0	0	0	+	0/-	+	+	-
	57	Removal of Contaminants & Pathogens	Treatment of wastewater prior to discharge	+	+	+	+	+/-	+/0	0	0	0	+/-	0	+	+	+
	58	Removal of Contaminants & Pathogens	Treatment of stormwater prior to discharge	+	+/-	+	+	0	-	-	0	0	+/-	0	+	+	+
	59	Removal of Contaminants & Pathogens	Enhance/create emergent vegetation (e.g. mangrove, saltmarsh)	+	-	+/-	+	+	+	-	0/-	-	+	+	+	+	+
	60	Removal of Contaminants & Pathogens	Restore and enhance shellfish (filtration; e.g. oysters)	+	0	+	+	0	+	0/-	0	-	0	+/0	+	+	+/-
	61	Removal of Contaminants & Pathogens	Create bioswale/retention ponds	+	+	+	+	+	+	0	0	0	+	+/0	+	+	+
	62	Removal of Contaminants & Pathogens	Water disposal: direct untreated water into estuary	-	+/-	-	?	0	-	0	0	0	+	0/-	?	+	-
Conserving Native Biodiversity	63	Conserving Native Biodiversity	Species protection	+	-	+/-	0	0	+/-	0/-	0/-	0/-	+/-	+/-	+/-	+/-	+
	64	Conserving Native Biodiversity	Habitat restoration/creation	+	-	+/-	+	+	+	-	-	0/-	+/-	+	+	+	+
	65	Conserving Native Biodiversity	Reintroduction of natives	+	-	+/-	0	0	+/-	0/-	0/-	0/-	+/0	+/0	0	+/-	+
	66	Conserving Native Biodiversity	Removal of non-native species (poison or mechanical)	+	+/-	+	0/-	0/-	+/-	0	+	+/0	0/-	0/-	-	0/-	+
	67	Conserving Native Biodiversity	Creating a fishery for invasives	+	0	+	0	0	+	0	0	0	+/0	0	0	+/-	+
	68	Conserving Native Biodiversity	Physical barriers	+/-	0	-	0	0	0	0	0	-	0	0	0	0	+/-
	69	Conserving Native Biodiversity	Treatment of ballast discharge	+	0	+/0	?	0/-	+/0	0	+/0	-	0	0	0	+	+
	70	Conserving Native Biodiversity	Offshore ballast exchange	+	0	0	?	0	+/0	0	+/0	-	0	0	0	+	+
	71	Conserving Native Biodiversity	Hull fouling regulations	+	0	0	?	+	+/0	0	+/0	-	0	0	0	0	+
	72	Conserve Native Biodiversity	Spatial closures	+	-	+/-	+	+	+/-	-	-	-	+/-	+/-	+	+/-	+

Effect of management actions across services. Signs indicate a positive (+), negative (−) or neutral (0) overall effect. Though arguments can sometimes be made for the opposite effect, the assigned value represents the preponderance of evidence. A question mark indicates that there was not enough evidence to assign an effect. References for the cell assignments can be found in the Electronic supplementary material. The cell colors indicate the certainty of the directional effect: high (light grey), medium (medium gray), and low (black). Cells for which the management action for a service intersects with that same service are represented in white

MS meta-service, *HS* aesthetic, historical, and cultural, *DV* development, *RC* recreation, *CY* nutrient cycling, *CM* climate regulation, *BP* biotic provisioning, *NBP* non-biotic provisioning, *PP* physical provisioning, *TR* transportation, *FP* flood protection, *SS* shoreline stabilization, *NC* nutrient capture and cycling, *CP* removal of contaminants and pathogens, *BD* conserving native biodiversity

"Pareto-efficient" options; the frontier depicts management options providing the optimal delivery of the two or more services, given a set cost of management (Bevacqua et al. 2007; Nelson et al. 2008; Polasky et al. 2008; Lester et al. 2013). Management options interior to the frontier represent inferior decisions, because one or more services could be increased at no cost to any other service by using a different management option on the frontier. Therefore, the relationship between services (i.e., the shape of the frontier) and where options lie relative to the frontier can narrow the scope of potential management decisions and reveal which, if any, services invoke strong tradeoffs.

There are a number of reasons why management would be improved by adopting more explicit and systematic assessments of tradeoffs among services before implementing management options. For one, there may often be

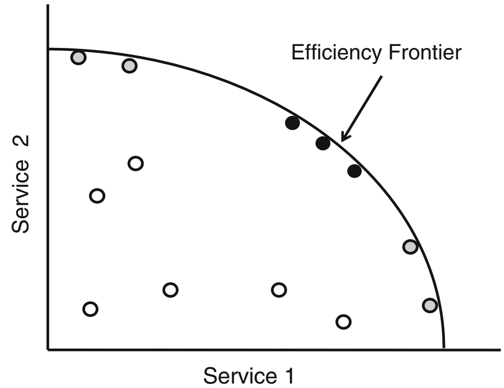


Fig. 1 Efficiency frontier framework. The efficiency frontier diagram illustrates the effect of different management options on two different services. *Open circles* represent inferior or suboptimal management options; neither service derives substantial benefit from the management option. The *filled circles* along the efficiency frontier represent optimal management options. Societal values then may further inform management options for service preferences. *Gray circles* along the efficiency frontier represent management options that place extreme value on one service over the other; whereas, *black circles* represent management options that more evenly balance the two services

unintended and unexpected consequences if tradeoffs are ignored; the value of services may not be fully appreciated until they are lost and must be compensated for with investments of human capital. Second, in some cases stakeholders may perceive that tradeoffs among services will be strong even when both services could be enhanced by taking a different, previously unexplored management approach. An explicit tradeoff analysis can reduce conflict by revealing win–win solutions when only suboptimal decisions are being pitted against one another.

The primary obstacle in real management situations to applying an ecosystem based management (EBM) approach via a service tradeoff analysis, is the availability of models and data capable of predicting service delivery. However, we assert that knowing the basic shape of the frontier can inform management decisions even when the details of the frontier are unknown. The frontier can be derived by using complex simulation models, empirical data, or from a conceptual understanding of the system. Even a conceptual understanding can yield benefits over a business-as-usual approach of ignoring service interactions. Here, we suggest a critical first step to developing a more sophisticated tradeoff analysis.

We developed a management option-service matrix for bay and estuarine ecosystems as a general thought experiment that could be further refined for individual bays and estuaries. The qualitative impacts of different management actions typically taken to promote one service are evaluated for all other services potentially provided by the system. We define services broadly as things people value, which includes ecosystem services (MEA 2005) as well as biodiversity and economic activities. Although not conventionally recognized as an ecosystem service, we include biodiversity as a service in our matrix since several agencies (e.g., US Fish and Wildlife Service) and stakeholder groups (e.g., Audubon Society) have a directive to protect native biodiversity. We consider biodiversity here in the loosest sense to be representative of protecting and maintaining native species and communities, not necessarily increasing richness or evenness of either system attribute. We also include economic activities (such as providing for transport of goods and people, and providing area for development) as services that estuaries can provide because managers often have to weigh the economic, social and political costs of managing for economic activities with traditional ecosystem services (and biodiversity).

This matrix reveals “easy” management decisions that tend to benefit most services and “challenging” management decisions that may benefit one service at the expense of other services. This matrix can be populated using expert opinion and a review of the scientific literature. In populating the matrix, we assess general outcomes that could be applied to any estuarine system (e.g., tropical and temperate) and any locale. This type of assessment provides a general framework for a feasible first step towards considering service interactions when it is not yet possible to develop a sophisticated production function model to simulate service outcomes.

Methods

We assembled a working group of scientists and estuarine managers with diverse expertise in estuarine health and ecosystem services. We generated a list of services (including economic activities and biodiversity) that estuaries provide and grouped these into six meta-service categories (cultural, climate regulation, provisioning, storm protection, water quality, and biodiversity). We also developed lists of actions used to manage or enhance each of the services. We considered management actions that would enhance the ecosystems' natural ability to provide the service as well as human engineered solutions. We used expert opinion, case studies, and evidence from the literature (see Electronic supplementary material (ESM)) to determine the dominant effect of a management action on all of the other services. We assigned + and − values to indicate overall positive or negative effects, and a null value (0) was assigned when a management action did not strongly impact that service. We assigned either a +/−, +/0, or 0/− value when the direction or presence of the effect was context dependent, and we could provide examples for each outcome. We considered the dominant direction of the effect, recognizing that there are exceptions to some of these directional effects which could be taken into account when applying our approach to a specific estuary. We did not assess the magnitude of the impact of a management action on a service, because without formal forecasting models we lacked an adequate method to standardize such an assessment. We did estimate the certainty of the effect as either high, medium, or low based on expert opinion. In many cases, this reflected the number of examples available from the scientific literature or technical reports (see ESM). However, in some cases we estimated the certainty as high when no literature was available because there was not a compelling logical argument for a different directional effect.

We assembled our findings into a management action/service matrix with each service listed in both the rows and columns of the matrix. Under each row of a service heading, we listed the management actions that could be used to manage (i.e., conserve, enhance, or substitute for) that particular service. Several management actions were applicable to more than one service and were listed more than once in the matrix.

Management actions for each of the meta-services delineated below were evaluated for their benefit to multiple services by using the matrix to identify those for which the majority of the cells showed a positive impact on other services. Likewise, strong tradeoffs were identified by searching for management actions showing overwhelmingly negative effects for other services.

Cultural Services

We defined cultural services as including recreational opportunities (e.g., hiking, bird watching, kayaking, and recreational fishing), aesthetic, historical, and spiritual values, as well as providing area for development through the filling of salt marsh and wetland habitats (e.g., San Francisco Bay communities). Management actions could be taken to enhance the historic, aesthetic, and spiritual cultural services by maintaining open views characteristic of low estuarine vegetation, preserving historical components of estuaries (e.g., archeology), protecting iconic species (e.g., flamingoes, whales, sea otters, and manatees), or implementing wetland or estuary conservation measures. Management actions we considered for the enhancement of recreational opportunities included coastal access creation or enhancement (trails, parking lots, and roads), beach creation, boating infrastructure (piers and ramps), dredging for boat channels, and stock enhancement for recreational fishing. Finally, we considered estuaries as providing the cultural service of development for airports, commercial business, and recreational areas as they are located in coastal zones where land values are generally high. The management action of "siting and development" (Table 1), included the development of existing land as well as infilling of the estuary itself to create new areas for development.

Climate Regulation Services

Projections of future climate indicate that dramatic changes can be expected in the earth's ecosystems (Harley et al. 2006; Hoegh-Guldberg and Bruno 2010; Chen et al. 2011). Increasingly, managers are grappling with the likely consequences of future climate change to the systems they manage, and seeking management options to increase the resilience of estuarine ecosystems to climatic variations. However, most of these types of management actions were intended to ameliorate the impacts of climate change (i.e., adaptation), rather than directly affect the provisioning of climate regulation services. Of course, it is possible that future management actions will target climate regulating services. This is especially true for climate mitigation through carbon sequestration. The possible management action we considered for the enhancement of carbon sequestration included habitat protection and habitat creation or restoration.

Estuarine managers can implement management actions to mitigate climate change through the reduction of greenhouse gas emissions. Most simply, this would involve the reduction of fossil fuel combustion in the managed areas. We have considered one such action—providing shore-side power (also known as cold ironing or alternative maritime power) for ships in commercial ports—that has already been implemented in some areas (Hall 2010). Shore-side power is expected to have little effect on other services; it would impose some infrastructure requirements and associated costs on ports, but would also bring local benefits, namely lower emissions of local air pollutants and greenhouse gases to the atmosphere (Hall 2010).

Other possible measures considered for reducing fossil fuel combustion included restrictions on personal motorcraft use and imposing fuel efficiency standards for motorized vessels in an area. A second approach to reducing greenhouse gas emissions would be the conversion of high-emitting habitats to low-emitting habitats. For example, freshwater marshes emit relatively large quantities of methane and nitrous oxide, potent greenhouse gases, whereas salt marshes have minimal emissions of these greenhouse gases (Bridgham et al. 2006). Although this is a possible management action, we have not considered this action in the matrix because there are few opportunities for this type of conversion in estuarine ecosystems as a result of technical, ecological, and social impediments. However, conversion of coastal freshwater marshes to brackish marshes is already underway in some areas as a result of sea level rise (Voss et al. 2013).

Provisioning Services

Within the provisioning meta-service, we identified four specific estuarine services: biotic provisioning (i.e., food), non-biotic provisioning (i.e., freshwater, minerals, sand and gravel), physical provisioning (i.e., energy), and transportation (i.e., creation and maintenance of port facilities for shipping). Management actions to directly promote biotic provisioning services included imposing fishery regulations, developing aquaculture, and introducing non-native species to provide food. Additionally, management actions that indirectly support fisheries by providing access included harbor development and channel dredging. For non-biotic provisioning, management actions included the construction and creation of desalination plants, salt ponds, and sand mining. Physical provisioning management actions included providing a water source for cooling power plants and infrastructure for tidal power. Management actions to increase transportation services were focused primarily on port development, through hardscaping (including breakwaters and/or jetties, as well as piers and docks), dredging to maintain navigational channels, and creating port facilities to transport people and goods. These operations often occur at large (i.e., tens of kilometers) scales and could have sizeable impacts to other services. Impacts from hardscaping could include: associated coastal erosion of downstream localities as a function of "sediment starvation" (Ceia et al. 2010) and increased wave action (Peterson and Lowe 2009), as well as erosion (or increased sedimentation) of navigation channels (PIANC 1997).

Storm Protection Services

Estuaries can provide protection from storms and flooding and aid in the stabilization of shorelines. Mangroves, seagrass beds, and salt marshes can attenuate waves generated by storms and mitigate the effects to developed shorelines and inland areas (Turner 2006; Koch et al. 2009; Engle 2011). During a storm event, salt marshes and mangroves can also act as a catchment for floodwater from rivers, storm drains, runoff, and excess effluent from sewage treatment plants; water that would otherwise flood surrounding areas. Conversion of mangroves to shrimp farms and filling in salt marshes for development are major threats to the continued delivery of storm protection services provided by estuaries (Diana 2009). While habitat alteration is decreasing the ability of estuaries to provide storm protection services, the demand for the service is expected to rise because the intensity, frequency, and severity of storm events is likely to increase with climate change.

Management strategies we considered that are typical for promoting storm protection services fell under three broad categories: shoreline hardening, control of water flow, and restoring or maintaining living shorelines. Shoreline hardening involves management strategies such as installations of bulkheads, riprap, or groins to reduce natural erosion processes of shorelines. Management actions that fell under controlling the water flow included construction of large water diversion structures, which can release sediments and nutrients to marshes from rivers, thus building protective salt marsh habitat or diverting flood waters away from major population centers to prevent flooding. Lastly, living shorelines included management strategies such as creating or maintaining natural habitat (mangroves, sea grass beds, and salt marsh) to reduce the effects of storm surge on the surrounding land.

Water Quality Services

For centuries, populations living near the coast have depended on the mixing and flushing capability of tidal exchange to maintain good water quality. Since the Clean Water Act (1972), bay and estuarine managers have undertaken extensive water quality management actions to meet the goal of protecting the health of ecological communities and people. The focus of managers has begun to shift from specific infrastructure treating point sources and non-point sources of pollution to an integrative approach that considers pollution management, resource management, and habitat restoration to provide a better natural balance. In many of our estuaries, water quality management actions are occurring side-by-side with management actions focused on providing other ecosystem services. These joint management needs are seen by the increasing efforts of the EPA and NOAA to coordinate their chief place-based management programs, the EPA's National Estuary Program and NOAA's National Estuarine Research Reserves System.

We broke down the water quality meta-service into two separate services that estuaries provide: nutrient capture and cycling and the removal of contaminants and pathogens. Management actions to enhance both services included the treatment of wastewater prior to discharge, creating and protecting wetland vegetation and shellfish, aerating the estuary, creating bioswale and retention ponds, and directing untreated water into the estuary (as opposed to coastal waters).

Biodiversity

We defined biodiversity as protecting and maintaining native species and communities, not necessarily increasing richness or evenness of either system attribute. There are many definitions of biodiversity that managers use and a management action may have a different effect depending on the definition. For example, the response of common estuarine species to a particular management action may be vastly different than that of threatened and endangered species of concern. It is therefore principally important when applying this matrix to an individual site to specifically identify what aspect(s) of biodiversity one is interested in increasing or maintaining.

Management actions aimed at protecting native biodiversity in our matrix included habitat creation or enhancement, habitat protection, species protection, native species re-introduction, and the management of invasive species. Management for invasive species had two main strategies: prevention and control. Prevention measures considered included ballast water treatment and regulations forbidding the sale and possession of non-native species. Management actions considered for established invasive species included: (1) poisons (herbicides, pesticides), (2) physical removal of the species in question, (3) biocontrol, and (4) physical barriers to keep the invasive species within a limited area. Regulations that improve water quality (e.g., regulating point and non-point sources of pollution) could also maintain or enhance native biodiversity. We did not include water quality management in our matrix evaluation for conserving native biodiversity since this is not the primary intent of these measures, although we do note their positive effects for native biodiversity. Indeed, increasingly water quality management measures are incorporating biodiversity conservation as an essential component, especially for stormwater management.

Results

Expert estimates of the effect of a particular management action on a specific service can be found in Table 1. After examining the number of positive versus negative effects of a management action across all services, we found that, in general, management actions with a net positive effect on other services outnumber management actions with net negative effects (Fig. 2). The majority of the management actions focused on climate regulation, storm protection, and water quality had the most net positive effects on the other services considered here (Fig. 2a). In general, management actions that had the fewest tradeoffs with other services were those that enhanced or conserved natural vegetation (e.g., wetlands, mangroves, seagrass beds, and salt marsh), restored and enhanced shellfish, regulated development (i.e., buffers and zoning), enhanced barrier islands, and treated wastewater (Fig. 2b). Management actions such as shore-side power, fishery regulations, restriction of motorcraft use, aeration, and creating a fishery for already established invasive species had few positive effects on other services but had a negative effect on no more than one other service. In contrast, management actions such as sand mining, salt pond creation, desalination, and allowing large container shipping to occur had generally negative effects on other services by a 2:1 ratio (Fig. 2b). Below we address the main results for management actions of each of the six meta-service categories.

Cultural Services

For historical, aesthetic, and spiritual services, the management action of protecting viewsheds had the most conflicts with other services, including other cultural services. In particular, viewshed protection had a negative effect on development and other services that require the alteration of habitat such as non-biotic provisioning (i.e., sand mining and siting of a desalination plant) and physical provisioning (i.e., siting of a power plant). Management of estuaries for the purpose of development had a greater proportion of negative impacts on other services than did the other cultural categories. In fact, development was often at odds with other cultural services (i.e., management for historic, aesthetic, and spiritual services and recreation services). This negative impact to other services can largely be attributed to the conversion of saltmarsh or estuary to land suitable for development.

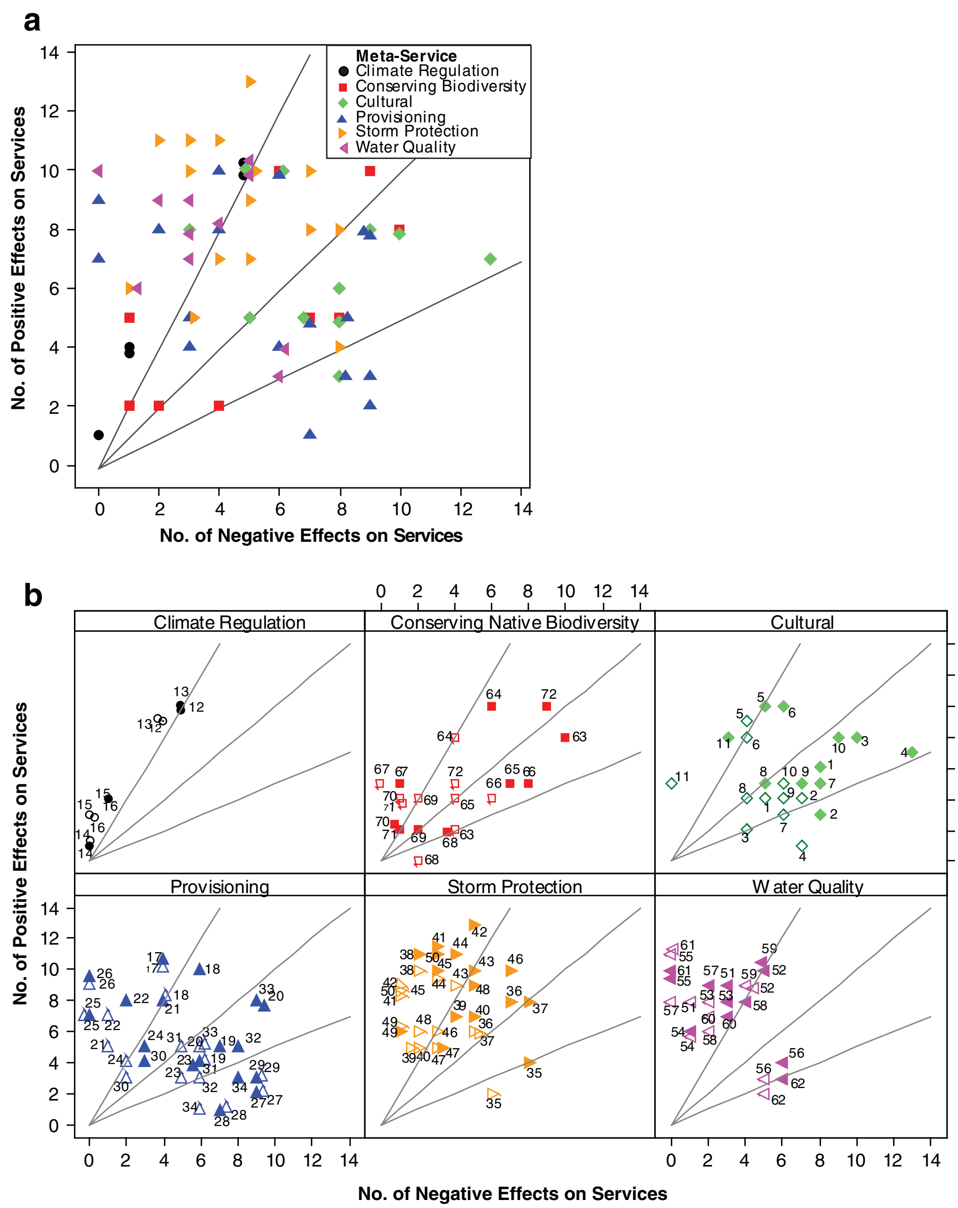
Among cultural services, there were management actions that had generally positive effects on other services that directly benefit people. Parking lots, piers, trails, and coastal access facilitate a range of recreational activities and increase land values. Some cultural management actions could also coincide positively with a range of commercial activities. For example, stock enhancement can improve recreational and/or commercial fisheries and, if done correctly, restore biodiversity (Lenihan et al. 2001; Grabowski and Peterson 2007). Habitat protection can improve viewsheds and maintain biodiversity, thereby supporting ecotourism. Moreover, dredging can support recreational boating, commercial shipping, and fisheries (i.e., by providing access to fishing boats). Management for public access can simultaneously increase several services provided by estuaries, including transportation, food, recreation, fishing, and adjacent development. On the other hand, increased access can generally have a negative effect on biodiversity.

The effect of management for cultural services on biotic provisioning varied by cultural service. It was generally positive for management actions that enhanced recreation while negative for management actions that enhanced development. Effects on non-biotic provisioning and energy were either largely negative (e.g., management actions 1–3 and 5–7) and/or neutral (e.g., management actions 8, 9, and 11). Overall effects of cultural management actions on shipping/transportation/ballast discharge and water quality were less clear or were contradictory.

Climate Regulation Services

There were no management strategies focused on climate regulation that were positive across all services. However, the number of negative impacts to other services across all climate regulation management actions was minimal (Fig. 2b). Among climate regulation management actions, shore-side power stands out because it was neutral across all other services. The strongest tradeoffs involved the habitat-based management actions (habitat protection and habitat creation/restoration) and area for development or non-biotic, physical and transportation provisioning. This conflict resulted from the requirement for

Fig. 2 Net effect of management actions on services. Management actions for all services plotted together (**a**) and separately (**b**). Numbers reflect associated management actions in Table 1. *Closed symbols* consider matrix cells where any positive or negative value occurred (i.e., +, +/0, +/−, −, −/0, and +/−); whereas, open *symbols* excluded cells with mixed effects (i.e., +/−). Isoclines of 1:1, 1:2, and 2:1 distinguish net positive effects from net negative effects for each meta-service



mutually exclusive use of a particular area for habitat, development or extraction of non-biotic resources. A second strong tradeoff existed for restricting the use of motorcraft. The very nature of this management measure means that motorcraft users would not be able to boat when or where they would like (in contrast to use of non-motorized watercraft, which may benefit). This tradeoff contrasted with the imposition of fuel efficiency standards, which would impose an initial cost but over the long term would likely be economically beneficial to motorcraft users.

Restricting motorcraft use negatively impacted boating activities, but had positive effects on non-motorized recreational activities such as kayaking and snorkeling, aesthetic values, and native biodiversity (by reducing disturbance and the number of invasive species introduced by motorcraft). Imposing fuel efficiency standards could have a negative effect on motorized boating if it increased the cost of buying motorcraft or restricted their availability. If motorcraft use were reduced, the overall effects would be the same as direct restrictions on motorcraft use. However, higher fuel efficiency would mean lower fuel costs, so the net effect of this management action might be neutral.

Provisioning Services

Overall, the provisioning management actions that had the highest positive to negative ratios for impacts on other services were those implemented for biotic provisioning (Fig. 2). Even within biotic provisioning though, several management actions had strong tradeoffs with other services. For example, tradeoffs existed between dredging and channelization (to increase access to fish and boating) and nine of the other services (Table 1). In addition, dredging and channelization could negatively impact biotic provisioning itself if the sedimentation from these activities affects larvae or adults of species that are harvested by people. Increased turbidity from dredging could also harm seagrass beds, and the deposition of dredged spoil material could have severe benthic and fish community impacts both inside and outside of estuaries where the material is released, especially during beach renourishment (Lindeman and Snyder 1999; Bishop et al. 2006).

Research reviewed indicated that few biotic provisioning management actions had no influence on other services, although relatively little is known about effects on services related to material cycling. Fishery regulation had the fewest tradeoffs of biotic provisioning management actions on other services, and included only positive and neutral effects. Stock enhancement also had mostly positive influences on other services (Table 1; Fig. 2). Habitat protection, restoration, and enhancement had mostly positive effects across the entire matrix (Table 1, Fig. 2), but there were also tradeoffs for some services (i.e., development, non-biotic provisioning, physical provisioning, and transportation) (Table 1). Management actions associated with habitat protection for the purposes of enhancing fisheries usually had a substantial positive impact on other services.

In contrast to biotic provisioning, management actions for non-biotic, physical and transportation services had a lower positive to negative services effect ratio (Fig. 2b). The management actions that had the most negative effects on other services were desalination, salt pond creation, and sand mining. Desalination had negative impacts on biotic provisioning services as well as other services through discharges of brines and releases of toxic metals (Roberts et al. 2010), particularly in areas with little water exchange, and has been shown to impact soft sediment and plant communities (Roberts et al. 2010). Furthermore, salt ponds have led to major deforestation in some coastal areas. In Mozambique, salt production ranks second among human activities contributing to mangrove deforestation, occurring at an estimated rate of 1,800 ha year^{-1} in 2001 (Semesi 1998; Barbosa et al. 2001).

Storm Protection Services

There were clearly differential, uneven, and nonlinear impacts of storm protection management actions on services (i.e., Lindeman and Snyder 1999; CSA 2009; Peterson and Lowe 2009; Bilkovic 2011), with many management actions resulting in a range of negative effects on other services (Finkl 2002; Brody et al. 2008; Peterson and Lowe 2009). For example, altering intertidal shoreline with riprap, bulkheads, levees, and channelization in order to protect local populations from storm surge and flooding has significantly reduced nekton abundance, and size distributions of common taxa in salt marsh ecosystems (reviewed in Peterson et al. 2000; Reed et al. 2006; Bilkovic and Roggero 2008). These alterations also have eliminated or markedly reduced intertidal habitat, which, in many bay and estuarine ecosystems, provide nursery habitat and other services vital to society (e.g., salt marsh, seagrass, mangrove, etc.; Finkl 2002; Peterson and Lowe 2009; Bilkovic 2011). Additionally, many small-scale alterations noted above (also including piers and docks) can have larger cumulative impacts (Johnston 1994; Brody et al. 2008; Peterson and Lowe 2009) reducing biodiversity and sustainability of vital intertidal habitat types (Seitz et al. 2006; Bilkovic and Roggero 2008).

Although our research found no single management action taken to enhance or maintain storm protection had a positive influence on all other services, living shoreline treatments and wetland creation scored the highest across the matrix. For example, building rock sills in the low marsh to stabilize marsh elevations (i.e., a living shoreline approach) impacts benthic algal production but does not influence marsh cordgrass growth in North Carolina (O'Connor et al. 2011). Finally, implementing development regulations that reduce conversion of natural habitat (such as buffers and zoning) had a positive effect on all but two services; non-biotic and physical provisioning. In this case, development regulations would likely negatively affect the siting of a power or desalination plant.

Water Quality Services

Management actions to enhance water quality services provided by estuaries generally had a positive effect on several other services. With the exception of directing untreated water into an estuary, management actions to improve water quality services had a 2:1 or higher ratio of positive to negative effects on other services (Fig. 2). In this case, engineered systems (e.g., multi-million dollar sewage treatment or stormwater treatment plants) did not incur stronger tradeoffs than more natural management actions (i.e., saltmarsh and shellfish restoration and bioswales). However, a sewage treatment plant in general will be more effective than saltmarsh and shellfish restoration for improving water quality.

The restoration of salt marshes and enhancement of shellfish, particularly oysters, can increase an estuary's ability to improve water quality through filtration of contaminants and pathogens (Cerrato et al. 2004; Lipton 2004; Newell and Koch 2004; zu Ermgassen et al. 2013), though consuming the shellfish themselves has led to norovirus outbreaks in humans (Webby et al. 2007). Moreover, the establishment, protection, and enhancement, of oyster reefs had multiple positive effects on other services. Oyster beds have increased recreational fisheries, tourism, element cycling, flood protection, and shoreline stabilization (Meyer et al. 1997; Lipton 2004; Newell et al. 2005; Piazza et al. 2005).

Biodiversity

Among management actions for biodiversity, those aimed at preventing establishment of invasive species had the fewest tradeoffs whereas spatial closures and species protection had the most tradeoffs. In fact, most management actions for biodiversity had strong tradeoffs with other services (Fig. 2; Table 1). Therefore, maintaining biodiversity alongside alternative uses requires substantial creativity to minimize tradeoffs. One common practice is to zone activities in time and space. For instance, areas crucial for breeding birds might be closed to recreation, especially during the breeding season. There may be some win–win opportunities, such as providing observation points to areas where wildlife are protected, conducting habitat restoration in a way that improves viewsheds, restoring plants that improve water quality, reintroducing native fisheries species, or permitting fisheries for invasive pests. For example, a lionfish fishery is being developed throughout the Caribbean, where this fish is doing extensive damage to populations of native fishes (Morris and Whitfield 2009).

Conservation of biodiversity has a strong spatial component. Benefits of preserving biodiversity can be global, while the impacts to other services are usually local. For this reason, regulations developed at large spatial scales (e.g., nationally) are often necessary to achieve the conservation of biodiversity locally. Additionally, the impacts of management may be temporary. If biodiversity management requires altering viewsheds (e.g., removal of exotic eucalyptus from the San Francisco Presidio National Park), there may be resistance to controlling invasives or restoring habitat until people become accustomed to new viewsheds. Physical removal, habitat creation, or poisoning of invasive species may have temporary impacts. However, when the benefits are long lasting, conservation trade-offs should be assessed over a long time horizon.

It is important to also consider that biodiversity can be measured in a number of ways and depending on which metric a manager applies, the management action effect on other services may be different. For example, spatial closures that protect a threatened or endangered predator could have a negative effect on biotic provisioning (e.g., the southern sea otter and urchin fishery) but a spatial closure to protect an overfished species could have a positive effect on biotic provisioning.

Discussion

When applying the management-service matrix provided here (or refined for a specific bay or estuary), managers may lack the more detailed service production models required to identify actual tradeoff curves (e.g., Fig. 1). Given two services of interest, they may not know the shape of the tradeoff curve nor where current management falls relative to the frontier in the tradeoff space. We assert that our matrix framework provides an important and practical first step towards managing for multiple services, for both minimizing tradeoffs and managing as close to the frontier as possible.

For each service, the matrix lists a number of management actions that could be taken to enhance that service. In other words, if the service is plotted on the *x*-axis of the tradeoff space, any of the management actions for that particular service moves the system towards the right. However, the various management actions do not all have the same impact on the other services provided by the system; those management actions could have no effect, a positive effect, or a negative effect on another service (Fig. 2). If the effect is positive on the other service, this action moves the system closer to the frontier regardless of where it was prior to the implementation of the management intervention. If the effect is negative for the other service, then the net effect is more likely to depend on the starting location in the tradeoff space. For a system already on the frontier, this may represent a movement along the frontier (enhancing one service while decreasing another in a way that is in theory optimal, although may have negative social consequences depending on values for one service over the other). If the system is interior to the frontier, the negative impact on the other service is likely to move the system further from the frontier. Similar logic applies to management actions that are neutral to other services. Thus, even in the absence of detailed forecasting models, it is useful for managers to identify matrix rows that are beneficial to numerous other services. Choosing as many of these multiservice management actions as possible will likely move management of the system towards the frontier.

Although the matrix provides a sounding board for managers to determine how a proposed management action might affect other services, often the issues regarding balancing tradeoffs among services are socially and politically driven (Hughes et al. 2005; Palmer and Bernhardt 2006). Altman et al. (2011) discussed a qualitative approach to account for multiple human activities and tradeoffs with ecosystem services such that important components of an EBM strategy emerge. This approach can account for activities that have strong negative effects on ecosystem services through cumulative and indirect effects (Altman et al. 2011). de Groot et al. (2010) also noted these tradeoffs in terms of land use/land cover planning but determined that nature conservation and planning do not always require tradeoffs between nature and development and that investments in sustainable ecosystem use are viewed as a "win–win" situation.

There are some important caveats to using the matrix framework as a step towards a more formal tradeoff analysis. For one, the matrix does not provide information about the magnitude of the effect of a management action on a service. A large gain in one service may be socially and environmentally desirable despite a decrease in another service, particularly if that decrease is relatively small compared with the increase in the first service. Finding common currencies to assess tradeoffs can be difficult in many cases and should be the focus of further research. Second, the matrix lists commonly used management approaches; which should not be viewed as constraints. While in some cases, there are innovative approaches listed here (including so-called "soft" vs. "hard" shoreline protection approaches) that could reduce or eliminate existing tradeoffs, there may well be additional approaches that should be investigated. Lastly, we think a matrix approach is most useful for identifying "easy" (many positive effects across a row) and "challenging" (some negatives across all rows for management actions taken to enhance a particular service) choices. For tough choices, it may often be worth investing in more science to be able to conduct a more quantitative tradeoff analysis that can inform more nuanced decision making that minimizes strong tradeoffs (White et al. 2012).

In applying this matrix to a specific estuary, site-specific information will be necessary especially in cases where the matrix indicated mixed directional effects (+/−). These types of outcomes occurred in 12 % of the cells of our matrix and would warrant further examination for a specific locale or situation. For example, the management action of species protection (management action 3 in the matrix) would have a different directional effect on recreation (and several other services) depending on the species being protected (Table 1). Lastly, our estimations of the directional effect of a management action on corresponding service had different levels of associated certainty (Table 1). More investment in the effect of a management action on a particular service may also be warranted in cases where the certainty of the effect is low (Table 1). Regardless of the limitations, using the matrix approach is an important first step to help managers' progress beyond single sector management.

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