Modeling Marine Ecosystem Services

Jade MS Delevaux, Natural Capital Project, Stanford University, Stanford, CA, United States and Seascape Solutions LLC, HI, United States
Anne D Guerry, Natural Capital Project, Stanford University, Stanford, CA, United States and School of Environmental and Forest Sciences, University of Washington, Seattle, WA, United States
Robert Griffin, Natural Capital Project, Stanford University, Stanford, CA, United States and School for Marine Science and Technology, University of Massachusetts Dartmouth, Dartmouth, MA, United States
Mary H Ruckelshaus, Natural Capital Project, Stanford University, Stanford, CA, United States and School of Environmental and Forest Sciences, University of Washington, Seattle, WA, United States

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This is an update of Anne D. Guerry, Mary H. Ruckelshaus, Mark L. Plummer, Dan Holland, Modeling Marine Ecosystem Services, Editor(s): Simon A Levin, Encyclopedia of Biodiversity (Second Edition), Academic Press,2013, Pages 329–346, ISBN 9780123847201, https://doi.org/10.1016/B978-0-12-384719-5.00333-6.

Abstract

Marine ecosystems support human wellbeing, through blue economy, food security, mental health, and supporting identities. The lens of ecosystem services can shed light on nature's contributions to people's wellbeing. We discuss the importance of assessing ecosystem services to inform more inclusive decisions in coastal and marine systems. We explore methods for mapping, modeling, and valuing marine ecosystem services and outline new approaches to incorporate land-sea interactions. We also highlight key challenges and emerging technologies to advance our capabilities to model marine ecosystem services. Last, we introduce four case-studies that demonstrate applications of these concepts. Ultimately, modeling marine services can help society preserve the flows of benefits from oceans and coasts and incorporate multiple values into planning decisions to build a more equitable and sustainable future.

Glossary

While terms such as ecosystem services and nature's contribution to people may be used interchangeably in colloquial settings, each has a distinct definition. The precise definitions given here are those used in this chapter; they integrate meanings associated with the terms in the literature (see sample references).

Blue economy The range of economic uses of all waterbodies (oceans, lakes, rivers and wetlands) such as energy, shipping, fisheries, aquaculture, mining, and tourism. It also includes economic benefits that may not be marketed, such as carbon storage, coastal protection, cultural values, and biodiversity (Bax *et al.*, 2021).
Ecosystem services The material and non-material benefits that ecosystems and biodiversity provide to humanity, which sustain and fulfill human life (MEA, 2005). A closely related concept is nature's contributions to people, which is defined as all the contributions, both positive and negative, of living nature to the quality of life for people (Díaz *et al.*, 2018).
Integrated land-sea planning A planning approach that aims at allocating human use of land and freshwater spatially and temporally as a function of downstream users and ecosystems.
Marine Broadly defined to include coastal (on land, within a narrow fringe adjacent to saltwater), intertidal, nearshore, and open ocean.
Marine spatial planning A planning process that aims at allocating human activities spatially and temporally in the marine space to meet ecological, economic, and social objectives through stakeholder engagement (Ehler and Douvere, 2009). Related terms include: Marine Planning, Ocean Zoning, Ocean Planning.
Nature-based solutions Management interventions that involve the protection, restoration or management of natural and modified ecosystems to simultaneously provide ecological, social and economic benefits (EESI, 2019).
Production function approach An approach that models ecosystem services as the relationship between ecological and human inputs (e.g., the structure and functions of an ecological system, human labor and capital) and outputs valued by humans (National Research Council 2005a).
Value Relative worth, merit, or importance formed through individual preferences and resource availability.
Averting expenditures Valuing an ecosystem good or service based on expenditures to mitigate damage incurred by a change in environmental conditions.
Ecosystem service assessment Mapping the cascading effects of a management intervention on ecological functioning, ecosystem service provision, and people's values (Olander *et al.*, 2017).
Expected damage functions Valuing an ecosystem good or service based on its ability to mitigate damages from a change in environmental conditions.
Hedonic analysis Valuing an ecosystem good or service based on its contribution to the value of another good in an adjacent market. Typically employed to measure environmental features' influence on housing prices.
Market-based valuation methods Methods for valuation that rely on observable prices and quantities exchanged in markets.
Replacement costs Valuing an ecosystem good or service based on the costs of providing replacement services in place of naturally provided services.
Stated preference methods These methods rely on surveying approaches that ask individuals to make a choice, describe a behavior, or state directly what they would be willing to pay for specified changes in non-market goods or services.
Valuation Act of estimating or setting the value of something.

Key Points

- Brief overview of the importance of marine ecosystem services.
- Present modeling approaches for coastal and marine ecosystem services.
- Present key methods for the valuation of ecosystem services.
- Discuss challenges and advancements to modeling marine ecosystem services.
- Showcase four case studies where modeling marine ecosystem services informed smart decision-making.

Introduction to Marine Ecosystem Services

Coastal and marine ecosystems provide a wide range of ecosystem services vital for human well-being and the global economy (Barbier, 2017). The closely-related concepts of "ecosystem services" and "nature's contributions to people" link human wellbeing to the integrity of ecosystems (**Table 1**) (Daily, 1997; Díaz *et al.*, 2018; MEA, 2005). Globally, more than 3 billion people rely on the oceans for their livelihoods with more than 820 million directly linked to blue economy activities and nearly half of that workforce being women (Blue Food Assessment, 2021). Seafood provides 20% of animal protein to more than 3.2 billion people (FAO, 2018). Over 80% of the world's traded goods travel by sea and roughly 70% of urban centers are located around coasts or waterfronts (Habitat UN, 2018), with about 1 billion people living in low-lying coastal zones and 230 million below 1 m (Kulp and Strauss, 2019). In addition, oceans absorb about 30% of carbon dioxide emitted by human activities, thus significantly buffering the impacts of global warming (UNDP, 2018). In summary, our oceans make the Earth habitable for humankind by regulating rainfall, weather, and climate, thereby providing us with drinking water, food, oxygen, livelihoods, and more.

Table 1 Ecosystem services provided by marine systems

Ecosystem service	*Examples*
Food production (capture fisheries; aquaculture; and wild foods)	Tuna, crab, lobster; salmon, oysters, shrimp, seaweed; mussels, clams
Fiber production	Mangrove wood, seagrass fiber
Biomass fuel production	Mangrove wood, biofuel from algae
Maintenance of aquatic systems	Shipping, tidal turbines
Generation of genetic resources	Individual salmon stocks, marine diversity for bioprospecting
Production of biochemicals, natural medicines, and pharmaceuticals	Antiviral and anticancer drugs from sponges, carrageenans from seaweed
Climate regulation	Major role in global CO2 cycle
Water regulation	Natural stormwater management by coastal wetlands and floodplains
Erosion regulation	Nearshore vegetation stabilizes shorelines
Water purification and waste treatment	Uptake of nutrients from sewage wastewater, detoxification of Polycyclic Aromatic Hydrocarbon by marine microbes, sequestration of heavy metals
Disease regulation	Natural processes may keep harmful algal blooms and waterborne pathogens in check
Pest regulation	Grazing fish help keep algae from overgrowing coral reefs
Pollination/Assistance of external fertilization	Innumerable marine species require seawater to deliver sperm to egg
Natural hazard regulation	Coastal and estuarine wetlands and coral reefs protect coastlines from storms
Provision of conditions that support or enhance ethical values (non-use)	Spiritual fulfillment derived from estuaries, coastlines, and marine waters
Provision of conditions that support or enhance existence values (non-use)	Belief that a species is worth protecting, no matter its use value to humans
Provision of recreation and ecotourism opportunities	Scuba diving, beachcombing, whale watching, boating, snorkeling; fishing, clamming
Nutrient cycling	Major role in carbon, nitrogen, oxygen, phosphorus, and sulfur cycles
Soil formation	Many salt-marsh surfaces vertically accrete; eelgrass slows water and traps sediment
Primary production	Significant portion of global net primary productivity
Water cycling	Most of Earth's water is in oceans; they are central to the global water cycle
Support identities	Personal, cultural, national, gender, sexual, social, ethnic and religious dimensions of identity
Learning and inspiration	Living classrooms, place-based practices

Source: Adapted from Guerry, A., Plummer, M., Ruckelshaus, M. and Harvey, C. (2011). Ecosystem service assessments for marine conservation. In: Kareiva, P., Tallis, H., Ricketts, T., Daily, G., and Polasky, S. (eds.) Natural capital: Theory and practice of mapping ecosystem services. Oxford: Oxford University Press.

Although coastal and marine services are essential to human existence, demands for services often exceed the ecosystem's capacity to supply them, thereby leading to overexploitation and ecosystem degradation. The delivery of services is mediated by the physical, chemical, and biological processes that shape marine ecosystems, like biomass production, organic matter transformation, and nutrient cycling (Strong *et al.*, 2015). In recent decades, marine ecosystems have been degraded by human activities including overfishing, land-based source pollution, invasive species, habitat destruction, and climate change (Worm *et al.*, 2006). Thus, there is a compelling need for biophysical and economic assessment of marine ecosystem services–to both communicate the importance of natural resources to diverse stakeholders and policy makers and to support the implementation of policies aimed at sustaining coastal and marine systems and the people who depend upon them (Buonocore *et al.*, 2021).

Recent broad marine ecosystem services assessments include the global assessment report on biodiversity and ecosystem services by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019), the First Global Integrated Marine Assessment by the United Nations (UN, 2017), and the Second World Ocean Assessment (UN, 2021). Other example of marine ecosystem services assessments at the global scale include: a review of blue forest valuations (salt marshes, seagrass and mangroves) by Himes-Cornell *et al.* (2018), a monetary valuation of coastal, coral reefs, and open oceans by de Groot *et al.* (2012), and revised estimate of marine ecosystem services value (49.7 trillion USD per year) by Costanza *et al.* (2014). In addition, Mapping Ocean Wealth released a mapping portal that quantifies and displays the world's ocean wealth to better understand where and how ocean wealth is generated and valued to inform smarter investments for the ocean of tomorrow (Spalding *et al.*, 2016).

Several conceptual frameworks emphasize the notion that humans are an integral part of ecosystems and provide the context within which ecosystem service information can be used to understand feedbacks between humans and ecosystem conditions in marine and other environments (e.g., Levin *et al.*, 2009; Liu *et al.*, 2007; Ostrom, 2009). For instance, Integrated Ecosystem Assessments (IEAs) are one example of iterative approaches to the management of marine ecosystems that can use ecosystem services in a modeling framework to support management decisions that address a range of social, economic, and natural conditions (e.g., Dennison *et al.*, 2007; Samhouri and Levin, 2012; Tallis *et al.*, 2010).

Ecosystem services can provide a set of metrics for assessing these conditions, and modeled changes in their levels can then provide decision makers with a way to compare alternative policies (Tallis *et al.*, 2012). Marine ecosystem services can be assessed, using indicators derived from biophysical, sociocultural, and economic methods, to support decision making (Arkema *et al.*, 2015; Guerry *et al.*, 2012; Harrison *et al.*, 2018). Biophysical methods quantify the attributes of ecosystems that support the stock and flow values of ecosystem services in physical units (e.g., kg per year) and fall into three categories: direct measurement, indirect measurement, and modeling methods. Typically, direct measurements methods rely on direct observations, surveys, and questionnaires, while indirect measurement methods use different data sources (remote sensing and other datasets), combined with some data processing, analysis, and assumptions. Modeling methods leverage those measurements coupled with approaches from different disciplines, including ecology, statistics, climatology, anthropology, and economics to quantify and map ecosystem services.

Bringing ecosystem services into active management requires more than a catalog of services and their total values. More pragmatic is the assessment of the ecological and economic consequences of management activities in particular places. An understanding of how changes in ecosystems are likely to lead to changes in ecosystem services, their values, and the beneficiaries can provide helpful information to decision makers. Modeling marine ecosystem services can play an important role in providing such insights while increasing transparency and stakeholder confidence into the decision process through replicable and quantifiable ecosystem services assessments (Bagstad *et al.*, 2013). Building models that account for human behavior can provide fundamental insights into the provision and value of ecosystem services (Holland *et al.*, 2012). For example, people catching fish from the marine environment is what transforms the potential ecological supply into the actual provision of the ecosystem service (Tallis *et al.*, 2012). Human values that vary in form, such as the demand for seafood, the willingness to pay for recreation, and the costs of commercial harvest or recreational angling all determine the value of these services.

Marine & Coastal Ecosystem Services Modeling Tools

Existing marine ecosystem service modeling tools range from simple spreadsheet models to complex software packages. More complicated models involve complex decisions about where and when to fish, which species to fish for, and so forth (e.g., Sanchirico and Wilen, 1999; Wilen *et al.*, 2002). Similarly, human behavior has more latitude to adjust over longer periods of time, and so modeling short-run versus long-run behavior of a system can account for such differences (Holland and Brazee, 1996). More recent marine ecosystem services models can include how humans interact with biophysical components of the system and can incorporate realistic mechanisms for changing those interactions based on economic and other incentives. Spatially explicit modeling tools that can map and track changes in marine ecosystem services under different futures are essential to mainstream ecosystem services into policy and make informed decisions (Buonocore *et al.*, 2021). They provide a way of exploring future scenarios that lie outside the range of past experiences, as well as possible unexpected consequences of policy actions. Ecosystem service models that couple biophysical and social values provide policy makers with a set of metrics for assessing the changes brought about by alternative management interventions and their potential impacts on economic or social well-being.

Models that integrate multiple processes (biophysical, social and economic) and how they respond to various changes can be useful to inform the design and implementation of environmental policies. The production of ecosystem services involves a combination of ecological functions and human actions and values (**Fig. 1**). A production function approach is fundamentally process-based and has been used extensively in agriculture, manufacturing, and other sectors of the economy. It represents the relationship between inputs (e.g., the density of mangroves) and outputs (e.g., the degree of protection from storms). Ecological production functions can be used to explore how changes in ecosystem structure and function lead to changes in the flows of services (National Research Council, 2005a). Many models of ecosystem services take a production function approach in which the structure and functions of an ecological system are combined with human actions and capital to produce an output valued by people (National Research Council, 2005a). This approach has been used to analyze a variety of individual ecosystem services, as well to provide the framework for developing suites of models that encompass multiple services on land (Kareiva and Marvier, 2011; Ricketts *et al.*, 2004) and in marine systems (Barbier *et al.*, 2008; Guerry *et al.*, 2012).

Modeling Single Ecosystem Services: Fisheries

Of all marine ecosystem service modeling, fisheries models are by far the most sophisticated and have the longest history of use in managing marine systems. While, we do not focus on single ecosystem services (i.e., fisheries) modeling in this chapter, some example of popular ecosystem models to explore fishery management options include Ecopath with Ecosim (EwE) (Christensen and Walters, 2004) and Atlantis (Fulton *et al.*, 2011). EwE is a free ecological modeling software to assess biomass change over time and space to explore the impact of fishing, trophic interactions, and placement of protected areas. Atlantis is a dynamic, spatially explicit modeling framework that connects the biophysical system (climate, oceanography, nutrient availability, and food web interactions), the users (industry) and their socioeconomic drivers (Fulton *et al.*, 2011). Atlantis has been primarily applied in Australia, North America, and Europe (Audzijonyte *et al.*, 2019). These models also have the potential to assess changes in the delivery of ecosystem services by exploring ecosystem dynamics, human activities, and fisheries management options in terms of trade-offs among species, fishing gear types, and management policies. Incorporating these models in the development of management solutions can help consider multiple objectives and trade-offs among objectives.

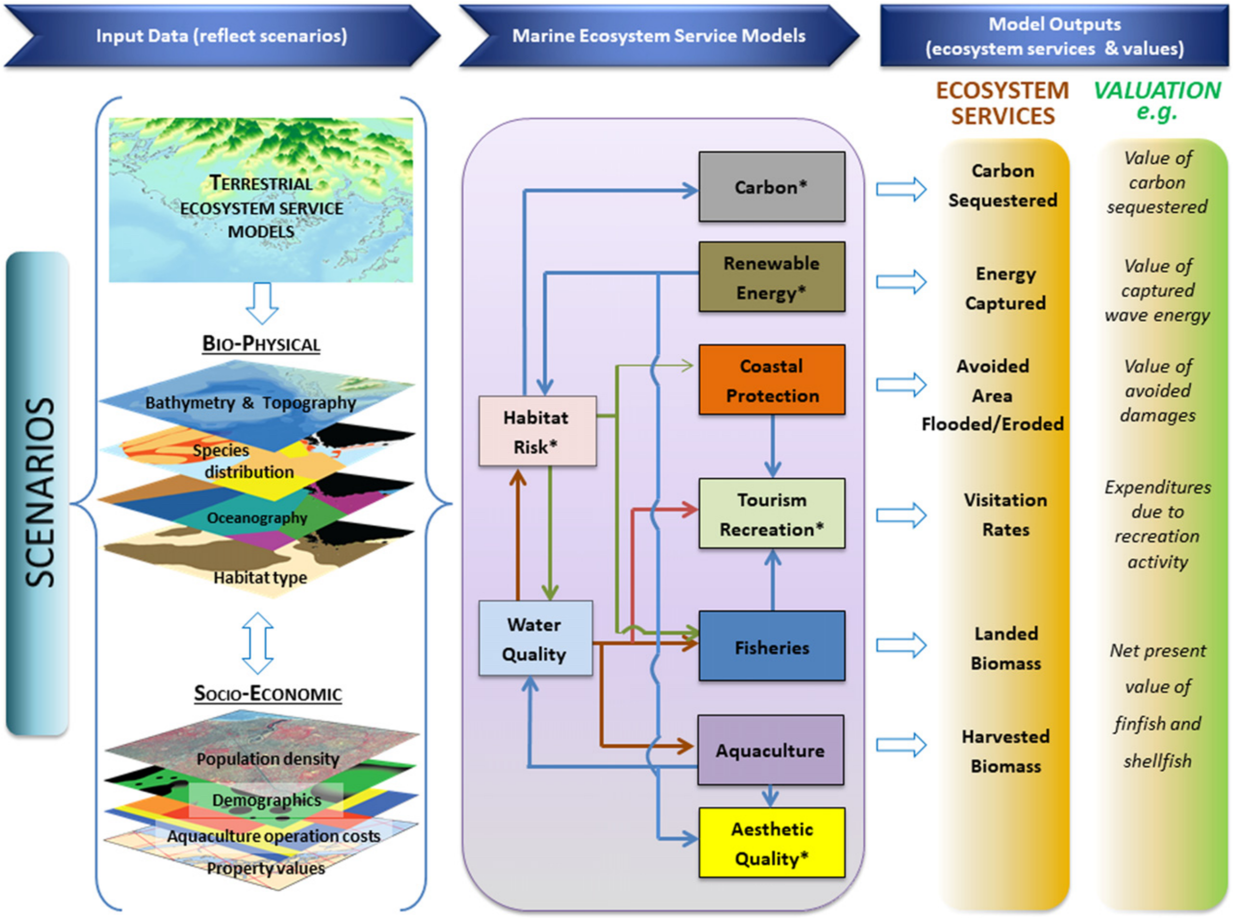

Fig. 1 Marine ecosystem services models evaluate how alternative scenarios yield changes in the flow of ecosystem services. First, one translates management or climate scenarios into input data. Inputs can include spatially explicit biophysical and socioeconomic information or can be derived from terrestrial ecosystem services in a land-sea planning approach. Next, one feeds input maps into models that predict the delivery of services across the seascape. Intermediate effects of management choices and climate on the flow of services can be evaluated in terms of risks to habitats and changes in water quality. Ecosystem service outputs are expressed in biophysical or socioeconomic units. The model marked by * are InVEST models. Adapted from Guerry A. D., Ruckelshaus M. H., Arkema K. K. *et al.* (2012). Modeling benefits from nature: using ecosystem services to inform coastal and marine spatial planning. International Journal of Biodiversity Science, Ecosystem Services & Management 8, 107–121.

Modeling Multiple Ecosystem Services

Single-sector management that proceeds without the explicit consideration of how single decisions impact the full suite of things people care about and need can lead to misguided assessments of the true costs and benefits to the environment and society of natural resource management options. For example, mangroves are routinely cleared, and the resultant open areas used for shrimp aquaculture. A singular focus on aquaculture as an ecosystem service derived from cleared areas often shows a positive bottom line, as the high market price of shrimp provides strong support for this action from a private perspective. Standing mangroves provide other social and ecological benefits that private owners cannot capture, however. More complete accounting using a multiple ecosystem service framework shows that keeping mangroves intact often has higher social benefits once other services such as wood products, support for offshore fisheries, and coastal protection are considered (Sathirathai and Barbier, 2001). In other words, a single-sector approach risks ignoring the multitude of connections among components of natural and social systems. These connections are often important for the maintenance of ecosystem health, human well-being, and the sector of interest itself (MEA, 2005).

The explicit recognition of connections between activities and their consequences for multiple ecosystem benefits allows for the exploration of trade-offs and win–wins faced by society (Rodríguez *et al.*, 2006). In some cases, trade-offs and win–wins can be explored using a common currency (e.g., dollars, Sathirathai and Barbier, 2001), but various metrics can be used (Lester *et al.*, 2013; Tallis *et al.*, 2008, 2012). As one example, the MA explored trade-offs among various ecosystem services under different heuristic scenarios using axes for each service scaled from -1 to 1 to represent positive or negative change from the baseline (MEA, 2005). Explorations of multiple ecosystem services and how they are likely to change under various management scenarios has proceeded in two important directions: detailed explorations of situations and the development of tools designed to be applicable in various contexts. We focus here on tools. Research teams have taken different approaches to modeling the flow of multiple ecosystem services and examining trade-offs between them. Here we describe some of the approaches and tools that are most applicable to modeling marine ecosystem services.

Modeling the flows of ecosystem services can take many forms. Artificial Intelligence for Ecosystem Services (see "Relevant Websites" section) offers a range of approaches including probabilistic Bayesian models, machine learning, and pattern recognition to assess the provision, use, and flow of ecosystem services on a landscape (Villa *et al.*, 2014). The tool allows users to evaluate and compare alternative policy and land-use scenarios and their impacts on ecosystem services. ARIES team originally built eight ecosystem service modules: Carbon sequestration and storage, Flood regulation, Coastal flood regulation, Aesthetic views and open space proximity, Freshwater supply, Sediment regulation, Subsistence fisheries and Recreation (ARIES team, 2021). The technology underlying ARIES is constantly changing toward a flexible agent-based and multi-purpose modeling platform for collaborative and integrated modeling that serves a scientific and policy community globally (Martínez-López *et al.*, 2019).

Integrated Valuation of Ecosystem Services and Trade-offs (Sharp *et al.*, 2021) helps decision makers visualize the impacts of potential management activities or climate change by modeling and mapping the delivery, distribution, and economic value of terrestrial, freshwater, and marine ecosystem services under alternative scenarios (Kareiva and Marvier, 2011). InVEST's marine tools includes models for blue carbon sequestration, renewable energy, coastal vulnerability, recreation, habitat quality and risk assessment, aesthetic views, and more (**Fig. 1**) (Arkema *et al.*, 2014; Griffin *et al.*, 2015; Guerry *et al.*, 2012; Wedding *et al.*, 2021; Wood *et al.*, 2013). Applicable at a range of scales – from local to global (Chaplin-Kramer *et al.*, 2019) – InVEST was designed to play a key role in real-world decision-making processes. InVEST is process-based and thus uses primarily a production function approach to simulate how environmental change due to management decisions or exogenous factors affects the delivery of ecosystem services. To facilitate the use of InVEST in real decision-making contexts, InVEST models require relatively simple input data and are freely available online. InVEST is best used in an iterative and interactive fashion with stakeholders to develop scenarios that project how the provision of services might change in response to management options, climate change, population, and so on, and identify management solutions (Ruckelshaus *et al.*, 2015). InVEST outputs provide decision makers with information about costs, benefits, trade-offs, and synergies of alternative management strategies to identify compatibility between environmental, economic, and social benefits.

Other tools that can map and assess ecosystem services trade offs, inform marine spatial planning, or inform renewable energy sitting. For instance, the Multiscale Integrated Models of Ecosystem Services (MIMES) is another suite of models that assess the values of ecosystem services to allow managers to understand the dynamics of ecosystem services under various management scenarios in both terrestrial and marine systems (Boumans *et al.*, 2015). Additional tools that can assess conservation tradeoff in the design of protected areas networks include MarineMap, a web-based decision support toolkit to support marine spatial planning processes and design prospective marine protected areas network; Marxan, a program to allocate protected areas that meet biodiversity conservation targets while minimizing the cost of the network. Last, the Bureau of Ocean Energy Management (BOEM) and NOAA Coastal Services Center developed the Multipurpose Marine Cadastre (MMC), a web-based geospatial data viewer to support the assessment of offshore energy projects.

Modeling Linked Land-Sea Ecosystem Services

Marine ecosystem services are indirectly impacted by pollution and eutrophication, with about 80% of marine and coastal pollution originating from land-based activities (e.g., coastal development; nutrient, sediment, and pathogen inputs to freshwater; increases in impervious surfaces) (Carlson *et al.*, 2019; Diaz and Rosenberg, 2008; Moore, 2010; UNDP, 2018). Research shows that accounting for land-sea linkages in conservation planning shifts the areas to prioritize for management, compared to approaches that ignore those linkages (Makino *et al.*, 2013; Tsang *et al.*, 2019). Therefore, modeling tools that trace and map linkages between land and sea in the design of management interventions can help maximize benefits across land and sea and minimize the adverse effects of land-use change (Brown *et al.*, 2019; Tulloch *et al.*, 2021). To inform management and promote benefits from mountain tops to sea, modeling tools need to quantify and map changes in (1) land-based pollution loads, (2) marine water quality, (3) biodiversity, and/or coastal and marine habitat, and/or coastal and marine ecosystem services.

Existing studies aimed at understanding the impacts of terrestrial runoff on marine resources to prioritize conservation and restoration investments range from local-scale, data-intensive models to regional/global-scale, coarse data set models (Brown *et al.*, 2017a,b; Delevaux *et al.*, 2018a,b; Delevaux and Stamoulis, 2021; Halpern *et al.*, 2009; Klein *et al.*, 2010, 2012; Oleson *et al.*, 2020; Paris and Chérubin, 2008; Rude *et al.*, 2016; Suárez-Castro *et al.*, 2021; Tulloch *et al.*, 2016, 2021; Wada *et al.*, 2021; Wenger *et al.*, 2020). Leveraging this body of work, we examine and provide an overview of the decision support tools available to assess the effects of land-use change on marine ecosystem services. We focus on the drivers of land-use change, water quality, marine ecological responses to land-based source pollution, and the design of management responses.

Land Use Change Modeling

Mapping existing and future land use and cover change is essential to assess land-based source pollutant loadings. Typically, current, and historical land use cover can be derived from satellite data (Brown *et al.*, 2017a,b; Suárez-Castro *et al.*, 2021), or land-use maps from governmental repositories (Álvarez-Romero *et al.,* 2015). Government priorities and future land use change can be derived from historical land use cover change (Delevaux and Stamoulis, 2021), from predictive modeling of land use change (Álvarez-Romero *et al.,* 2015), and from stakeholder consultation (Patel *et al.,* 2007).

Land-Based Source Pollutant Modeling

In the past decade, existing hydrological models have been applied to land-sea planning (Brown *et al.,* 2019). Linking land use cover to pollutant runoff in the context of land-sea planning can be done using complex dynamic hydrological models (Álvarez-Romero *et al.,* 2015; Delevaux *et al.,* 2018a,b; Hutley *et al.,* 2020; Wada *et al.,* 2021) or simple static empirical models (Delevaux and Stamoulis, 2021; Suárez-Castro *et al.,* 2021; Tulloch *et al.,* 2016). The dynamic models generally predict water discharge on a daily time-step to estimate sediment and nutrient fluxes, while the empirical models estimate soil erosion and nutrient loading rates and then use a delivery ratio approach to estimate loads at the coast (Borah and Bera, 2003; Hamel *et al.,* 2015; Pittman, 2017). Both types of models require spatial parameter inputs such as DEM, land cover, soil property, precipitation, erosion, and nutrient loading factors per land use cover types (see Yuan *et al.,* 2020 for a review on pollution models).

Empirical-based models, such as Nonpoint Source Pollution and Erosion Comparison Tool (N-SPECT), InVEST Sediment and Nutrient Delivery Ratio, Urban Stormwater Retention models (Griffin *et al.,* 2020; Hamel *et al.,* 2015, 2021), can be applied to data poor regions and are particularly useful for identifying sources of pollutants within a watershed (Brown *et al.,* 2019). Parameterizing those models sometimes require borrowing parameters from other regions, which may under- or over-estimate actual pollutant loads by orders of magnitude (Hamel *et al.,* 2017). When calibrating those models is not possible due to lack of gauge data, they are still useful to assess the relative changes in pollutant loads between present and future scenarios to inform management actions (Hamel *et al.,* 2017).

Dynamic hydrological models, such as the Soil-Water-Assessment Tool (SWAT) (Arnold *et al.,* 1998) and Groundwater Modeling System (GMS) (Xiaobin, 2003), are more costly to implement. However, those models can be account for more sources of pollutants, such hillslopes and gully erosion (Sharp *et al.,* 2021), or link land and sea through submarine groundwater discharge, which is a key vector for land-based source pollutants particularly in drier and volcanic geographies (Delevaux *et al.,* 2018a,b). GMS is an application from Aquaveo, which models multiple aspects of groundwater in 3-dimensions, such as MODFLOW (groundwater budget), MODPATH (groundwater flow path), MT3DMS (multi-species transport model). GMS has been applied in Hawaii to inform wastewater management in the land-sea planning context (Delevaux *et al.,* 2018a,b; Wada *et al.,* 2021).

Marine Water Quality Modeling

At the land-sea interface, three types of approaches have been developed to diffuse the pollutant loads into the marine environments (Brown *et al.,* 2019). The first approach disperses the pollutant load from discharge points at the shoreline (e.g., streams or groundwater springs) with distance from shore using linear or non-linear decay functions into the marine environment (Halpern *et al.,* 2009; Wedding *et al.,* 2018). The second approach models the dispersion of the pollutant with a combination of simple process models and GIS (Brown *et al.,* 2017a,b). This method can incorporate marine conditions that influence the diffusion and advection of the pollutant, such as bathymetry, wave power, currents and wind velocities, and soil particle settling rates (Delevaux *et al.,* 2018a,b; Delevaux and Stamoulis, 2021; Hutley *et al.,* 2020; Rude *et al.,* 2016; Wenger *et al.,* 2020). The third approach is hydrodynamic modeling, such as the Regional Ocean Modeling System (ROMS) for the Meso-American Reef region (Paris and Chérubin, 2008) and the open source Delft3D (Lesser *et al.,* 2004), which explicitly model spatial and temporal ocean circulation and transport by currents of river discharge as a function of bathymetry. Those models generally account for the state of the ocean (temperature, salinity, currents, and tides) and the surface fluxes (wind, rain, solar, and radiative heat fluxes) in their simulations. However, those complex models are not easily transferable to data poor regions or scaled up to large areas because they require data that often are too coarse to capture small scale hydrodynamic patterns along the coast. In addition, more work is needed to ground truth those simple approaches against in situ water quality measurements (Brown *et al.,* 2019). Others have leveraged Bayesian models to compare those GIS based water quality modeling approaches against satellite data (Brown *et al.,* 2017a,b).

Marine Ecosystem Response Modeling

Several methods have been applied to estimate the potential impact of land-based source pollution on marine habitats and associated ecosystem services. The simplest approach assesses the overlap between the pollutants and the habitats of interest (Rude *et al.,* 2016). Others built on this approach by weighting the habitat area relative pollutant exposure to each watershed discharge point (Delevaux and Stamoulis, 2021; Suárez-Castro *et al.,* 2021). The latter is useful to prioritize watersheds to target with management interventions that can mitigate land-based source pollution. Some have incorporated sensitivity thresholds of those ecosystems to sediment and nutrient loads to explicitly model the response of the coastal and marine habitats to the pollutant (Tulloch *et al.,* 2016). Another approach is empirical-based and leverages species distribution modeling to derive and explicitly incorporate the effect of the pollutant on the species of interest for a given geography (Delevaux *et al.,* 2018a,b). This static approach requires in situ data on the abundance of the species modeled and geospatial data to calibrate the models and geographically extrapolate those relationships.

Alternatively, existing software tools like Marxan, InVEST and ARIES can be leveraged. Marxan with Connectivity allows users to account for land-sea connectivity in the area selection algorithm when prioritizing terrestrial and marine strategies based on their cost-effective contribution to meeting conservation targets (Ball *et al.*, 2009; Beger *et al.*, 2010; Tulloch *et al.*, 2021). The land-sea connectivity "cost" layer requires spatial information on the magnitude and sources of the pollutants and associated marine water quality outputs across the area of interest. The InVEST Habitat Risk Assessment model can be applied to quantify changes in coastal and marine habitats in response to change in land-based source pollution and associated ecosystem services supply (e.g., coastal protection, lobster fisheries, and marine recreation) (Arkema *et al.*, 2014; Wyatt *et al.*, 2017). ARIES was applied in Hawaii to assess how land use practices impact marine recreation (Oleson *et al.*, 2020).

Ecosystem Service Valuation Approaches

Values for marine ecosystems are formed through individual preferences and resource availability. The goods and services that a marine ecosystem provides can be directly consumed, experienced ambiently, or can consist entirely of non-use value. As a result of this diversity, values can often be difficult to quantify in some cases, especially when goods and services are not directly exchanged in markets. Despite this challenge, it is essential that we incorporate these values into decision making as these values reflect the motivations behind individual and community interest in the environment.

Decision Frameworks

Change analysis

Appropriate approaches for valuing marine ecosystem services depend on how decisions will be made. Modern economics relies on the principle of defining value in the context of meaningful changes in the amount or quality of goods and services and this applies no less to measuring ecosystem service value. This means that value measurements are derived by comparing two fully articulated states of the world (Bockstael *et al.*, 2000). In practice, this could be as simple as catching another fish, or as complex as restoring hundreds of hectares of salt marsh with new recreational amenities and altered species composition and hydrology, affecting dozens of potential goods and services. These different states represent potential choices with environmental and social outcomes that need to be evaluated relative to a decision maker's objectives. Ecosystem service assessments use causal chains to map the network of ecological impacts resulting from an action, their subsequent effects on ecosystem service provision, and finally the effect on values people hold for those services (Olander *et al.*, 2017). By simulating all these cascading effects, it is possible to compare a wide variety of actions on the relevant merits considered in the decision-making process (**Fig. 2**).

Cost benefit analysis

Cost benefit analysis relies on the notion of welfare, or the aggregate well-being across a population of interest. For a given social policy, changes in aggregate producer and consumer surplus are summed and if the net change in welfare is positive the action is worthwhile and should be undertaken. Here, producer surplus refers to net revenue, inclusive of all costs, and consumer surplus refers to the aggregate difference between willingness to pay and market prices for all relevant consumers. In practice, budget or resource constraints typically result in a situation where several alternative actions are being considered and only some of them can be chosen. In this case, the alternatives with the highest (positive) net welfare should be prioritized.

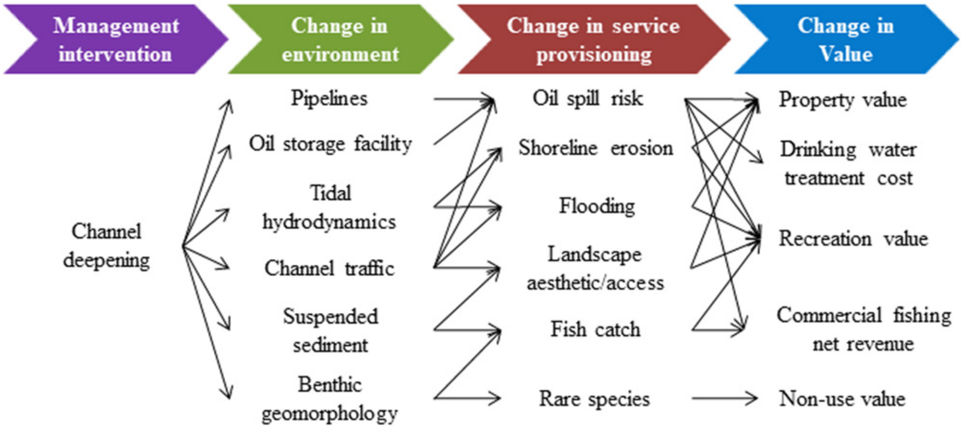

Fig. 2 A network of causal chains for an ecosystem service assessment, using an example of dredging a coastal waterway to allow for larger ships.

The total net welfare impact is typically referred to as the change in total economic value, which includes the direct, indirect, and non-use contributions of ecosystems to all relevant parties, measured dynamically through time as an expected net present value that reflects time preferences and uncertainty in estimates (Bergstrom *et al.*, 1990). For actions that affect a range of services and parties, this calculation can become challenging and requires careful thought to define and model the geospatial extent of impacts for each good or service that changes and care to avoid common pitfalls like double counting or miscategorizing costs and benefits. Causal chains are helpful here to articulate all the pathways to changes in social welfare and the ways these manifest through the environment, allowing for a complete accounting of all value changes.

Cost-effectiveness analysis is a close corollary of cost benefit analysis, in that it includes all the same principles except it is less demanding in terms of measuring benefits. In this case, decisions are made by assuming that all options provide the same level of benefit, and then choosing the option that is the least costly to implement. A key shortcoming here is that it is impossible to know if the net welfare from any option is positive without measuring benefits, so the best option may still be a net social loss. It may also seem impractical to assume all options provide the same benefits, given the myriad direct and indirect environmental and social changes that can be induced; in practice, this approach can be useful when the scope of the impacts of an action is limited.

Multicriteria analysis

While monetary valuation is useful to assess the costs and benefits of policies affecting marine ecosystem services, decision makers and their stakeholders may care about a broader range of ecological and sociocultural factors associated with marine ecosystems. In this case, multicriteria analysis provides a general framework for incorporating these factors into decisions and is flexible enough to deal with information gaps that cost benefit analysis cannot (OECD, 2018). In the most generic formulation of multicriteria analysis, decision makers and stakeholders identify various criteria of importance, assign relative weights for these factors, and create an aggregate score for each policy alternative using a linear summation of these factors and weights. When factors are qualitative, rules are needed to transform them to quantitative, such as using a ranking index. The policy alternative with the highest score is the preferred action.

The flexibility that allows multicriteria analysis to incorporate a wide range of potential factors means that, in practice, it is an umbrella decision framework that encompasses many other familiar decision aids like environmental impact assessments, gross domestic product and other tracking indices, life cycle assessments, cost benefit analysis, and more. If desired, any combinations of these could be considered as factors in a multicriteria decision framework, though due to information demands multicriteria analysis in practice tends to be opportunistic in meeting decision needs and available information. For example, ecosystem service assessments often stop short of identifying the value implications of ecological change needed for a full cost benefit analysis (Mandle *et al.*, 2021). Despite that, changes in benefit-relevant indicators such as the number of people affected, change in hazard exposure, or jobs created can still be a useful part of decisions in a multicriteria framework (Olander *et al.*, 2018).

Revealed and Stated Preference

The foundation of cost benefit analysis assumes that observable choices made by individuals reveal their expected value of a good or activity (Slesnick, 1998). Revealed preference models are a collection of methods for estimating economic values that rely on observable behavior. In general, values estimated through revealed preference are considered more reliably predictive than those elicited through stated preference approaches (Kling *et al.*, 2012), though each has their own respective uses that are summarized below.

Market-based valuation methods rely on market transactions to define the value that people assign to goods and services. Generally, the approach begins by defining a particular geographic location and then identifying the set of ecosystem services flowing from that area. The assessment can then be as simple as compiling local information on each of these services for that region, such as market prices and quantities to estimate the gross revenue change from a policy. Social welfare measurement relies on net revenue calculations above opportunity costs and consumer surplus. While these values can be extracted from market data, production costs are often unavailable and gross revenue is sometimes used as a proxy for net revenue in a cost benefit or multicriteria analysis.

Often prices and quantities of a marine ecosystem service are unavailable due to the absence of direct exchange for the good or service. In this case, values can be reconstructed using adjacent markets or simulated based on theory. Hedonic analysis (Palmquist, 2005) analyzes exchange prices of goods that feature multidimensional characteristics (e.g., housing) that include environmental amenities such as adjacent air and water quality or proximity to open space. If ecosystem services are a part of these bundled characteristics the change in value of the service can be estimated using a multiple regression framework.

Expected damage functions are another means for using adjacent markets to value ecosystem services. If damage to an asset can be mitigated through ecosystems or ecosystem processes, the avoided damage (potentially based on repair costs or other methods) can be considered as a consistent welfare measure for cost benefit analysis, with some assumptions (Barbier, 2015). The value of this service could also be proxied based on expenditures to mitigate damage incurred by a change in environmental conditions. These averting expenditures, such as raising the foundation of a house to avoid flooding or driving further for recreation due to low nearby water quality, can be considered a lower bound of the change in social welfare (Tietenberg and Lewis, 2018), as naturally people would not spend more on the averting behavior than the expected damage itself.

A closely related concept uses replacement costs as a value measure for marine ecosystem services. This assumes that some goods and services provided by nature can be replaced by manufactured goods and services. The empirical approach uses market-based estimates of the costs of providing replacement services as proxies for the value of the associated naturally provided services. Although its calculation is relatively simple (construction and engineering costs) and easily understood, in general this cost does not represent the value of the services it may be replacing as it is based on technological aspects of design and construction, not service values (Heal, 1999). As such, it is not recommended for cost benefit analysis and its use elsewhere should be done with care.

A final revealed preference method is useful for cultural ecosystem services such as recreation and other environmental experiences that take place outside any formal market. In this approach, the cost of engaging in the activity can be used to derive estimates of its economic value (Clawson and Knetsch, 2013). Like the assumptions for hedonic models, the recreation "good" can be viewed as a bundle of characteristics, some of which are the environmental features important to the recreational experience. If data are available for visits to multiple sites with varying levels of those features, one can then estimate the contribution of a particular feature to the demand for that recreation and from this estimate the feature's value (Morey, 1981).

Stated preference methods also can provide legitimate estimates of economic value. These methods rely on survey questions that ask individuals to make a choice, describe a behavior, or state directly what they would be willing to pay for specified changes in non-market goods or services. These methods are the only current way to estimate non-use value of ecosystem attributes, such as being willing to pay to conserve an area despite never intending to visit it. Revealed preference is of no help here as there are no actions to observe. If conducted with attention to the many standards of care for its execution, this method can provide welfare-consistent estimates of ecosystem service values for use in cost benefit analysis. Contemporary guidance on best practices for stated preference approaches is available (Johnston *et al.*, 2021).

Benefit Transfer

Benefit transfer is a method for taking economic data on benefits (or values in general) gathered in one context and applying it to another context. This method is rarely the best choice for estimating economic values but the costs of gathering primary, site-specific data have made it a common practice for studies of ecosystem service value (e.g., Rosenberger and Loomis (2001) and National Research Council (2005b)). Human pressures on ecosystems and the services they provide can result in impacts that respond nonlinearly to changes in the scale of the pressure or change discontinuously if a threshold is crossed (Groffman *et al.*, 2006). The valuation of ecosystem services should therefore account for such nonlinearities if the scale of change under consideration is more than minimal (Barbier *et al.*, 2008; Koch *et al.*, 2009). Meta function benefit transfer employs a multivariate value function derived from a multiple regression meta-analysis of relevant primary valuation studies, and generally provides a more flexible approach for accounting for environmental and social context differences between the study site and other sites from which values are being borrowed (Johnston *et al.*, 2021).

Valuing Cultural Ecosystem Services

Cultural ecosystem services – diverse, nonmaterial benefits that people obtain through their interactions with ecosystems, including spiritual inspiration, cultural identity, and recreation – are difficult but not impossible to value in models. Sociocultural methods aim to expand ecosystem service assessments by explicitly incorporating cultural and social metrics into the analysis. These approaches create "benefit relevant indicators" that can be used in multicriteria decision processes such as those as summarized above.

Recent work guided by indigenous researchers highlights the importance of reflecting "relational values," defined as preferences, principles, and virtues associated with interpersonal relationships and social norms, such as reciprocity, connection to place, and biocultural resources (Chan *et al.*, 2016; Pascua *et al.*, 2017; Gould *et al.*, 2020). Various methods (e.g., narrative methods, paired comparisons, structured decision making, participatory mapping) can be used to elicit the relative weight that people place on these services (Chan *et al.*, 2012; Hirons *et al.*, 2016). For instance, participatory ecosystem service mapping has been used to spatially measure social values and preferences (Bryan *et al.*, 2010; Chan *et al.*, 2012). Participatory modeling methods have been developed to integrate social values and knowledge of local systems into decision making frameworks by involving stakeholders in modeling (Davies *et al.*, 2015; Townsend *et al.*, 2018). However, those participatory processes need to consider local power dynamics (Davies *et al.*, 2015). Those methods can be used to depict the importance or preferences expressed by people towards nature (Díaz *et al.*, 2015; Queiroz *et al.*, 2017), which can be instrumentally, intrinsically, and relationally motivated (Chan *et al.*, 2016) and highlight that nature supports social well-being (Walz *et al.*, 2019).

Challenges to Modeling Marine Ecosystem Services

Although mapping marine ecosystem service is needed for decisions, most marine ecosystems lack spatial data which limits our ability to map, model, and value marine ecosystem services, as compared to terrestrial ecosystems (Townsend *et al.*, 2018). In marine environments, many processes are driven by winds, tides, and currents, and change along gradients of depth, temperature, light, and salinity. As a result, habitats are more tightly connected, species disperse further and can show spatially separated ontogenesis, and processes are more dynamic. But high-resolution bathymetry data remains patchy, and the best publicly available global bathymetry data is at 500 m GEBCO (2021), while topography data exist at 30 m for the globe (NASA SRTM, 2013). Likewise, seamless topography-bathymetry data is lacking for most places, nearshore oceanographic conditions (currents, wind, and wave) are also coarse and rarely capture nearshore processes.

Additionally, a lack of basic life history information for most marine species, coupled with difficulties tracking marine species through water, means that the full extent of habitat usage and home range limits are often unknown (Townsend *et al.*, 2018). Knowing that a marine habitat or species can be linked to the provision of multiple services typically operating over different spatial scales (Raffaelli and White, 2013), a lack of information on connectivity through time and space poses a challenge for defining modeling boundaries and limits our ability to model species-habitat association and food-web dynamics at a relevant spatial scale (Townsend *et al.*, 2018). In the absence of data, datasets may be built using different methods, bridging global and local datasets, and data sources which may lead to different representations.

Over the last decade, benthic habitat mapping efforts are on the rise thanks to new technology and earth observation systems. For instance, tropical marine habitats (e.g., seagrass, mangroves, and corals) have been mapped globally (Andréfouët *et al.*, 2006; Andréfouët and Bionaz, 2021; Bunting *et al.*, 2018; McKenzie *et al.*, 2020) and now the Allen Coral Atlas is updating this effort using Planet Dove imagery at 3.7 m (Allen Coral Atlas, 2020). Although those mapping efforts are limited to presence/absence data and do not provide information on habitat characteristics (e.g., mangrove height, coral % cover), which mediate services supply, emerging technology and methods are beginning to gather this type of information over large areas at fine spatial scale.

Understanding and modeling marine ecosystem services is also made more difficult by the dearth of direct control or knowledge of human actions. In terrestrial areas, property rights are the norm, and zoning often dictates what and where actions can take place (both on public and private property). In marine areas, human activities are not typically managed explicitly at a fine scale, and many areas are effectively open access, despite the public trust aspect of exclusive economic zones. Spatially explicit and temporal data on human activities (e.g., fishing, recreation, transportation, energy) and beneficiaries' characteristics (social, cultural, economic) in coastal and marine environments remain scarce or need harmonization. In response to this data gap, Global Fishing Watch leveraged night lights to map global fishing effort. Likewise, WorldPop works to map the distribution of people and their characteristics around the globe at a fine spatial scale to support policy analyses and equitable decisions (see "Relevant Websites" section).

Applications of Marine Ecosystem Service Modeling to Decision Making

Here, we present four case studies describing how modeling multiple ecosystem services in various decision-making contexts and geographies has led to more integrated, positive outcomes for ecosystems and people. We start with the co-development of climate change adaptation at the land-sea intersection around the San Francisco Bay area, followed by an integrated ridge-to-reef approach for countries bordering the Mesoamerican reefs. Next, we present how blue strategies can support Belize meet its Nationally Determined Contribution and we end on a valuation of ecosystem services provided by MPAs in the Bahamas.

Nature-Based Adaptation in the San Francisco Bay Area

Globally, rising seas threaten massive numbers of people and significant infrastructure (Blackburn *et al.*, 2019; Kulp and Strauss, 2019). California is amongst the US states most vulnerable to sea-level rise and the San Francisco Bay area–where rising seas and land subsidence have already increased flooding–is particularly at-risk (California Ocean Protection Council, 2018). With approximately 75% of the bay's shoreline consisting of berms, embankments, transportation infrastructure, or other engineering, there is a long history of traditional shoreline engineering in the bay (SFEI, 2016). However, nature-based adaptation strategies are also under consideration as design, evaluation of costs and benefits, and expertize about these approaches grows.

In 2016, a team of researchers from the Stanford Natural Capital Project and the San Francisco Estuary Institute embarked on a partnership with local and regional practitioners to bring an ecosystem services approach to informing adaptation planning for a resilient San Francisco Bay Area coastline. The team worked at two scales, one regional and one local. Through partnership with the Bay Area Conservation and Development Commission (BCDC) at the regional scale, we mapped and measured three key ecosystem services (recreation, storm-water retention, and coastal protection) as well as habitat for biodiversity that are provided by natural areas throughout the region and explored how the delivery of those ecosystem services is at risk from sea-level rise. These analyses contributed to a report, commissioned by the Metropolitan Transportation Commission and the Association of Bay Area Governments that lays out the vulnerability of the region's key assets to sea-level rise (Adapting to Rising Tides, 2020). Also at the regional scale, we conducted detailed modeling of the ways in which urban greening (e.g., increasing of pervious surfaces) can reduce flooding (Webber *et al.*, 2021) and explored how seawalls affect regional hydrodynamics, flooding, and economic damages–identifying the need for the creation of regional adaptation plans that avoid building seawalls in places that make matters much worse for neighbors and highlighting regions where floodwaters can be guided to natural areas that act as overflow zones (**Fig. 3**) (Hummel *et al.*, 2021).

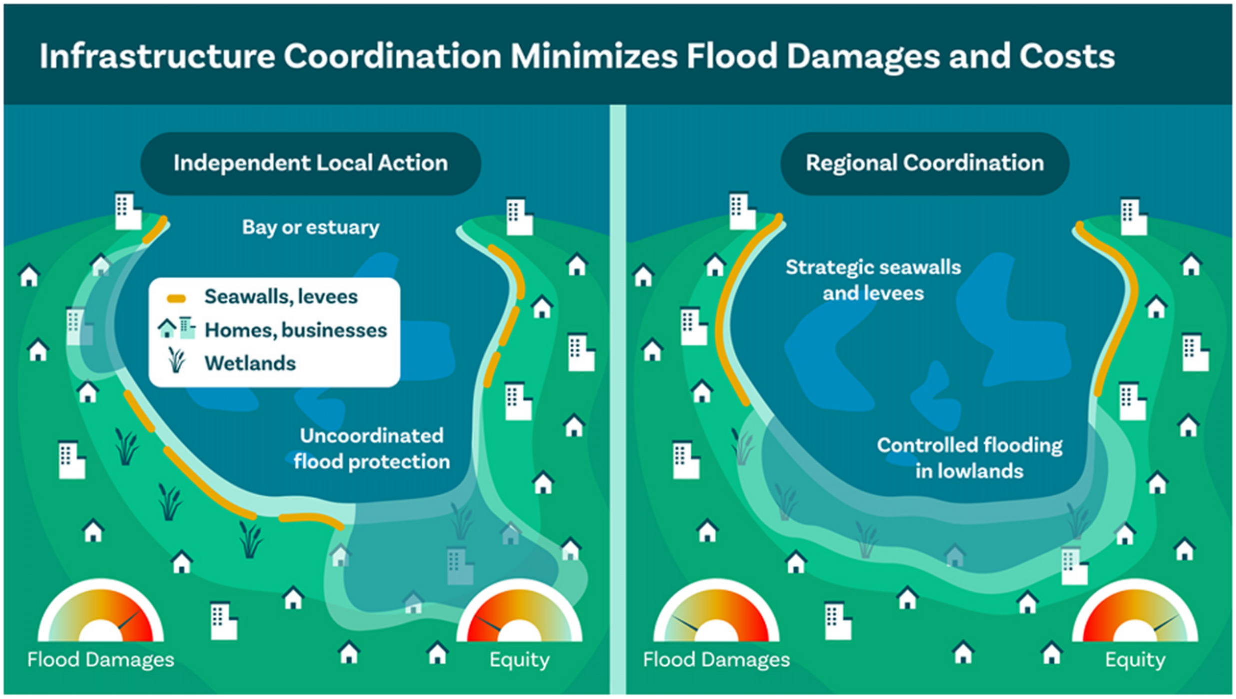

Fig. 3 Schematic diagram comparing outcomes with independent local action vs. regional coordination to address sea-level rise in an enclosed system such as San Francisco Bay. If individual jurisdictions operate independently, flood damages throughout the region can increase and socially vulnerable populations tend to experience the worst flooding. Through regional coordination, walls can be built in strategic locations and flood waters can be directed to areas that naturally store water, decreasing flood damages across the region and increasing equity.

At a more local scale, the team worked with leaders in the San Mateo County Office of Sustainability to co-develop nature-based adaptation solutions for the County's shoreline and to compare the multiple benefits (recreation, carbon storage, and stormwater pollution reduction) provided by each scenario to those that would be provided by an entirely engineered solution. Adaptation scenarios that included investments in nature-based solutions delivered up to eight times the benefits of an engineered baseline as well as additional habitat for biodiversity (Guerry *et al.*, 2022).

Ridge-to-Reef Approach to Climate Change Adaptation in the Mesoamerican Reefs

Tropical forests and coral reefs ecosystems provide multiple ecosystem services to people. Globally, they help regulate climate by absorbing carbon and reducing the net emissions in the atmosphere (Alongi, 2012). Locally, they generate economic, social, and environmental benefits to communities, such as reducing climate related-risks, fisheries, and tourism livelihoods (Barbier, 2017). Deforestation degrades terrestrial ecosystems and affects downstream coastal and marine systems. To strengthen the adaptive capacity of governments and local communities in countries bordering the Mesoamerican Reef (i.e., Belize, Guatemala, and Honduras), a partnership of scientists (The Natural Capital Project, Columbia University), practitioners (WWF), and local and national governments came together under the Smart coast Project, funded by the International Climate Initiative. The team conducted a land-sea assessment of ecosystem services that incorporates land-sea connections in the design and implementation of three watershed adaptation measure to help achieve ecological and societal benefits. For each country, we mapped all plausible locations for implementation of three adaptation measures: (1) watershed restoration, where agriculture is converted to forest; (2) watershed protection, focused on the retention of existing forest; and (3) sustainable agriculture, where conventional agriculture and ranching are converted to agroforestry and silvopasture (**Fig. 4**a). Then, we quantified the impact of each adaptation measure on a suite of ecological and societal benefits: sediment retention, coral health, forest-based and coral reef-based tourism, coastal risk reduction, and coral reef-based fisheries production (**Fig. 4**b-e). We computed a watershed index to identify the watersheds most important for safeguarding coastal and marine ecosystem services when implementing each adaptation measure (Fig 4g). The index reflects the extent of coral habitat that becomes healthier and delivers greater societal benefits due to greater sediment retention from the implementation of each adaptation measure. . Due to limited capacity, each country identified a target area for each watershed adaptation measure to inform revised Nationally Determined Contributions (NDC) in Belize and Honduras, and Guatemalan management plans. By coupling these models with Restoration Opportunity Optimization Tool (ROOT) (Beatty *et al.*, 2018; Kennedy *et al.*, 2016) to prioritize the three adaptation measures, meet their target area, and maximize ecological and societal benefits for each nation (**Fig. 4**e).

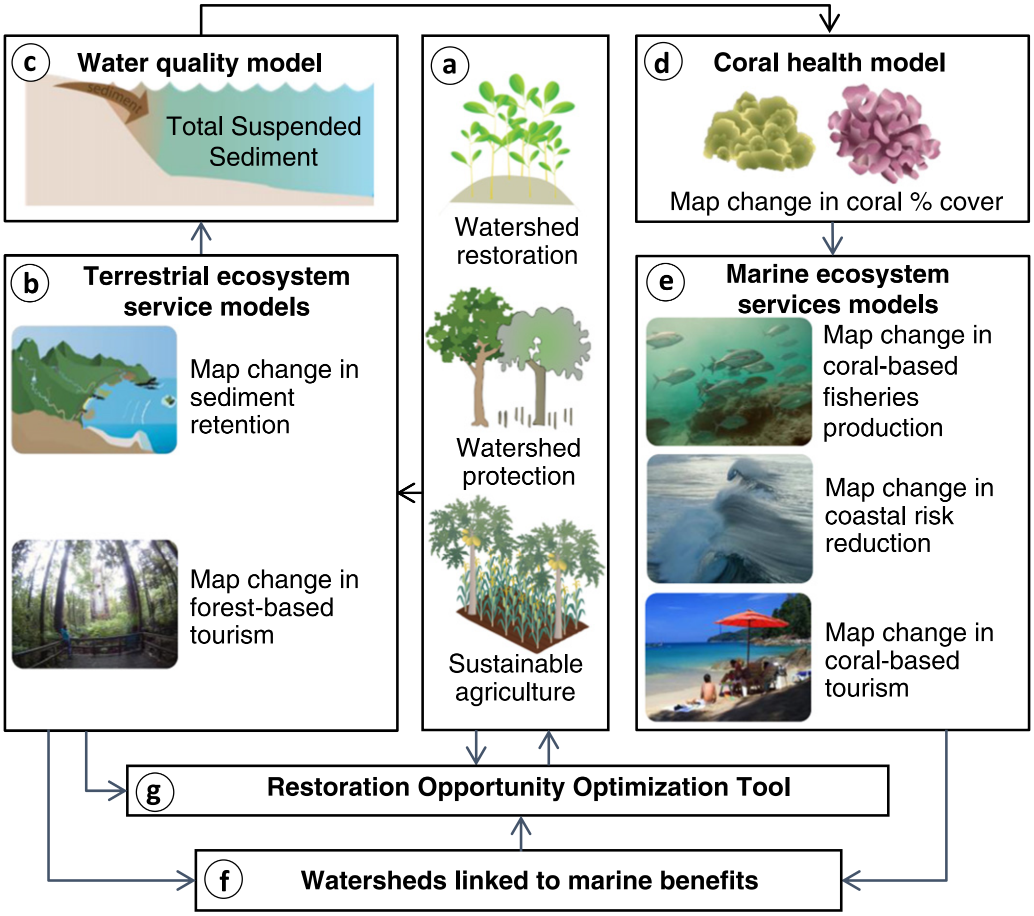

Fig. 4 Modeling framework to inform land-sea planning in the Mesoamerican region. (a) Develop climate adaptation strategies based on local engagement. (b) Model change in terrestrial ecosystem services (i.e., sediment retention and forest-based tourism) based on the full possible implementation of climate change adaptation strategies in (a) and associated downstream (c) change in marine water quality and (d) coral habitat health, and (e) marine ecosystem services (coral-based fisheries production, coastal risk reduction, and coral-based tourism). (f) Apply the ROOT optimization software to identify where best to implement the considered strategies while maximizing return on terrestrial and marine services using ecosystem services accounting, maps, and efficiency frontiers.

Results indicated that prioritized adaptation measures shifted locations when seeking to maximize benefits either for the broader region (regardless of the countries' borders) or each country individually. With a regional approach, adaptation measures are prioritized in larger transboundary watersheds, resulting in overall more sediment retention and greater increase in healthier corals for neighboring nations. The national approach prioritizes non-transboundary, often smaller, watersheds, trading increases in coral health in neighboring nations for more societal benefits for each nation individually, especially decreased coastal risk and increased nature-based tourism. Our findings highlight that adopting both land-sea planning scales can provide a win-win approach by improving the health of forests and corals across the region while increasing societal benefits for communities from each nation.

Belize Nationally Determined Contributions With Blue Carbon Solutions

Global climate change threatens coastal communities with sea level rise, flooding, and storms. To mitigate and adapt to those impacts, countries seek to increase their ambition and improve the implementation of their Nationally Determined Contributions (NDCs). An NDC provides a set of measures a country aims to advance the global goal outlined in the Paris Agreement of stabilizing warming below 1.5°C. To bolster NDCs, countries are adopting nature-based solutions, like blue carbon strategies which involve protecting or restoring coastal and marine ecosystems that store and sequester carbon while providing co-benefits, such as coastal protection, fisheries, and recreation for climate adaptation. To determine where and how to direct investments when designing and implementing blue carbon solutions that can also maximize other benefits is an opportunity and challenge for countries with limited resources and competing interests.

Belize defined two blue carbon solutions: mangrove protection and restoration. The government then suggested a range of possible targets for the area of investment in each of these solutions by 2030, when the next round of NDCs updates is due. Through a partnership of researchers (Stanford Natural Capital Project), practitioners (WWF), consultants (Silvestrum Climate Associates), and decision makers (Belize Coastal Zone Management Institute) and with support from Pew Charitable Trusts, Belize quantified carbon storage and sequestration using existing field estimates, and modeled coastal risk reduction, tourism, and lobster fisheries co-benefits provided by mangroves under current conditions and in 2030. For the 2030 scenarios, the team considered restoring 5000 ha, 10000 ha, and 25000 ha; and protecting 1000 ha, 5000 ha, 10000 ha of mangroves. Next, this partnership assessed where investments in mangrove protection and restoration would lead to the greatest return in all those benefits. This study demonstrates an approach to quantify co-benefits provided by blue carbon nature-based solutions that helped inform the Belize revised NDCs and can support local climate adaptation (Arkema *et al.*, 2023).

Economic Evaluation of Bahamian MPAs

The marine and coastal environment of the 700 islands and cayes of The Bahamas provides habitat for a diversity of animals and plants and numerous benefits for the Bahamian people. Yet coral reefs, mangroves, seagrasses, coppice forests, and other ecosystems across the archipelago suffer from a growing intensity of activities in the coastal zone, putting at risk the fisheries, tourism, storm protection, and other benefits from nature that underlie the country's economy and ensure human wellbeing. Tourism accounts for 60% of the country's GDP (Bahamas Ministry of Tourism, 2019), with Financial Services the second most valuable sector at 20% (The Commonwealth of The Bahamas 2010). Since the global market downturn in the late 1980s-early 1990s, The Bahamian government has focused on building a more self-sufficient, sustainable economy. The country boasts a wealth of natural capital assets upon which to chart this path, including the potential to boost a host of natural resource-based livelihood options around fisheries and tourism. In addition, the coral reefs, seagrasses, and mangrove forests offer valuable protection from sea-level rise and storms, providing security to people, property and infrastructure, and can help reduce damage costs in the face of hazards.

A team of scientists from Stanford's Natural Capital Project was invited by the Bahamian Office of the Prime Minister and a local group called Bahamas Protected (a joint effort between The Nature Conservancy (TNC), Bahamas National Trust (BNT), Bahamas Reef Environment Educational Foundation (BREEF) and other community stakeholders) to quantify the economic value of ecosystems within the network of 39 Marine Protected Areas (MPAs) in The Bahamas and the influence of alternative management scenarios on future benefits.

The research team reviewed past studies of economic value of marine ecosystems, species, and MPAs in The Bahamas, and used the InVEST open-source software to quantify the economic value of ecosystem services within the existing network of MPAs (Arkema *et al.*, 2017, 2019). The team also explored management issues and quantified ecosystem services at an island scale for five regions with MPAs of varying management regimes.

The economic value of ecosystem services provided by habitats within the current network differs among MPA sites, as does management status. According to the analysis, visitation within MPAs provides $67.6 million annually in tourism expenditures. Ecosystems within the existing MPA network are worth more than $23.5 million annually in nursery habitat values for spiny lobster. The nursery habitat within the MPA network contributes to 50% of the overall value of the lobster fishery, which in turn provides more than 1300 active lobster jobs (Sullivan Sealey, 2011). In addition, ecosystems in the network reduce the risk of coastal hazards, such as Hurricanes Mathew and Joaquin, to nearly 40,000 people living along coastlines throughout the country and $806 million in annual income. Mangroves and seagrass within the MPA network store 400 million tons of carbon, worth $5 billion in avoided emissions damage globally. This research is forming the foundation for a loan from the Inter-American Development Bank to The Bahamian government to expand the MPA network and support its management.

Conclusions

Our oceans are critical foundations of human wellbeing and serve as building blocks of our economy, yet marine ecosystem services are at risk from growing demand. Ecosystem services are widely and differently valued by people around the world. Here, we reviewed existing models that can integrate multiple processes (biophysical, social, and economic) and assess trade-offs in response to change. In addition, we laid out the importance of considering linkages between land and sea in the design of management interventions through modeling to help maximize benefits across land and sea and minimize the adverse effects of land-use change. We discussed the latest methods available to undertake valuations and their limitations when values are non-marketable. We highlighted existing challenges and emerging solutions to modeling marine ecosystem services. Last, we described some examples of how these approaches can and are being used in real decision making. Overall, ecosystem service modeling can help optimize resources, accommodate a broader suite of actors, and determine where to prioritize actions more transparently. Models are useful tools for examining the dynamic interconnections among nature, people, and governance systems in marine ecosystems and can help inform the design and implementation of environmental policies. Ultimately, outputs from ecosystem service modeling can help society appropriately value marine natural capital, and help people make more informed decisions about the future of our blue world.

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