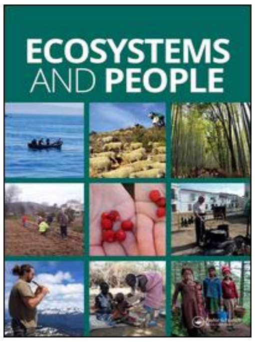

International Journal of Biodiversity Science, Ecosystem Services & Management

ISSN: 2151-3732 (Print) 2151-3740 (Online) Journal homepage: https://www.tandfonline.com/loi/tbsm21

Modeling benefits from nature: using ecosystem services to inform coastal and marine spatial planning

Anne D. Guerry , Mary H. Ruckelshaus , Katie K. Arkema , Joey R. Bernhardt , Gregory Guannel , Choong-Ki Kim , Matthew Marsik , Michael Papenfus , Jodie E. Toft , Gregory Verutes , Spencer A. Wood , Michael Beck , Francis Chan , Kai M.A. Chan , Guy Gelfenbaum , Barry D. Gold , Benjamin S. Halpern , William B. Labiosa , Sarah E. Lester , Phil S. Levin , Melanie McField , Malin L. Pinsky , Mark Plummer , Stephen Polasky , Peter Ruggiero , David A. Sutherland , Heather Tallis , Andrew Day & Jennifer Spencer

To cite this article: Anne D. Guerry , Mary H. Ruckelshaus , Katie K. Arkema , Joey R. Bernhardt , Gregory Guannel , Choong-Ki Kim , Matthew Marsik , Michael Papenfus , Jodie E. Toft , Gregory Verutes , Spencer A. Wood , Michael Beck , Francis Chan , Kai M.A. Chan , Guy Gelfenbaum , Barry D. Gold , Benjamin S. Halpern , William B. Labiosa , Sarah E. Lester , Phil S. Levin , Melanie McField , Malin L. Pinsky , Mark Plummer , Stephen Polasky , Peter Ruggiero , David A. Sutherland , Heather Tallis , Andrew Day & Jennifer Spencer (2012) Modeling benefits from nature: using ecosystem services to inform coastal and marine spatial planning, International Journal of Biodiversity Science, Ecosystem Services & Management, 8:1-2, 107-121, DOI: 10.1080/21513732.2011.647835

To link to this article: https://doi.org/10.1080/21513732.2011.647835

Published online: 31 Jan 2012.

International Journal of Biodiversity Science, Ecosystem Services & Management
Vol. 8, Nos. 1–2, June 2012, 107–121

Taylor & Francis
Taylor & Francis Group

Modeling benefits from nature: using ecosystem services to inform coastal and marine spatial planning

Anne D. Guerry[a]*, Mary H. Ruckelshaus[a], Katie K. Arkema[a], Joey R. Bernhardt[a], Gregory Guannel[a], Choong-Ki Kim[a], Matthew Marsik[b], Michael Papenfus[a], Jodie E. Toft[a], Gregory Verutes[a], Spencer A. Wood[a], Michael Beck[c], Francis Chan[d], Kai M.A. Chan[e], Guy Gelfenbaum[f], Barry D. Gold[g], Benjamin S. Halpern[h], William B. Labiosa[i], Sarah E. Lester[j], Phil S. Levin[b], Melanie McField[k], Malin L. Pinsky[l], Mark Plummer[b], Stephen Polasky[m], Peter Ruggiero[d], David A. Sutherland[b], Heather Tallis[a], Andrew Day[m] and Jennifer Spencer[n]

[a]Natural Capital Project, Woods Institute for the Environment, Stanford University, Stanford, CA, USA; [b]NOAA Northwest Fisheries Science Center, Seattle, WA, USA; [c]Global Marine Team, The Nature Conservancy, Santa Cruz, CA, USA; [d]Oregon State University, Corvallis, OR, USA; [e]IRES, University of British Columbia, Vancouver, BC, Canada; [f]USGS, Menlo Park, CA, USA; [g]Marine Conservation Initiative, Gordon and Betty Moore Foundation, Palo Alto, CA, USA; [h]National Center for Ecological Analysis and Synthesis, Santa Barbara, CA, USA; [i]USGS, Seattle, WA, USA; [j]Marine Science Institute and Bren School of Environmental Science and Management, University of California, Santa Barbara, CA, USA; [k]Healthy Reefs, Belize City, Belize; [l]Hopkins Marine Station, Department of Biology, Stanford University, Pacific Grove, CA, USA; [m]Department of Applied Economics, University of Minnesota, St Paul, MN, USA; [n]West Coast Aquatic, Port Alberni, BC, Canada

People around the world are looking to marine ecosystems to provide additional benefits to society. As they consider expanding current uses and investing in new ones, new management approaches are needed that will sustain the delivery of the diverse benefits that people want and need. An ecosystem services framework provides metrics for assessing the quantity, quality, and value of benefits obtained from different portfolios of uses. Such a framework has been developed for assessments on land, and is now being developed for application to marine ecosystems. Here, we present marine Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST), a new tool to assess (i.e., map, model, and value) multiple services provided by marine ecosystems. It allows one to estimate changes in a suite of services under different management scenarios and to investigate trade-offs among the scenarios, including implications of drivers like climate. We describe key inputs and outputs of each of the component ecosystem service models and present results from an application to the West Coast of Vancouver Island, British Columbia, Canada. The results demonstrate how marine InVEST can be used to help shape the dialogue and inform decision making in a marine spatial planning context.

Keywords: decision support tool; ecological production function; scenario; marine InVEST; modeling marine ecosystem services; coastal and marine spatial planning; Vancouver Island

Introduction

As 50 million people are added to the planet's population annually, and an equivalent number seek to raise their standard of living, the Earth's oceans and coastal environments face expanding human impacts in the form of fisheries, aquaculture, energy production, runoff from land, shipping, recreation, climate change, and other activities and stressors (MA 2005, Halpern et al. 2008). If done carefully, society can obtain additional benefits from the oceans while protecting the natural capital that sustains life on Earth. Done haphazardly, society will likely degrade the oceans and squander the potential benefits available from healthy marine ecosystems. To maintain and enhance the multiple benefits available from marine ecosystems that society is seeking, it has become clear to governments and leaders around the world that these systems need to be managed for multiple uses, in ways that account for the many marine ecosystem services, and that guide the patterns and types of use to sustain ocean productivity for the needs of present and future generations (Convention on Biological Diversity 2004; Obama 2009; CEQ 2010; European Commission 2010; UN General Assembly 2010).

On the international stage, both the Convention on Biological Diversity and the new Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services explicitly call for scientific assessments and setting targets to maintain biodiversity and ecosystem services (Convention on Biological Diversity 2004; UN General Assembly 2010). In addition, the European Commission and the US government recently have implemented processes for coastal and marine (or in Europe,

*Corresponding author. Email: anne.guerry@stanford.edu
AG and MR led this effort. KA, JB, GG, CK, MM, MP, JT, GV, and SW are the core model development team responsible for building, testing, and applying the models. MB, FC, KC, GG, BG, BH, WL, SL, PL, MM, MP, MP, SP, PR, DS, and HT are our technical working group responsible for intellectual guidance and critical review throughout the project. AD and JS are two practitioners instrumental to the execution of the case study.

ISSN 2151-3732 print/ISSN 2151-3740 online

http://dx.doi.org/10.1080/21513732.2011.647835
http://www.tandfonline.com

'maritime') spatial planning (CMSP) (Obama 2009; CEQ 2010; European Commission 2010). Irrespective of the terminology used, marine spatial planning (MSP) represents decision-making approaches that use scientific and geospatial information to address conflicts and organize human activities in the ocean while maintaining ecosystem health, function, and services (Center for Ocean Solutions 2011). As one example of an attempt at implementation, the new US Ocean Policy includes a mandate for CMSP or MSP to 'reduce conflicts among uses and between using and preserving the environment to sustain critical ecological, economic, and cultural services for this and future generations' (CEQ 2010).

These are tall orders but, fortunately, there is a great deal of work to build on. The scientific community has articulated conceptual and practical frameworks for MSP (Ehler and Douvere 2009; Foley et al. 2010) and ecosystem-based management (EBM) (Rosenberg and McLeod 2005; McLeod and Leslie 2009; Lester et al. 2010; Tallis et al. 2010). EBM is a framework for perceiving the big picture, recognizing connections, and striving to maintain both the elements of ecosystems and the processes that link them (Guerry 2005). It reflects a set of principles for considering the diverse human impacts that affect an ecosystem; when combined with MSP and an ecosystem services framework there is great potential to ensure the sustainability of marine ecosystems and the services they provide. In addition, the utility of ecosystem service metrics for identifying how to secure sustainable benefits without overly degrading the resilience and productivity of natural systems has become increasingly clear (Granek et al. 2010; Halpern et al. 2012; Tallis, Lester, et al. 2012). The framework of ecosystem services enables the explicit examination of trade-offs in services and it provides a quantitative approach for assessing the value of MSP versus sectoral or uncoordinated planning. Ecosystem services are directly relevant to people and tracking them facilitates communication that resonates with stakeholders and managers.

While the political will for MSP and the scientific basis for comprehensive approaches and assessments of marine ecosystem services have been growing (Guerry et al. Forthcoming 2012), there remains a dearth of practical technical tools for doing this work. Decision makers with a mandate for MSP face competing demands but typically have limited capacity to map and integrate the many and potentially conflicting uses. Existing tools for bridging the gap between the ideals of EBM and CMSP and on the ground and in the water practicality include both relatively simple mapping tools and more complicated production function-based approaches (Chan and Ruckelshaus 2010; Center for Ocean Solutions 2011). Most tools do not handle a wide array of services, lack mechanisms for modeling changes in ecosystem services with changes in management, and/or are not practical for MSP (e.g., because of a singular focus on fisheries management).

In this article we introduce a family of models and approaches that we have developed to meet the need for assessments of changes in the delivery of multiple ecosystem services under alternative future scenarios. The models quantify the delivery of ecosystem benefits from marine systems under different scenarios of use and human impact. They are based on related models developed for terrestrial and freshwater systems (Kareiva et al. 2011), but are retooled and reenvisioned for use in marine systems. In addition, we present the results from a pilot study on the West Coast of Vancouver Island to illustrate how they are informing real decisions.

Foundations

Why are marine systems different?

From seafood to climate regulation to recreation and inspiration, marine ecosystems provide a rich array of benefits to people (Peterson and Lubchenco 1997; Guerry et al. 2010). Marine ecosystems also present new challenges and opportunities for the science and application of an ecosystem services framework. The Millennium Ecosystem Assessment raised awareness about ecosystem services, the explicit dependence of humans upon them, and the threatened status of many of them (MA 2005). Since the MA, much work has been done on modeling, mapping, and valuing ecosystem services (United Nations Environment Program (UNEP) and Intergovernmental Oceanographic Commission-United Nations Educational Scientific and Cultural Organization; UK National Ecosystem Assessment 2011). While some work has included a focus on marine systems, a preponderance of research in this field has focused on terrestrial systems.

Marine systems present new challenges and opportunities for both the science and the application of an ecosystem services framework. From a scientific perspective, models for terrestrial systems generally use a land use/land cover data layer as critical input for the assessment of ecosystem services (e.g., Kareiva et al. 2011). A similar approach works for marine environments, since marine systems have habitats that are affected by various human activities. Habitat maps in marine systems are analogous to land cover (the biophysical condition of the land surface). However, benthic habitats often are not visible on satellite imagery or from other remote-sensing technology (some exceptions include coral reefs and kelp forests; Wabnitz et al. 2010; Cavanaugh et al. 2011). Thus, maps of habitat type and condition are significantly more costly to create for marine systems than they are on land. In addition, marine habitats and the processes that maintain them are arguably more dynamic and three dimensional than terrestrial habitats and associations between species and habitat patches can be more difficult to discern (Carr et al. 2003; Schmidt et al. 2011). These characteristics point to an approach for modeling marine ecosystem services that is less tightly coupled to detailed habitat maps.

From a management perspective, human use of marine systems is distinct from our use of terrestrial systems in some important ways. Land use describes the intended human use of the land surface (Turner et al. 1995). Marine use often can be of the sea surface (e.g., shipping), the water column (e.g., hook and line fishing), and/or the benthic habitats beneath (e.g., cable laying or mining). Even in cases where detailed habitat maps are available, knowledge of the spatial distribution of certain uses, and their potential impacts on habitat, is often lacking. In addition, with limited private ownership, marine environments are often managed as commons (Gordon 1954; Ostrom 1990). With a tradition of management as commons, the appearance of a featureless water surface, and human settlement remote from all but coastal waters, people generally are reticent to draw lines of ownership or even use on maps of the ocean. But many place-based activities happen on that supposedly 'featureless' expanse (Crowder et al. 2006; Turnipseed et al. 2009; Multipurpose Marine Cadastre 2011). The lack of private ownership and some of the familiar management techniques that accompany it (e.g., protection by purchase) has led to an increasing interest in finding new ways to manage these environments effectively. In conclusion, unique aspects of marine systems – from both biophysical and management standpoints – serve as a catalyst for advances in the modeling and mapping of ecosystem services.

The studies that have documented, assessed, or modeled marine ecosystem services have addressed mostly one service at a time, such as shoreline protection, fisheries, and aquaculture (e.g., Sathirathai and Barbier 2001; Soderqvist et al. 2005; Barbier et al. 2008). Until now, there has been a gap in decision support tools that allow mapping, modeling, and valuing of multiple services provided by marine systems; estimation of changes in a suite of services under different climate and management scenarios; and the ability to look at trade-offs among them.

Production functions

To be useful in most decision contexts, assessments need to be able to evaluate how changes in ecosystem structure and function will affect the flows of services – commonly referred to as an ecological production function approach (Balvanera et al. 2005; National Research Council 2005; Nelson et al. 2009; Barbier et al. 2011; Kareiva et al. 2011; Tallis, Lester, et al. 2012). Put simply, this approach uses information about inputs (e.g., labor, materials, habitat) to estimate the production of outputs (e.g., widgets, fish). Its specification allows for the exploration of how changes in inputs will lead to changes in outputs. Without this focus on how changes in ecosystems give rise to changes in the delivery of ecosystem services, projections of likely future states under alternative management and climate conditions are not possible. In addition, valuing such changes in flow of services in economic and other terms (e.g., biomass, meters eroded) helps provide a common language for decision making. This requires using social and economic methods to link outputs from ecological models with the values people hold for different ecosystem services (National Research Council 2005; Barbier et al. 2011). With ecological production functions (linked to valuation or not), one can explore trade-offs among ecosystem services that emerge from alternative uses of marine and coastal environments. One can also explore various schemes for MSP and inform selection of those that best manage conflicts among uses. Generalizing the production function approach to make it broadly useful for MSP is an essential next step.

InVEST

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) tool maps, quantifies, and values the services provided by landscapes and, now, seascapes. The tool is a flexible and scientifically grounded set of computer-based models that (1) focuses on ecosystem services (derived from the underlying biophysical processes that produce them); (2) is spatially explicit; (3) provides outputs in both biophysical and monetary and non-monetary value terms; (4) is scenario driven; (5) clearly reveals relationships among multiple services; and (6) has a modular, tiered approach to accommodate a range of data availability and the state of system knowledge (Tallis and Polasky 2009; Kareiva et al. 2011; Tallis, Ricketts, et al. 2012). We designed InVEST to be integrated with stakeholder engagement processes (Figure 1), where it is best used in an iterative, interactive fashion. At full complexity (see Table 1), our approach incorporates process-based production function models that consist of three key steps (Table 2): (1) *biophysical*, which characterizes the production function – how the supply of services varies with ecosystem structure and function; (2) *service*, which combines information about supply and quantifies demand for

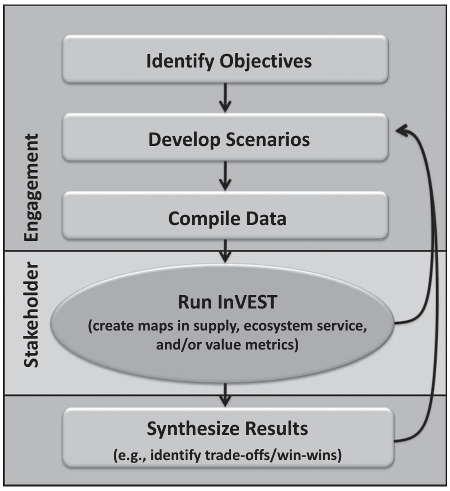

Figure 1. Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) is designed to be used as part of a stakeholder engagement process with decision makers who participate in every step of the process. First, stakeholders identify a set of objectives and several alternative management scenarios that may help achieve stated objectives. InVEST models estimate the level of ecosystem services produced in each scenario. The outputs of InVEST can be visualized as maps of ecosystem service delivery, trade-offs, or balance sheets. After evaluating scenarios with respect to objectives and within the context of local social and cultural values, stakeholders may choose to reiterate the process with newly created scenarios.

Table 1. An outline of the tiered structure of Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) models and some hallmarks of each tier.

	Some characteristics	Data requirements	Useful for	Currently available in InVEST?
Tier 0	The simplest models. Mapping tools; no production functions and no valuation	Minimal. Can be applicable in data-poor regions using global data sets often packaged with models (although local data can always be substituted)	Mapping relative levels of ecosystem services highlighting regions of high ecosystem service demand; mapping of suitability and vulnerability	Yes
Tier 1	Slightly more complex models; generally use production functions; option for valuation	Relatively minimal. Some data packaged with models. Guidance given for locating, gathering, and/or estimating necessary parameters	Identifying areas of high or low ecosystem service production and the trade-offs and synergies among services under current or future conditions	Yes
Tier 2	Complex models; production functions; option for valuation	Significant	More precise estimates of ecosystem services and values; assessing change on fine temporal scales; assessing change when explicit quantification of complex biophysical or socioeconomic processes is critical for decisions	No, but see details in Kareiva et al. (2011)
Tier 3	Existing, complex models outside of InVEST (e.g., Atlantis, Fulton, Parslow, et al. 2004; Fulton, Smith, et al. 2004), option for valuation	Significant to intense	Avoiding duplication of efforts when existing models are already parameterized for the area of interest; communicating with communities using native models	None planned; InVEST communicates with existing models

the service; and (3) *valuation*, which values the service in social and/or economic terms (Tallis, Lester, et al. 2012). In general, InVEST models are used to evaluate how human activities and climate change may affect the delivery of things that people care about and need from the environment.

InVEST is currently available as a set of tools for the Geographic Information System software ArcGIS (Environmental Systems Research Institute 2011), and a growing number of modules are being served on non-proprietary software.[1] InVEST has a tiered design, with lower tiers representing the simplest models with minimal data requirements and higher tiers getting increasingly complex (Table 1). Users can mix and match Tier 0, 1, and 2 models for several services to create the best suite of models for a particular context.

InVEST is most effectively used within a decision-making process that starts with a series of stakeholder consultations (Figure 1) to identify questions and services of interest to policy makers, communities, and various interest groups. These questions may concern current service delivery and how services may be affected by new programs, policies, and conditions in the future. For questions regarding the future, stakeholders develop scenarios of management interventions or natural changes to explore the consequences of potential changes on natural resources.

Introduction to marine models

We have expanded the InVEST toolbox that previously contained only terrestrial and freshwater models (Kareiva et al. 2011; Tallis, Ricketts, et al. 2012) to include models for marine and coastal systems. Alternative scenarios for marine InVEST typically include a map of future coastal and ocean uses, coastal and marine habitats, and estimates of future climate conditions. The current set of marine InVEST models (those released or in advanced stages of development) includes renewable energy (Tier 1), food from fisheries (Tiers 0 and 1) and aquaculture (Tier 1), coastal protection (Tiers 0 and 1), the provisioning of aesthetic views (Tier 0), recreation (Tiers 0 and 1), and carbon storage and sequestration (Tier 1). Marine InVEST also currently includes two supporting service models that account for ecological linkages between the processes that generate changes in the ecosystem services listed above: water quality (Tiers 0 and 1) and habitat risk assessment (Tier 0) (Table 2, Figure 2). As we highlight below, the development of new models and refinements to the existing models are ongoing.

A critical component of marine InVEST is the ability to link service models to represent how a change in one service can impact delivery of other services. We achieve this through the water quality and habitat risk assessment models. These models reflect the importance of supporting services (MA 2005) as important end points in their own right for many constituents and also serve to link the various final service models (Figure 2). For example,

Table 2. The nine categories of models within Marine Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) and some example metrics that can be used to measure their supply, the delivery of the service (supply plus demand), and the value of that service (see Tallis, Ricketts, et al. (2012) for further description of the supply, service, and value framework).

Model category	Supply	Service	Value
Renewable energy	Power density, potential energy	Captured power	NPV of wave or wind energy
Food from fisheries	Finfish and shellfish biomass	Landed biomass	Net revenue, NPV
Food from aquaculture	Fish and shellfish biomass	Harvested biomass	Net revenue, NPV
Coastal protection	Wave attenuation, avoided loss of land, accumulation of sediments, flooding	Avoided loss or flooding of property or infrastructure, number of people affected	Avoided damages, beach nourishment costs
Aesthetic quality	Unobstructed view	Unobstructed view from important vantage points, number of people affected by changes	Property value change
Recreation	Whale, fish abundance; beach, reef conditions	Number of sightings, catch rates, visitation rates, number of passengers	Net revenue, consumer surplus
Marine carbon	Biomass/ha C stored or sequestered by habitat	Biomass/ha C stored or sequestered by habitat	Avoided social damages, market price
Water quality	Concentrations of particular substances, fate/movement of substances	Not treated as a service	Not directly valued; value captured in ‘final services’ above
Habitat risk	Estimate of risk to habitat posed by particular stressors, ability to provide ecosystem services	Not treated as a service	Not directly valued; value captured in ‘final services’ above

Notes: Some of these metrics can be output from the current version of InVEST, others are under development. NPV is the net present value.

the aquaculture model can evaluate how operations of the aquaculture farming process (e.g., habitat alterations due to farm management) and climate change can affect the quantity and monetary value of farmed fish available for harvest. The model also produces outputs estimating the amount of waste generated or processed at the aquaculture facilities, as well as the propensity for pathogens (e.g., sea lice for salmon) to exist on the farm. Effects of pathogens and wastes/filtration can then be reflected in the water quality and habitat risk assessment models, and in turn those changes can be reflected in the fisheries and recreation models. The sections below provide brief overviews of each model currently featured in marine InVEST or under advanced stages of development. Please see www.naturalcapitalproject.org and the InVEST User’s Guide (Tallis, Ricketts, et al. 2012) for additional detailed documentation, model updates, and to download the InVEST toolbox.

Marine renewable energy

Wind and waves are promising sources for renewable energy in some regions of the globe. Marine InVEST models energy production from waves, and a model for offshore wind energy production is under development. The Tier 1 wave energy model uses a process-based approach to map the supply (ocean energy), service (captured wave energy), and net present value (NPV) of energy that is harnessed from ocean waves. The model assesses potential wave power and harvested wave energy based on wave conditions (significant wave height and peak wave period) and technology-specific capabilities of wave energy conversion devices (e.g., performance tables and maximum capacity). The model then evaluates the NPV of building and operating a wave energy conversion facility over its life span using economic parameters (e.g., price of electricity, discount rate, as well as installation and maintenance costs). The outputs of the model are maps of energy production and value that can be used, in concert with other mapped ocean uses, to inform the siting of facilities. This model includes coarse, global data (e.g., Wavewatch III, Tolman 2009) and technology-specific information for a number of wave energy conversion devices.

Food from fisheries

Fishing has long been one of humankind’s most direct connections to the ocean. The Tier 0 Fisheries model is an overlap analysis tool (shared by the Tier 0 recreation model) that is designed to produce maps that identify the most important marine and coastal areas across a variety of fishing fleets. Inputs include information about where fishing occurs for each fleet, and optional information on the relative importance of different fleets (e.g., value of landings) and spatial distribution and quality variability of an individual fleet’s fishing grounds. This Tier 0 model simply maps (and, if desired, weights the importance of) current uses and highlights areas with heavy use. It does not model behavior. For that reason, it is not well suited to the evaluation of how human uses may change in response to changes in the coastal and marine environment. It can be used, however, to model scenarios that reflect changes in the areas used by different activities or changes in attributes such as total landings or number of trips that are used to weight activities.

The Tier 1 fisheries model estimates the quantity and monetary value of fish harvested by commercial fisheries.

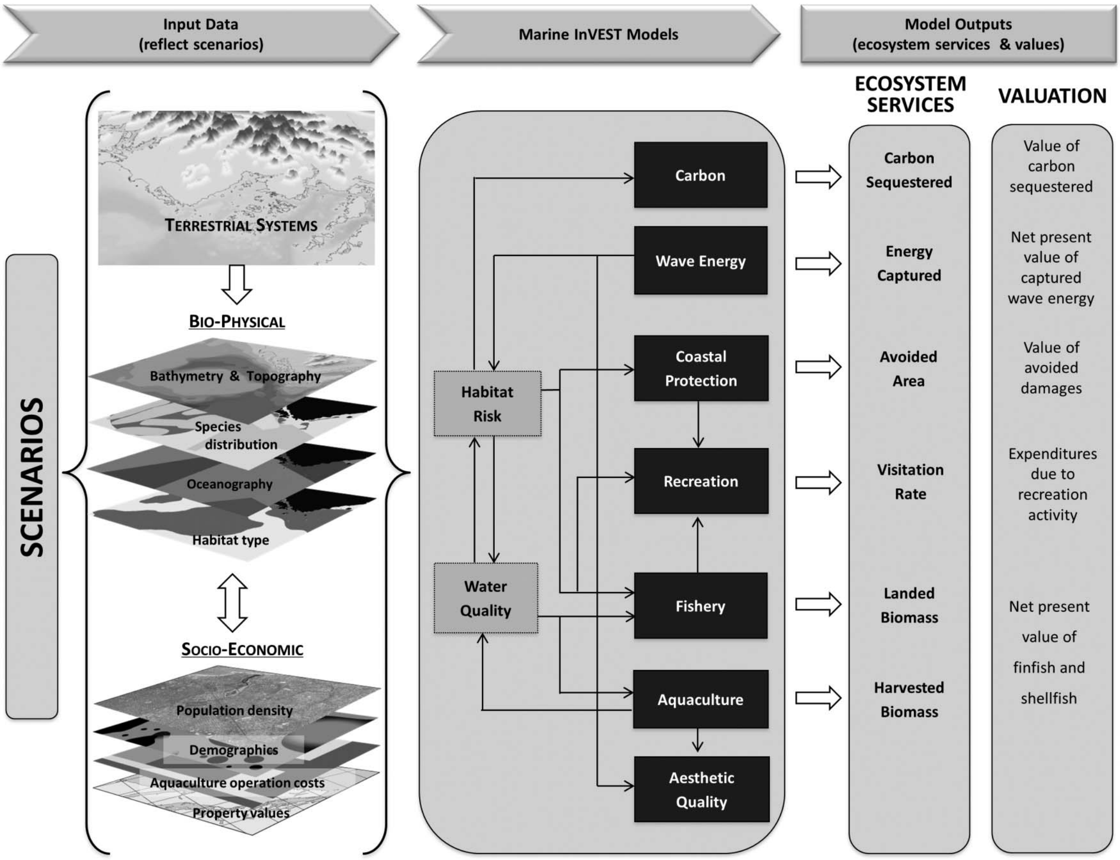

Figure 2. Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) evaluates how alternative management or climate scenarios yield changes in the flow of ecosystem services. First, one translates scenarios based on choices under consideration by stakeholders into input data. Inputs include spatially explicit biophysical (e.g., bathymetry) and socioeconomic information (e.g., human population density). Next, one feeds input maps into models that predict the delivery of ecosystem 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 units (e.g., landed biomass) or socioeconomic units (e.g., net present value (NPV) of finfish).

It is appropriate for use with single species or groups of species with similar life histories. The model estimates annual production of fish, which is the biomass in the previous year multiplied by a function that captures changes in survival due to changes in habitat or fishing, or from climate change. We use a flexible matrix structure to model the transition fish from one year to the next, with user-defined spatial delineation of populations or subpopulations. The user parameterizes the matrix with stage- or age-specific survival, recruitment rate, and harvest rate information for a scenario of interest. Users can include economic data (e.g., price of harvested product, fixed, and variable costs) to ascribe monetary value of the portion of fish production harvested by the commercial sector. A submodule for valuing the portion of fish harvested recreationally is under development.

We are extending the fisheries models in two directions. Where data exist, we are developing process-based models to incorporate impacts of biogenic habitat on the survival and fecundity of different life stages of target species (e.g., nursery habitat effects). In addition, we are developing an interface to wrap around complex Tier 3 food web and stock assessment models (e.g., Atlantis, Fulton, Parslow, et al. 2004; Fulton, Smith, et al. 2004; Ecopath with Ecosim, Christensen and Walters 2004; Stock Synthesis 3, NOAA Fisheries Toolbox 2011) that already exist in a particular location so that their outputs can be compared with outputs from other service models.

Food from aquaculture

Cultivation of marine finfish and shellfish is one of the most tangible uses of coastal and marine ecosystems for human benefit. The InVEST Tier 1 aquaculture model can be used to analyze the production and monetary value of farmed shellfish (currently Pacific and eastern oysters – *Crassostrea gigas* and *Crassostrea virginica* and Manila clam – *Venerupis philippinarum*) and finfish (currently Atlantic salmon, *Salmo salar*) and quantify by-products of farming. We model shellfish and finfish growth using individual growth models that are integrated in a population dynamics model. We include population-level density-dependent feedbacks through growth in the shellfish model through food availability. Both models are driven by inputs reflecting farming practices (e.g., size of organism at harvest, outplanting size, fallowing period, culture technique), environmental conditions (e.g., water temperature for finfish and shellfish, nutrient concentration, and seston abundance for shellfish), and economic factors (e.g., price per pound of harvested product, variable costs of finfish feed, labor costs). The models also quantify filtration by shellfish, production of finfish and shellfish, dissolved and particulate wastes, and the potential transfer of disease vectors from farmed Atlantic salmon to wild populations. These outputs are inputs to other InVEST models, such as water quality and wild salmon fisheries, allowing for the exploration of a more complete picture of the costs and benefits of aquaculture.

Coastal protection

As highlighted by the human losses wrought by hurricanes and tsunamis, coastal and estuarine wetlands have value for their ability to reduce storm surge elevations and wave heights (Danielsen et al. 2005; Travis 2005; Wamsley et al. 2010; Barbier et al. 2011). The Tier 0 coastal protection model identifies areas of the coastline that may be of greatest risk to erosion or flooding, and regions where that risk is reduced because of the presence of natural habitats. It can be used to explore the protective role played by natural features (e.g., coral reefs, dunes) when run using scenarios with and without those features – differences in the resulting vulnerability maps highlight the protective services played by the features in question. It can also identify parts of the coast where specific activities should be focused or avoided. The model is based on a coastal vulnerability to sea level rise model (Gornitz et al. 1997; Thieler and Hammar-Klose 1999) and produces a qualitative estimate of the exposure of coastal communities to storm-induced erosion and flooding. Like the models on which it is based, it is an index that requires users to input information on geologic (e.g., geomorphology) and physical process (e.g., wind speed, wave power) variables, but it also requires information on the type and distribution of natural habitats (e.g., corals, mangroves, wetlands). It uses the same globally available data on wind speed and wave characteristics as the marine renewable energy model. In addition, it uses human population data (Center for International Earth Science Information Network and Centro Internacional de Agricultura Tropical 2005) to relate model outputs to important population centers. Outputs can be used to identify regions of greater risk to coastal hazards, inform development strategies and permitting, and to highlight the protective services offered by natural habitats to coastal populations. Tier 0 outputs can be used to determine where more sophisticated Tier 1 modeling should be targeted to quantify the protective role provided by natural habitats.

The process-based Tier 1 model quantitatively estimates erosion, flooding, and consequences for people and property from a single storm event. The model requires similar inputs to the Tier 0 model, but with more user-provided parameter values. For example, users can value the protective services provided by ecosystems based on a particular hurricane that was observed in their region. Outputs include the quantity and value of the protection provided by natural habitats in various units including biophysical (e.g., avoided area eroded or flooded), economic (e.g., dollars of avoided damage), and social (e.g., avoided number of people affected). The model can be used to compare natural (e.g., restoration of natural habitat) and engineered (e.g., coastal armoring, rock walls) strategies for climate adaptation, inform coastal development plans and permitting, and understand where and how conservation of natural habitats might help protect communities from coastal hazards.

Aesthetic quality

The natural and scenic views of coastal and marine seascapes can contribute to the well-being of local communities in a number of ways. The Tier 0 aesthetic quality model explores how natural and scenic views provided by marine and coastal seascapes can be affected by human activities. It allows users to determine the locations from which new or existing terrestrial, nearshore, or offshore features can be seen. It generates viewshed maps that identify the visual footprint of development. Inputs to the model include topography and bathymetry, locations of facilities of interest (things to be viewed), and the locations of viewers (e.g., population centers or areas of interest such as parks or trails). The model does not quantify economic impacts of altering the viewshed, but it can be adapted to compute viewshed metrics for use in a more detailed valuation study.

Recreation

Marine and coastal systems provide opportunities for diverse forms of recreation such as beach going, recreational fishing, whale watching, and snorkeling. Our Tier 0 model for recreation is the overlap analysis described in the fisheries section. To use this tool for recreation, one inputs maps of the areas used by various recreational users, and, optionally, information about the relative importance of different activities (e.g., intensity of use or quality of area). Similar to the output when used as a fisheries mapping tool, this tool creates maps of recreational use summarized across various activities. If desired, the tool can be used with any type of place-based human activities to generate maps of cumulative use.

Our Tier 1 approach to modeling nature-based tourism and recreation uses information about demography and the environment to predict visitation rates. Users can, for example, submit data on land use, population size, and natural features across the landscape in order to generate spatially explicit estimates of visitation, as well as economic values for a limited set of recreational activities.

Carbon storage and sequestration

Coastal marine plants such as mangrove trees and sea grasses store (primarily in biomass) and sequester (primarily in sediments associated with nearshore marine habitats) large amounts of carbon. Management strategies that change the cover of marine vegetation, such as seagrass restoration and mangrove clearing, can change carbon storage and the potential for carbon sequestration. The Tier 1 marine carbon model estimates how much carbon is stored in coastal vegetation, how much carbon is sequestered in the sediments, and the economic value of storage and sequestration. Inputs include maps of the distribution of nearshore marine vegetation, the amount of carbon stored in four carbon 'pools' in each habitat type (with an optional fifth pool for harvested mangrove wood products), the rate of carbon accumulation in the sediments for each habitat type, and economic information such as the market or non-market (avoided social cost) value of stored/sequestered carbon (see Conte et al. (2011) for a similar approach).

Water quality

Although regulation of water quality is not a final ecosystem service (sensu Boyd and Banzhaf 2007), it is important to many stakeholders and is an important supporting service that can be connected to other InVEST models. The water quality model simulates the movement and fate of water quality constituents (e.g., nutrients, dissolved oxygen) in response to changes in ecosystem structure driven by various management decisions and human activities. The Tier 0 model uses information about point sources, directional flow, and decay rates to produce a map of concentrations of a particular substance (e.g., fecal coliform bacteria).

The Tier 1 model is a physical transport model that explicitly simulates circulation within coastal systems such as estuaries or bays. Within the Tier 1 model, we use two approaches. For shallow areas or regions where data are scarce, we use a one- or two-dimensional finite segment configuration (with the choice being set by the characteristics of the system) that incorporates processes driven by river discharge and tidal dispersion. For other regions where depth stratification is important, the model uses two vertical layers and assumes that an estuarine exchange flow dominates circulation. This second approach is more flexible for use across multiple scales, but is more data intensive. Water quality variables are linked to the physical transport model to incorporate basic biogeochemical processes along with advection and diffusion. Residence times can be calculated from the modeled circulation, which – when coupled with river and nutrient inputs – provides an overview of where water quality issues such as hypoxia or eutrophication may occur. Data for some relevant features (e.g., bathymetry, tides) are globally available at coarse scales (although local data can be substituted), while other features require local data (e.g., salinity, river discharge).

As described above, the water quality model is an important connector to other models. For example, changes in water quality due to aquaculture (e.g., filtration or deposition of nutrients and particulates, transmission of disease) can affect the delivery of other services adjacent to or further away from aquaculture facilities. The water quality model uses outputs from the aquaculture model to determine where water quality changes.

Habitat risk assessment

Nearshore and coastal habitats are important for the delivery of many ecosystem services (e.g., nursery habitat for harvested species, protection from storms, recreation). Human activities within marine and coastal environments can alter these habitats. For example, human activities such as fishing and shoreline development can negatively impact nearshore habitats. Similarly, activities such as habitat restoration and protection can mitigate the risk posed by these human activities. The Tier 0 habitat risk assessment model produces a qualitative estimate of the risk that various human activities and climate change pose to habitats. Risk from human activities (e.g., aquaculture, coastal development) to habitats (e.g., seagrasses, mangroves, reefs) is a function of the exposure of each habitat to each activity (temporal and spatial overlap and management effectiveness) and the habitat-specific consequence of that activity. Consequence depends on the effects of activities to habitat area and density, and the ability of habitats to recover (i.e., through processes such as recruitment and regeneration). Outputs from the model are useful for understanding the relative risk of human activities and climate change to habitats within a study region and among alternative future scenarios. The model can help prioritize areas for conservation or restoration and inform the design and configuration of marine spatial plans.

Future directions

Our efforts to expand and improve marine InVEST are proceeding on three primary fronts. First, although we have conducted sensitivity analyses and model validation throughout the model-building process (see Tallis, Ricketts, et al. (2012) for details), further model testing and better communication of uncertainty is of the utmost importance. Second, we are building new models and improving the functionality of existing models. For example, we have populated some ecosystem service model categories (e.g., renewable energy) with one specific model (e.g., wave energy) and are working to increase the tool's generality with additional models (e.g., off-shore wind). Third, we continue to explore possibilities for expanding the options for model outputs (i.e., connecting biophysical metrics to more valuation metrics) and for helping users to synthesize outputs to better examine trade-offs and win-wins. As we use InVEST in new applications around the world, we learn from each new context and expect to adapt and improve the tool accordingly.

Case study: application of marine InVEST to the West Coast of Vancouver Island

Here, we describe the decision context, our methods, and some initial results from our first application of the marine InVEST tool along the West Coast of Vancouver Island (WCVI), British Columbia, Canada. Our work there is in progress; we show results that demonstrate the types of outputs InVEST produces and how the planners can incorporate this information into design of their MSP. These results are illustrative of the ways in which InVEST models can be used to shape the dialogue and inform decision making in a MSP context. It is important to note that InVEST is never prescriptive in what should be done but instead is intended to inform decisions with likely outcomes, such that decision making is more rational, transparent, and informed.

Case study background

Along the WCVI, multiple, often competing interests have come together to try to envision the future character of the place and how myriad human uses can occur without undermining each other and the marine ecosystem on which they depend. The West Coast Aquatic Management Board (WCA), a public–private partnership with participation from four levels of government (federal, provincial, local, and First Nations), and diverse stakeholders, is in the process of creating a marine spatial plan for the region. Existing extractive, industrial, and commercial uses, traditional First Nations subsistence and ceremonial uses, recreation and tourism, and emerging ocean uses such as the extraction of wave energy are all in the mix. Ultimately, WCA's vision is to manage resources for the benefit of current and future generations of people and the natural systems on which they depend. WCA has partnered with the Natural Capital Project, a collaboration between Stanford University, the Nature Conservancy, World Wildlife Fund, and the University of Minnesota (Natural Capital Project c2006–2012) to explore how alternative spatial plans might affect a wide range of ecosystem services and to provide information about trade-offs among multiple key ecosystem services to governments and stakeholders in the region.

Some key considerations for WCA and their constituents include balancing important industrial and commercial activities (such as shipping, mining, logging, aquaculture, and fisheries), increasing development of tourism, recreation and renewable energy generation, and accommodating a strong cultural desire to sustain the remote, wild feeling of the place. Aesthetic, spiritual, and cultural values, benefits that are not readily monetized or even quantified, are universally important across the diverse communities in the region. These cultural services are being included in the MSP process in two ways: through articulation of acceptable future activities in scenarios (e.g., by excluding or encouraging some activities in areas of spiritual or cultural significance) and through the selection of models to run (e.g., aesthetic values, provision of culturally valuable shellfish landings). For illustration, we focus here on one of WCA's planning regions: Lemmens Inlet, near Tofino, British Columbia. It is an important tourist destination with a long history of stewardship by First Nations and extractive activities such as shellfish harvest and logging (Figure 3).

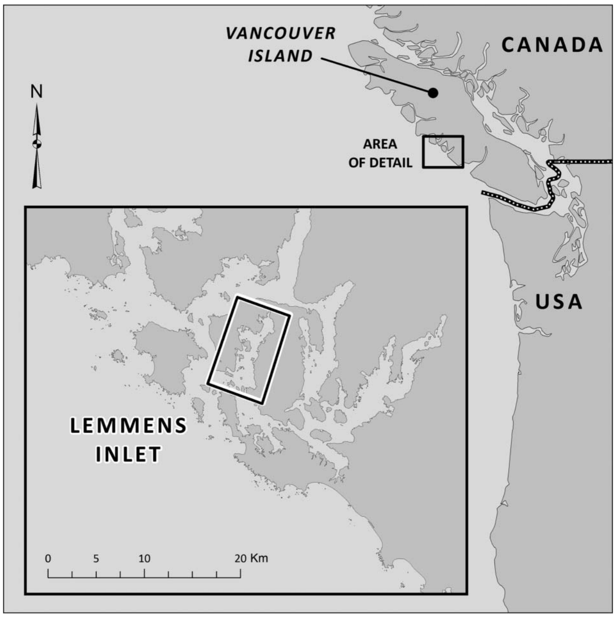

Figure 3. Lemmens Inlet, near Tofino, on the West Coast of Vancouver Island.

WCA conducted extensive stakeholder interviews and surveys to identify the values and visions that residents hold for the future of the region. WCA then translated these narrative visions into scenarios representing the spatial arrangement of current and potential future uses of coastal areas. The scenarios reflect alternative visions for the region (i.e., expanding industrial uses vs. increasing protected areas) and alternative spatial configuration and intensities of multiple activities. Thus, each scenario represents potential zoning choices (e.g., areas set aside primarily for ecological significance, aquaculture, industrial use, community development, tourism, cultural management). Included in these planning options are local cultural values such as maintaining access to local seafood, preserving important spiritual sites, and providing dependable sources of income to residents.

Residents in the Lemmens Inlet region reported that they are interested in balancing human uses including seafood harvest (wild geoduck, clam, crab harvest, and cultured oysters), float homes (houseboats with little to no sewage treatment), and recreational activities such as kayaking and wildlife viewing. In addition, Lemmens Inlet is prized for its water quality, and residents would like to maintain its clean waters and healthy habitats well into the future. Thus, WCA identified three management scenarios that reflect these visions and values for initial exploration: (1) 'baseline,' zoning reflecting current uses; (2) 'conservation,' zoning the inlet as a tribal marine park (i.e., a mix of low impact activities and no-take zones); and (3) 'industry expansion,' leasing more shellfish aquaculture tenures and allowing more float home leases (Figure 4a–c).

Case study methods

To provide WCA with information that would help them assess the scenarios with respect to their stated objectives (i.e., to maintain habitat and water quality, access to local seafood and opportunities for recreation), we adapted the InVEST framework to WCA's specific needs and interests. For those benefits for which InVEST models exist (i.e., shellfish production, water quality, and habitat quality) we used the models 'off the shelf', with little to no modification. For those benefits of interest for which specific InVEST models do not exist (i.e., float homes and kayaking), we used the InVEST Tier 0 recreation model to quantify the spatial extent and importance of these key activities throughout the Inlet and to summarize how that extent might change under the three scenarios. In this way, even though InVEST does not have specific float home or kayaking models, we were able to provide information about how these activities might change under each scenario to help inform planning conversations.

We used InVEST to investigate how the management options under consideration would impact a range of benefits that residents derive from Lemmens Inlet. We used the InVEST Tier 1 shellfish aquaculture model to estimate the production of Pacific oysters (*C. gigas*; the primary farmed shellfish product in Lemmens Inlet) in deepwater culture under each scenario. To estimate the current value of the annual oyster harvest, we used the average regional density of harvestable oysters per square meter, the size of each oyster farm, and the 2011 regional average retail value of shucked oyster product. We used information about float home tenures and the use of kayaking routes in Lemmens Inlet from WCA's community surveys as inputs to the Tier 0 recreation model to quantify the number of 250 m^2 grid cells in the Inlet in which kayaking or float homes would occur under each scenario. Using information from stakeholder interviews, we assumed that if the Inlet were a marine park, the entire Inlet would be used by kayakers, thus increasing the spatial extent of kayaking routes. And finally, we modeled two supporting services, risk to habitat (Figure 4d–f) and water quality (Figure 4g–i) as biophysical outputs to compare against outputs from other models. We used the InVEST Tier 0 water quality model to estimate the dispersion and concentration of fecal coliform bacteria released from float homes throughout the Inlet. We used the habitat risk assessment model to compare the risk posed to habitats by human activities under each management scenario. The habitat risk assessment model provides a relative risk score for eelgrass, kelp, soft bottom, and rocky bottom habitats. We used habitat maps of approximately 50 m resolution. We compared the cumulative risk posed by shellfish aquaculture, wild shellfish harvest, and float homes under each scenario for each 250 m^2 cell in Lemmens Inlet.

Case study results

Our analysis indicates that zoning Lemmens Inlet as an ecologically significant area (the 'conservation' scenario) would yield large gains in the extent of kayaking routes (57% increase in spatial extent), a \$98,998 (18%) increase in the value of the 2011 shellfish harvest from a small increase in oyster tenures, some losses in float home numbers (four fewer float homes in the Inlet), and significant improvements in habitat risk and water quality (75% decrease in relative habitat risk and 32% increase in relative water quality) (Figure 5). In this example, we did not account for potential increases in the intensity of use of kayaking routes if the Inlet drew more tourists after designation as a marine park. Designating the region as ecologically significant would lead to a decrease in the number of float homes (in this scenario by 4) because with such a designation, float homes would be restricted in areas with eelgrass habitat, which covers a substantial portion of the inlet. Risk to habitats posed by human activities (quantified in relative terms by the InVEST Habitat Risk Assessment) would decrease by 75% over the entire Inlet because exposure of sensitive habitats to pollution from float homes would be greatly reduced by removing some float homes entirely and relocating others to less sensitive areas. Water quality (indicated by the concentration of fecal coliform bacteria in each grid cell relative to the concentration at the contaminant source) would increase by 32% relative to the baseline.

In the 'expansion' scenario, shellfish harvest would increase substantially because five new oyster tenures would be allowed. These additional shellfish tenures would lead to a \$367,726 increase in value, which represents a 67% increase. These tenures could have minimal impacts on habitat and water quality if they are not sited near eelgrass beds. Similarly, placement of five new float homes could be harmful if located too close to sensitive eelgrass, but appropriate locations could yield benefits with minimal impacts to habitats. Adding five new float homes would decrease water quality by 31% over the entire Inlet. The combination of adding five new oyster tenures and five new float homes would lead to an 18% increase in habitat risk. This increase in risk is lower than may be expected from the substantial increases in damaging activities (five new shellfish farms and float homes); however, the careful spatial arrangement of these activities to avoid conflicts with sensitive habitats mitigated the risk. The spatial extent of kayaking routes did not change in the 'industry expansion' scenario because local stakeholders reported that additional float homes and oyster aquaculture facilities would not significantly impact kayaking routes.

Case study discussion

The spatially explicit nature of InVEST allowed us to identify siting conditions that provide a range of benefits (e.g., shellfish harvest, good water quality) while minimizing conflicts among damaging uses and sensitive habitats in a first round of modeling ecosystem service changes in

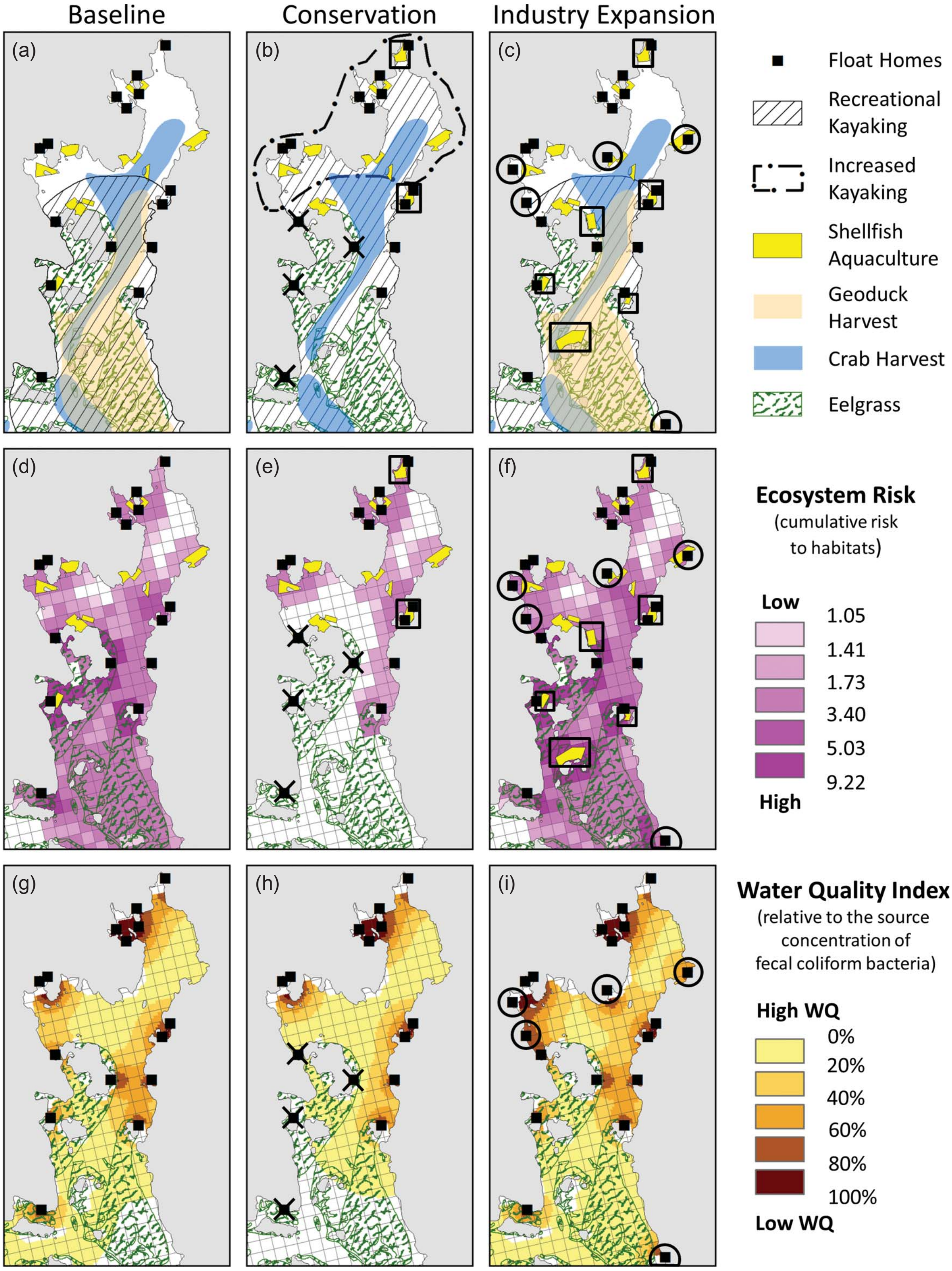

Figure 4. Three alternative management scenarios for Lemmens Inlet, BC identified by West Coast Aquatic (a–c) and some InVEST outputs (d–i). The three scenarios explored were: (a) Baseline (no changes to current uses or zones); (b) Conservation (zoning rules restrict float homes and aquaculture in areas near eelgrass beds). Four float homes are removed from areas where they overlap with eelgrass (shown under black X's). Two new oyster deepwater tenures are located outside of sensitive habitat zones (shown in black squares). Kayaking routes expand into previously unused areas (shown in dashed line). Geoduck harvest is prohibited throughout the Inlet; (c) Industry expansion (five new float home leases are added, as shown in black circles; five new oyster tenures are added, as shown in black squares; and wild geoduck harvest is allowed). InVEST model outputs are shown in the remaining 6 panels. (d–f) Ecosystem risk, which is the cumulative risk of human activities (float homes, aquaculture, geoduck harvest) to nearshore habitats (eelgrass, soft, and hard bottom) under the three alternative management scenarios. (g–i) Concentration of fecal coliform bacteria relative to concentrations at float home sources under the three scenarios.

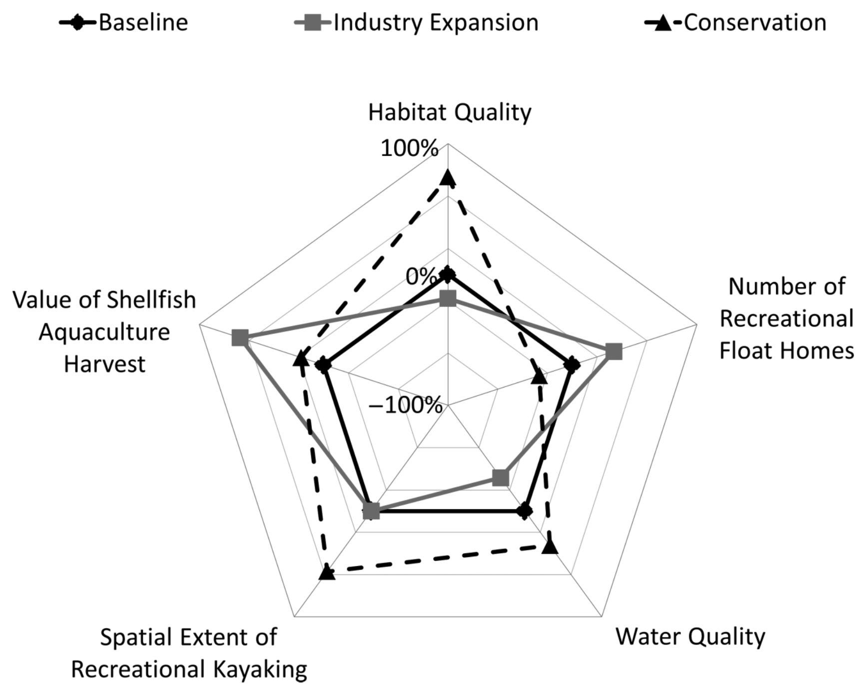

Figure 5. Overall changes in ecosystem service production relative to current conditions (baseline, solid black pentagon) under three alternative management scenarios in Lemmens Inlet, BC (see Figure 4 for details). Expansions of the shape toward the exterior represent gains relative to the baseline and contractions represent losses. A scenario with only gains (and no trade-offs) would be represented by a shape that completely includes or exceeds the baseline shape. Native units – in which each ecosystem service was originally measured – are as follows: habitat quality (inverse of habitat risk; measured in relative qualitative units), number of recreational float homes, water quality (measured as concentration of fecal coliform bacteria relative to concentrations at contaminant source), spatial extent of kayaking area (measured in square meters), and value of shellfish aquaculture harvest (measured in dollars). Note that the axis for water quality is reversed (i.e., points further from the origin have lower concentrations of fecal coliform bacteria and indicate higher water quality).

the WCVI. The models allowed us to explore alternative uses at various locations throughout the area and identify options that increased float home use and shellfish harvest while attempting to avoid potential threats to eelgrass habitats. These results are helping to make stakeholder discussions less polarized by encouraging those strongly opposed to certain human uses, such as float homes, to consider that appropriate siting could reduce environmental impacts, making those uses more palatable to a wider range of stakeholders. And while the results were generally intuitive to ecologists, our ability to generate quantitative outputs and to document explicit connections between activities has helped shape the dialogue and further the planning process.

In the Lemmens Inlet application, we compare model outputs in relative terms (percentage change in the relevant output metric, Figure 5). We found that percentage changes in relative terms were sufficient for stakeholders to compare among alternative scenarios. Absolute values for some services, such as water quality and habitat risk, were neither necessary nor appropriate for stakeholders to compare among scenarios, particularly because stakeholders are concerned with maintaining good water and habitat quality over the entire Inlet. Relative values that integrate changes in these metrics over the entire inlet are more helpful than many point estimates distributed over the Inlet.

Only one of the output metrics (shellfish harvest, NPV) is in dollar values. The stakeholders in this early, exploratory phase of planning do not find valuation metrics necessary for the other priority ecosystem services they have identified in Lemmens Inlet. Although the valuation (particularly in economic terms) of ecosystem services can be of great utility, it is not required to enable the explicit inclusion of a fuller suite of services in decision making.

Often, people equate an ecosystem services framework with economic valuation. Dollars are but one of several valuation metrics that can be included in ecosystem service approaches. One important lesson from our engagement thus far in the WCVI spatial planning process is that stakeholders and decision makers do not have trouble using different currencies when considering the value of ecosystem services. Ecosystem services with clear market value (e.g., fisheries, aquaculture, wave energy) are relatively straightforward to ascribe a dollar value. As mentioned above, existence, subsistence, and aesthetic values are generally the most universally and strongly held among the communities living in the region. Attaching monetary metrics to these ‘cultural’ values is a difficult and controversial task that is not needed (or desired) to inform ongoing decisions (Chan et al. 2011). In our WCVI application, cultural values are included prominently in both the framing of scenario options, and also in interpretation of trade-offs among legitimate uses, as illustrated in the Lemmens Inlet example. However, our work in Lemmens Inlet did not explicitly include the consideration of existence values from people outside the region or the characterization of many subsistence or esthetic values. The explicit inclusion of these types of values in environmental decision making remains a frontier (Chan et al. in review).

Our initial engagement with complex decision-making processes on the WCVI has illuminated the critical importance of embedding decision support tools in stakeholder engagement processes. WCA worked closely with local stakeholders to develop potential scenarios to model with InVEST, yielding results that are grounded in local ecological knowledge and reflective of the diverse values, conflicts, and aspirations in the area. The process of building relationships with people, having them create a common vision, values, and goals, as well as providing and validating information all were important steps undertaken by WCA. Building upon this foundation, our use of InVEST helped people understand and use models to explore different scenarios. This enabled people to explore solutions that reflected the values and visions they had expressed. While it is too early to know whether consensus will be achieved on a final plan, and whether the outcomes will be implemented by authorities, the process to date has been a significant advance on typical positional disputes. Without being part of an effective stakeholder process decision support tools are merely academic; without good decision support tools, planning processes can miss opportunities to find common ground, base decisions on sound science, and integrate the costs and benefits of a wide range of activities.

The Lemmens Inlet example described here portrays a relatively fine-scale use of the marine InVEST models. The scale of inquiry for this example was determined by the scale at which many local decisions are being made. However, we designed InVEST to be applicable across a range of spatial scales. When questions of interest span broader scales, analyses can be tailored to represent them. For example, we are using our wave energy model to help stakeholders on the larger scale of the West Coast of Vancouver Island explore suitable locations for wave energy facilities based on wave climate and economic factors. In many instances, it may be important to explore model results at nested spatial scales that mirror nested decision contexts (i.e., local to regional to national).

Conclusion

Quantifying and incorporating multiple ecosystem services in decisions

The multiple ecosystem service nature of InVEST helps expand the scope of planning conversations from single-issue perspectives to more comprehensive discussions about cumulative impacts and benefits. Presenting a broad suite of ecosystem service outputs (i.e., seafood harvest, water quality, tourist visitation rates) encourages stakeholders to acknowledge the multiple competing uses and values at stake. For example, an ecosystem services approach encourages proponents of aquaculture to consider the wide-ranging effects of aquaculture practices on other valued ecosystem properties such as water quality. Similarly, opponents of aquaculture are encouraged to consider not only the environmental impacts but also the benefits to local communities (e.g., monetary, local food).

An ecosystem service approach can reveal gains and losses in ecological and economic benefits under alternative management scenarios. When trade-offs are communicated clearly in metrics that resonate with stakeholders (e.g., NPV of shellfish harvest or bacterial content in water), people are equipped to make their own decisions about which trade-offs are acceptable and which are not. By using process-based models linked through impacts to habitat and water quality, InVEST allows users to identify unexpected consequences and compatibilities among human uses that could not be gleaned from simple maps alone. These trade-offs can be expressed in biophysical as well as monetary units; however, the interpretation of these results and the resulting planning choices will depend largely on the local cultural and social context.

The process of using InVEST, or any decision support tool, is most effective when used in an iterative fashion (Figure 1). After synthesizing model outputs, stakeholders might decide that one scenario is a preferable course of action – or, they might decide to rearrange some uses, to emphasize some and deemphasize others, and to generally revise and reassess their plan for uses of their region.

Modeling and integrating multiple marine ecosystem services is no easy task and significant challenges remain. Communicating model uncertainty in ways that resonate with non-scientific audiences is an important frontier. In addition, incorporating ecosystem service information into complex and time-consuming planning processes can seem daunting to governments and NGOs with limited science capacity or timeframes for their decision processes. As decision support tools like InVEST become more widely tested and data-sharing efforts bear fruit, the usability and transferability of such tools will improve, reducing capacity and time constraints.

Marine InVEST is a general, flexible, freely available decision support tool for use in MSP, EBM, climate adaptation planning, and other comprehensive decision contexts in marine environments. It simplifies the difficult task of assessing comprehensively how human activities in one sector affect a whole suite of benefits that people want and need, thereby enabling decision makers to explore explicitly trade-offs and win-wins. Ultimately, it is our hope that this tool – developed both in computer labs and on the frontlines of MSP – can lower the barriers to the inclusion of nature's myriad benefits in natural resource decision making.

In conclusion, an ecosystem services approach can inform CMSP by broadening planning discussions from single-sector perspectives to more comprehensive ones that explore cumulative impacts and benefits and are explicit about trade-offs and win-wins. Using ecosystem services – the things and experiences people want and need from natural systems – as metrics can help decision makers and their stakeholders meaningfully assess alternative management strategies and their potential impacts on economic or social well-being. Management and planning that recognize the diverse connections between humans and the environment are likely to improve outcomes for both.

Acknowledgements

We would like to thank the Gordon and Betty Moore Foundation for funding for this work.

Note

1. http://www.naturalcapitalproject.org/.

References

Balvanera P, Kremen C, Martínez-Ramos M. 2005. Applying community structure analysis to ecosystem function: examples from pollination and carbon storage. Ecol Appl. 15(1):360–375.

Barbier EB, Hacker S, Kennedy C, Koch EW, Stier A, Silliman BR. 2011. The value of estuarine and coastal ecosystem services. Ecol Monogr. 81(2):169–193.

Barbier EB, Koch EW, Siliman BR, Hacker S, Wolanski E, Primavera J, Granke E, Polasky S, Aswani S, Cramer L, et al. 2008. Coastal ecosystem-based management with nonlinear ecological functions and values. Science. 319(5861):321–323.

Boyd J, Banzhaf S. 2007. What are ecosystem services? The need for standardized environmental accounting units. Ecol Econ. 63(2–3):616–626.

Carr M, Neigel J, Estes JA, Andelman S, Warner RR, Largier J. 2003. Comparing marine and terrestrial ecosystems: implications for the design of coastal marine reserves. Ecol Appl. 13(1):S90–S107.

Cavanaugh K, Siegel D, Reed D, Dennison P. 2011. Environmental controls of giant kelp biomass in the Santa Barbara Channel, California. Mar Ecol Prog Ser. 429:1–17.

Center for International Earth Science Information Network and Centro Internacional de Agricultura Tropical. 2005. Gridded population of the world version 3 (GPWv3). New York (NY): Palisades.

Center for Ocean Solutions. 2011. Decision-guide: selecting decision-support tools for marine spatial planning [Internet]. Stanford (CA): COS. [cited 2012 Jan 2]. Available from: http://centerforoceansolutions.org/sites/default/files/cos_msp_guide_6.pdf.

[CEQ] White House Council on Environmental Quality. 2010. Final recommendations of the Interagency Ocean Policy Task Force. Washington (DC): CEQ [cited 2012 Jan 2]. Available from: http://www.whitehouse.gov/administration/eop/oceans.

Chan K, Goldstein J, Satterfield T, Hannahs N, Kikiloi K, Naidoo R, Vadeboncoeur N, Woodside U. in review. Cultural services and non-use values. In: Kareiva P, Tallis H, Ricketts T, Daily G, Polasky S, editors. Natural capital: theory and practice of mapping ecosystem services. Oxford (UK): Oxford University Press. p. 206–228.

Chan K, Ruckelshaus M. 2010. Characterizing changes in marine ecosystem services. F1000 Biol Rep. 2:54–60.

Christensen V, Walters C. 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecol Model. 172(2–4):109–139.

Conte M, Nelson E, Carney K, Fissore C, Olwero N, Plantinga A, Stanley B, Ricketts T. 2011. Terrestrial carbon sequestration and storage. In: Kareiva P, Tallis H, Ricketts T, Daily G, Polasky S, editors. Natural capital: theory and practice of mapping ecosystem services. Oxford (UK): Oxford University Press. p. 111–128.

Convention on Biological Diversity. 2004. Decision VII/5, App. 3 of the Conference of the Parties to the Convention on Biological Diversity. Elements of a Marine and Coastal Biodiversity Management Framework: Marine and Coastal Biological Diversity; 2004 Feb 9–20, 27; Kuala Lumpur.

Crowder LB, Osherenko G, Young OR, Airamé S, Norse EA, Baron N, Day JC, Douvere F, Ehler CN, Halpern BS, et al. 2006. Resolving mismatches in US Ocean Governance. Science. 313(5787):617–618.

Danielsen F, Sorensen M, Olwig M, Selvam V, Parish F, Burgess N, Hiralshi T, Karunagaran V, Rasmussen M, Hansen L, et al. 2005. The asian tsunami: a protective role for coastal vegetation. Science. 310(5748):643.

Ehler C, Douvere F. 2009. Marine spatial planning: a step-by-step approach toward ecosystem-based management. UNESCO Intergovernmental Oceanographic Commission and Man and the Biosphere Programme. Paris (France): UNESCO. IOCAM dossier #6.

Environmental Systems Research Institute. 2011. ArcGIS desktop: release 10. Redlands (CA): ESRI.

European Commission. 2010. Maritime spatial planning in the EU: achievements and future development. Brussels (Belgium): European Commission.

Foley M, Halpern B, Micheli F, Armsby M, Caldwell M, Crain C, Prahler E, Rohr N, Sivas D, Beck M, et al. 2010. Guiding ecological principles for marine spatial planning. Mar Pol. 34(5):955–966.

Fulton EA, Parslow JS, Smith ADM, Johnson CR. 2004. Biogeochemical marine ecosystem models II: the effect of physiological detail on model performance. Ecol Model. 173(4):371–406.

Fulton EA, Smith ADM, Johnson CR. 2004. Biogeochemical marine ecosystem models I: IGBEM – a model of marine bay ecosystems. Ecol Model. 174(3):267–307.

Gordon HS. 1954. The economic theory of a common-property resource: the fishery. J Polit Econ. 62(2):124–142.

Gornitz VM, Beaty TW, Daniels RC. 1997. A coastal hazards database for the US West Coast. Oak Ridge (TN): Oak Ridge National Laboratory.

Granek EF, Polasky S, Kappel CV, Reed DJ, Stoms DM, Koch EW, Kennedy CJ, Cramer LA, Hacker SD, Barbier EB, et al. 2010. Ecosystem services as a common language for coastal ecosystem-based management. Conserv Biol. 24(1):207–216.

Guerry AD. 2005. Icarus and Daedalus: conceptual and tactical lessons for marine ecosystem-based management. Front Ecol Environ. 3(4):202–211.

Guerry AD, Plummer ML, Ruckelshaus MH, Harvey C. 2010. Ecosystem service assessments for marine conservation. In: Kareiva P, Tallis H, Ricketts T, Daily G, Polasky S, editors. Natural capital: theory and practice of mapping ecosystem services. Oxford (UK): Oxford University Press. p. 296–322.

Guerry AD, Plummer ML, Ruckelshaus MH, Holland DS. Forthcoming 2012. Modelling marine ecosystem services. In: Levin S, editor. Encyclopedia of biodiversity. 2nd ed. Oxford (UK): Elsevier.

Halpern BS, Diamond J, Gaines S, Gelcich S, Gleason M, Jennings S, Lester S, Mace A, McCook L, McLeod K, et al. 2012. Near-term priorities for the science, policy, and practice of Coastal and Marine Spatial Planning (CMSP). Mar Pol. 36(1):198–205.

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno J, Casey KS, Ebert C, Fox HE, et al. 2008. A global map of human impact on marine ecosystems. Science. 319(5865): 948–952.

Kareiva P, Tallis H, Ricketts T, Daily G, Polasky S, editors. 2011. Natural capital: theory and practice of mapping ecosystem services. Cambridge (UK): Oxford University Press.

Lester SE, McLeod K, Tallis H, Ruckelshaus M, Halpern B, Levin P, Chavez F, Pomeroy C, McCay B, Costello C, et al. 2010. Science in support of ecosystem-based management for the US West Coast and beyond. Biol Conserv. 143(3): 576–587.

McLeod K, Leslie H, editors. 2009. Ecosystem-based management for the oceans. Washington (DC): Island Press.

[MA] Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: synthesis. Washington (DC): Island Press.

Multipurpose Marine Cadastre. 2011. Multipurpose Marine Cadastre [Internet]. Washington (DC): NOAA Coastal Services Center and Bureau of Ocean Energy Management Regulation and Enforcement; [cited 2011 Oct 27]. Available from: http://www.marinecadastre.gov.2011.

National Research Council. 2005. Valuing ecosystem services: toward better environmental decision-making. Washington (DC): National Academies Press.

Natural Capital Project. c2006–2012. Natural Capital Project [Internet]. Palo Alto (CA): The Natural Capital Project; [cited 2012 Jan 2]. Available from: http://www.naturalcapitalproject.org.

Nelson E, Mendoza G, Regetz J, Polasky S, Tallis H, Cameron DR, Chan KM, Daily GC, Goldstein J, Kareiva PM, et al. 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. Front Ecol Environ. 7(1):4–11.

NOAA Fisheries Toolbox. 2011. Stock synthesis version 3 [Internet]. [cited 2012 Jan 2]. Available from: http://nft.nefsc.noaa.gov/test/SS3.html

Obama B. 2009. Memorandum for the Heads of Executive Departments and Agencies regarding: National policy for the oceans, our coasts, and the Great Lakes. The White House Office of the Press Secretary. 2009 Jun 12. Memorandum.

Ostrom E. 1990. Governing the commons: the evolution of institutions for collective action. New York (NY): Cambridge University Press.

Peterson C, Lubchenco J. 1997. Marine ecosystem services. In: Daily G, editor. Nature's services: societal dependence on natural ecosystems. Washington (DC): Island Press p. 177–194.

Rosenberg AA, McLeod KL. 2005. Implementing ecosystem-based approaches to management for the conservation of ecosystem services. Mar Ecol Prog Ser. 300:270–274.

Sathirathai S, Barbier EB. 2001. Valuing mangrove conservation in southern Thailand. Contemp Econ Pol. 19(2):109–122.

Schmidt A, Coll M, Romanuk T, Lotze H. 2011. Ecosystem structure and services in eelgrass Zostera marina and rockweed Ascophyllum nodosum habitats. Mar Ecol Prog Ser. 437:51–68.

Soderqvist T, Eggert H, Olsson B, Soutukorva A. 2005. Economic valuation for sustainable development in the Swedish coastal zone. Ambio. 34(2):169–175.

Tallis H, Lester S, Ruckelshaus M, Plummer M, McLeod K, Guerry A, Andelman S, Caldwell M, Conte M, Copps S, et al. 2012. New metrics for managing and sustaining the ocean's bounty. Mar Pol. 36(1):303–306.

Tallis H, Levin PS, Ruckelshaus M, Lester SE, McLeod KL, Fluharty DL, Halpern BS. 2010. The many faces of ecosystem-based management: making the process work today in real places. Mar Pol. 34(2):340–348.

Tallis H, Polasky S. 2009. Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. Ann N Y Acad Sci. 1162:265–283.

Tallis H, Ricketts T, Guerry AD, Nelson E, Ennaanay D, Wolny S, Olwero N, Vigerstol K, Pennington D, Mendoza G, et al. 2012. InVEST 2.0 User's guide [Internet]. Palo Alto (CA): Natural Capital Project. Stanford University. [cited 2012 Jan 2]. Available from: http://www.naturalcaptialproject.org.

Thieler ER, Hammar-Klose ES. 1999. National assessment of coastal vulnerability to future sea-level rise: preliminary results for the US Atlantic Coast [Internet]. US Geological Survey. Open-File Report. [cited 2012 Jan 2]. Available from: http://pubs.usgs.gov/of/of99-593/.

Tolman HL. 2009. User manual and system documentation of WAVEWATCH III version 3.14. NOAA/NWS/NCEP/MMAB. Technical note [Internet]. [cited 2012 Jan 2]. Available from: http://polar.ncep.noaa.gov/waves/wavewatch/.

Travis J. 2005. Hurricane Katrina: scientists' fears come true as hurricane floods New Orleans. Science. 309(5741): 1656–1659.

Turner BL, Skole D, Sanderson S, Fischer G, Fresco L, Leemans R. 1995. Land-use and land-cover change science/research plan. Joint publication of the International Geosphere-Biosphere Programme (Report No. 35) and the Human Dimensions of Global Environmental Change Programme (Report No. 7). Stockholm (Sweden): Royal Swedish Academy of Sciences.

Turnipseed M, Crowder LB, Sagarin R, Roady SE. 2009. Legal bedrock for rebuilding America's ocean ecosystems. Science. 324(5924):183–184.

UK National Ecosystem Assessment. 2011. The UK National Ecosystem Assessment: synthesis of the key findings. Cambridge (UK): UNEP-WCMC.

United Nations Environment Program Intergovernmental Oceanographic Commission-United Nations Educational Scientific and Cultural Organization. 2009. An assessment of assessments, findings of the group of experts. Start up phase of a regular process for global reporting and assessment of the state of the marine environment including socio-economic aspects. ISBN 978-92-807-2976-4.

UN General Assembly. 2010. Sustainable Development: Report of the Governing Council of the United Nations Environment Programme on its Eleventh Special Session; 2010 Nov 12. Bali, Indonesia.

Wabnitz C, Andréfouët S, Muller-Karger FE. 2010. Measuring progress toward global marine conservation targets. Front Ecol Environ. 8(3):124–129.

Wamsley T, Cialone M, Smith J, Atkinson J, Rosati J. 2010. The potential of wetlands in reducing storm surge. Ocean Eng. 37(1):59–68.