Published in final edited form as:
Ecol Indic. 2018 ; 84: 404–415. doi:10.1016/j.ecolind.2017.08.047.

Developing qualitative ecosystem service relationships with the Driver-Pressure-State-Impact-Response framework: A case study on Cape Cod, Massachusetts

David M. Martin[*], **Amy N. Piscopo**, **Marnita M. Chintala**, **Timothy R. Gleason**, and **Walter Berry**
U.S. Environmental Protection Agency, Office of Research and Development, Atlantic Ecology Division, 27 Tarzwell Drive, Narragansett, Rhode Island 02882, U.S.A.

Abstract

Understanding the effects of environmental management strategies on society and the environment is critical for evaluating their effectiveness, but is often impeded by limited data availability. In this article, we present a method that can help scientists to support resource managers' thinking about social-ecological relationships in coupled human and natural systems. Our method aims to model qualitative cause-effect relationships between management strategies and ecosystem services, using information provided by knowledgeable participants, and the tradeoffs between strategies. Social, environmental, and cultural indicators are organized using the Driver-Pressure-State-Impact-Response, or DPSIR, framework. The relationships between indicators are evaluated using a decision tree and numerical representations of interaction strength. We use a matrix multiplication procedure to model direct and indirect interaction effects, and we provide guidelines for combining effects. Results include several data tables from which information can be visualized to understand the plausible interaction effects of implementing management strategies on ecosystem services. We illustrate our method with a water quality management case study on Cape Cod, Massachusetts.

Keywords

DPSIR; interaction strength; qualitative models; water quality management

1. Introduction

Ecosystem degradation caused by anthropogenic activities is a chronic problem (Vitousek et al., 1997; Steffen et al., 2007). Degradation depletes the structure and function of ecosystems, which provide ecosystem services that benefit humankind (Daily, 1997; Potschin and Haines-Young, 2011). Understanding the numerous, interdependent effects of anthropogenic inputs on the environment is critical for determining changes in the quality and value of ecosystems services (Carpenter et al., 2009; Doney, 2010). For these reasons,

---

[*] Corresponding author: Martin.DavidM@epa.gov.

Supplementary material
Supplementary data associated with this article can be found in the online version at: xyz

accounting for ecosystem services in environmental decision making has become a general focus for sustainable community development (Daily et al., 2009; Guerry et al., 2015).

To combat ecosystem degradation and work towards sustainability, communities must consider adaptations such as technological changes, human behavior changes, and the recovery of ecosystem structure and function (Blignaut et al., 2014). Local resource managers use scientific data and models, among other supporting information, to inform such adaptations by constructing a view or perception of social, economic, environmental, and cultural conditions in communities. A common approach is to identify key focal components and establish cause-effect relationships between those focal components to represent interactions between society and the environment. The focal points, often referred to as indicators, are used in models to reflect the human, social, and natural forms of capital that provide ecosystem services to people (Carpenter et al., 2006, 2009).

Modern paradigms for ecosystem-based management strongly emphasize interdependence between indicators in whole ecosystem contexts (Leslie and McLeod, 2007; Borgstrom et al., 2015). Ecosystem-scale analyses often require quantitative and qualitative evaluations on the relationships between management strategies and ecosystem services (Granek et al., 2009; Levin et al., 2009). Quantitative approaches are often subject to significant uncertainties associated with linking relevant biogeochemical models to changes in ecosystem services (Bennett et al., 2009; Wainger and Mazzotta, 2011). Furthermore, uncertainty increases in data-poor situations, where changes in ecosystem services cannot be evaluated with a natural or proxy metric.

In this article, we present a simple method for evaluating qualitative relationships between management strategies and ecosystem services in data-poor situations. Our approach involves a systems-based analysis to estimate cause-effect relationships through intermediate indicators. Any assumptions required for determining the relationships between indicators are clear and transparent. We propose this approach as a basis for scientists and stakeholders to partner on determining which management strategies have plausible causal connections to ecosystem services and to examine those connections, using expert opinion and literature reviews, to explain variations in outcome. We view this work as contributing to the greater arena of environmental decision support, in which the relationships derived from this approach between management strategies and ecosystem services could be used alongside other quantitative or qualitative social, environmental, and economic data to support environmental decision making.

We use the Driver-Pressure-State-Impact-Response (DPSIR) framework to structure the process of indicator selection needed to evaluate causal relationships between management strategies and ecosystem services. The European Environment Agency (EEA, 2003) has indicated that the DPSIR framework has been particularly useful for analyzing problems in coupled human and natural systems because it provides a relatively simple and generic structure for linking cause-effect relationships (for reviews, see Tscherning et al., 2012; Gari et al., 2015; Lewison et al., 2016; Patricio et al., 2016).

The DPSIR framework is composed of five categories of indicators:

- Driver indicators represent those factors and needs that motivate people, like food, water, health, education, agriculture, and industry;
- Pressure indicators are human activities in response to driving forces that put stress on the natural environment, like land development;
- State indicators reflect the quantity and quality of biological, chemical, and physical conditions, like chemical properties in water or the abundance of biota and habitat;
- Impact indicators reflect the social-ecological functionality of a watershed or community, like water purification and climate regulation; and
- Response indicators are societal actions, like storm water management or ecological restoration, that prevent, compensate, ameliorate, or adapt to impacts.

A core characteristic that makes DPSIR popular for sustainability research is that it organizes management strategies, or responses, and outcomes, or impacts, into indicator categories. Many publications have reported the usefulness of DPSIR as a scoping tool for conceptualizing interdependence in resource management problems (Lewison et al., 2016), particularly ones that advance the concept of “impact” to include ecosystem services (Kelble et al., 2013). Few studies, however, report on the relationships between environmental management as response indicators and variations in ecosystem service outcomes as they are reflected in either pressure, state, or impact indicators.

Some DPSIR studies attempt to link categories and indicators with quantitative models for measuring interactions between indicators (Nobre, 2009; Hou et al., 2014). However, linking quantitative models with DPSIR indicators is not straightforward because system complexity is hard to capture (Karageorgis et al., 2006; Spangenberg et al., 2015). A foremost challenge for DPSIR is data availability and the integration of different forms of data (Lewison et al., 2016). Qualitative studies using DPSIR (Rehr et al., 2012; Yee et al., 2015), including ones that incorporate numerical representations of qualitative cause-effect relationships (Cook et al., 2014; Shumchenia et al., 2015), allow flexibility in the type and amount of data for DPSIR indicator selection and in the measurability of individual indicators (OECD, 2001).

We use the concepts of DPSIR in our approach to determine relationships and interaction strengths between the components of coupled human and natural systems, particularly the impact of water quality management strategies on ecosystem services, for sustainable ecosystem-based assessment. We demonstrate our method with a collaborative water quality management case study on Cape Cod, Massachusetts. We established qualitative measures of interaction strength and used a matrix multiplication procedure to determine linkages between implementing nitrogen management strategy indicators (e.g., wastewater treatment, nature restoration) and their effects on ecosystem service indicators (e.g., erosion and flood control, recreational opportunity). A complete list of the indicators used in our case study is provided in Section 3 and the Appendix.

2. Methods

Our method is a scientific approach to develop causal relationships between response indicators as management strategies and driver, pressure, state, and/or impact (i.e., ecosystem services) indicators that resonate with stakeholder values and represent critical components of the management problem. The method includes several distinct steps, which are presented in Fig. 1.

2.1 DPSIR pathways

In the first step of our method, we use DPSIR to identify important components of the decision context (e.g., desirable management strategies, important social-ecological indicators, valued ecosystem services) where limited information about their interdependent relationships is available. Because results are sensitive to the number of indicators chosen, we suggest collaboration with stakeholders to select indicators. We organize the indicators into relevant DPSIR categories for causal analysis. Criterion-based selection approaches (Niemeijer and de Groot, 2008) or stakeholder focus groups (Yee et al., 2015) can aid the process.

Scientists and their stakeholder collaborators make a determination on the linkages and causal pathways between DPSIR indicator categories that are relevant to a particular management situation. The pathways can include linear (e.g., response-state) or non-linear (e.g., state-state) causal interactions. We suggest that DPSIR categories are linked with solid arrows to indicate a causal pathway for explicit analysis (Fig. 1a). We use dashed arrows to suggest likely cause-effect relationships, but those relationships are not formally included in the analysis because they are not relevant to the management situation.

2.2 Interaction strength

In this step, we assign qualitative estimates of interaction strength between DPSIR indicators among linked DPSIR categories in a causal pathway (e.g., response-state, state-state, state-impact). A targeted outcome for this step is a numerical score (a_i in Fig. 1b) that represents the interaction strength between two DPSIR indicators in linked DPSIR categories. In this context, interaction strength reflects a causal relationship among pairs of indicators.

Qualitative methods for determining the type and strength of interaction among environmental indicators are not well-established (for recent reviews, see Crain et al., 2008; Côté et al., 2016). Some models use statistical simulations (Reum et al., 2015), whereas others draw on expert opinions (Benitez-Capistros et al., 2014; Cook et al., 2014). Our approach resembles the Altman et al. (2011) approach in that we develop a decision tree with scoring rules and a dimensionless scale of numerical interaction strength values (Fig. 1b; Section 3.3). Answers to scoring rules may be categorical and use modifiers like “large” and “small” or “poor,” “fair,” and “excellent.” As with the selection of DPSIR indicators, results are sensitive to the number of scoring rules and ranges of interaction strength values in a decision tree. We organize the final interaction strength scores for each set of paired comparisons into interaction strength data tables. Each cell in the data table, x_{ij}, is a final interaction strength score between row *i* and column *j* indicators in a causal direction (see example response-state data table in Fig. 1b).

2.3 Interaction effects

In this step, we determine interaction effects for an individual DPSIR pathway using the combined normalization and matrix multiplication procedure from Cook et al. (2014) (Fig. 1c). We normalize the columns of the interaction strength data tables to sum to unity (1), which provides an estimate of each indicator's contribution, $\tilde{x}_{ij}$, where ~ represents normalization, to the overall (column) indicator goal relative to the other (row) indicators in a DPSIR category:

$$\tilde{x}_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \quad (1)$$

The normalized values in Eq. (1) sum to unity because we want to distribute the relative effects of a DPSIR category among the indicators being compared. Other normalization approaches could be applied depending on how scientists and stakeholders want to interpret the data. The normalized data table is the multiplicand. The multiplier is the next data table of interaction strength values in the DPSIR pathway. The product is a new data table that estimates the relative interaction effects on each DPSIR indicator via the preceding DPSIR category.

To estimate direct interaction effects, the normalized data table of response-state interaction strength values ($\tilde{x}_{RS}$ in Fig. 1c) is multiplied by the data table of state-impact interaction strength values (x_{SI} in Fig. 1c). The product is a data table of response-impact interaction effect values (x^{*}_{RI}), where * indicates direct effects. This new table describes the interaction effects on the impact indicators broken down by individual response. The first cell in the new data table (x^{*}_{11} in Fig. 1c) represents the interaction effect of the first response indicator on the first impact indicator as mediated (using the additive assumption of matrix multiplication) through all of the interaction effects of those indicators on each state indicator.

If the desired pathway is to investigate indirect cause-effect relationships, an additional multiplicative step is required to estimate the effects of response indicators on state indicators via the response indicators' interaction effects on all other states and those state indicators' consequential non-linear influence on each other. For this step, we develop an intermediate table of indirect response-state interaction strength values ($\hat{x}_{RS}$ in Fig. 1c), where ^ indicates an intermediate calculation. We multiply the table of normalized values ($\hat{\tilde{x}}_{RS}$ in Fig. 1c) by the table of state-impact interaction strength values (x_{SI} in Fig. 1c) to develop a table of indirect response-impact values (x^{**}_{RI} in Fig. 1c), where ** indicates indirect effects.

2.4 Combined effects

Stakeholders may prefer a single interaction effect data table to analyze all potential, or combined, interaction effects. To combine effects, weighted values of direct response-state interaction effect ($w*\left(\tilde{x}_{RS}\right)$ in Fig. 1c) are added to weighted values of indirect response-state interaction effect ($w**\left(\hat{\tilde{x}}_{RS}\right)$ in Fig. 1c). We multiply the table of normalized values from this step ($\tilde{x}^{\wedge\wedge}_{RS}$ in Fig. 1c) by the table of state-impact interaction strength values (x_{SI} in Fig. 1c) to develop a table of cumulative response-impact values (x^{***}_{RI} in Fig. 1c, where *** indicates combined effects).

Double counting occurs when the estimated values of a causal linkage is added to or used in a separate estimate of interaction effect along the same causal linkage. We avoid double counting because separate response-state interaction strength tables are used in the combined effect calculation. However, we have found that if nonlinearity is incorporated into multiple DPSIR linkages along the same causal chain (e.g., response-pressure-state + response-state), it may be difficult to avoid double counting while combining effects.

Direct and indirect interaction effects can be weighted evenly or unevenly when combining effects. In our method, the choice of how to combine effects depends on which of the effects is the biggest contributor to overall interaction effect in the ecosystem. In this context, weighting is not synonymous with the relative importance of an indicator as it is assigned by stakeholders in a decision analytic approach because different biogeochemical processes facilitate interactions among the indicators in shorter causal chains (i.e., direct effects) versus longer causal chains (i.e., indirect effects). In other words, the question of what combination of weights are used to combine effects is dependent on spatial, temporal, and ecological interactions that scientists are attempting to combine. If scientists are unable to assign a specific weighting scheme, then a sensitivity analysis using multiple weight combinations can reveal important thresholds between indicator relationships in the model results (Section 4).

2.5 Tradeoff analysis

The normalized tables of response-impact interaction effect values ($\tilde{x}^{*}_{RI}$, $\tilde{x}^{**}_{RI}$, $\tilde{x}^{***}_{RI}$ in Fig. 1d) describe which management strategy or response indicator draws higher or lower contributions to impact or ecosystem service indicators. Because the numerical tradeoffs between response indicators have dimensionless units, visualizing these relationships provide community stakeholders with valuable information in a simple, understandable manner. Based on the type of normalization that is performed, pie charts (Section 4) or histograms can be used.

Evaluating numerical tradeoffs focus on seeking the response indicators that perform better than others across impacts and prioritizing the indicators as decision instruments for technical investigations. Cost-benefit analysis (Nobre, 2009) often is not useful because monetary values of ecosystem service indicators are not generally known in data-poor situations. Optimization methods and multi-criteria decision analysis are useful (Cinelli et al., 2014; for DPSIR examples, see Chung and Lee, 2009; Benini et al., 2010), particularly when a common but non-monetary metric is sought for comparing management strategies. Because other important social, economic, and environmental indicators may need to be modeled and incorporated into such an analysis, technical method development for tradeoff analysis is not a focus of this article but will be incorporated in future work on our case study.

3. Illustration

3.1 Study area

Human activities in the coastal zones of Southern New England have influenced the quality and quantity of ecosystem services provided by coastal wetlands, estuaries, and seas (Driscoll et al., 2003). Among the more pressing concerns is increased nitrogen loading into coastal water bodies (Howarth et al., 2000; Compton et al., 2011). Over the past several decades, the southeastern cape of Massachusetts, or Cape Cod, has experienced a significant increase in reactive nitrogen compounds due in large part to on-site household wastewater disposal (Fig. 2;Valiela et al., 2016; Williamson et al., 2017), resulting in declining water quality. There is a need and often a mandate for local communities to focus on human-induced changes to water quality and how they may be ameliorated in their resident watershed(s).

The towns on Cape Cod are currently developing comprehensive water quality management plans with guidance from the U.S. Environmental Protection Agency (EPA), Massachusetts Department of Environmental Protection, Massachusetts Estuaries Project at the University of Massachusetts-Dartmouth, and the Cape Cod Commission, the regional land use planning organization responsible for ensuring environmental protection and economic progress. The management plans aim to investigate how combinations of management strategies and technologies may be implemented to abate coastal water quality impairment. The plans focus on nitrogen loading into coastal water bodies to meet total maximum daily load mandates for nitrogen.

Selected actions and technologies to meet the nitrogen mandate can potentially affect other ecosystem services in addition to water quality effects. For example, wetland restoration may attenuate nitrogen from surface waters while also providing wildlife habitat and pleasing views. Although the management plans focus more directly on how nitrogen loads are reduced, there is a growing interest from several Cape Cod towns and the Cape Cod Commission to incorporate “co-benefits” into the water quality management dialogue, reflecting the potential ancillary influences that management strategies might have on communities. Since many of the potential nitrogen management strategies are non-traditional and in testing phases on Cape Cod, we developed a qualitative investigation of potential ecosystem services using our method to facilitate the dialogue.

3.2 DPSIR pathways

Following our method (Fig. 1), we used the DPSIR framework to select and organize indicators in the context of water quality management on Cape Cod (Fig. 3). Definitions for each DPSIR indicator are given in the Appendix. These definitions provided the management context from which we considered the interaction of response, state, and impact indicators. Regarding its hierarchical structure, we aimed to describe the changes in ecosystem states and ecosystem service impacts after management strategy responses were initiated for nitrogen pollution abatement.

Our selection was informed by our stakeholder collaborators in the Three Bays watershed (Fig. 2) and by a team of experts on coastal ecosystems including ecologists, biologists, environmental engineers, environmental economists, and restoration and aquaculture practitioners. Five response indicators to the nitrogen problem were agreed as representations of the dozens of management strategies and technologies that are currently considered for nitrogen-related management on Cape Cod (Fig. 4;Cape Cod Commission, 2015). We selected a wastewater treatment facility, eco-toilets, and permeable reactive barriers because they intercept nitrogen before it is distributed into surface and groundwater. We selected nature restoration because it interacts in or adjacent to water bodiesand shellfish aquaculture because it is a water-based strategy and a cultural heritage on Cape Cod. We selected the state indicators as ecosystem-based considerations for investigating effects from the management responses on important ecological aspects of coastal water bodies on Cape Cod.

Regarding impacts, we aimed to capture a simple representation of possible ecosystem services with emphasis on understanding how nitrogen management strategies affect tourism-based coastal communities with strong recreation, erosion and flood control, and amenity values. We used the term “socio-cultural amenity” to combine relevant cultural and amenity services defined in de Groot et al. (2005). We did not include quantitative indicators in this model nor did we include other socio-economic indicators that may influence ecosystem services. However, we plan to combine these factors with results from our qualitative model for a more comprehensive tradeoff analysis in a companion tool being developed for this project.

3.3 Interaction strength

We investigated the strength of interaction between pairs of DPSIR indicators in linked DPSIR categories. First, we developed a decision tree with emphasis on the Cape Cod problem (Fig. 5). As in Altman et al. (2011), our inquiry required consideration of spatial and temporal scales of interaction. However, we modified their decision tree to filter interaction effects into “weak” and “strong” scoring ranges based on a specific magnitude of effect. It is important to note that the decision tree questions required us to clarify specific assumptions (e.g., magnitude and locations of potential effect) for the response indicators. We used the Three Bays watershed (Fig. 2) as a case context for our scoring assumptions.

Our interaction strength scores assume a positive direction of effect (i.e., potential improvements) because our stakeholder collaborators desired to understand how the management strategies could provide improvements to state indicators and, consequently, beneficial changes in ecosystem services. For example, the construction footprint of a wastewater treatment facility may negatively affect biota and suspended sediment conditions because of impervious surface runoff and disruption of the magnitude and timing of water flows in coastal water bodies. However, we only considered the ability of a wastewater treatment plant to process household water and how that affects coastal water bodies, which we determined to have no effect on biota or suspended sediment conditions in our model (Section 4, Supplementary material).

We agreed on interaction strength scores for each paired interaction in linked DPSIR categories using these assumptions and information about the proposed management strategies in the draft Three Bays watershed report (www.capecodcommission.org), and also by fostering support from colleagues with expertise in the subject areas.. Based on these scores, we performed the matrix multiplication calculations to develop response-impact data tables for direct, indirect, and combined interaction effects. We performed a sensitivity analysis to investigate how sensitive different combinations of weights for direct and indirect effect were to cumulative response-impact interaction effects.

4. Results

Tables 1–3 include tentative interaction strength scores that reflect the expert conceptualization of qualitative interactions in the Three Bays watershed on Cape Cod. Scoring assumptions and comments on each interaction strength score are included in the Supplementary material for this article. Our matrix multiplication calculations generated data tables of direct and indirect response-impact interaction effect values; we present visualizations of those relationships in Fig. 6a-b. We also calculated several data tables of combined effect values using different weighting schemes for direct and indirect interaction effects; a sub-set of those calculations are visualized in Fig. 7a-c.

The direct and indirect interaction effects from implementing shellfish aquaculture as a nitrogen management strategy are high among the ecosystem service impact indicators, relative to the other management strategies (Fig. 6a-b). The model shows a high proportion of interaction effect from implementing nature restoration on the ecosystem service impact indicators as well. Implementation of a wastewater treatment facility is estimated to improve conditions for the three ecosystem services, but the relative effects vary from none (direct effect on shoreline erosion and flood control) to relatively high (direct effect on socio-cultural amenity) (Fig. 6a). The potential influences from permeable reactive barriers and eco-toilets were minimal among the management strategies.

The same trends for direct and indirect interaction effect were estimated for combined effects (Fig. 7). Although we performed numerous sensitivity iterations using different weighing schemes for direct and indirect effects, the order of effect from the management strategies did not change with the exception that effects from nature restoration and a wastewater treatment facility on socio-cultural amenity become divergent depending on the direction of weighting (Section 5). Other than this trend, the effects are similar, which is why we chose to include only results from three sensitivity iterations in Fig. 7 for discussion purposes. Shellfish aquaculture and nature restoration have higher interaction effects on recreation and shoreline erosion and flood control, relative to the other management strategies. Only the proportion of effect increased or decreased according to which ecosystem service was being analyzed.

5. Discussion

In general, our results are logical from scientific and management viewpoints. Our stakeholder collaborators agreed that the method and results are influential to convert the single-objective outlook to minimize costs in the Three Bays watershed, which is currently the sole nitrogen management viewpoint, into a multi-objective outlook to minimize costs and maximize ecosystem services. They respected the manner in which the analysis was performed and the simplicity of visualizing the interdependence between indicators in the watershed. They also appreciated that our qualitative model is adaptive to changes in interaction strength data and the amount and type of management strategies implemented in the watershed to calculate changes in outcome.

Insights from the case study can be explained by tracing the interaction effects from the results back through the interaction strength data tables. According to our results, nature restoration and shellfish aquaculture are the only management strategies that directly affect shoreline erosion and flood control (Fig. 6a). This is because (i) coastal habitat is the only state indicator that affects shoreline erosion and flood control (Table 3) and (ii) nature restoration and shellfish aquaculture are the only response indicators that affect habitat (Table 1). However, our model infers that implementing a wastewater treatment facility, permeable reactive barriers, and eco-toilets will have indirect interaction effects on shoreline erosion and flood control (Fig. 6b). This is because (i) implementing these strategies affect nitrogen concentration and pathogens with various interaction strengths (Table 1) and (ii) nitrogen concentration and pathogens affect habitat with various interaction strengths (Table 2). The simplicity of the matrix multiplication makes the potential complexity of communicating interaction effect tractable.

Eco-toilets and permeable reactive barriers do not interact with many of our DPSIR state indicators other than by affecting nitrogen concentration and pathogens. For these reasons, their potential effect on the ecosystem services are minimal in this iteration of the model. However, these strategies are important to water quality management on Cape Cod. Although eco-toilets and permeable reactive barriers are only in testing and pilot phases, it has been documented that each can intercept over 80% of nitrogen in household black waste water and groundwater, respectively (Cape Cod Commission, 2015). Likewise, they are being considered as a low-cost alternative strategy to higher cost strategies like construction and maintenance of a wastewater treatment facility. They also provide jobs, local income, and specialized knowledge and skills, among other forms of capital (Guerry et al., 2015), that do not explicitly impact ecosystem services. These characteristics make the strategies extremely interesting as communication topics, but their influence on decision making and implementation has yet to have an effect beyond testing. It is in this context where different relationships between the management strategies and costs and benefits may increase the overall attraction of eco-toilets and permeable reactive barriers, among other management strategies, in a more comprehensive, multi-objective tradeoff analysis (see below).

Combining effects (Fig. 7) changed how the management strategies impacted socio-cultural amenity more so than recreation and shoreline erosion and flood control. For example, as direct interaction effects were weighted more heavily, the effect of wastewater treatment facility on socio-cultural amenity grew while diminishing thee effect from nature restoration. This is because the land-based management strategy has proportionately larger direct effects on socio-cultural amenity via direct (Table 1) effects on nitrogen concentration and pathogens, which have an effect on socio-cultural amenity (Table 3), whereas the water-based strategies have proportionately larger indirect effects via effects on biota. This difference is not apparent for the other two ecosystem service impact indicators, where the direct and indirect interaction effects are less evenly distributed for recreation and shoreline erosion and flood control (Fig. 6); their combined effects do not change greatly with changing weighting schemes (Fig. 7). Many of the state indicators (i.e., biota, pathogens, sediment, plankton) affect recreation and shoreline erosion and flood control in our case study watershed (Table 3), and the management strategies affect two or more of those state indicators at varying interaction strengths (Table 1). Based on this, we concluded that the more causal links there are, the more robust the results are to changes in combined effect.

As we have shown, there is value to linking qualitative cause-effect interactions using DPSIR. If ecosystem services were the only considerations for implementation, then shellfish aquaculture would be a priority strategy. But we know that a wastewater treatment facility would almost completely achieve the nitrogen load mandate in the case study watershed and its design, construction, and operation and maintenance costs are significantly higher than the other management strategies. For these reasons, other indicators like economic costs and nitrogen load reduction would be required for a more comprehensive multi-objective tradeoff analysis.

Based on the results, our stakeholder collaborators are interested in exploring the adaptability of our model by investigating multiple scenarios with different assumptions on the amount and type of management strategies and outcomes that are predicted for nitrogen management in the watershed. We determined that multi-objective optimization and multi-criteria decision analysis methods are necessary to achieve a more comprehensive tradeoff analysis because those methods will assist us in analyzing both quantitative and qualitative data. Our method provides the opportunity for qualitative social-ecological information on ecosystem services to be part of that integrated analysis.

6. Conclusion

Our simple, understandable method helps community stakeholders think about ecosystem-based management in data-poor situations. Our method may be applied to other management problems with similar characteristics, such as supporting the objectives of the Long Island Sound Study, which has recently developed a comprehensive conservation and management plan to abate nitrogen pollution, among other factors, in New York and Connecticut (Long Island Sound Study, 2015). Our method may also apply to other problems where data availability is limited for investigating social-ecological relationships, including but not limited to ecosystem services, or for investigating potential indirect relationships between ecosystem services (Bennett et al., 2009). Results are useful as a communication tool to discuss these relationships and to incorporate into more detailed analytical assessments. It is also adaptable to new information or data as they become available. Future investigations using our method should rely heavily on the characteristics of the system under investigation. Limitations of our method include its subjectivity, the sensitivity of results to the number of DPSIR indicators chosen and number and range of interaction strength scores in a decision tree, and the difficulties associated with weighting direct and indirect interaction effects to produce combined effects. With these limitations in mind, our method returns solid data and visualizations that are easy to interpret.

Our case study was dependent on expert opinion and based on general physical, biological, ecological, and socio-cultural conditions of Cape Cod watersheds. By using ecosystem service indicators in the analysis, our method allows the Three Bays watershed and its resident constituents to examine additional co-benefits other than nitrogen removal, among other environmental and economic factors, for their selected management strategies. Future work on the project will attempt to investigate the desirability of the management alternatives using decision analytic procedures that will combine our results with other quantitative factors like economic costs and benefits, public acceptability, and nitrogen load reductions. For the purposes of this initial investigation, our method allows our stakeholder partners to consider the social and cultural implications of coastal management strategies in a way that benefits future scientific investigation.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

Special thanks to Geoffrey S. Cook for helpful comments on the method and an early version of the manuscript, Lindsey B. Counsell and Scott Horsley for helpful comments on the case study application, the Cape Cod Commission for drafting Fig. 2, Marisa Mazzotta and John Kiddon for helpful comments on early versions of the manuscript, and two anonymous referees and the editor(s) who reviewed the manuscript. The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency. This contribution is identified by tracking number ORD-20647 of the Atlantic Ecology Division, Office of Research and Development, National Health and Environmental Effects Research Laboratory, U.S. Environmental Protection Agency.

Appendix

Definitions of DPSIR indicators relevant to cause-effect modeling for coastal nitrogen management on Cape Cod

Category	**Indicator**	**Definition**	**Considerations**
States	Nitrogen concentration	Reactive nitrogen compounds in coastal water bodies based on natural fixation, decomposition, and transformation, among other ecosystem processes	Concentrations in coastal water bodies
	Biota	Amount and type of flora and fauna in coastal water bodies	Population numbers, species richness, e.g., shellfish, fish, nitrogen-processing bacteria
	Pathogens	Amount and type of undesirable microorganisms in water bodies	Concentrations or colonies of harmful bacteria and viruses to people (*E. coli*, coliforms, *V. parahaemolyticus*)
	Sediment	Amount of suspended organic and inorganic minerals in water bodies	Suspended silt, industrial wastes
	Plankton/micro/macro algae	Amount of suspended photosynthetic organisms in water bodies	Suspended plankton and cyanobacteria biomass
	Habitat	Preferred physical and biological living conditions for desirable flora and fauna in or adjacent to water bodies	Size of habitat types, e.g., river floodplains, wetlands, shoreline salt marsh, seagrass habitat, non-commercial shellfish reefs
Impacts	Recreation (opportunity)	Opportunity for enjoyment or appreciation of a recreational activity (e.g. boating, non-commercial fishing, nature viewing)	Number of beachgoers, fisherman, boaters
	Shoreline erosion and flood control	Persistent reduction in acute storm water flooding and erosion	Water infrastructure; wetland type and amount
	Socio-cultural amenity[1]	Special meaning to local publics, based on cultural identity, heritage values, and sense of place	Public satisfaction, contentment
Responses	Wastewater treatment facility	Industrial operations that process municipal waste water in stages before filtered water is delivered to water bodies	N/A
	Permeable reactive barriers	Land barriers of reactive material that is placed in the path of a migrating plume of polluted water that absorbs a portion of the contaminants	N/A
	Eco-toilets	Bathroom receptacles that collects human wastes for composting or sustainable reuse	N/A
	Nature restoration	Coastal strategies that facilitate living habitat or species growth	N/A
	Shellfish aquaculture	Propagation of mature shellfish for direct consumption and/or commercial sale	N/A

[1] We used this term to combine relevant cultural and amenity services defined in de Groot et al. (2005)

References

Albert C, Galler C, Hermes J, Neuendorf F, von Haaren C, Lovett A, 2016 Applying ecosystem services indicators in landscape planning and management: the ES-in-Planning framework. Ecological Indicators 61, 100–113, 10.1016/j.ecolind.2015.03.029.

Altman I, Blakeslee AMH, Osio GC, Rillahan CB, Teck SJ, Meyer JJ, Byers JE, Rosenberg AA, 2011 A practical approach to implementation of ecosystem-based management: a case study using the Gulf of Maine marine ecosystem. Frontiers in Ecology and the Environment 9, 183–189, 10.1890/080186.

Benini L, Bandini V, Marazza D, Contin A, 2010 Assessment of land use changes through an indicator-based approach: a case study from the Lamone river basin in Northern Italy. Ecological Indicators 10, 4–14, 10.1016/j.ecolind.2009.03.016.

Benitez-Capistros F, Hugé J, Koedam N, 2014 Environmental impacts on the Galapogos Islands: identification of interactions, perceptions and steps ahead. Ecological Indicators 38, 113–123, 10.1016/j.ecolind.2013.10.019.

Bennett EM, Peterson GD, Gordon LJ, 2009 Understanding relationships among multiple ecosystem services. Ecology Letters 12, 1394–1404, 10.1111/j.1461-0248.2009.01387.x. [PubMed: 19845725]

Blignaut J, Aronson J, de Groot R, 2014 Restoration of natural capital: a key strategy on the path to sustainability. Ecological Engineering 65, 54–61, 10.1016/j.ecoleng.2013.09.003.

Borgström S, Bodin Ö, Sandström A, Crona B, 2015 Developing an analytical framework for assessing progress toward ecosystem-based management. AMBIO 44 (Suppl. 3), S357–S369, 10.1007/s13280-015-0655-7.

Cape Cod Commission, 2015 Cape Cod Area Wide Water Quality Management Plan Update. Cape Cod Commission, https://sp.barnstablecounty.org/ccc/public/Documents/208%20Final/Cape_Cod_Area_Wide_Water_Quality_Management_Plan_Update_June_15_2015-Printable.pdf (accessed 07.11.16).

Carpenter SR, DeFries R, Dietz T Mooney HA, Polasky S, Reid WV, Scholes RJ, 2006 Millennium ecosystem assessment: research needs. Science 314, 257–258, 10.1126/science.1131946. [PubMed: 17038608]

Carpenter SR, Mooney HA, Agard J, Capistrano D, DeFries RS, Diaz S, Dietz T, Duralappah AK, Oteng-Yeboah A, Pereira HM, Perrings C, Reid WV, Sarukhan J, Scholes RJ, Whyte A, 2009 Science for managing ecosystem services: beyond the millennium ecosystem assessment. Proceedings of the National Academy of Sciences 106, 1305–1312, 10.1073/pnas.0808772106.

Chung E-S, Lee KS, 2009 Prioritization of water management for sustainability using hydrologic simulation model and multicriteria decision making techniques. Journal of Environmental Management 90, 1502–1511, 10.1016/j.jenvman.2008.10.008. [PubMed: 19062153]

Cinelli M, Coles SR, Kirwan K, 2014 Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecological Indicators 46, 138–148, http://dx.doi.org/j.ecolind.2014.06.011.

Compton JE, Harrison JA, Dennis RL, Greaver TL, Hill BH, Jordan SJ, Walker H, Campbell HV, 2011 Ecosystem services altered by human changes in the nitrogen cycle: a new perspective for US decision making. Ecology Letters 14, 804–815, 10.1111/j.1461-0248.2011.01631.x. [PubMed: 21624028]

Cook GS, Fletcher PJ, Kelble CR, 2014 Towards marine ecosystem based management in South Florida: investigating the connections among ecosystem pressures, states, and services in a complex coastal system. Ecological Indicators 44, 26–39, 10.1016/j.ecolind.2013.10.026.

Côté IM, Darling ES, Brown CJ, 2016 Interactions among ecosystem stressors and their importance in conservation. Proceedings of the Royal Society B 283, 10.1098/rspb.2015.2592.

Crain CM, Kroeker K, Halpern BS, 2008 Interactive and cumulative effects of multiple human stressors in marine systems. Ecology Letters 11, 1304–1315, 10.1111/j.1461-0248.2008.01253.x. [PubMed: 19046359]

Daily GC, 1997 Nature’s Services. Island Press, Washington, D.C.

Daily GC, Polasky S, Goldstein J, Kareiva PM, Mooney HA, Pejchar L, Ricketts TH, Salzman J, Shallenberger R, 2009 Ecosystem services in decision making: time to deliver. Frontiers in Ecology and the Environment 7, 21–28, 10.1890/080025.

de Groot R, Ramakrishnan PS, Berg A.v.d., Kulenthran T, Muller S, Pitt D, Wascher D, Wijesuriya G, Amelung B, Eliezer N, Gopal AR, Rossler M, 2005 Cultural and amenity services In: Millennium Ecosystem Assessment (Ed.), Ecosystems and Human Well-being: Current Status and Trends. Island Press, Washington, DC, pp. 455–476.

Doney SC, 2010 The growing human footprint on coastal and open-ocean biogeochemistry. Science 328, 1512–1516, 10.1126/science.1185198. [PubMed: 20558706]

Driscoll CT, Whitall D, Aber J, Boyer E, Castro M, Cronan C, Goodale CL, Groffman P, Hopkinson C, Lambert K, Lawrence G, Ollinger S, 2003 Nitrogen pollution in the Northeastern United States: sources, effects, and management options. BioScience 53, 357–374.

EEA, 2003 Environmental Indicators: Typology and Use in Reporting. European Environment Agency.

Gari SR, Newton A, Icely JD, 2015 A review of the application and evolution of the DPSIR framework with an emphasis on coastal social-ecological systems. Ocean & Coastal Management 103, 63–77, 10.1016/j.ocecoaman.2014.11.013.

Granek EF, Polasky S, Kappel CV, Reed DJ, Stoms DM, Koch EW, Kennedy CJ, Cramer LA, Hacker SD, Barbier EB, Aswani S, Ruckelshaus M, Perillo GME, Silliman BR, Muthiga N, Bael D, Wolanski E, 2009 Ecosystem services as a common language for coastal ecosystem-based management. Conservation Biology 24, 207–216, 10.1111/j.1523-1739.2009.01355.x. [PubMed: 19906066]

Guerry AD, Polasky S, Lubchenco J, Chaplin-Kramer R, Daily GC, Griffin R, Ruckelshaus M, Bateman IJ, Duraippah A, Elmqvist T, Feldman MW, Folke C, Hoekstra J, Kareiva PM, Keeler BL, Li S, McKenzie E, Ouyang Z, Reyers B, Ricketss TH, Rockström J, Tallis H, Vira B, 2015 Natural capital and ecosystem services informing decisions: from promise to practice. Proceedings of the National Academy of Sciences 112, 7348–7355, 10.1073/pnas.1503751112.

Hou Y, Zhou S, Burkhard B, Müller F, 2014 Socioeconomic influences on biodiversity, ecosystem services and human well-being: a quantitative application of the DPSIR model in Jiangsu, China. Science of the Total Environment 490, 1012–1028, 10.1016/j.scitotenv.2014.05.071. [PubMed: 24914530]

Howarth R, Anderson D, Cloern J, Elfring C, Hopkinson C, Lapointe B, Malone T, Marcus N, McGlathery K, Sharpley A, Walker D, 2000 Nutrient pollution of coastal rivers, bays, and seas. Issues in Ecology 7, 14.

Karageorgis AP, Kapsimalis V, Kontogianni A, Skourtos M, Turner KR, Salomons W, 2006 Impact of 100-year human interventions on the deltaic coastal zone of the inner thermaikos gulf (Greece): a DPSIR framework analysis. Environmental Management 38, 304–315. [PubMed: 16779699]

Kelble CR, Loomis DK, Lovelace S, Nuttle WK, Ortner PB, Fletcher P, Cook GS, Lorenz JJ, Boyer JN, 2013 The EBM-DPSER conceptual model: integrating ecosystem services into the DPSIR framework. PLOS One 8, 10.1371/journal.pone.0070766.

Levin PS, Fogarty MJ, Murawski SA, Fluharty D, 2009 Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. PLoS Biology 7, e1000014, 10.1371/journal.pbio.1000014.

Leslie HM, McLeod KL, 2007 Confronting the challenges of implementing marine ecosystem-based management. Frontiers in Ecology and the Environment 5, 540–548.

Lewison RL, Rudd MA, Al-Hayek W, Baldwin C, Beger M, Lieske SN, Jones C, Satumanatpan S, Junchompoo C, Hines E, 2016 How the DPSIR framework can be used for structuring problems and facilitating empirical research in coastal systems. Environmental Science & Policy 56, 110–119, 10.1016/j.envsci.2015.11.001.

Long Island Sound Study, 2015 Long Island Sound Comprehensive Conservation and Management Plan 2015: Returning the Urban Sea to Abundance. Long Island Sound Study, http://longislandsoundstudy.net/wp-content/uploads/2015/10/LISS_CCMP.pdf (accessed 04.20.2017).

Niemeijer D, de Groot RS, 2008 A conceptual framework for selecting environmental indicator sets. Ecological Indicators 8, 14–25, 10.1016/j.ecolind.2006.11.012.

Nobre AM, 2009 An ecological and economic assessment methodology for coastal ecosystem management. Environmental Management 44, 185–204, 10.1007/s00267-009-9291-y. [PubMed: 19471999]

[OECD] Organisation for Economic Co-operation and Development, 2001 OECD Environmental Indicators: Towards Sustainable Development. Organisation for Economic Co-operation and Development, France.

Patricio J, Elliott M, Mazik K, Papadopoulou K-N, Smith CJ, 2016 DPSIR – two decades of trying to develop a unifying framework for marine environmental management? Frontiers in Marine Science 3, 10.3389/fmars.2016.00177.

Potschin MB, Haines-Young RH, 2011 Ecosystem services: exploring a geographical perspective. Progress in Physical Geography 35, 575–594, 10.1177/0309133311423172.

Rehr AP, Small MJ, Bradley P, Fisher WS, Vega A, Black K, Stockton T, 2012 A decision support framework for science-based, multi-stakeholder deliberation: a coral reef example. Environmental Management 50, 1204–1218, 10.1007/s00267-012-9941-3. [PubMed: 23052473]

Reum JCP, McDonald PS, Ferriss BE, Farrell DM, Harvey CJ, Levin PS, 2015 Qualitative network models in support of ecosystem approaches to bivalve aquaculture. ICES Journal of Marine Science, 10.1093/icesjms/fsv119.

Shumchenia EJ, Pelletier MC, Cicchetti G, Davies S, Pesch CE, Deacutis CF, Pryor M, 2015 A biological condition gradient model for historical assessment of estuarine habitat structure. Environmental Management 55, 143–158, 10.1007/s00267-014-0401-0. [PubMed: 25387456]

Spangenberg JH, Douguet J-M, Settele J, Heong KL, 2015 Escaping the lock-in of continuous insecticide spraying in rice: developing an integrated ecological and socio-political DPSIR analysis. Ecological Modelling 295, 188–195, 10.1016/j.ecolmodel.2014.05.010.

Steffen W, Crutzen PJ, McNeill JR, 2007 The Anthropocene, are humans now overwhelming the great forces of nature? AMBIO 36, 614–621. [PubMed: 18240674]

Tscherning K, Helming K, Krippner B, Sieber S, Paloma SG, 2012 Does research applying the DPSIR framework support decision making? Land Use Policy 29, 102–110, 10.1016/j.landusepol.2011.05.009.

Valiela I, Owens C, Elmstrom E, Lloret J, 2016 Eutrophication of Cape Cod estuaries: effect of decadal changes in global-driven atmospheric and local-scale wastewater nutrient loads. Marine Pollution Bulletin 110, 309–315, 10.1016/j.marpolbul.2016.06.047. [PubMed: 27417571]

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM, 1997 Human domination of Earth's ecosystems. Science 277, 494–499.

Wainger L, Mazzotta M, 2011 Realizing the potential of ecosystem services: a framework for relating ecological changes to economic benefits. Environmental Management 48, 710–733, 10.1007/s00267-011-9726-0. [PubMed: 21786182]

Williamson SC, Rheuban JE, Costa JE, Glover DM, Doney SC, 2017 Assessing the impact of local and regional influences on nitrogen loads to Buzzards Bay, MA. Frontiers in Marine Science 3, 10.3389/fmars.2016.00279.

Yee SH, Carriger JF, Bradley P, Fisher WS, Dyson B, 2015 Developing scientific information to support decisions for sustainable coral reef ecosystem services. Ecological Economics 115, 39–50, 10.1016/j.ecolecon.2014.02.016.

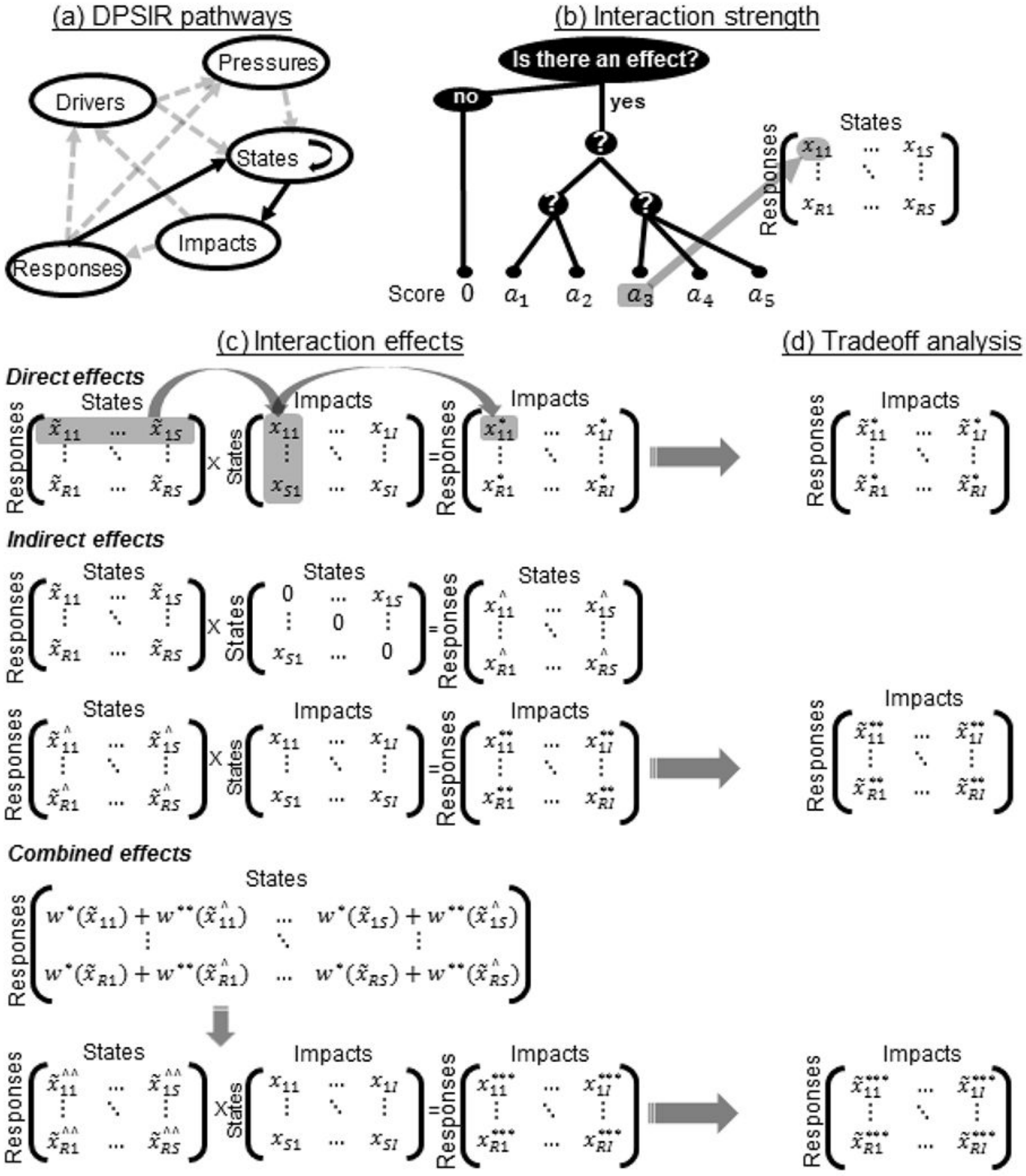

Fig. 1.

A method to develop qualitative relationships between indicators using the DPSIR framework. The approach begins (a) by scoping the problem and identifying relevant indicators using DPSIR. One or more DPSIR pathways between DPSIR categories are chosen for causal modeling based on scale and their relevance to the problem (e.g., response-state-impact). We determine the interaction strengths of indicators in linked DPSIR categories (b) using a scoring technique. We organize the interaction strength values into interaction strength data tables. Interaction effects (c) are estimated with a combined normalization and matrix multiplication procedure for multiple linked DPSIR pathways (see text for description of each interaction effect calculation). Tradeoff relationships between indicators (d) are analyzed based on the interaction effect calculations.

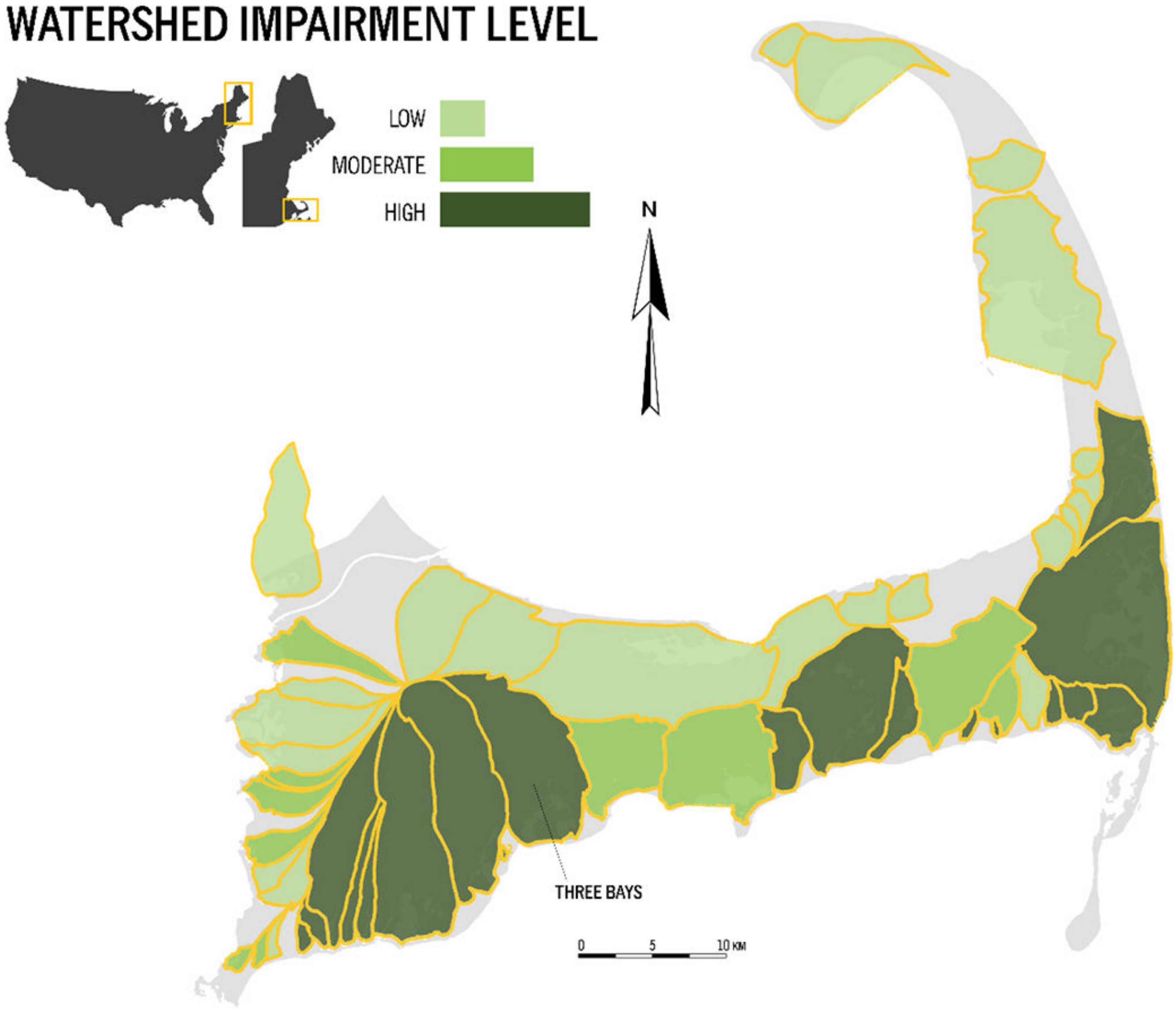

Fig. 2.

Map of 53 Cape Cod watersheds and general degrees of nitrogen related water quality impairment as determined by stakeholder watershed working groups. (Credit: Cape Cod Commission).

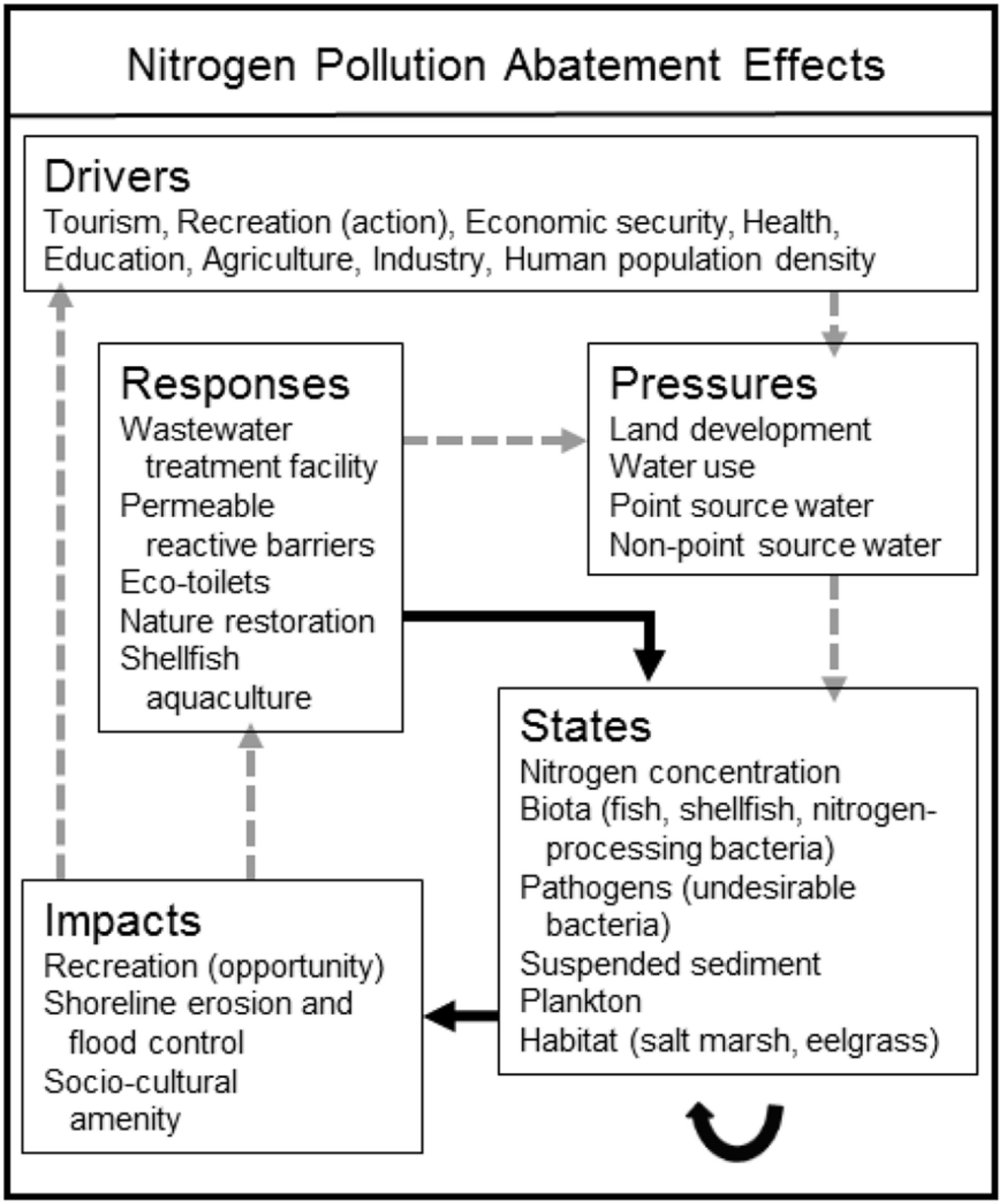

Fig. 3.

Indicators in our DPSIR framework. Arrows depict a conceptualization of how the categories are linked to develop cause-effect relationships. Solid arrows depict the relationships that we used to model qualitative interactions between watershed management responses and ecosystem service impacts. Dashed arrows depict likely relationships among other DPSIR categories but were not used in the analysis.

Fig. 4.

The effectiveness of strategies to reduce anthropogenic nitrogen inputs in coastal water bodies is being evaluated on Cape Cod. (a) Urine-diverting and composting eco-toilets (top panel) are options for individual homes, businesses, or public areas. The waste collection system (bottom panel) uses gravity to separate urine from solids for nitrogen removal. (b) Wastewater treatment facilities provide industrial scale means to remove nitrogen from human waste. (c) Commercial aquaculture of oysters, clams, and mussels is a cultural heritage on Cape Cod. More recently, the practice is considered to be an option to denitrify coastal rivers and estuaries. (d) Nature restoration may include planting new salt marsh habitat or seeding coastal reefs with unpalatable shellfish. Restoration restores eroded coastlines that have been fragmented by human use and helps to denitrify the surrounding waters. (e) A backhoe and trench box with woodchips are installed near an estuary coastline as a permeable reactive barrier to local groundwater flow (top panel). The barrier denitrifies groundwater coming into an estuary (approximate barrier location and flow direction in bottom panel). Photo credits: panel (a) by Clivus New England; panel (b) by Save the Bay; panel (c) by Brian Switzer; panel (d) by Lauren Josephs; panel (e) by Waquoit Bay National Estuarine Research Reserve.

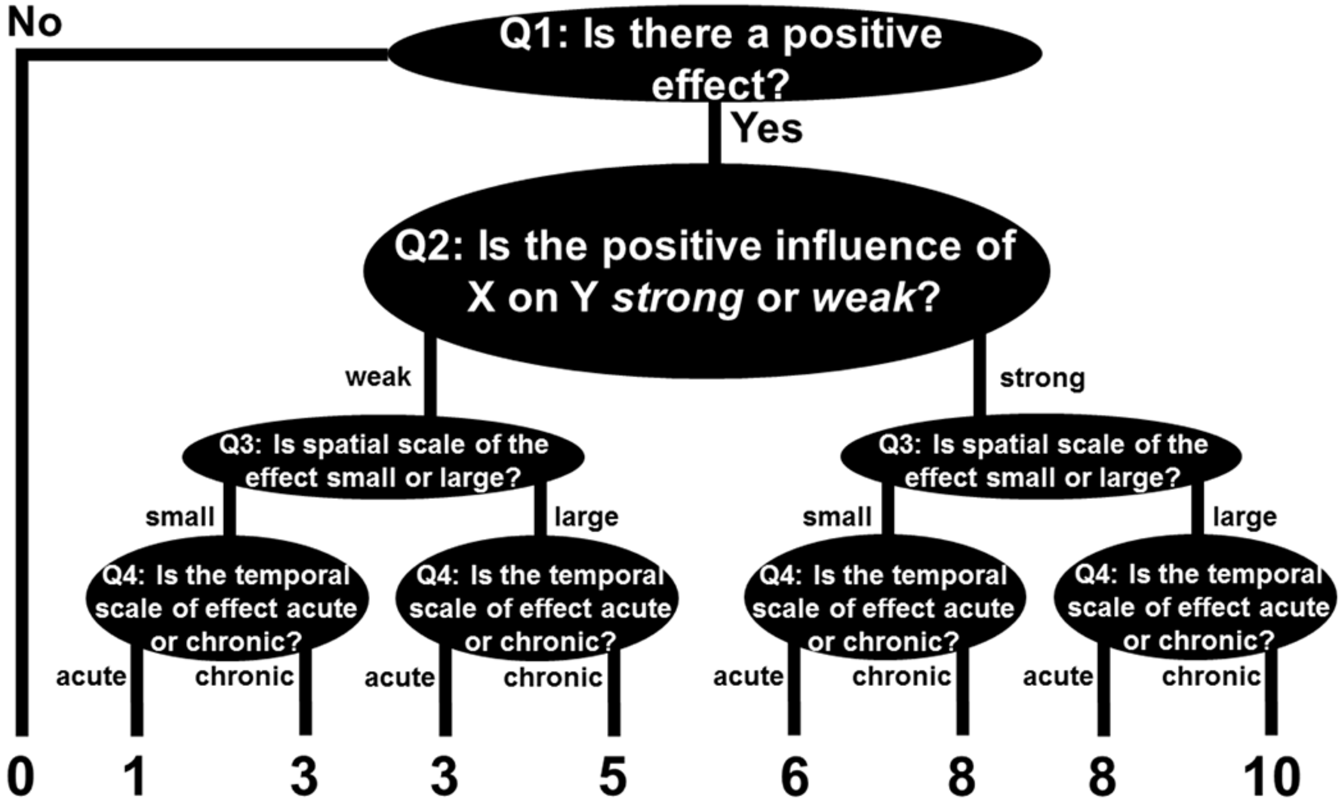

Fig. 5.

Decision tree used to determine interaction strength between pairs of DPSIR indicators in linked DPSIR pathways.

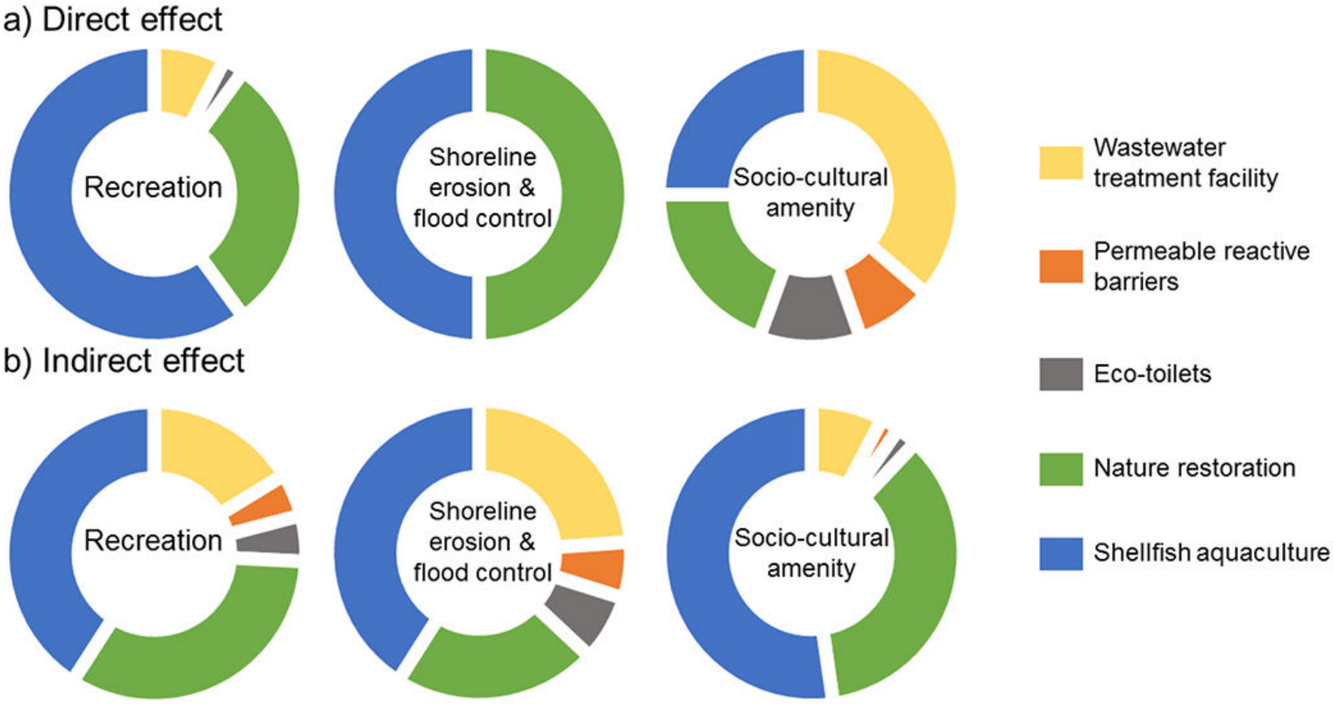

Fig. 6.

The relative effect from nitrogen management strategy response indicators on the ecosystem service impact indicators: (a) direct response-impact relationships, (b) indirect response-impact relationships. Proportion of pie chart is equivalent to relative interaction effect.

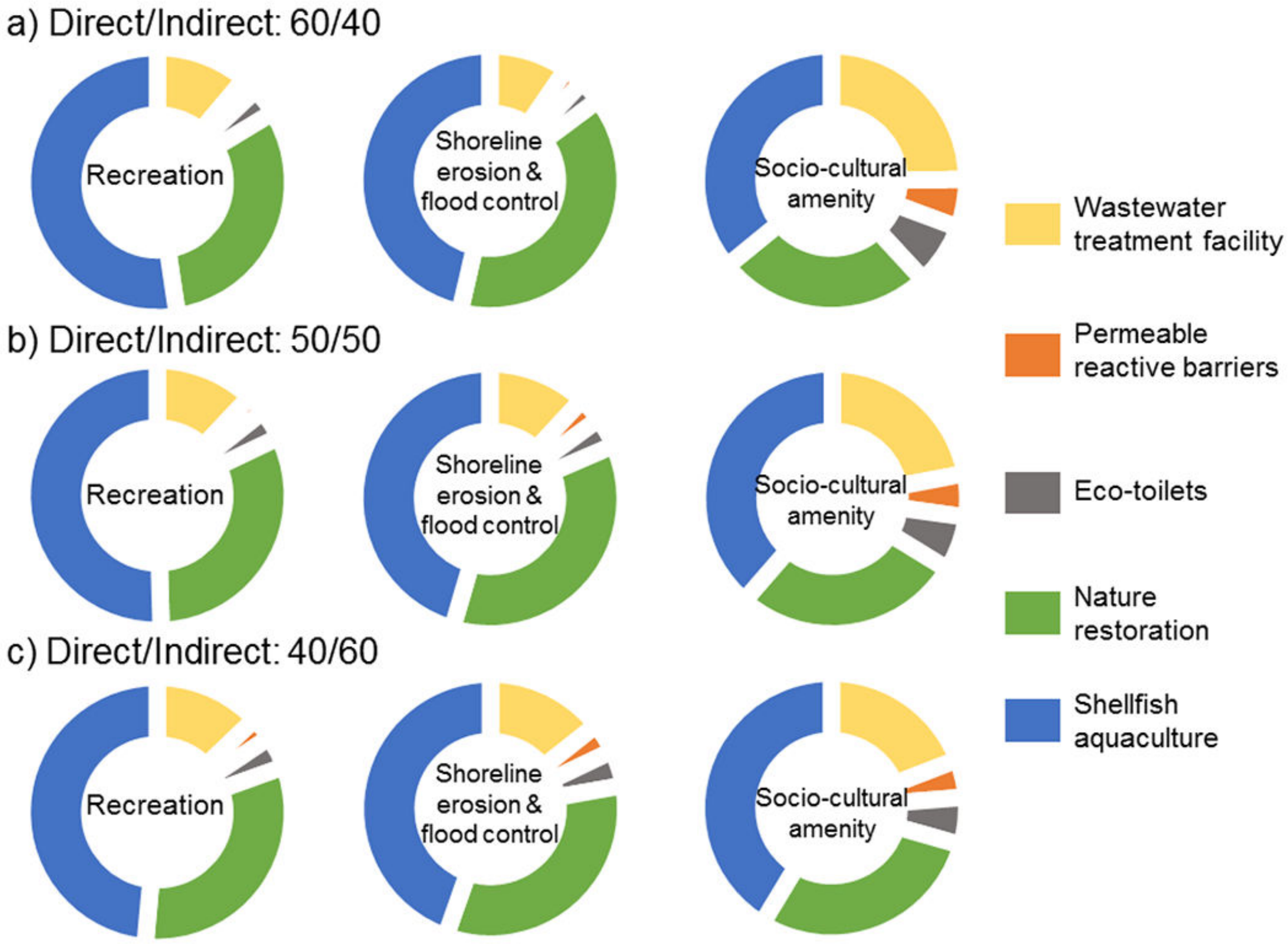

Fig. 7.

Combined response-impact interaction effects based on sensitivity iterations that distributed the relative weight of impact between direct and indirect effects; direct:indirect weight ratios are shown. Proportion of pie chart is equivalent to relative interaction effect.

Table 1.

Interaction strength scores that describe the influence of response indicators (rows) on state indicators (columns)

	Nitrogen concentration	Biota	Pathogens	Suspended sediment	Plankton, macro/micro algae	Habitat
Waste treatment facility	10	0	10	0	0	0
Permeable reactive barriers	3	0	0	0	0	0
Eco-toilets	3	0	3	0	0	0
Nature restoration	1	3	0	3	0	3
Shellfish aquaculture	3	3	0	3	3	3

Table 2.

Interaction strength scores that describe the influence of state indicators (rows) on state indicators (columns)

	Nitrogen concentration	Biota	Pathogens	Suspended sediment	Plankton, micro/macro algae	Habitat
Nitrogen concentration	0	10	0	0	10	8
Biota	10	0	0	5	3	5
Pathogens	0	1	0	0	0	1
Suspended sediment	0	5	1	0	0	3
Plankton, micro/macro algae	6	1	0	1	0	3
Habitat	8	8	0	3	3	0

Table 3.

Interaction strength scores that describe the influence of state indicators (rows) on impact indicators (columns)

	Recreation	Shoreline erosion & flood control	Socio-cultural amenity
Nitrogen concentration	0	0	5
Biota	3	0	3
Pathogens	1	0	1
Suspended sediment	3	0	0
Plankton, micro/macro algae	3	0	0
Habitat	0	8	0