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Conceptual Model Series

Building Ecosystem Services Conceptual Models

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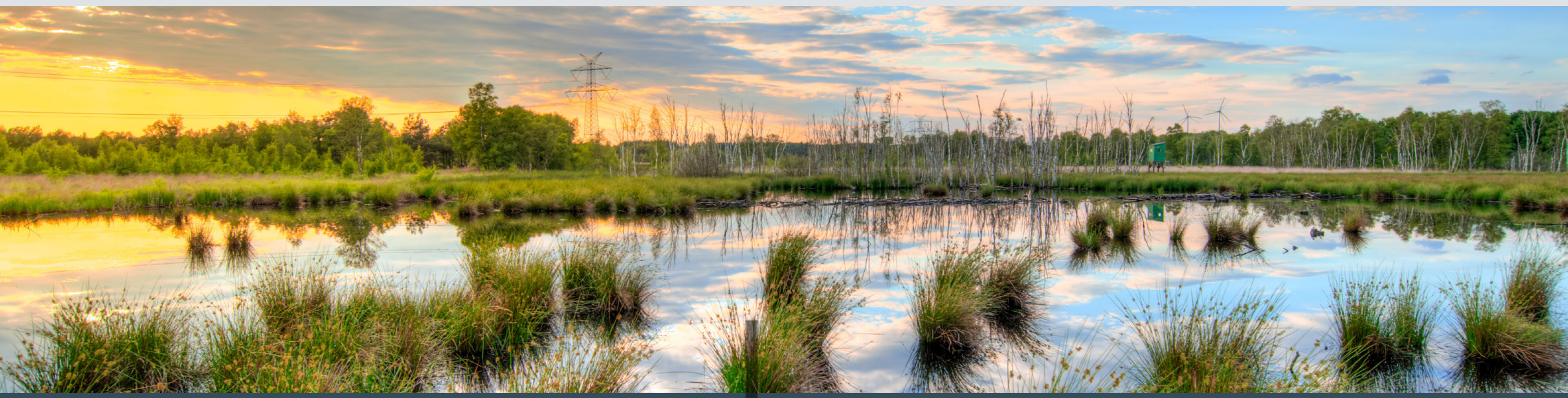

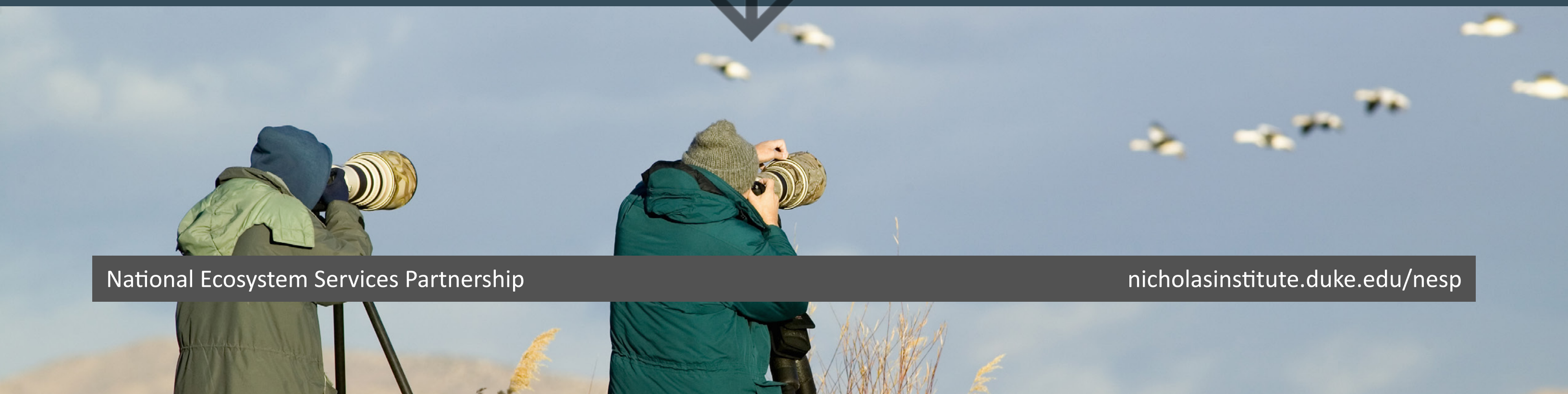

Building Ecosystem Services Conceptual Models

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SUMMARY

Funders and developers of infrastructure projects and businesses and managers overseeing critical natural resources are becoming increasingly aware of and interested in ecosystem services. The idea of more fully assessing how management decisions and policies enhance, sustain, or degrade the benefits nature provides to people is compelling for many reasons. Although methods for incorporating ecosystem services into decisions have been established through academic research, practical guidance for how to do so in the quick, simple, transparent, and low-cost, feasible ways often required for widespread implementation are just now under development.

One tool that can support widespread implementation is the use of ecosystem services conceptual models, which can underpin both simple and complex methods while helping to improve consistency and credibility. These conceptual models link changes caused by an external stressor or intervention through the ecological system to socio-economic and human well-being outcomes. These models can also include direct (not ecologically mediated) changes in human well-being.

Ecosystem services conceptual models can be developed for any given site and intervention or created as reference models for a general type of intervention across sites. Given a constrained set of ways in which managers manipulate the natural environment and a fixed number of effects such management can have on the environment and people, it seems possible to establish a reference set of evidence-based conceptual models that become a go-to resource that can provide efficiency and consistency in application. The development of such a repository would transition ecosystem services consideration from an interesting concept to an actionable approach to natural resource management.

This report facilitates development and use of evidence-based ecosystem services conceptual models in federal decision making by presenting a "how-to" guide and illustrative examples.

WHY AGENCIES SHOULD DEVELOP ECOSYSTEM SERVICES CONCEPTUAL MODELS

Funders and developers of infrastructure projects and businesses and managers of natural systems are becoming increasingly aware of and interested in ecosystem services. For example, the World Bank and the United Nations developed the Wealth Accounting and Valuation of Ecosystem Services (WAVES) project to incorporate ecosystem services into sustainable development, the Natural Capital Coalition is working with companies to incorporate ecosystem services into business decisions, and the U.S. federal government is expanding its use of ecosystem services in federal natural resource decisions.

> "Ecosystem services are benefits people receive from nature. Broadly defined, they are the benefits that flow from nature to people, for example, nature's contributions to food and timber; life-support processes, such as water purification and coastal protection; and life-fulfilling benefits, such as places to recreate or to be inspired by nature's diversity. There can also be ecosystem disservices, such as mosquito-borne illnesses and pollen-induced allergies."
>
> *—Federal Resource Management and Ecosystem Services Guidebook*

The idea of more fully assessing how management decisions and policies enhance, sustain, or degrade the benefits nature provides to people is compelling for many reasons. First, including additional outcomes that are important but often not targeted or assessed can more fully and transparently enable assessment of trade-offs. Such clarity allows managers to identify unforeseen benefits or costs and unexpected creation of inequities whereby one community or social group may benefit while others do not (e.g., Tallis et al. 2015). For example, the U.S. Clean Water Act is intended to provide clean water for all. However, its enforcement over 30 years led to the redistribution of U.S. wetlands, unintentionally transferring wetlands and their services, like clean water and fishing opportunities, away from the urban poor and to rural areas where fewer people benefit (Ruhl and Salzman2006). Second, in some cases additional co-benefits or synergies can be identified that may suggest new solutions, partners, or funders. For example, when forest fires led to costly siltation of drinking water supplies in Denver, Colorado, Denver's municipal water utility developed a new partnership with the U.S. Forest Service to establish municipal water fees that support forest management to reduce the risk of catastrophic fires near Denver source waters. And third, thinking beyond the biophysical processes and effects to the social and economic outcomes can identify options that yield the greatest benefits for stakeholders and the public at large. Such an example can be seen in the U.S. Restore Council's recognition of these connections in their goals to restore the Gulf of Mexico's ecosystem and its associated clean water, recreation, and income-generating benefits to the gulf states' populations.

Academic research on ecosystem services is abundant (Seppelt et al. 2011), and numerous guides describe consensus methods that can be used by practitioners (e.g., NESP 2016; Waite et al. 2014; TEEB 2009, 2010; NRC 2004; WBCSD 201l; Brown et al. 2014). Some recently produced tools, toolkits, and worksheets (Table 1) give resource managers and decision makers some simple, transparent, and low-cost ways to reflect ecosystem services in their decision making. Nevertheless, ecosystem services are broadly considered only when managers, decision makers, or project partners are knowledgeable and interested, and when there are resources for more complex analysis conducted by consultants or partner organizations (e.g., the Natural Capital Project). Ecosystem services likely need to be incorporated into agency and decision-specific tools before their consideration will be widespread.

Table 1. Ecosystem services toolkits

ES toolkit	Description
Tessa	Site-based assessment of ecosystem services ***Includes:*** site-based data, measurement, uncertainty guidance ***Does not include:*** valuation, distributional assessment, monitoring
Canadian ES Toolkit	Assessment for decision making for managers and analysts ***Includes:*** scoping and assessment workshops, conceptual model frameworks, valuation tools, indicators, data gathering methods, policy integration methods Does not include: monitoring methods, guidance on uncertainty
Conservation by Design 2.0	Guidance document for The Nature Conservancy ***Includes:*** scoping and assessment methods, conceptual model frameworks, non-monetary valuation (multi-criteria methods), return on investment, monitoring) ***Does not include:*** Economic valuation methods, site-based data collection
ValuES	Experience-based and purpose-targeted methods for integrating ecosystem services into policy, planning and practice. ***Includes:*** Example assessments for different purposes, options for indicators ***Does not include:*** standards, worksheets, tools, distributional assessment
Forest Stewardship Council	Demonstration of impact of forest stewardship on ecosystem services ***Includes:*** Overview of methods and how to report ecosystem services claims ***Does not include:*** valuation, distributional assessment, non-target effects

A number of quantitative tools are available for modeling ecosystem services. One is the InVest Toolkit, which focuses on modeling ecological and social variables affecting ecosystem services with GIS tools. Another is ARIES, an artificial intelligence model that takes in available data and creates an ecosystem services assessment. Co$ting Nature is a web-based tool for natural capital accounting and analyzing ecosystem services, identifying beneficiaries, and assessing impacts of human intervention. I-Tree developed by the USDA Forest Service provides a suite of tools that can estimate the benefits of urban and rural forest management.

Another issue to be resolved is consistency. The production of a variety of user-friendly tools and resources may speed implementation; however, if everyone uses different methods, implementation will be inconsistent, making it harder to assess the credibility of any given approach and to compare outcomes across applications. A common conceptual framework, an ecosystem services conceptual model (ESCM), can be a foundation on which to build consistency and credibility in application.

An ESCM can be developed for any given site and context-specific intervention or created as general reference model for a type of intervention. Given a constrained set of ways in which managers manipulate the natural environment and a fixed number of effects such management can have on the environment and people, it seems possible to establish a ***reference set of evidence-based conceptual models*** that become a go-to resource that can provide desired efficiency and consistency in application (Olander et al. 2016). For example, typical national forest plans include a set of common goals such as fire risk reduction, wildlife support, timber production, drinking water provision, healthy forest systems, and increased recreational opportunities. Each of these goals tends to have a related and often overlapping set of management activities; for example, healthy forest management may focus on invasive species and pest management, which can overlap with fire risk reduction and timber production activities. As a result, a fixed set of related conceptual models can potentially cover the most common management needs for national forest planning (Olander et al. 2016). Each model in this conceptual model reference set can come with associated evidence (research reviews), quantification methods (information on tools, models, and so on that can be used for quantifying identified outcomes), and a list of critical indicators (with information on how they can be measured and included in monitoring). The reference set of models will provide an implementation tool targeted to managers' needs that will foster consistency and credibility in application.

Conceptual models have been proposed as a transformative approach to holistic and systematic understanding of how management strategies and policy actions alter ecosystems, the services they sustain, and ultimate human wellbeing in complex social-ecological systems (NAS 2017; Tallis et al. 2017; Stem and Flores 2016; Potschin-Young et al 2017; Wainger and Ervin 2017; Salafsky 2011; Margoluis et al. 2013; Kelble et al. 2013). Agencies and experts that worked with the National Ecosystem Services Partnership (NESP) over the years have identified conceptual models as a useful tool for streamlining environmental impacts statements, engaging stakeholders, encouraging a common understanding among experts, and improving project planning and alternatives assessments (NESP 2016). Non-federal land managers like The Nature Conservancy (2016) use similar methods. Conceptual models can also be useful for prioritization by allowing better comparison of projects, selection of key indicators (Brown et al. 2014; NAS 2017), visioning efforts (NOAA Office for Coastal Management, NH Department of Environmental Services Coastal Program, and Eastern Research Group 2016), and identification of knowledge gaps and research priorities. These models can help incorporate ecosystem services into decision making by helping to

- Get stakeholders and experts on the same page.
- Provide an intuitive entry point for those new to considering ecosystem services because no particular expertise in ecosystem services is needed to understand these models.
- Capture priorities and link them to interventions in a transparent and systematic way.
- Make sure there are no critical outcomes/impacts that are missing from consideration to help identify unintended effects both positive and negative.
- Provide an evidence-based qualitative assessment of ecosystem services implications of potential interventions/alternatives/scenarios that indicates the expected magnitude and direction of change.
- Provide a common foundation of best available science to reduce time and expertise needed for use and to reduce duplication of effort.
- Identify critical information or research gaps that generate significant uncertainty for decision makers.
- Identify a subset of socio-economic metrics that best capture important endpoints.
- Provide consistency in services assessed, evidence considered, and metrics selected.
- Provide a consistent and credible foundation for qualitative assessments, quantitative assessments, or monetary or non-monetary valuation where such methods are desired.

Despite the potential usefulness of these models there are few examples and little-to-no guidance for agencies on how to construct and use them (Box 1). This report presents "how-to" guide for developing evidence-based ecosystem services conceptual models.

Box 1. Four Efforts to Develop ESCMs for Federal Agency Decision Making

Four efforts are underway to develop ESCMs for federal agency decision making.

The Council on Food, Agriculture & Resource Economics hosted a series of experts to assess three decision contexts for U.S. Department of Agriculture conservation programs: (1) optimizing conservation programs to provide pollinator habitat services, (2) using conservation programs to generate ecosystem services benefits from improved water quality, and (3) using forest management policy to sequester carbon (Wainger and Ervin 2017). For the first two contexts, the experts developed evidence-based ESCMs providing a foundation for an ESCM reference library for USDA.

The National Ecosystem Services Partnership (NESP) at Duke University, through the project that funded this report, has been building ESCMs for the Bureau of Land Management on solar power installation and for the National Estuarine Research Reserves System (NERRS) on salt marsh restoration. The work with the National Oceanic and Atmospheric Administration's NERRS may expand to include oyster reef and mangrove restoration.

Duke University (through NESP), The Nature Conservancy, and the Harte Research Institute in partnership with the Bridge Collaborative with support from the National Academies of Sciences Gulf Research Program are planning the development of an initial ESCM reference library for restoration activities within the Gulf of Mexico to support federal and state restoration efforts (GEMS).

The Institute for Nature Resources at Oregon State University and Duke University (NESP) will be working with the Department of Defense Strategic Environmental Research and Development Program to explore how ESCMs could form the foundation for a predictive model to support base management decisions.

OVERVIEW OF CONCEPTUAL MODELS

ESCMs can show not just how an intervention (or external stressor) can bring about biophysical and ecological changes but also how those changes can affect human well-being and social welfare. ESCMs can also indicate direct, non-environmentally mediated effects on people (like jobs or displacement) (Figure 1) (Olander et al. 2017; TNC 2016). The conceptual models proposed here are similar to models used by others and can be called results chains, influence diagrams, and logic models (see Table 2 for more examples). These models can be used as a starting place for the use of any ecosystem service method or tool. When provided as a decision-specific resource for managers, they can also simplify and streamline incorporation of ecosystem services into decision making. We use the idea of conceptual models very generally to allow flexibility in application. Although ESCMs can play an integral role in planning and implementation, prioritization, and selection of performance measures or indicators, they are only one tool in a toolkit that needs to support the decision and adaptive management process.

Figure 1. Illustrative conceptual model showing direct benefits to people and environmentally mediated ecosystem services

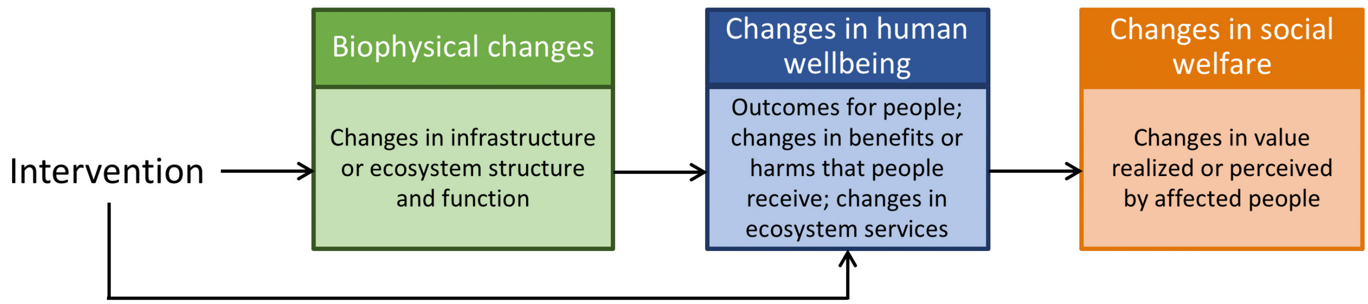


Table 2. Variants of conceptual models adopted in different sectors and disciplines

Discipline and sector	Conceptual model variants	Exemplary references
Medical/health	Directed acyclic graphs (DAGs) Logical framework analysis (Logframe) Single-chain epidemiology modeling	(VanderWeele and Robins 2007) (Lerer 1999) (Joffe et al. 2012)
Development	Path diagram analysis Input-output model Log frame Results chain	(Duncan 1966, Cantor and Land 1985) (Druckman and Jackson 2009; Miller and Blair 2009) (Coleman 1987) (Stem and Flores 2016)
Environmental/decision analysis	Result chain Cascade model Structural path analysis Fuzzy modeling Bayesian belief network Drivers–Pressures–State–Impacts–Responses (DPSIR) Causal Analysis/Diagnosis Decision Information System (CADDIS)	(Margoluis et al. 2013; Salasfsky 2011) (Potschin–Young et al. 2017) (Grace 2006) (Özesmi and Özesmi 2004) (Marcot et al. 2006) (Svarstad et al. 2008) (EPA 2004)

Source: Adapted from Table 1 in Qui et al. (2018).
Note: This list is not exhaustive.

Types of Conceptual Models

Variations of conceptual models can be adapted and used for different aspects of and steps in decision making. This report describes three model variations.[1]

- ***Exploratory conceptual models*** are preliminary models that illustrate major relationships but are most often incomplete and unrefined. These preliminary models are often developed over the course of a few hours or a day with the input of experts, practitioners, and stakeholders that bring together a range of perspectives (e.g., cultures, roles, socio-economic status) and knowledge (e.g., ecology, economics, medicine, anthropology). These models help stakeholders and experts get on the same page and communicate priorities. However, they can be challenging to produce when teams are unfamiliar with ecosystem or human well-being aspects of a system. In these situations, general conceptual models provide a starting point for exploration.

- ***General conceptual models*** are completed and refined models that capture the cascade of changes through the system and that fully articulate, in generalized categories, the benefits for and impacts on human well-being. These models are designed to be the parent model for a type of intervention (e.g., salt marsh restoration, utility-scale solar development) that can be adapted to different contexts. The models can be developed by aggregating common elements across site-specific conceptual models for a given intervention or by directly creating a generalized model, which will require expert knowledge and evidence review. In addition to helping stakeholders and experts get on the same page, these general models are particularly useful for providing consistency in application/implementation and, often, a key set of services and indicators to include. They also provide a user-friendly starting point for those not knowledgeable about ecosystem services, and they can increase efficiency of implementation. General conceptual models made accessible through a library type resource can ensure teams have access to the best available science and can reduce duplication of effort.

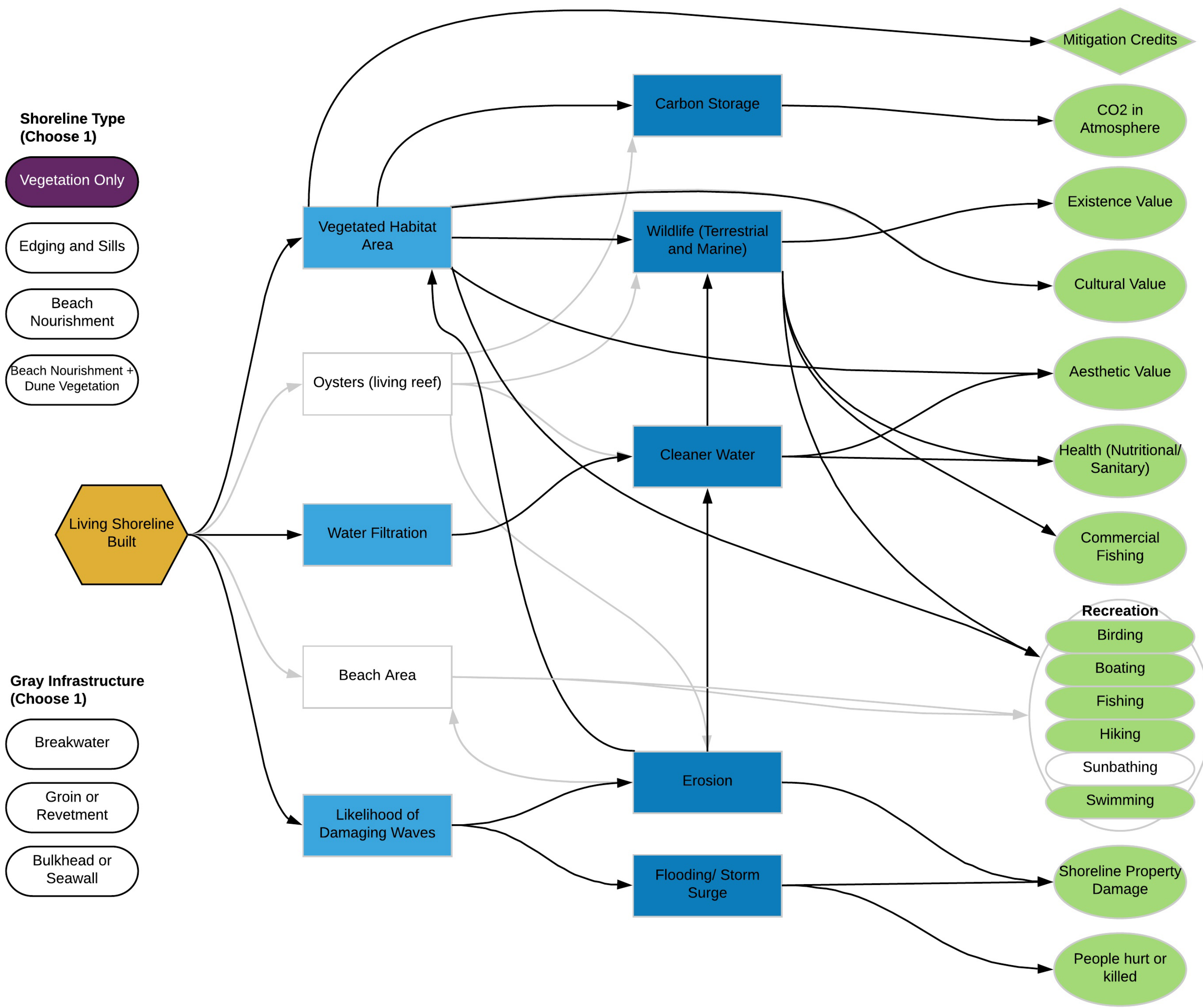
- ***Specified conceptual models*** are complete and refined versions of either exploratory or general models that are adapted and specified for a particular place and decision context. These models are more likely to follow best practices and to include measurable indicators (Figure 4). These are the models that will most often be used in decision making because they'll have stakeholder and expert buy in and will be targeted to the relevant decision context. These models can be developed directly from an exploratory model when no general model exists, but it will be most efficient to adapt them from a general model when possible. Adapting a general model to a local context should require comparatively less time and effort and less expertise in ecosystem services. It can also provide a common level of underlying knowledge (best available science) and offer consistency in application. Specified conceptual models can be the foundation for further assessment of evidence for a particular site or context, construction of a predictive model, or monetary or non-monetary valuation.

Because general conceptual models can be adapted to and specified for different contexts and applications to streamline application and enhance consistency of ecosystem services consideration, their use could be incorporated into agency directives, manuals, handbooks, or other resources provided to managers. Agencies—with help from consultants, environmental NGOs, and other interested partners—could develop a limited reference set of general conceptual models and associated evidence libraries (collections of studies, models, and other information that explain the relationships between arrows in a conceptual model) for common types of interventions that typically have important effects on ecosystem services. These general models would then provide a common set of endpoints (including ecosystem services) to be considered, a common set of metrics/indicators to use, and credible best available science evidence (vetted by the agency and other experts) as a starting place for assessment. They could also be populated with quantification methods to allow consistency in quantification across applications.

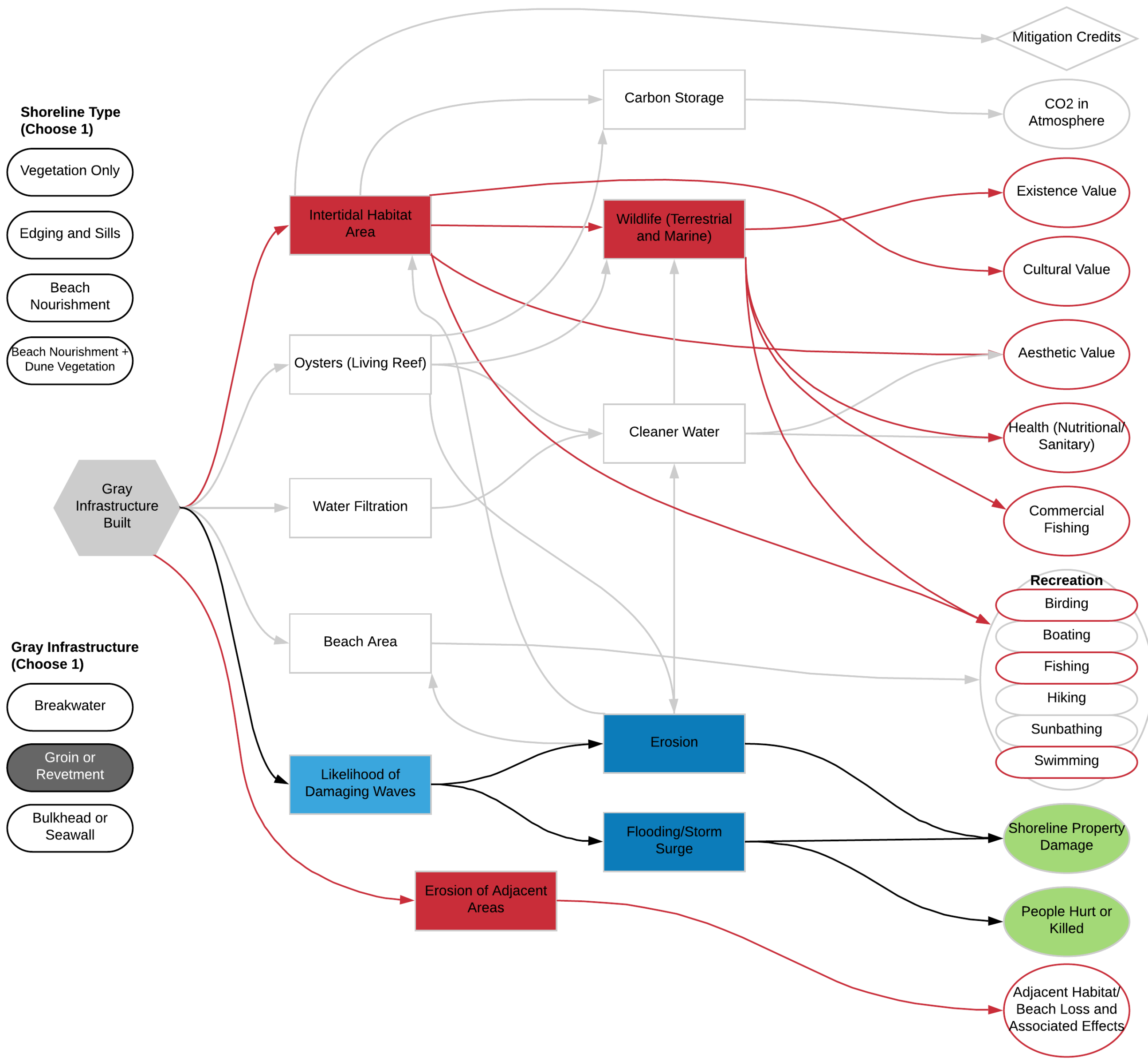
General conceptual models could be useful for applications like streamlining National Environmental Policy Act (NEPA)-related assessments and building common assessment templates for activities ranging from forest planning (Olander et al. 2016), to coastal restoration (Mason et al. 2018), to energy development siting (Warnell et al. 2018), and to incentivizing of native plantings in agricultural fields (Iovanna et al. 2017).

[1] In the field of structural equation modeling these different types of conceptual models are called causal diagrams and have been termed the meta model, causal model, and analytical model (Pearl 2012; Grace et al. 2012).

Figure 2. Conceptual models comparing green and gray infrastructure alternatives for coastal protection
(a) Causal pathways associated with a vegetative living shoreline



(b) Causal pathways associated with a groin or revetment



Note: Alternative ESCMs can be built using the same base model, and different interventions can be "turned on" (using shaded boxes) to easily display how these alternative interventions cascade through the system and result in different outcomes.

Model Considerations

Models can be developed for specific interventions and ecosystems, and it may also be possible to develop an overlapping system of models that show how different interventions in one ecosystem compare (how outcomes are similar or different) or how similar interventions in different ecosystems compare (Figure 2). Such a system may be especially useful where there are significant overlaps in the types of outcomes and evidence across interventions or habitats (e.g., Appendix A).

Ecosystem Service, Social, and Economic Endpoints

ESCMs always start with an action or an intervention, then cascade through the resulting changes in the system to indicate intended and unintended outcomes (Figure 1). Sometimes these outcomes are expressed as values or progress toward human welfare goals. Different experts use different terms for model endpoints. For example, the environmental and natural resource management communities often refer to the intended change in the system as an "outcome," whereas the health and development communities often call intended changes "impacts." Groups using ESCMs will be helped by conversations where team members agree to definitions of key terms at the outset of design.

Sometimes ESCMs end with ecosystem service and social outcome endpoints (blue boxes in Figure 1). These endpoints are meant to align with the concept of benefit-relevant indicators (BRIs), which are indicators that reflect changes in ecological condition that are relevant to people (NESP 2016; Olander et al. 2018). Although the endpoints listed in exploratory and general conceptual models are often not BRIs, they represent categories of services or benefits that could be specified to BRIs that are relevant to a particular site. If economic effects of ecosystem and social services are important, the model can be extended to include these values (orange boxes in Figure 1). Various economic indicators can be used, some of which may be aligned with monetary valuation methods. Economic effects are not always required. Stopping at benefit-relevant indicators may be sufficient for many decisions. Ideally, BRI or economic indicators will be selected and used for measurement and monitoring.

Spatial and Temporal Considerations

ESCMs are a conceptual schematic to help think through the logic of changes in a system but do not depict all important aspects of these changes. They can sometimes include a simplified indication of the temporal dimensions of changes, such as temporary changes versus persistent changes, but often the temporal dimension is missing. These models do not explicitly show the spatial dimensions of service provision, but they can help identify where spatial dynamics will be critical for example where distance to a resource or exposure can affect human use or impact. These spatial issues should be captured in evidence collection.

Feedback Loops

To avoid introducing complexity into the ESCMs, we do not initially represent system feedbacks, but they can be added in to these models where they are considered critical.

External Drivers

ESCMs include only outcomes that are affected directly or indirectly by the intervention of focus. Typical external drivers include climate change, land use change, invasive species, and storms, all of which should be captured as "other factors" in evidence collection. It is useful to identify the external drivers when they are likely to have a strong effect on outcomes, perhaps even stronger than that of the intervention.

Information on feedbacks, spatial and temporal dynamics, and external drivers should be built into any quantitative version of ESCMs.

HOW TO DEVELOP EVIDENCE-BASED CONCEPTUAL MODELS

The development and use of conceptual models can range from simply sketching and using exploratory models to creating fully specified and refined evidence-based models with selected metrics and evidence evaluation. These models might be taken a step further to provide a foundation for development of predictive quantitative models. Development of the conceptual models can involve different steps and produce different products, which are detailed in this section (Table 3).

Table 3. Steps in developing conceptual models and related resources and a description of their use

Ecosystem service/ social outcome	Details
1. Conceptual models	Getting stakeholders and experts on the same page Transparently communicating what is considered in an assessment
Exploratory	Same as above and providing a starting place for building general or specified conceptual models
General	Providing a foundation for consistency in application/implementation Providing a common starting place and often a key set of services and indicators Providing an onramp and user-friendly starting point for those not knowledgeable about ecosystem services Reducing duplication of effort
Specified	Providing the foundation for further assessment of evidence or building of a predictive model to support other assessments like valuation, risk assessment, cumulative effects assessment, and so on Providing a starting place to consider important socio-economic indicators for monitoring
2. Specifying outcomes	(Required for building a specified conceptual model) Adapting general or exploratory models to a specific site or context Developing indicators
3. Model assumptions	Clarifying hypotheses and refining models (which often leads to a process of adding missing nodes and removing extraneous ones) Identifying necessary evidence
4. Evidence library	Assessing and documenting what is generally known about the relationships in the model (collection of evidence for each assumption) Providing an initial indication of magnitude and direction of change where it is known Refining model relationships (add/drop nodes and arrows as needed to represent what is learned)
5. Evidence assessment	Documenting confidence in evidence for each relationship described in the model Further informing selection of indicators for monitoring and evaluation (more important where we have less evidence) Further specifying evidence gaps to prioritize research agendas
6. Strength of evidence map	Visualizing and communicating level of confidence in existing evidence Identifying gaps in understanding that could create risks for decisions

Note: How many and which of these ESCM-related resources are needed will depend on the decision process.

Ideally, conceptual models are developed in collaboration with a diverse set of experts and, when relevant, the stakeholders and communities that will be affected. The Bridge Collaborative has identified some general principles to improve trust and collaboration in the model development process (Box 2).

Box 2. Principles for Collaboration

Use evidence to inform decisions.
By learning from evidence of what has and has not worked in the past, decision makers can make faster progress, cut costs, and avoid failures and backtracking.

Act now and learn by doing.
Acknowledge that progress can be made now even in the absence of complete understanding, evidence, or political or social alignment. Encourage flexibility and intentional learning along the way to improve actions and impact.

Seek and respect other perspectives.
Believe and act as if goals for one type of objective (e.g., economic) may be met more effectively, efficiently, or sustainably by embracing ideas, interventions, approaches, or concepts from other areas (e.g., conservation).

Be intentional about inclusion.
Use established tools for including and empowering under-represented groups.

Strive to do no harm.
Seek out and circumvent potential harmful outcomes, strive for positive outcomes that do not come at the expense of negative outcomes for other sectors (economic, health, environment), other groups, or future generations. When trade-offs occur, make efforts to minimize and mitigate negative outcomes.

Share information.
Share data, frameworks, and concepts quickly, openly, and transparently.

Source: Adapted from the Bridge Collaborative (Tallis et al. 2017).

1. Build ESCMs

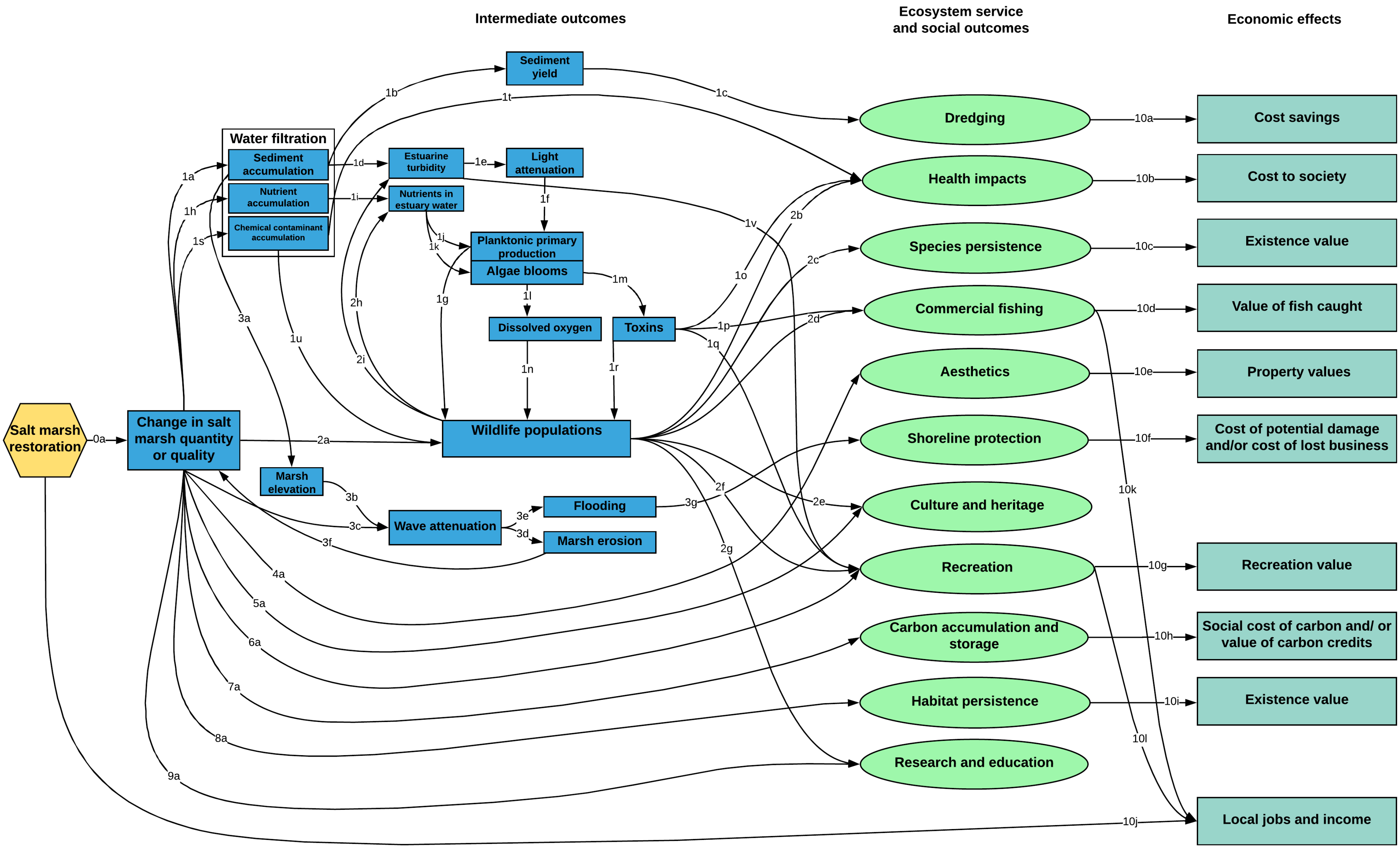
An exploratory model is the first conception of how selected interventions cascade through ecological and social systems and change outcomes for human well-being. Developing an exploratory model can take anywhere from one hour to a few days, depending on how many different experts and stakeholders need to be included and how refined the initial model needs to be. Different models must be developed for each type of intervention or alternative project/policy scenario (e.g., salt marsh restoration, utility-scale solar development, payments for native plantings in agricultural fields).

Exploratory models start with a single intervention or management action (or, if necessary, with a set of linked interventions), then map changes in the system to identify the outcomes important to the people involved (e.g., Figure 3). It may be possible to link exploratory models that cover multiple interventions or ecosystems, because there are often significant areas of similarity or overlap (Figure 2), but it is usually simpler to build the initial models independently.

Interventions can result in direct social and well-being outcomes as well as outcomes mediated through ecosystems. Both are represented in Figure 1. Four questions can help start the model building process (Olander et al. 2015):

- How does a policy, management decision, or program action affect biophysical and ecological conditions (e.g., infrastructure, ecosystem structure and function)?
- How do the changes in biophysical and ecological conditions lead to changes in the delivery of goods and services, including ecosystem services to the specific people who are using them, affected by them, or appreciating them (e.g., availability of irrigation water for farmers, sustainability of rare bird population)?
- How do those changes in the delivery of good and services affect benefits or costs to individuals or groups (e.g., time spent in traffic, cost of hospital visits, additional fish caught, value of property)?
- How does the policy, management decision, or program directly affect people (e.g., job creation, access to resources, capacity building)?

Figure 3. Illustrative general ecosystem services conceptual model for salt marsh restoration

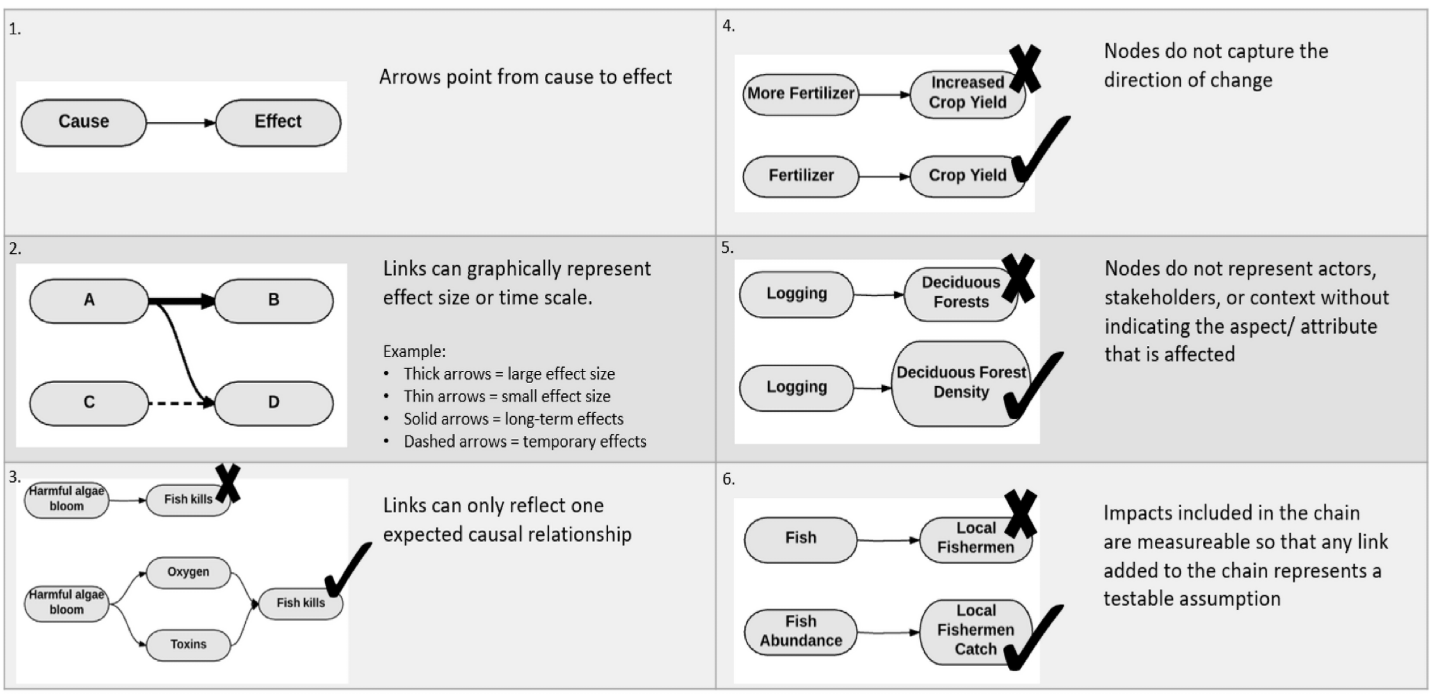


Source: Mason et al. (2018).

Endpoints in the exploratory (and the general) models are often categories of outcomes but ideally, they should link to a specific beneficiary group or groups. For example, instead of water storage capacity, the end point would be late-season water available for boating recreation; instead of aesthetics, the endpoint would be viewshed from cultural heritage sites; and instead of air quality, the endpoint would be particulate levels for populations vulnerable to respiratory distress. It can be helpful to consider lists of ecosystem services or beneficiaries. For example, the TESSA tool provides a list of services from the Common International Classification of Ecosystem Good and Services (CICES 2017). The Canadian Ecosystem Services Toolkit also provides a list of services (Table 1.1, page 15; Preston and Raudseppe-Hearne 2017). Lists could also be pulled from other ecosystem services classification documents like the Final Ecosystem Goods and Services Classification System (Landers and Nahlik 2013) and the National Ecosystem Services Classification System (U.S. EPA 2015). The development and refinement of these models is an iterative process. Exploratory models are not expected to be perfect and will evolve when assumptions and evidence are considered. As models are refined and specified, some basic rules, shown in Figure 4, can help ensure some consistency and quality for these models (adapted from Tallis et al. 2017).

Not all of the illustrative ESCMs presented here fully follow these rules. A few of the rules can be difficult to fully implement in the general models depicted here. But use of these rules would improve comparability and transferability of ESCMs across projects and geographies. It would also help ensure greater clarity and transparency in what the models communicate and thus ease collaboration with experts from the many disciplines that are relevant to ecosystem services.

Figure 4. Rules for building conceptual models



Although ESCMs are often developed on white board, chalk boards, or paper, computer software can be useful for organizing, simplifying, and presenting them in a visually accessible way. A number of software options exist for developing clean models that are easy to interpret (Table 4). Organizing the models to reduce overlap of arrows and to group like nodes together can also be facilitated with computer software. If each of the pairwise nodes is entered into a spreadsheet, a software package-like igraph can be used to run algorithms that will display the nodes and links in an aesthetically pleasing way (see Appendix B for an example) (Csardi and Nepusz 2006).

Table 4. Software to support ESCM development (not a comprehensive list)

Software	Functionality
Powerpoint	Most people have it already. It is a bit clunky to use and offers no special features.
Lucidchart (our favorite)	It allows overlays for adding more detailed submodels or text explanations. It can be shared freely and easily on the cloud. It is low cost to purchase, and a free trial version is available.
Microsoft Visio	This microsoft-supported diagramming software can create professional-looking flowchart diagrams that are easily sharable on the cloud. It is expensive to license.
Miradi	The miradi software package makes it is easy to link miradi diagrams in the project management cycle. If you only want to create flowchart diagrams, Miradi is likely not the best option because it has many other features and is relatively expensive to license.
Analytica	Only for users who would like to adapt conceptual models into quantitative, predictive models. Model diagrams can be attached to datasets and mathematical formulas. A free version of the software is available.

To compare alternative interventions using a single base model (see Figure 2), it is important to begin by building individual models for each intervention. The similarities among these models can be identified, and those links and pathways form the core, base model framework. Variations in the models that are being combined can be added to that core model. These variations (for different alternatives or locations) can then be "layered on" to the core model framework to show how alternatives differ as they cascade through the system.

2. Specify Outcomes (Building-specified ESCMs)

It is often difficult to include all the details in conceptual models, particularly in general models. Often the endpoint nodes remain as categories (e.g., recreation), which need to be specified (e.g., fishing, hiking, mushroom picking). To specify a general model to a specific site or context, or to expand the details captured by an exploratory model, a simple process can be used to identify and prioritize the more specific outcomes and beneficiary groups associated with each outcome category. This process, when informed by the latest evidence, also helps to identify negligible outcomes that can be removed from further assessment. This process involves (1) identifying the endpoints that are categories, (2) suggesting more specific endpoints that may be important, and (3) getting feedback on which ones to include and which to leave out (see Table 5 for an example). These more specified outcomes can be added to the model to clarify the specific outcomes of interest, to help target reviews of evidence and analysis, and to increase the relevance of the model. In some cases, it may be necessary to use this process to narrow the scope of the model and to prioritize a set of outcomes, particularly if quantification or valuation is required. This exercise can take place with the groups of experts and stakeholders involved in model development, and it can be undertaken concurrently with model building.

Different methods such as voting, surveys, or interviews could be used to prioritize the list. However, if models are being dramatically simplified through a group process, use of evidence reviews and libraries is recommended to ensure that highly likely, large impacts are not removed from consideration. If the expert group has relatively narrow representation in terms of expertise, many potential outcomes can be dropped through prioritization solely on the basis of familiarity. Use of evidence in these cases will ensure that lack of knowledge does not lead to the exclusion of major impacts (either co-benefits or negative impacts).

Table 5. Illustrative questions to elicit specified outcomes and endpoints for a conceptual model for salt marsh restoration in San Francisco Bay

Ecosystem service/ social outcome	Details
Health impacts (water quality)	Health impacts could include illness from exposure to contaminated water by swimming or drinking. **Are these impacts important or relevant in San Francisco? Which contaminants introduce the greatest health risks? Are SF populations more vulnerable to certain contaminant risks because of other prevalent health conditions?**
Health impacts (dietary)	Health impacts could include nutritional changes based on changing fish/ shellfish populations and availability. **Which groups of people rely on fish/shellfish from SF Bay? What portion of their protein or micronutrient needs are met by local fish/shellfish? Do SF residents depending on wild local fish/ shellfish have access to dietary alternatives with similar nutritional qualities?**
Existence	Existence value represents the value that people place on the existence of elements of the ecosystem—for example, the marsh itself or specific species that use the marsh as habitat. Often endangered, threatened, or charismatic species have high existence value. **Which population's existence values do people care about capturing (local SF bay residents, U.S. residents, global residents)? Which species are most valued by the focal population? Which marsh characteristics are most valued?**
Commercial fishing	Commercial fishing represents the amount (or value) of fish/shellfish extracted from San Francisco Bay. **Which commercially harvested species (if any) are most economically important to Bay Area fishers? Which commercially harvested species are most culturally important to Bay Area fishers? Which commercial stocks are most likely to be affected by possible interventions?**
Aesthetics	Aesthetic value represents the value that people place on the beauty or scenery provided by the marsh, stream, or both. **What scenic elements of these marshes do people value most? Do different groups of people value different scenic elements? Do property values reflect marsh or stream aesthetics in the area?**
Culture and heritage	Cultural value represents any value provided by the marsh, stream, or both that is an element of culture. This value could include historic sites, species that have specific cultural meaning, or sites with religious/spiritual importance. **Are there any cultural sites or species of note in the Gallinas Creek watershed that would be relevant?**
Recreation	Birding, boating, hiking, biking, swimming, and fishing have been identified as important recreational activities in this area. **Should this list be changed?**
Shoreline protection	Shoreline protection can include maintenance of the coastline, protection of coastal properties and infrastructure, and protection of coastal habitats. **Are there other local shoreline protection concerns?**

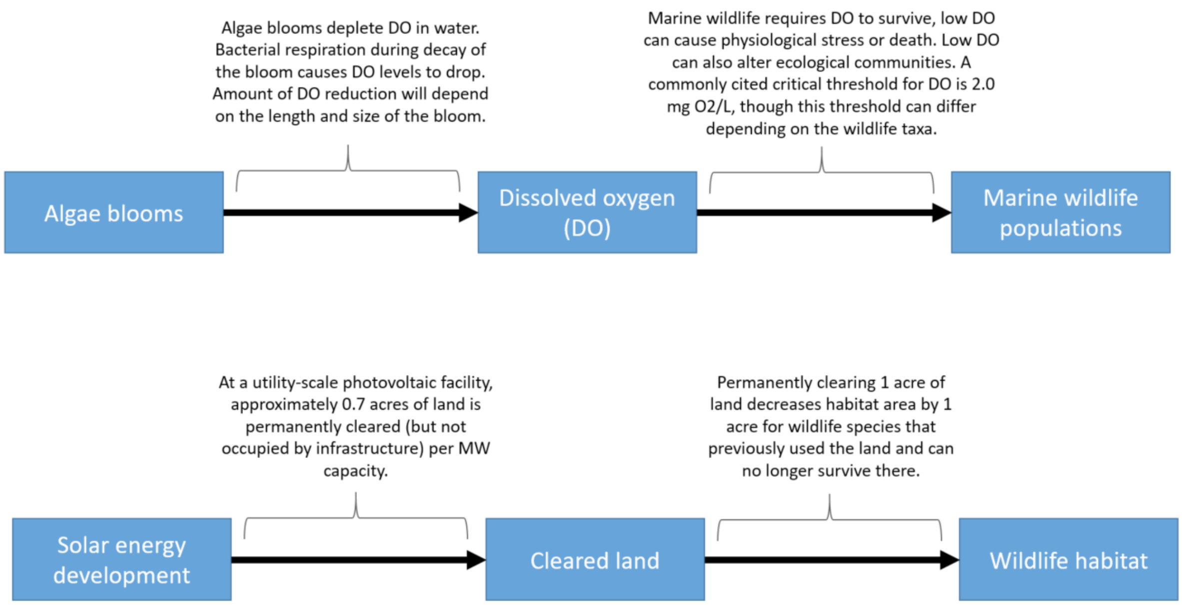
Source: Slightly adapted from Mason et al. (2018).

3. Articulate Model Assumptions

When developing a conceptual model, it is important to articulate the assumed relationships, the hypothesis, for each link connecting two nodes in the model (Figure 5). Doing so will help refine the model, ensuring that no critical links are missing, that nodes are measurable, and that links are testable hypotheses or assumptions representing one causal relationship (Figure 4). It is common for groups new to ESCM development to include 'leaps of faith' in their logic, usually reflecting a lack of specific knowledge within the group about how changes in the system could happen. For example, a group accustomed to planning for forest management may realize that managing for fire frequency may not only affect forest health, but also affect people living in downwind airsheds. They may add a link in an ESCM from forest thinning to respiratory health. Although this connection may exist, it represents a "leap-of-faith" link, capturing several hypotheses about changes in the system—from forest thinning to likelihood of fire to likelihood of generating smoke particulates to rate of human exposure and vulnerability to smoke. Articulating assumptions will reveal these leaps and help teams use focused outreach to new experts to further clarify their ESCMs.

The statement of assumptions can also quickly reveal differences in understanding or thinking among team members. Teams may think they are on the same page about cause and effect until assumptions are stated. Producing clear statements may reveal different assumptions and allow the team to specify in ways that all understand and agree on.

Figure 5. Example of articulating model assumptions describing the relationship (arrow) between starting and ending nodes



4. Create Evidence Library

Once assumptions are stated, available evidence can be synthesized to test them. Evidence libraries are a collection of studies, models, and other information that support or refute assumptions in an ESCM (see the illustrative evidence library entry from a model on solar energy installation; Table 5). Evidence libraries are used to refine the model further and to determine what is known about the direction and magnitude of changes in the biophysical system, in the production of ecosystem services and social benefits, and in the value of those changes.

A broad use of evidence is appropriate for ESCMs, given the diversity of disciplines they are likely to represent (Tallis et al. 2017). Evidence can include expert opinion (including traditional ecological knowledge, local stakeholder knowledge, and subject matter expertise), measurement results, quantitative/predictive models (e.g., universal soil loss equation for erosion or the SWAT model to assess changes in pollutants or water filtration), qualitative studies, quantitative studies, and theories. Evidence on the magnitude of expected changes can help identify which changes are likely to be significant and important to include and which are negligible and can perhaps be dropped from detailed assessments. The stakeholders and experts initially involved in model development can be a resource for gathering evidence. Additional experts can be brought in to fill in gaps and review evidence. An initial assessment of evidence does not require development of full systematic reviews for each relationship, but it could incorporate systematic reviews done by others. Collections of systematic reviews—like those created by conservation evidence and environmental evidence for environmental topics and by the Cochrane Collaboration for health topics and the Campbell Collaboration for development topics—can be a starting place. Over time and with resources, evidence libraries can be further developed and refined given users' needs. These libraries should contain the following information for each link in the conceptual model:

- Description of the relationship (starts as an assumption but it can become an evidence-based description through development of the library and assessment of evidence)

- Summary of the evidence found relating to the assumption
- List of factors that may result in variation (location, timing, external drivers, and so on) in direction or magnitude of effect described in the assumption
- Summary of confidence in the assumption given available evidence (see next section on evidence assessment)
- List of sources.

Two kinds of information are included in evidence libraries: evidence and examples. Evidence describes general or site-specific relationships between nodes and can include individual research studies, models, calculators, and meta-analysis results. Individual research studies can provide evidence for the existence of a relationship, but they are usually low-quality evidence for contexts other than the one in which the study was conducted (see "Strength of evidence assessment" below).

For links with missing or weak evidence, examples of site-specific studies that could be done at a site or for a particular intervention to fill an evidence gap are provided. In many cases, the example studies are individual research studies conducted in other contexts that are considered part of the body of evidence for the relationship but that also provide a useful example of how the relationship could be assessed in the focal context. The example studies can also be general methods papers that describe an approach but that do not contribute to evidence for the relationship.

An example of evidence for one link can be found in Table 6 and in illustrative evidence libraries for salt marsh restoration and utility-scale solar development that are part of this publication series. Another online evidence library is The Outcomes and Evidence Framework developed by the International Rescue Committee (2016).

Table 6. Illustrative evidence library entry describing the link between solar energy development and water use for solar energy installation on Bureau of Land Management lands

Evidence element	Example from solar energy development conceptual model
Link ID	10a: Solar energy development >> Water use
Description of relationship	Photovoltaic solar plants consume 11–226 gallons of water per MWh of electricity produced. This consumption includes water used to manufacture photovoltaic panels and for dust suppression during construction.
Summary of evidence	One meta-analysis harmonized lifecycle water consumption estimates for photovoltaic power plants and found the water consumption values listed above. It included 23 estimates of upstream (raw materials, manufacturing, construction, and transportation) and downstream (decommissioning) water consumption for crystalline silicon panels and 9 estimates of water consumption during operation.
Strength of evidence	Fair: The meta-analysis of water consumption by solar energy facilities was constrained by the number of studies available, and the included water consumption estimates ranged over an order of magnitude. This analysis did not account for site-specific factors including climate that may influence water consumption.
Other factors	The amount of water required for manufacturing photovoltaic panels varies by specific panel technology; for example, cadmium telluride panels require less water to produce than crystalline silicon panels.
Sources	Meldrum, J., S. Nettles-Anderson, G. Heath, and J. Macknick. 2013. "Life Cycle Water Use for Electricity Generation: A Review and Harmonization of Literature Estimates." *Environmental Research Letters* 8. stacks.iop.org/ERL/8/015031. Sinha, P. 2013. "Life Cycle Materials and Water Management for CdTe Photovoltaics." *Solar Energy Materials and Solar Cells* 119: 271–275. https://doi.org/10.1016/j.solmat.2013.08.022.

Source: Warnell, Olander, and Mason (2018).

5. Assess Evidence

Assessing the available evidence for a particular link requires two considerations**.** The first is the ***existence*** of a relationship between the two nodes—does a change in one node lead to some change in the other? The second consideration, which is dependent on the first, is the ***predictability*** of that change. Do we have evidence to show how one node will change with the other? Our evidence libraries and evidence assessment focus on the evidence for ***existence*** of a relationship, but where possible, we also highlight the ***predictability*** of the relationship. For general conceptual models, it is also useful to note whether predictive models are generalizable and how they might be transferred to other sites or contexts.

There are a number of common criteria for assessing the quality of evidence: types of evidence (is there more than one?), consistency of results (do multiple sources and types of evidence suggest similar results?), accepted methods (are the methods well documented and accepted?), and applicability (are the results likely to be relevant to the context or site of interest?) (Nichols et al. 2011; Balshem et al. 2011; Bilotta et al. 2014; Collaboration for Environmental Evidence 2013; Daly et al. 2007; Munn et al. 2014; Mupepele et al. 2016). One inclusive evidence assessment tool recently developed by the Bridge Collaborative provides an assessment matrix for evidence from multiple sectors—health, environment, and development—making it a good fit for ecosystem services applications (Table 7) (Tallis et al. 2017). Other broad evidence assessment tools that could be used include USDA's method for nutrition evidence (USDA 2015) and the approach used by the Intergovernmental Panel on Climate Change (Mastrandrea et al. 2010).

Table 7. Evidence assessment matrix

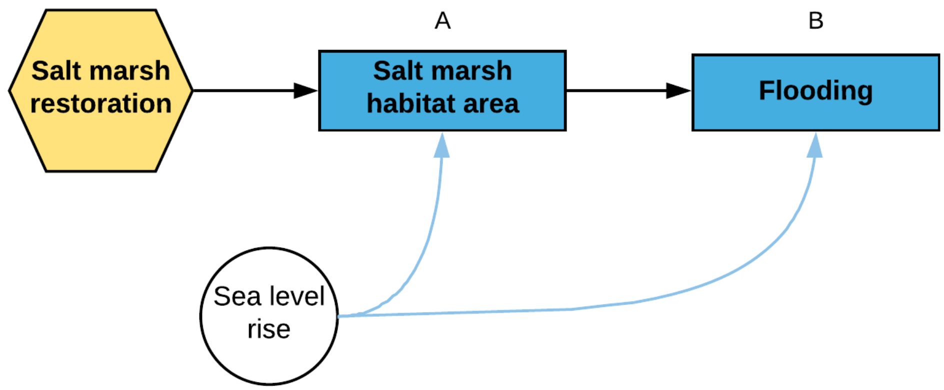
	Criteria			
Confidence level	**Types of evidence**	**Consistency of results**	**Methods**	**Applicability**
High	Multiple	Direction and magnitude of effects are consistent across sources, types of evidence, and contexts	Well documented and accepted	High
Moderate	Several	Some consistency	Some documentation, not fully accepted	Some
Fair	A few	Limited consistency	Limited documentation, emerging methods	Limited
Low	Limited, extrapolations	Inconsistent	Poor documentation or untested	Limited to none
None	None	Not applicable	Not applicable	Not applicable

Source: Adapted from Bridge Collaborative strength of evidence template.

When an evidence assessment template is used for a particular project, it is helpful to explicitly define how the criteria are being applied (e.g., what are the possible types of evidence, and what constitutes "multiple" types versus "several" types?). Explaining why evidence was given a certain score is helpful for others using the library who might want to consider different criteria for scoring.

Strength of evidence also needs to take "other factors" into consideration. Consider a hypothetical relationship between nodes A (tidal marsh habitat area) and B (coastal flooding). A large body of evidence might describe the existence of the relationship, but other factors like sea-level rise might influence B. Those other factors might not appear in the conceptual model diagram (because they are not affected by the intervention), but they may be important in the estimation of coastal flooding. The existence of these other factors will likely lower the evidence grade between nodes A and B because they reduce the applicability and consistency of the evidence that links A and B. Alternatively, they can be added to the ESCM, and the strength of evidence for their influence on intervention effects can be directly considered (Figure 6).

Figure 6. Example of the effects of an external factor (sea-level rise) on multiple nodes (A and B) in a conceptual model



Note: Integration of the effect of an external factor is important because it will affect the strength of evidence between nodes. That effect could also be captured in an evidence library.

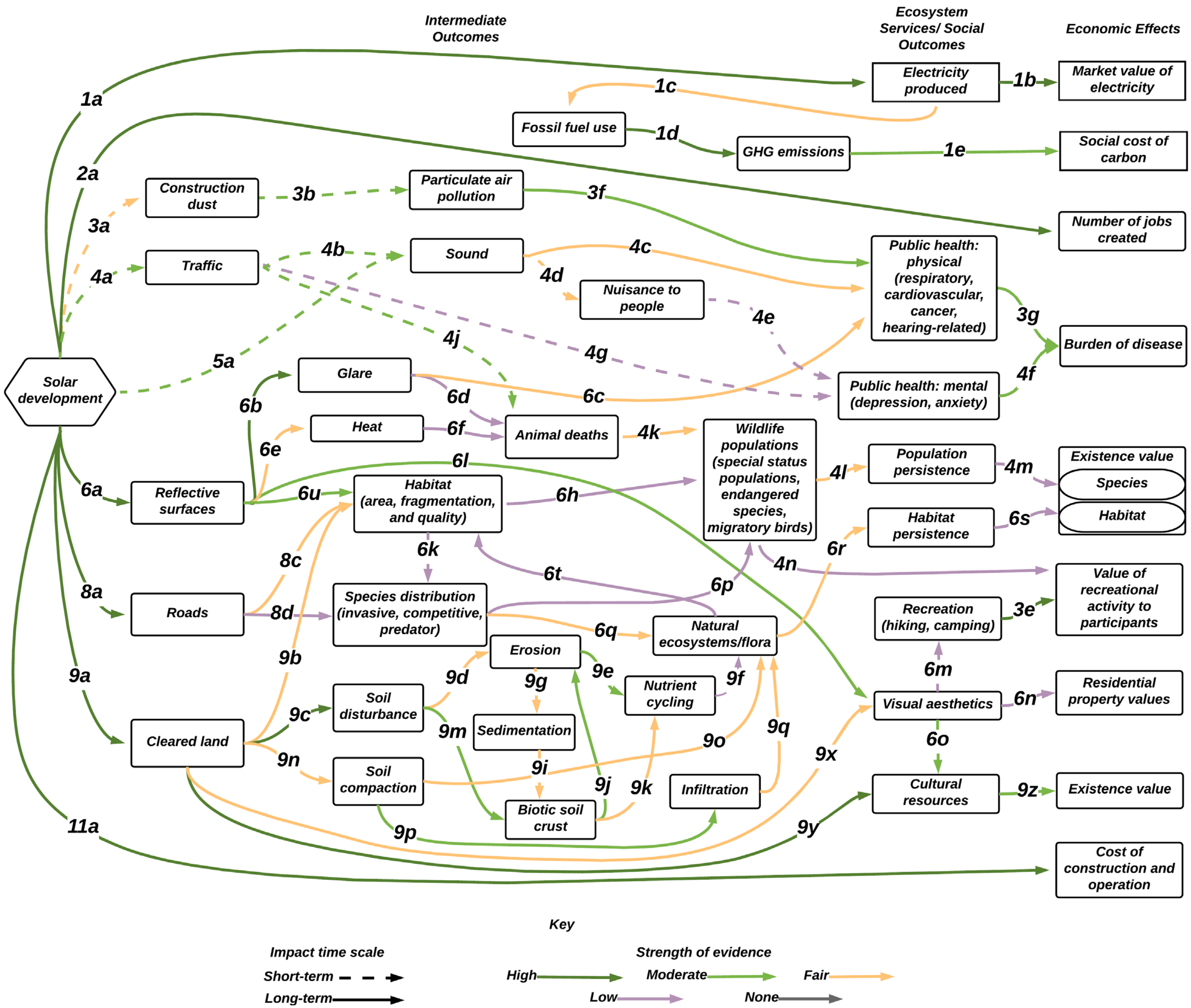
Notably, the evidence evaluation may be less useful for some elements of generalized conceptual models. For example, some nodes will need to be specified once a local site is chosen. For example, a "wildlife populations" node is general, and specific wildlife species will have to be selected when the general model is applied at a local site. Due to the general nature of that node and our inability to make definitive statements about the connection between other nodes and general wildlife populations, the evidence grade for those links in a general model will often be comparatively low. In many cases, these nodes will include a list of example studies to provide an illustration of how one might assess such linkages once a more specific node is selected for a local site.

6. Use Strength-of-Evidence Map

To display confidence in evidence for an evidence library for which we want to include details on intermediate outcomes as well as final outcomes, we suggest using the conceptual model framework.[2] The conceptual model can be used as the template, with arrows colored to represent the evidence grade. We call these strength-of-evidence maps. See Figure 7 for an example of an ESCM that shows a strength-of-evidence map that visualizes evidence evaluation information for solar developments. Strength-of-evidence maps can be used to inform research priorities because they identify research gaps and provide context for determining which gaps might be most important to address significant uncertainties or risks for decision makers.

[2] A number of researchers use what they call evidence-gap-map tables to visually summarize the number of studies done to test a broad suite of interventions and a broad suite of targeted outcomes. A number of examples (Snilstveit et al. 2017) have been developed by 3ie and others. Evidence-gap-maps do not assess the causal relationships within a model like the ESCM strength-of-evidence map presented here.

Figure 7. Illustrative intervention-specific strength-of-evidence map for utility-scale\solar development



Source: Warnell, Olander, and Mason (2018).

HOW ESCMS CAN HELP IDENTIFY AND PRIORITIZE INDICATORS

Identifying indicators that can be used to monitor how well an intervention performs is critical for assessing success. Monitoring of biophyisical indicators is relatively common in natural resource management, but indicators for socio-economic outcomes are often missing. Ecosystem services conceptual models can provide an entry point for selecting socio-economic indicators relevant to an intervention that can be added to monitoring plans (Brown et al. 2014). The outcomes identified in conceptual models should be either benefit relevant, linking ecological and social factors (provision and use; supply and demand), or values based on costs (e.g., loss of property) or people's willingness to pay (Olander et al. 2018) (see Table 8 for illustrative examples). An illustrative list of indicators related to coastal impacts and restoration can be found in Abt Associates (2015) and in a guide on incorporating ecosystem services values by The Nature Conservancy (Schuster and Doerr 2015). A more general list can be found in the Canadian Ecosystem Services Toolkit (Tools Tab 5, 127–136; Preston and Raudseppe-Hearne 2017). These example lists can be shared along with ESCMs to identify which indicators are most important for the decision context and to prioritize the best ones for monitoring. The feasibility of selected indicators, including the usability of existing data and estimated costs of new data collection, will need to be assessed. When completed, evidence evaluations can further inform which metrics are most important for monitoring and evaluation because they can identify key linkages and data gaps.

> "Ecological features and processes are essential for the provision of ecosystem services but are not the same as services. Until there is some person somewhere who benefits from a given element or process of an ecosystem, that element or process is not a service. **Benefit-relevant indicators (BRIs)** are measurable indicators that capture this connection by considering whether there is demand for the service, how much it is used (for use values) or enjoyed/valued (for nonuse values), and whether the site provides the access necessary for people to benefit from the service, among other considerations. An ecological measure can become a BRI if it is tied directly and causally to something important to people, for example, the presence of bald eagles, which is clearly identified as important to the American people."
>
> *—Federal Resource Management and Ecosystem Services Guidebook*

Table 8. Illustrative socio-economic monetary ($) and benefit-relevant indicators

Ecosystem services or social benefit	Indicator (benefit-relevant or monetary)
Health impacts	Numbers of households exposed to water-borne disease Number of hospitalizations resulting from forest fire smoke each year
Commercial fishing	Increase in commercial fishing revenues ($) Avoided number of days of shellfish bed closures (acre/day)
Recreation	Numbers of anglers visiting Distance people are willing to travel to recreate ($)
Existence	Willingness to pay for the existence of certain species or habitat ($) Number of books, art, or literature tied to a specific species or place
Flooding	Likelihood of flooding each year (likelihood/number of properties) Days of disruption due the closure of critical services
Education/research	Number of people participating in educational events Use of related science by other people

Source: Abt Associates (2015).

According to the *Federal Resource Management and Ecosystem Services Guidebook*, good indicators "should

- capture the intended ecological and social attribute as directly and precisely as possible,
- be quantifiable using efficient and cost-effective measures rather than expensive post processing in the lab or expensive field equipment,
- be free of observer bias (i.e., the indicator should be the same regardless of who estimates it),
- be repeatable over time, allowing monitoring to capture temporal trends, and
- be sensitive to changing conditions" (Maguire and Urban 2016).

The Canadian Ecosystem Services Toolkit also provides a worksheet for thinking through some of the questions relevant to selecting good indicators (Preston and Raudseppe-Hearne 2017, Worksheet 7, 120–122).

TIME AND EXPERTISE NEEDED TO BUILD CONCEPTUAL MODELS AND EVIDENCE LIBRARIES

Table 9 provides time estimates and expertise investments needed to develop conceptual models and evidence libraries.

Table 9. Time and expertise required for development of ESCMs and evidence libraries

Task	Time	Expertise
Exploratory model	1 hour to 1 day Depends on complexity of intervention and systems and number of experts/stakeholders engaged	Familiarity with building ecosystem services conceptual models, understanding of ecosystem services and ecological and social outcomes commonly considered
Refined model (specified or general)	1 to 2 weeks full time Requires articulation of assumptions and iteration with stakeholders and experts	Same as above
Identify socio-economic metrics	Part of initial 1-hour to 1-day session with experts and stakeholders or similar length time	Familiarity with socio-economic methods and measures
Assess metric feasibility for monitoring	0.5 to 6 months full time Depends on number of metrics to be assessed	Familiarity with socio-economic data sets and literature review
Initial evidence library and evidence assessment	6 weeks full time for new model library; 3 or fewer weeks for adaptations or similar applications that build on existing library	Experience with literature review and familiarity with building ESCMs, understanding of ecosystem services and ecological and social outcomes commonly considered

CONCLUSION

This report provides guidance on how to build ecosystem services conceptual models and evidence libraries and how to use them in the selection of performance metrics. ESCMs can be an effective and efficient tool for incorporating ecosystem services into decision making. The use of general ESCM reference libraries for each common decision context within agencies (e.g., forest planning, coastal restoration, energy facility installation) could help address many of the remaining barriers to widespread use of ecosystem services by decreasing expertise, time, and resources needed; by reducing duplication of effort; and by improving the consistency and credibility of ecosystem services incorporation into implementation decisions (Olander et al. 2016; 2017).

APPENDIX A: USE OF CONCEPTUAL MODELS TO COMPARE AN INTERVENTION ACROSS HABITAT TYPES

One way to easily compare different interventions is to develop multiple conceptual models using the same base model as a framework (Figure A.1). This technique enables visual comparison of different intervention types or of the same intervention in multiple locations. In the example shown here, the intervention—increasing habitat quantity or quality—remains constant, but the location differs. Using a base model, slight differences in the chains and outcomes for each habitat type (mangrove, oyster reef, salt marsh, and eel grass) can be visualized (see figures A.2–5, where links and nodes relevant to each habitat type are highlighted in color, using the base model as a framework). If the simplified exploratory models developed here for illustration purposes were quantified for each habitat, users could determine differences in services provision across habitats where the same services are affected.

Figure A.1. Simplified example of a base model framework, showing a wide array of possible outcomes stemming from a change in coastal habitat quantity or quality

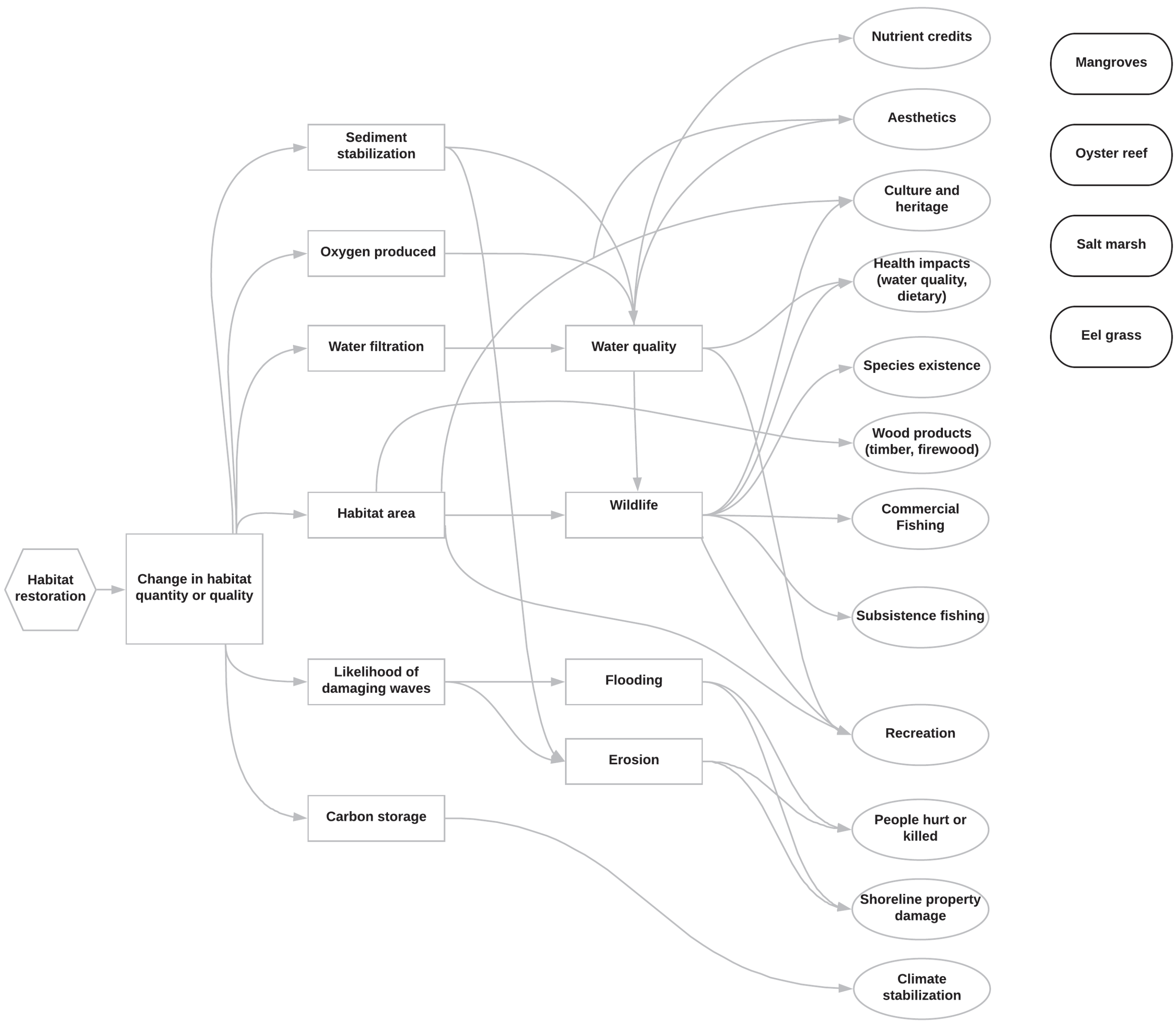


Figure A.2. Mangrove model

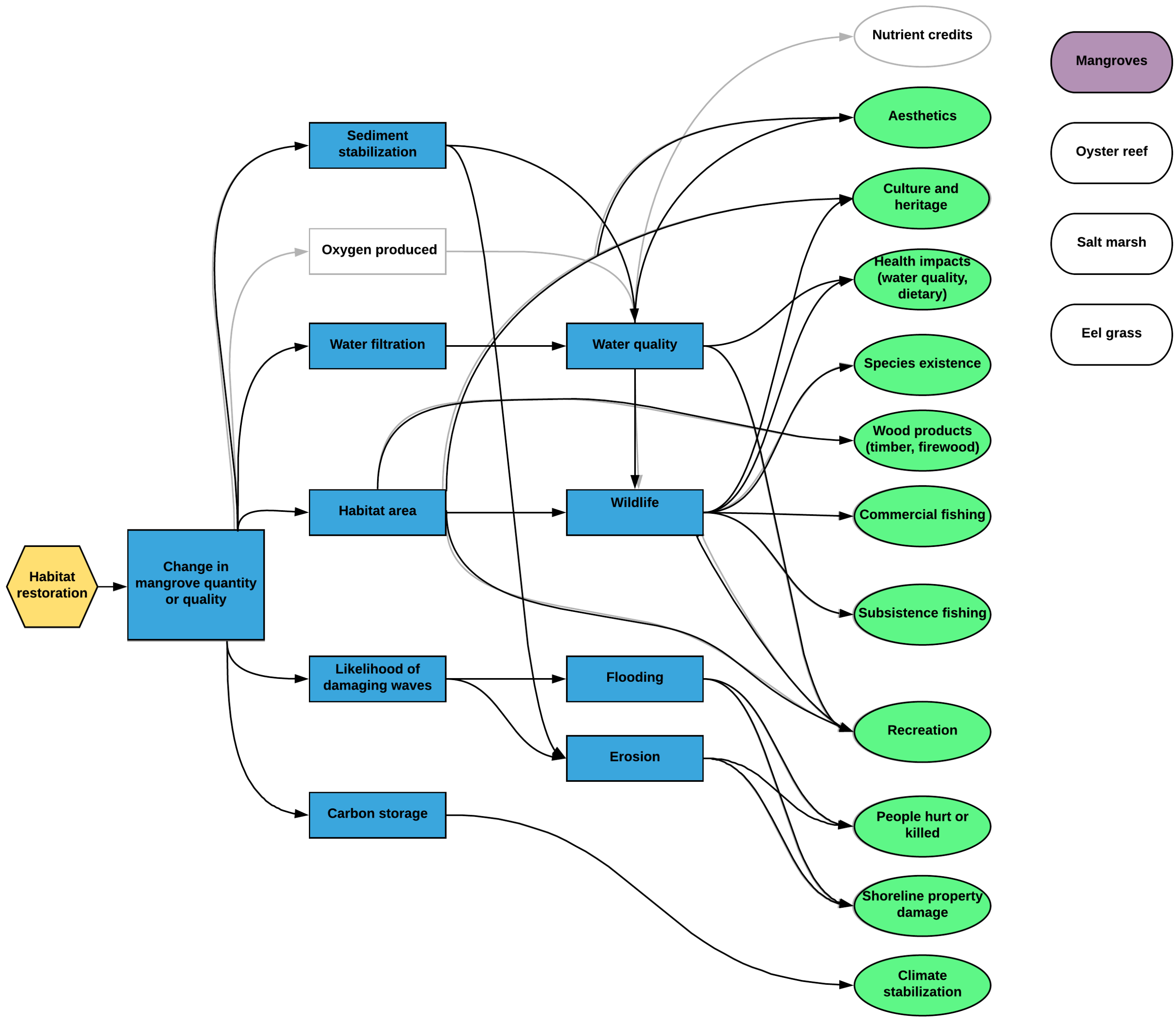


Figure A.3. Oyster reef model

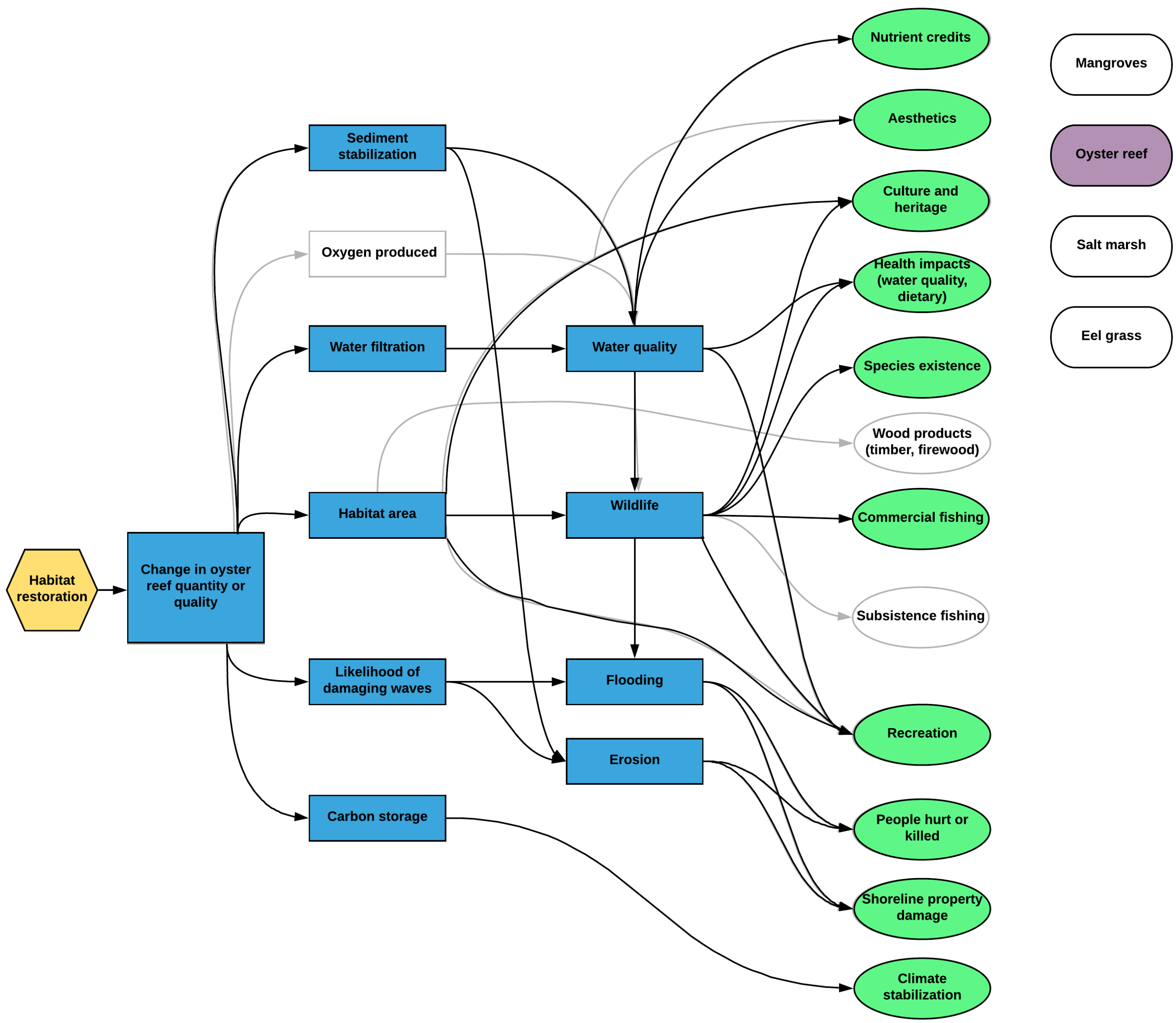


Figure A.4. Salt marsh model

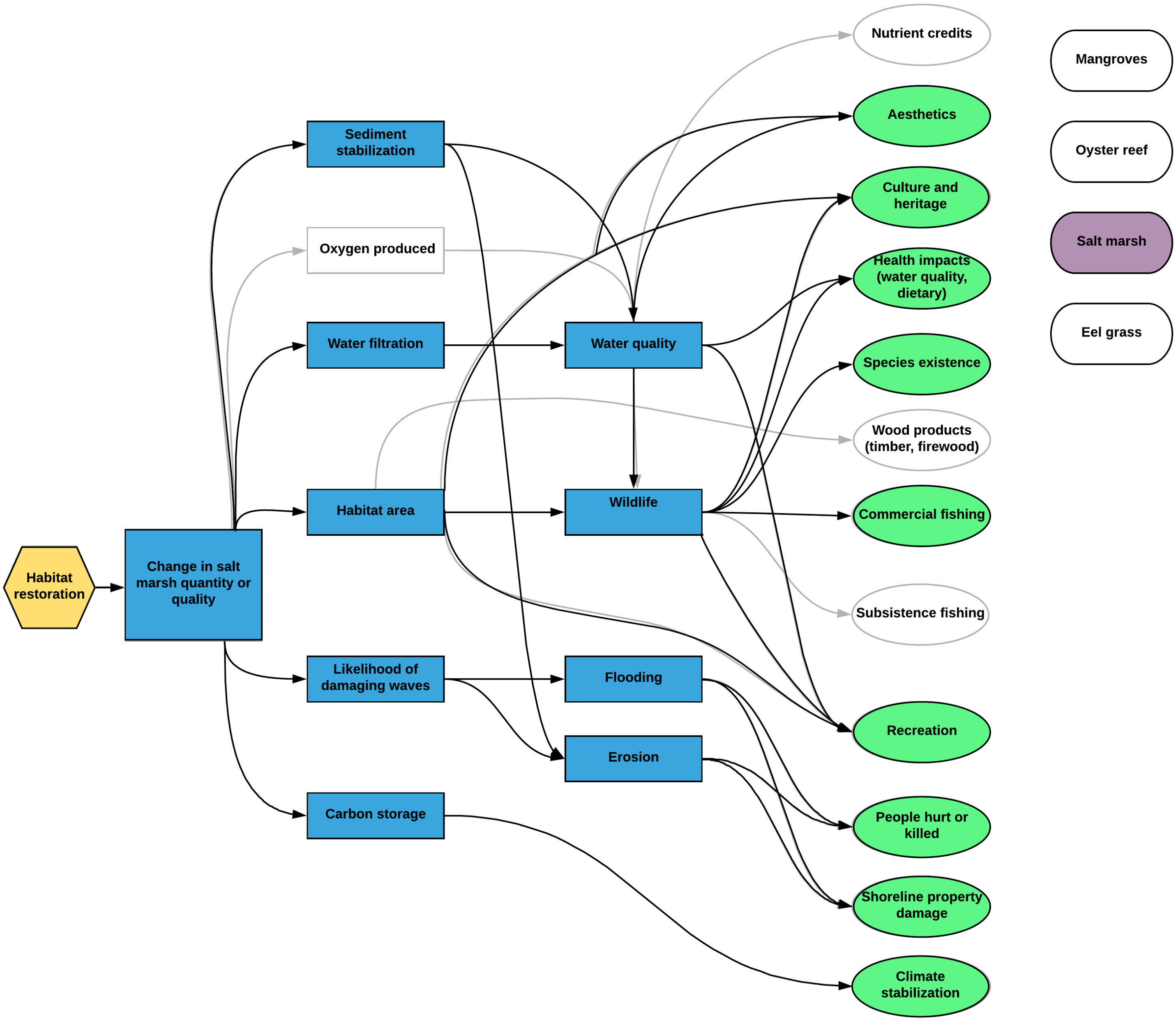
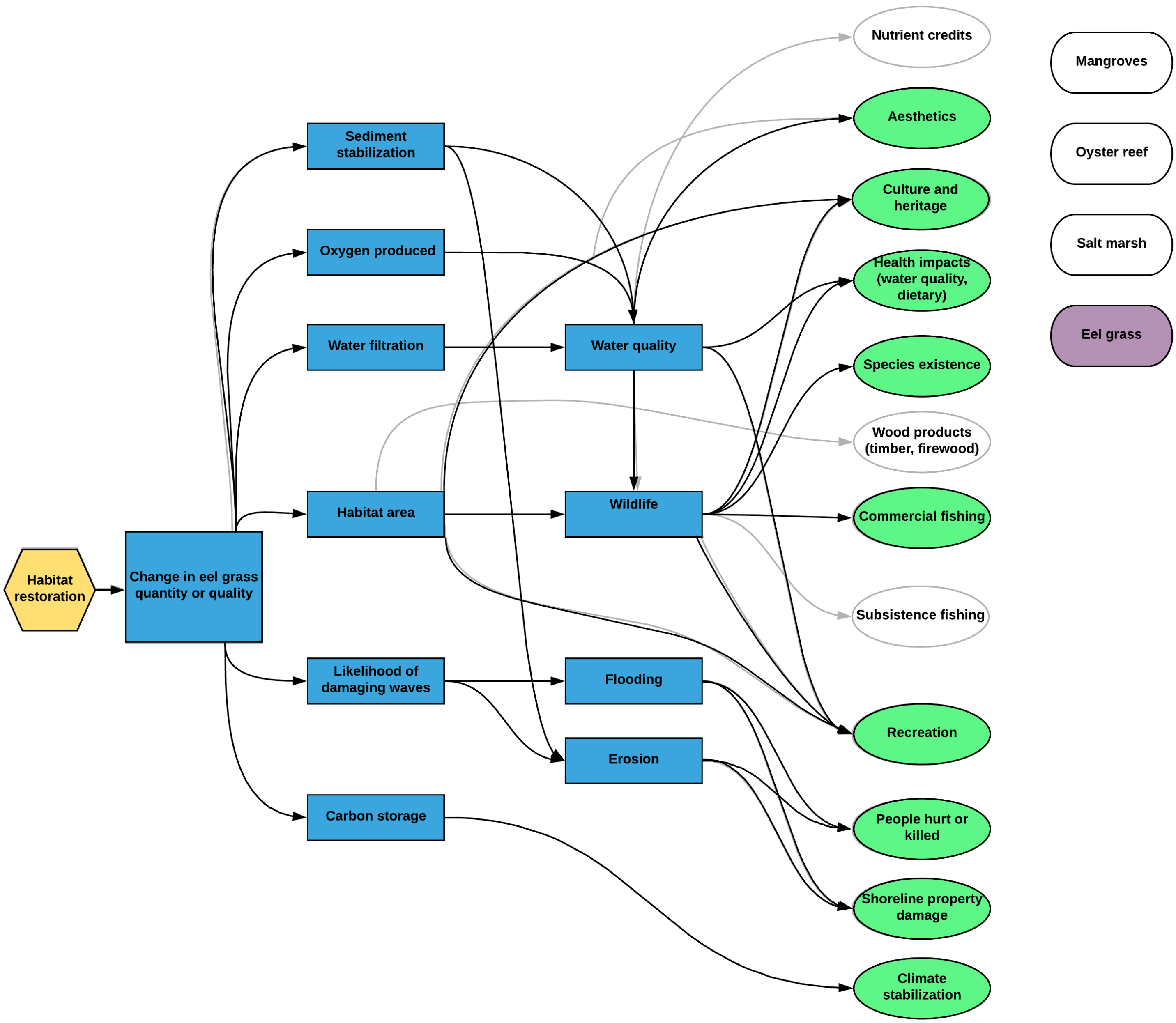


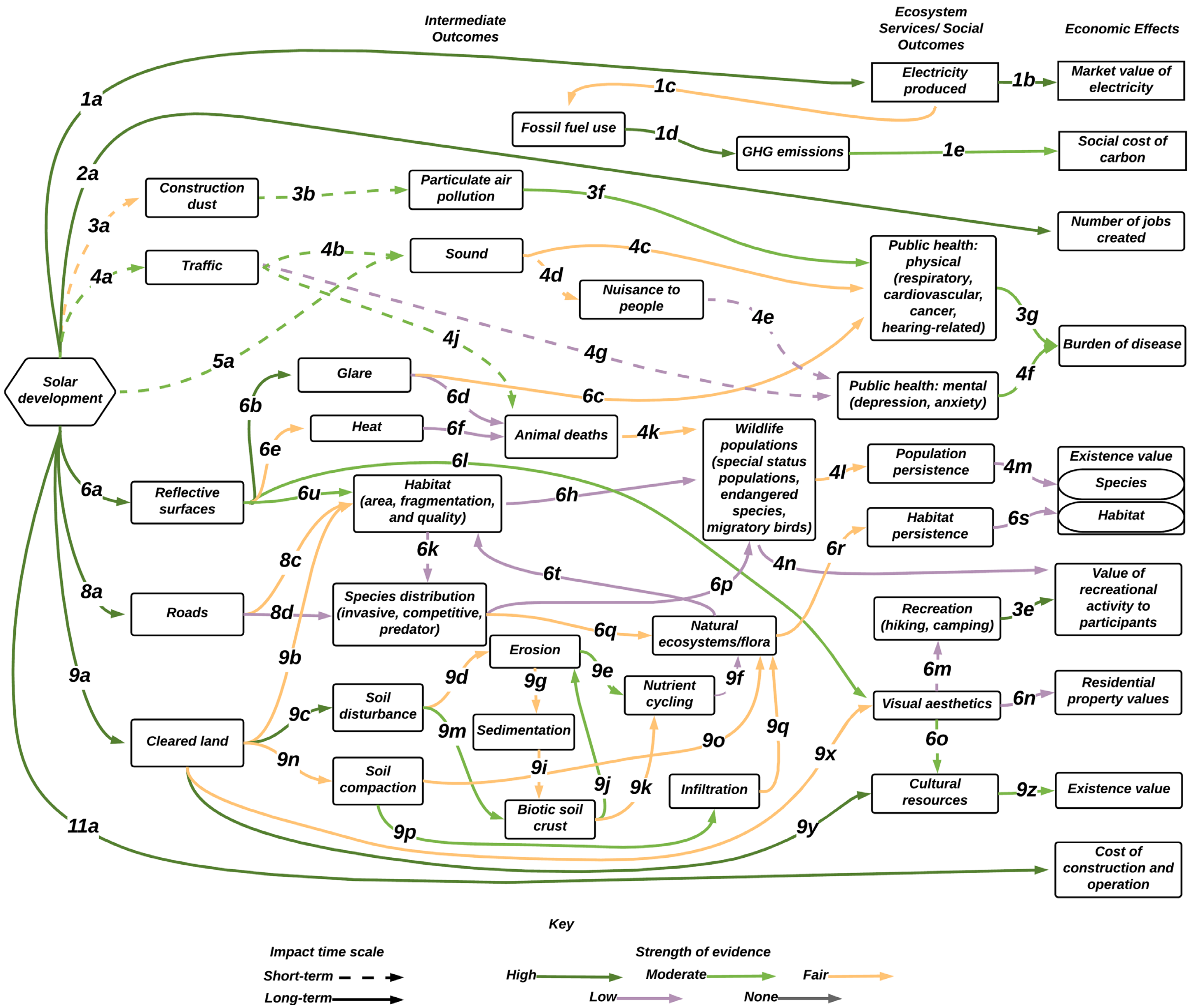
Figure A.5. Eel grass model



APPENDIX B: USING SOFTWARE TO DRAW CONCEPTUAL MODELS

Software programs can be helpful for identifying groups of nodes and for guiding initial attempts to translate conceptual model brainstorming sessions from paper/whiteboard into a digital format. Several social network analysis packages are available for the open-source statistical software R; an example using the igraph package (version 1.0.1) in R (version 3.4.1) for plotting the simplified solar energy development model (Figure B.1) is presented in this appendix (Csardi and Nepusz 2006; R Core Team 2017). Although the plots resulting from this method are not as polished or configurable as those created in some of the previously noted software packages (e.g., Lucidchart), they can provide a starting point for building a final model in another software package.

Figure B.1. Simplified conceptual model for solar energy development created with Lucidchart



The input required to plot a model with igraph is a matrix with two columns: starting node (from node) and ending node (to node). The matrix can initially be created as a comma-separated value file (.csv) in Microsoft Excel and imported into R. Each row represents one link; the matrix (called an edgelist) must contain a row for each link in the model (igraph 2015). To simplify layout options later, the starting node in the first row of the edgelist should be the intervention for the model (e.g., solar development). Part of the edgelist for the solar energy development model is shown in Table B.1.

Table B.1. Partial edgelist for simplified solar energy development conceptual model

From node	To node
Solar development	Electricity produced
Electricity produced	Market value of electricity
Electricity produced	Fossil fuel use
Fossil fuel use	GHGs emitted
GHGs emitted	Social cost of carbon
Solar development	Construction dust
Construction dust	Particulate air pollution
Particulate air pollution	Physical health

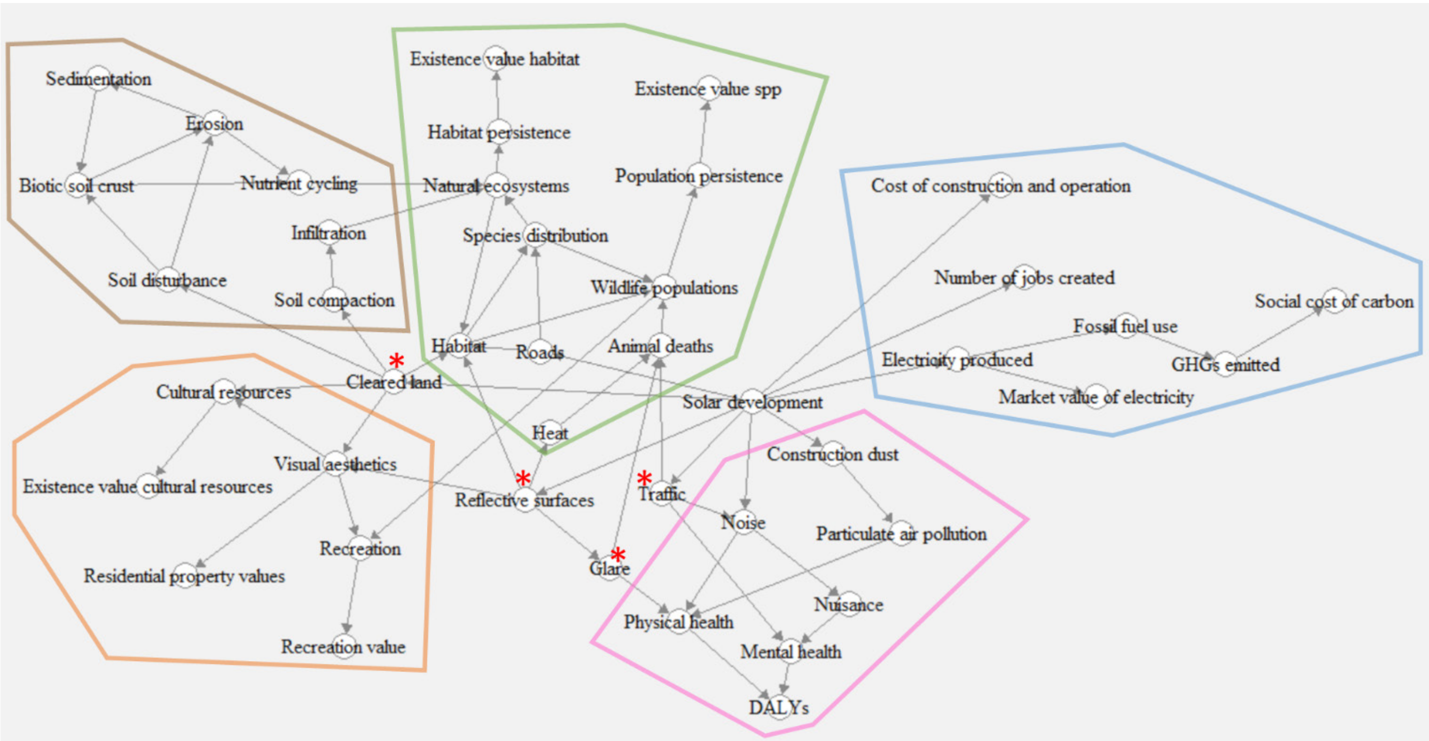
The following R script plots a conceptual model from an edgelist. Lines 1–3 install and load the igraph package, lines 5–7 read in the edgelist file and use it to create a graph object, and lines 9–10 create an initial plot. The remaining lines (12–33) contain options for changing the look and layout of the plot.

R script for plotting a conceptual model using the igraph package

```
1  #install igraph package (if not already installed) and load it
2  install.packages("igraph")
3  library("igraph")
4
5  #read in csv file as edgelist and create graph object from edgelist
6  edgelist <- as.matrix(read.csv("edgelist.csv", header=TRUE))
7  graph <- graph_from_edgelist(edgelist, directed=TRUE)
8
9  #default plot, auto-layout, no parameters specified
10 tkplot(graph)
11
12 #plot, auto-layout, some parameters specified to improve readability
13 tkplot(graph, canvas.width=1200, canvas.height=600, vertex.size=10, vertex.color="white",
14        vertex.frame.color="gray", vertex.label.color="black", edge.color="gray",
15        edge.arrow.size=0.8, edge.arrow.width=0.8, margin=0.25)
16
17 #Once graph opens, click/drag nodes to rearrange or select layout from top menu bar
18
19 #plot, Fruchterman-Reingold layout, some parameters specified to improve readability
20 tkplot(graph, canvas.width=1200, canvas.height=600, vertex.size=10, vertex.color="white",
21        vertex.frame.color="gray", vertex.label.color="black", edge.color="gray",
22        edge.arrow.size=0.8, edge.arrow.width=0.8, margin=0.25,
23        layout=layout.fruchterman.reingold)
24
25 #plot, Kamada-Kawai layout, some parameters specified to improve readability
26 tkplot(graph, canvas.width=1200, canvas.height=600, vertex.size=10, vertex.color="white",
27        vertex.frame.color="gray", vertex.label.color="black", edge.color="gray",
28        edge.arrow.size=0.8, edge.arrow.width=0.8, margin=0.25, layout=layout.kamada.kawai)
29
30 #plot, Reingold-tilford layout, some parameters specified to improve readability
31 tkplot(graph, canvas.width=1200, canvas.height=600, vertex.size=10, vertex.color="white",
32        vertex.frame.color="gray", vertex.label.color="black", edge.color="gray",
33        edge.arrow.size=0.8, edge.arrow.width=0.8, margin=0.25, layout=layout.reingold.tilford)
```

Several layout options use various algorithms to arrange the nodes. The default auto-layout is most useful for identifying groups of related nodes; other layouts that may also be helpful for this purpose are the Kamada-Kawai layout and the Fruchterman-Reingold layout, both of which aim to distribute nodes evenly and to place connected nodes near each other to minimize link-crossing (Fruchterman and Reingold 1991). Overlapping node labels can make the initial plots difficult to read, but the interactive graphing window allows individual nodes to be moved by dragging, which can improve readability (Figure B.2). This figure also identifies groups of related nodes and nodes that are linked to multiple groups.

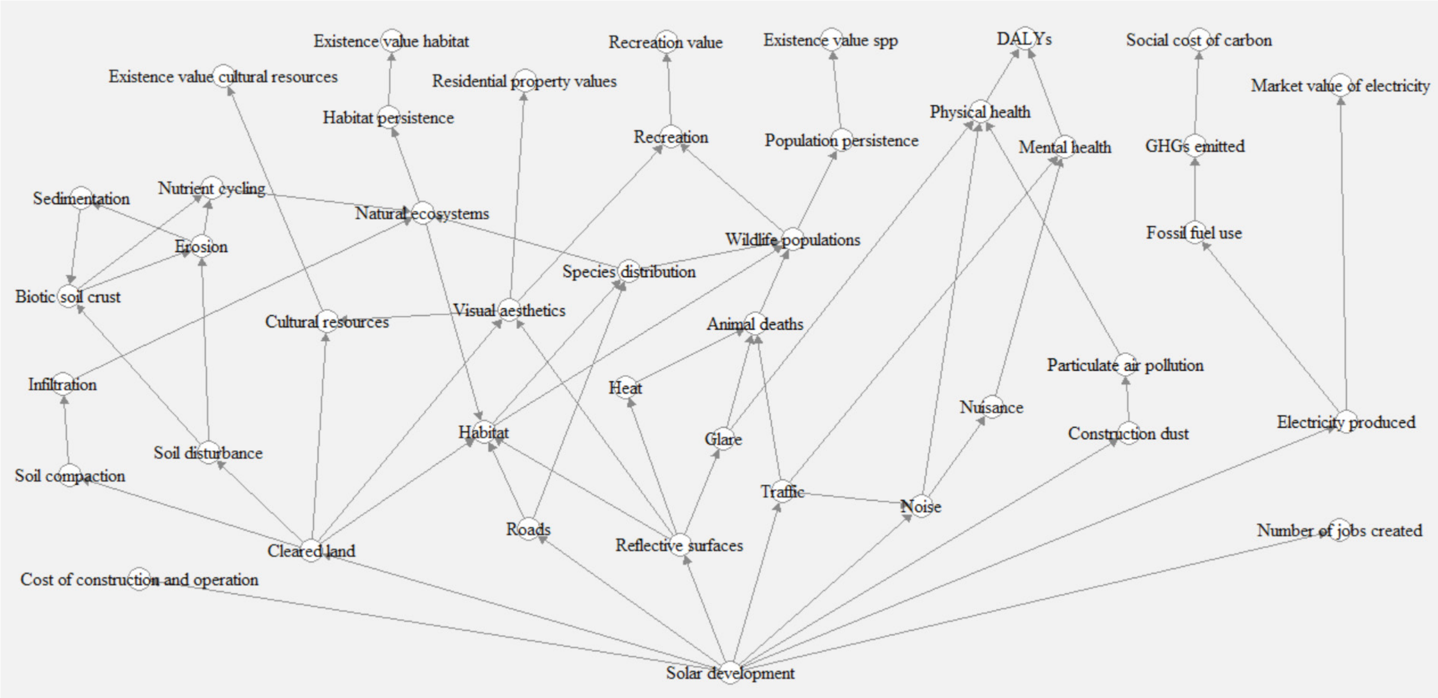
Figure B.2. Simplified solar energy development model, Fruchterman-Reingold layout, manually edited



Note: Node groups are energy economics and greenhouse gas production (blue), human health effects (pink), wildlife and habitats (green), soils (brown), and cultural effects (orange). Nodes that are linked to multiple groups of nodes are marked with red stars.

The Reingold-Tilford layout (Figure B.3) arranges nodes into a branching tree, which looks more similar to the finished conceptual models presented in the main body of this report, but it does not group related nodes as well as the previously mentioned options, because it focuses on tree aesthetics (Reingold and Tilford 1981). This layout uses the first starting node in the edgelist as the root of the tree, so it is important that the focal intervention (in this case, solar energy development) is the starting node in the first row of the edgelist.

Figure B.3. Simplified solar energy development model, Reingold-Tilford layout, manually edited

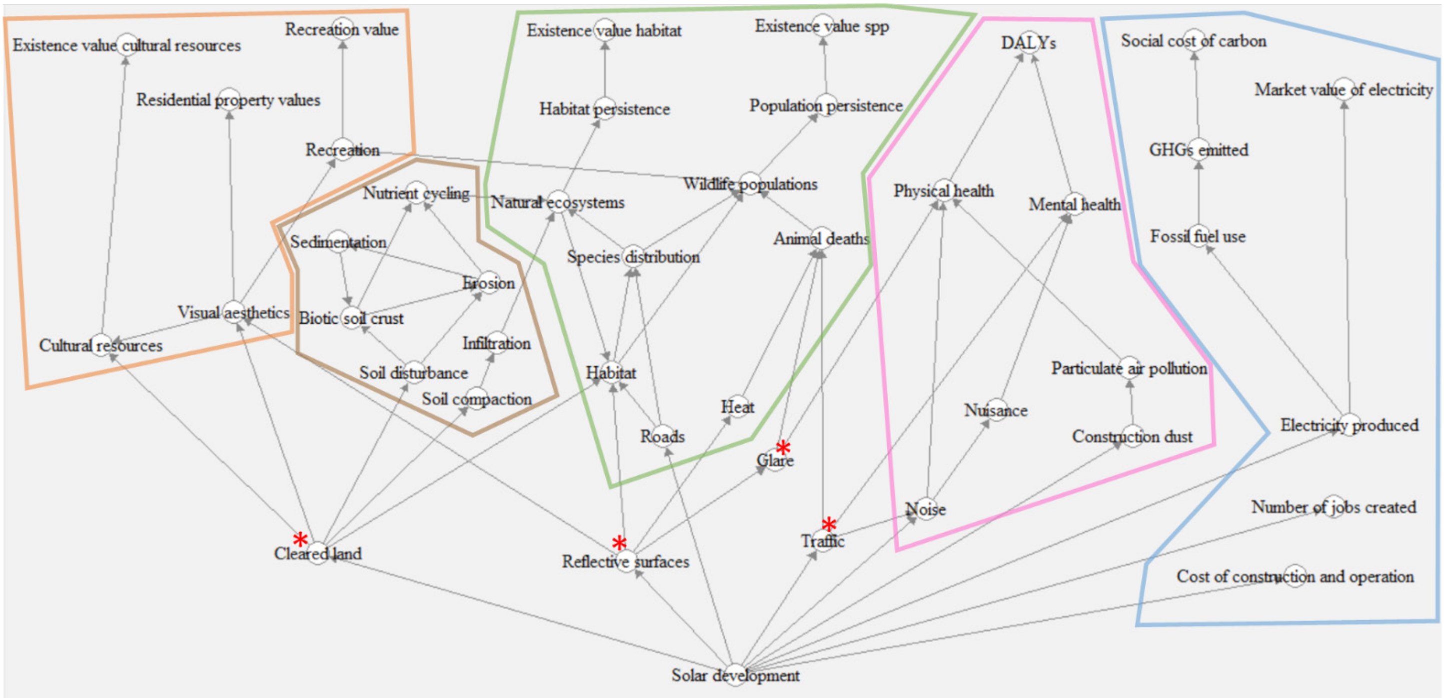


There is no universally best layout for conceptual models; the best approach is to experiment with several options. Layouts can be dynamically selected within the interactive graphing window or set ahead of time as a parameter in the tkplot function (lines 19–33).

Well-laid-out conceptual models minimize link crossings and group related nodes to enhance readability and make individual causal chains easier to follow through the model. The use of software tools such as igraph to initially translate models into a digital format can assist with this process by identifying groups of related nodes that should be located near each other in the final model and by providing a way to experiment with model layout and node placement without manually adding each node and link.

Specifically, a layout that groups related nodes can be used to identify groups of nodes that should be located near each other in the final model and nodes that are linked to multiple groups of nodes and should be placed between those groups. Then, a layout that creates a tree diagram can be used as a starting point, and nodes can be rearranged such that previously identified related nodes are grouped together and nodes linked to multiple groups can be placed near them to prevent links from crossing the entire model. Figure B.4 shows the result of modifying the tree diagram (Figure B.3) so that related nodes are arranged in the groups identified using the Fruchterman-Reingold layout (Figure B.2), and highly connected nodes are near the base of the diagram to minimize link crossing.

Figure B.4. Modified tree diagram based on node groupings and highly connected nodes identified in the Fruchterman-Reingold layout (Figure B.2)



Note: Node groups are energy economics and greenhouse gas production (blue), human health effects (pink), wildlife and habitats (green), soils (brown), and cultural effects (orange). Nodes that are linked to multiple groups of nodes are marked with red stars.

The interactive graphing window is an ideal venue for this kind of experimentation because it provides a quick way to display the entire model without requiring the user to decide where to place each individual node and it allows nodes to be moved without any chance of accidentally altering the links between nodes. Once the layout is finalized, the model can be built in another software program such as Lucidchart for final edits and polishing.

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National Ecosystem Services Partnership

The National Ecosystem Services Partnership (NESP) engages both public and private individuals and organizations to enhance collaboration within the ecosystem services community and to strengthen coordination of policy and market implementation and research at the national level. The partnership is an initiative of Duke University's Nicholas Institute for Environmental Policy Solutions and was developed with support from the U.S. Environmental Protection Agency and with donations of expertise and time from many public and private institutions. The partnership is led by Lydia Olander, director of the Ecosystem Services Program at the Nicholas Institute, and draws on the expertise of federal agency staff, academics, NGO leaders, and ecosystem services management practitioners.

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The NESP Conceptual Model Series provides a collection of resources explaining why ecosystem services conceptual models (ESCMs) are useful for decision making, providing guidance for building ESCMs, and describing NESP's initial efforts to standardize and apply these models with federal agency partners. It includes application examples of ESCMs and associated evidence libraries. The series aims to provide practical guidance for those who wish to apply ESCMs as a tool for incorporating ecosystem services considerations into their decisions.

NESP Conceptual Model Series Publications:
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