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Data and Modeling Infrastructure for National Integration of Ecosystem Services into Decision Making: Expert Summaries

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Review

Sections of this working paper have been reviewed but the full paper has not been formally reviewed.

Relationship of This Report to the *Federal Resource Management and Ecosystem Services Guidebook*

The online *Federal Resource Management and Ecosystem Services Guidebook* (nespguidebook.com) is designed to increase consistency in the use of ecosystem services in federal decision making. This working paper identifies data and modeling resources available at a national level for common ecosystem services to enhance the consistency and credibility of ecosystem services assessments for use in methods like those presented in the guidebook.

SUMMARY

Resource managers face increasingly complex decisions as they attempt to manage for the long-term sustainability and the health of natural resources. Incorporating ecosystem services into decision processes provides a means for increasing public engagement and generating more transparent consideration of tradeoffs that may help to garner participation and buy-in from communities and avoid unintended consequences.

A 2015 White House memorandum from the Council on Environmental Quality, Office of Management and Budget, and Office of Science Technology and Policy acknowledged these benefits and asked all federal agencies to incorporate ecosystem services into their decision making.

This working paper, which has been expanded since its initial publication in November 2016, describes the ecological and social data and models available for quantifying the production and value of many ecosystem services across the United States. To achieve nationwide inclusion of ecosystem services, federal agencies will need to continue to build out and provide support for this essential informational infrastructure.

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1. INTRODUCTION

Resource managers face increasingly complex decisions as they attempt to manage for the long-term sustainability and health of natural resources. They must address large spatial scale and long-term ecosystem dynamics, climate-related stressors (extreme heat and weather events, pest outbreaks, etc.), population growth and urbanization, the spread of invasive species, and dwindling public resources (Burke 2013). Growing threats, pressures, and uses of our lands and waters appear to be increasing the likelihood of significant tradeoffs in resource management decisions, affecting what benefits are provided and who receives them or loses them. For example, increasing energy infrastructure for solar and wind throughout the United States is resulting in damage to fragile habitats (e.g., Kuvlesky et al. 2007), impacts to species and majestic views, and in some cases important pollinators (Kunz et al. 2009) but at the same time are providing a clean source of energy to millions of people (U.S. EIA 2015). Better and more transparent ways to assess these difficult tradeoffs among easily monetized benefits (energy) and less easily expressed benefits (recreational and spiritual benefits and intrinsic values of species, habitats, and wide open spaces) are needed. Although the public depends on and derives substantial benefit from how natural resources are managed (health, happiness, money), these connections are not always apparent to them. Ecosystem services assessments provide a means for increasing public engagement and generating more transparent consideration of tradeoffs in resource management decisions that may help to garner greater support and participation from both public and private beneficiaries, hopefully reducing conflict and enhancing financial support. Incorporating ecosystem services into decision processes may also result in better integration of the less easily quantified and monetized benefits resulting in more sustainable and better ecological and social outcomes.

Recent policies and guidance at the federal level reflect a growing interest in ecosystem service approaches to natural resource planning and management that culminated in a 2015 White House memorandum from the Council on Environmental Quality, Office of Management and Budget, and Office of Science Technology and Policy, asking all federal agencies to incorporate ecosystem services into their decision making.

- Early use of ecosystem services valuation in the federal government occurred under the Natural Resources Damages Act in response to the Valdez oil spill (U.S. EPA 2016).
- Greater use of these approaches was sparked in part by the 1998 President's Council of Advisors on Science and Technology (PCAST) report "Teaming with Life: Investing in Science to Understand and Use America's Living Capital" (PCAST 1998).
- The 2008 Farm Bill called for federal agencies to explore ecosystem services and their potential application in environmental markets, resulting in the establishment at the U.S. Department of Agriculture (USDA) of an Office of Ecosystem Services and Markets that same year (Lucero & Doudrick 2008).
- In 2010, a large-scale appointee-level interagency dialogue on ecosystem services brought together all federal agencies with natural resource jurisdictions, with a focus on markets and payment for ecosystem services. Similar interagency dialogues have continued since then.
- In 2011 PCAST issued its report on "Sustaining Environmental Capital: Protecting Society and the Economy," which asserts the critical importance of both the environment and the economy to societal well-being and emphasizes the need for agencies to develop consistent ecosystem service valuation techniques across federal agencies (PCAST 2011).
- The U.S. Forest Service's (USFS) 2012 Planning Rule requires that planning activities consider ecosystem services, as part of an integrated resource management focus (USDA 2012). The

agency is moving quickly to phase in implementation of the rule, with many forest plans already under way.

- In 2013, the White House Council on Environmental Quality released new Principles and Requirements for Federal Investments in Water Resources, which shape water resource project decisions across a number of federal agencies and include specific guidance on using an ecosystem services framework for project evaluation (White House 2013).
- A number of other agencies, including the Bureau of Land Management (BLM), the U.S. Fish and Wildlife Service (FWS), the U.S. Geological Survey (USGS), the U.S. Army Corps of Engineers (USACE), and the National Oceanic and Atmospheric Administration (NOAA), are also exploring ways to implement ecosystem services approaches by assessing and testing methods for identifying and valuing ecosystem services and applying this information in a natural resources decision-making context.
- In 2014 the National Ecosystem Services Partnership launched an online guidebook (NESP 2016) on the integration of ecosystem services assessment into federal natural resource planning and management.
- In 2015, the White House released a policy memorandum (Donovan et al. 2015) asking agencies to incorporate ecosystem services into federal decision making and calls for further guidance to be released in 2016. The White House also released a report (Burke et al. 2015) that provided an ecosystem assessment of research needs for coastal green infrastructure.

These federal initiatives are a move toward wider recognition of the multiple ways in which society depends on natural resources and a move away from evaluations that focus narrowly on a limited subset of benefits. In general this shift involves moving from a narrow focus on high-profile user groups to a view that also recognizes benefits that flow to the general public and society.
Environmental nongovernmental organizations like the Nature Conservancy and World Wildlife Fund, as well as the land trust community, including the Land Trust Alliance and Trust for Public Land, are also building a broader consideration of ecosystem services and benefits to people into their decisions and communications. Corporations are also exploring how ecosystem services can inform their supply chains, infrastructure, and operations (Waage and Kester 2014).

Ecological production functions

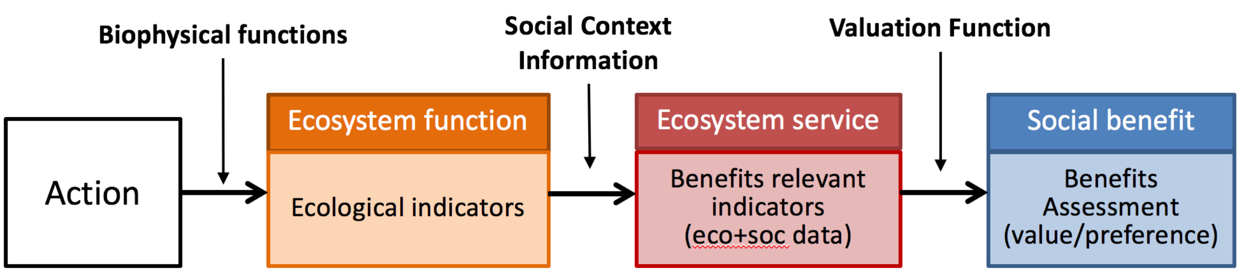
Ecological production functions are relationships that:

- can be measured or modeled;
- estimate the effects of changes in the structure, function, and dynamics of an ecosystem on outputs that are directly relevant to people;
- can take many forms, from conceptual relationships established through expert opinion to complex simulation models; and
- are often a series of statistical relationships connecting ecosystem condition to outputs.

Federal agencies need two things to achieve nationwide adoption of ecosystem services approaches that support use by private and nonprofit partners: (1) credible, consistent, and practical **methods** that clearly improve decision processes and outcomes and that can be incorporated into planning and management processes (NESP 2016; Olander et al. 2015; Van Wensem et al. 2016); and (2) ecological and social **data and models** that explain the relationships between management and the production and value of services. This working paper focuses on this second requirement.

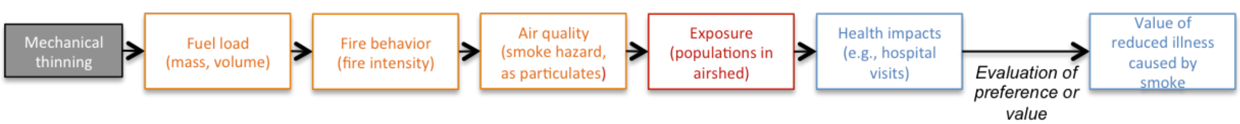
The data and modeling needs for an ecosystem services assessment include (1) the ecological data describing the status and trends of the resources being managed and affected, (2) the models that describe the effects of different management alternatives on the target and nontarget resources (the ecological production function), and (3) the social data on resource use and appreciation and, where available, value transfer models to assess the values and preferences associated with different outcomes on human well-being (Figure 1-1 with an example in Figure 1-2). The data and models for more traditional ecosystem services like timber, fishing, hunting, and hiking and management actions like timber, fishery, recreational access and trails, and fire management are more readily available. New data collection and research are likely needed to build the data and models for the less-often-quantified services related to air and water quality, viewsheds, disease risk (mosquito-borne, air or water quality-influenced, or exercise-related) and intrinsic biodiversity or cultural services, as well as a better understanding of how people value all of these services.

Figure 1-1. Needs for an ecosystem services assessment



Note: Data and models needed in ecosystem services assessments include ecological data, social data, value data, ecological production functions, and, where necessary, benefit transfer functions.

Figure 1-2. Ecosystem services causal chain illustrating the types of data and models that are needed



Note: Example of ecosystem services causal chain conceptual diagram linking the management of mechanical thinning of forests to changes in exposure to smoke and incidence of illness. Data to calibrate and test models that show the relationship between thinning and smoke produced, as well as those that show the relationships among smoke, exposures, and health impacts, are all needed. This requires data on the forest fuel load (size and type) as well as the location and number of people at potential risk of smoke exposure.

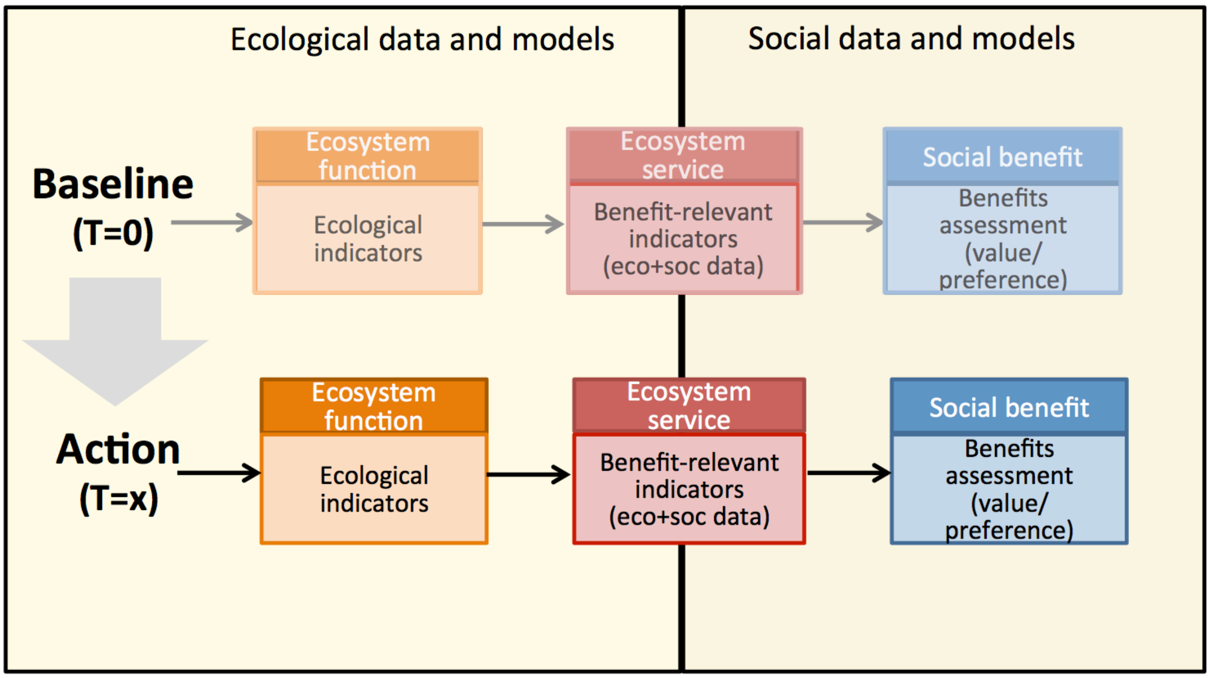
To date, ecosystem services applications to planning and management have been scattered and often one-off, with different approaches and tools used and with locally specific or locally calibrated data. While this has resulted in significant learning, it has not resulted in a consistent and commonly used set of approaches, data, or models that have been deemed credible by experts. If ecosystem services approaches are going to be widely applied across the country by federal agencies and other resource managers, a move toward more consistent, common, and accredited data, models, and tools is likely needed. A common infrastructure (whether centralized or networked) could supply essential data and models and, in doing so, greatly enhance consistency and credibility while reducing costs and effort associated with current assessments. There are efforts under way by the federal government to build needed data and modeling infrastructure, such as the EnviroAtlas (www.epa.gov/enviroatlas), which is part of a larger data effort called EcoInforma (www.data.gov/ecosystems/ecoinforma/), and an online searchable ecological production function library (Bruins et al. 2012) that is under development.

This working paper discusses the current state of data and models and points to supporting infrastructure to maintain and update them where such infrastructure is known. Where particular needs are recognized they are noted, including new data, modeling, and infrastructural support. Sections 2 and 3 describe the ecological data and ecological production functions available and needed. Section 4 focuses on use and value data or functions (Figure 1-1). The working paper covers a handful of common services that are likely to be widely relevant in resource management decisions including services related to biodiversity, water supply, water quality, recreation, and risk reduction (climate, fire, flood, and coastal inundation). A fundamental need that underlies the idea of nationwide infrastructure is that the data and models are sufficiently scalable and transferable so they can work across multiple scales, geographies, and management challenges. Given this need we focus much of the discussion on nationally or widely available data and models.

2. ECOLOGICAL DATA AND MODELS FOR ECOSYSTEM SERVICES ASSESSMENTS

The ecological data needed for ecosystem services assessments include the quantity, quality, and location of ecological systems or flows that produce ecosystem services. These data provide the baseline ecological status and trends from which we will model and predict changes due to management (Figure 2-1). Also needed are ecological production function models that will trace the ecological changes resulting from management through a system resulting in a predicted change in the ecological flow or system.

Figure 2-1. Ecological and social data and models



Note: The difference in ecosystem function, services, and benefits between the baseline scenario and what is changed due to a management action in the second scenario will provide an estimate of the outcomes due to the expected or suggested action. The arrows represent a series of assumptions or models that connect a change in ecosystem function to changes in ecosystem services supply to changes in social benefits.

Land Use and Land Cover Change Data

Simply stated, many ecosystems' goods and services can be estimated from information on land use and land use patterns. Both proximal (e.g., local harvesting of game) and distal (e.g., sequestration of carbon in a far-off forest or upstream stream buffer management) land use patterns have a significant impact on the flow of services from an ecosystem to a particular community or group of beneficiaries. Even ecosystem services derived from an aquatic system are significantly impacted by land use. Land use data can provide the foundation for ecosystem services assessments and are typically used in conjunction with many other data sources to arrive at an ecosystem services endpoint.

Historically, land use data have been largely unavailable, and it has become common practice to use land cover as a proxy for land use. While the terms "land cover" and "land use" are often used interchangeably or even lumped together as one entity (i.e., land cover/land use), there are noteworthy distinctions that are particularly relevant for the topic of ecosystem services. *Land cover* is defined as the observed biophysical cover on the earth's surface, whereas *land use* is characterized by the arrangements, activities, and inputs of people to produce, change, or maintain a land cover. For example, grassland is a cover type, but rangeland is a use (Theobald 2014). The use of land use or land cover data alone or in combination with additional qualitative and quantitative data has become an important part of methods to assess ecosystem service provision (Pickard et al. 2015, Burkhard et al. 2009; Burkhard et al. 2012; Eigenbrod et al. 2010). A land use map for the United States has recently been developed (Theobald 2014) and may prove to be of significant help in ecosystem services assessments.

Land cover data resolution is an important concept for an ecosystem services assessment and refers not only to the area on the ground represented by each data point or pixel (spatial resolution) but also to the specificity of the classes of land cover (thematic resolution) represented by the data. Temporal resolution is another important attribute. In the simplest of classification schemes, there may only be a few classes, such as impervious surface, tree cover, grass, and water, and in the most complex of systems, there may be hundreds of classes representing different ecosystem types. The requirements for spatial resolution and specificity of classes will depend on decision context, including scale, the ecosystem good or service being measured, the level of accuracy required, and the setting (e.g., urban, rural, agricultural, forest). If one is trying to measure, for example, the approximate quantities of carbon stored or sequestered in forests across the United States, then a coarse land cover data set with perhaps only two classes of forests may suffice. If one is trying to quantify carbon storage or sequestration more precisely across the United States, then a more finely resolved product with information about types of forests would be more appropriate. If a community is interested in knowing how much automobile emissions are being mitigated by roadside tree buffers, then obviously a much finer spatially resolved land cover data set is required in addition to perhaps more information about tree species. Likewise, fine spatial and thematic resolution land cover data may be required to measure pollination as a service. Temporal resolution is important for investigating changes over time and predicting future conditions.

Several sources of existing national land cover data exist for the conterminous United States with perhaps the best known being the National Land Cover Database (NLCD; MRLC 2015), a 30-meter-resolution, 16-class product developed by the Multi-Resolution Land Characteristics Consortium (MRLC) every five years, most recently in 2011. NLCD will be moving to an annual product in the future. NLCD maps land cover to 16 different land cover classes. Other nationally available land cover databases that can be used in addition to NLCD include:

- USDA's National Cropland Data Layer, a 30-meter-resolution annual product with specificity in types of crops across the United States;
- USGS Gap Analysis Program (GAP), the U.S. interagency Landscape Fire and Resource Planning (LANDFIRE) program, and the USGS and ESRI Global Ecosystems mapping product, all of which map ecosystems at a 30-meter resolution with hundreds of ecosystem classes; and
- NOAA's Coastal Change Analysis Program (C-CAP) Land Cover, available now for coastal areas at a 30-meter resolution, more finely resolved wetland classes than NLCD. NOAA will be producing a 1-meter product in the future.

Much more spatially resolved land cover data are necessary for many ecosystem services assessments where finely resolved landscape features are particularly important. Coarse scale data oversimplify land cover patterns in highly fragmented environments like urban environments and riparian corridors.

Ecosystem services assessments in urban areas also require spatial detail because it is important to know where the forests and other natural land cover types are in relation to where people are living and working, roadways, and other infrastructure. The Environmental Protection Agency (EPA) and the USFS are developing 1-meter land cover data for many communities across the United States that are being used in ecosystem services assessments (www.epa.gov/enviroatlas and http://gis.w3.uvm.edu/utc).The demand for high-resolution land cover data is beginning to result in investment in regional 1-meter land cover products, with a recent example being the Chesapeake and Delaware Bay watersheds.

The NLCD is completed every five years and thus allows for a historical land cover change analysis, which is important for evaluating ecosystem services changes over time. For future ecosystem services projections, the USGS has produced Forecasting Scenarios of Land-Use Change (FORE-SCE; Sohl and Sayler 2008), land cover projections out to the year 2100 with a spatial resolution of 250 meters, and about the same number of classification classes as NLCD. USGS has also released backward-looking products going back to 1938 (Sohl et al. 2016), while the EPA has produced the Integrated Climate and Land-Use Scenarios (ICLUS) report, which explores future changes in human population, housing density, and impervious surface for the United States.

The accuracy of land cover data varies across the different products and is something with which a user should become familiar. Typically land cover products with more classes will have a much lower accuracy for each class than will a land cover product with fewer classes.

Terrestrial and Freshwater Biodiversity

Biodiversity is the variety of life and the ecological processes and interactions that characterize ecosystems on earth. That variety is commonly characterized at multiple levels of ecological organization, from genetic diversity within organisms to species diversity within natural communities, to community diversity within landscapes or regions. Since it supports the core benefits that people derive from their environment, biodiversity is fundamental for the provision of many ecosystem services. Many services related to outdoor recreation and nature appreciation or existence are tied directly to a given place's biodiversity.

In practical terms, biodiversity information applicable to ecosystem service assessment includes data that describe and locate biodiversity on land and in water. It also includes information on biodiversity's response to human alterations that affect primary ecological processes. These ecological processes and their continued function determine the impacts on biodiversity and the sustainability of continued flows for related services. These data and models can be organized in terms of species and communities in terrestrial or aquatic environments.

Data Sources: Status and Trends

Species: What We Have

Species are one common starting point for addressing biodiversity. In the United States, NatureServe is a primary source of information on the taxonomy, description, distribution, and relative at-risk status that would be needed to address the services they might provide. NatureServe has data available on several web portals including NatureServe Explorer and Landscope America (www.landscope.org). NatureServe Explorer includes information on nearly 60,000 species in the United States, with taxonomy, generalized distribution, life history, and at-risk status. Because Natural Heritage programs originated as field inventories for species considered to be at some risk of extinction, species information is best developed for that subset of all species. For many at-risk species, additional information on how to document local occurrences and their viability, as well as their conservation management and monitoring, is summarized. NatureServe compiles detailed location information from Natural Heritage programs in all 50 U.S. states, the Navajo Nation, and all of the Canadian provinces for species of conservation concern, including legally listed species. Over one million locations have been documented in this cumulative database since systematic inventories began in the 1970s. Programs apply specific rules for delineating locations so they provide a high-confidence prediction of occurrence for each species. Given data sensitivity, access to documented field locations for at-risk species are not posted publicly but are available under license or by subscription (www.natureserve.org/conservation-tools/natureserve-surveyor) with NatureServe (2016b) or individual Natural Heritage programs.

Another major source of data for species assessment in the United States is the USGS through two sources. The first is their national Gap Analysis Program (GAP; http://gapanalysis.usgs.gov), which has downloadable spatial data showing the range and distribution of almost all vertebrate species in the United States. The program has existed for over 20 years and over the last few years has focused on creating access to relatively consistent nationwide information for vertebrates. Habitat relationships for each species have been documented by GAP for subsequent use in distribution mapping. It should be emphasized that GAP models are aimed at predicting species distributions, reflecting potential range rather than more narrowly defined habitat associations. GAP data are also available on the new EPA EnviroAtlas (http://enviroatlas.epa.gov/enviroatlas), designed to provide access to national data on ecosystem services.

Another portal for location data in the United States is the new Biodiversity Information Serving Our Nation (BISON) resource (http://bison.usgs.ornl.gov), which has detailed specimen data from as many sources as could be identified, along with selected observations of species. BISON is the U.S. node of the Global Biodiversity Information Facility (GBIF, www.gbif.org) and therefore hosts essentially all records of species occurrences available for the country, including those data sets mentioned here specifically. From a practical standpoint, addressing terrestrial, freshwater, and marine species separately makes sense, since most services-focused ecosystem analyses would need to be different for each of these groups of species. However, currently, as described previously, most species information is organized primarily by the type of information provided and then by taxonomy.

The National Resource Conservation Service (NRCS) PLANTS Database (http://plants.usda.gov), with its generalized distribution data, is widely used for plant taxonomy in the United States. The database and portal provide straightforward downloads and are largely up to date but provide no information on distribution trends over time.

The most extensive network of species data for any specific group of taxa has been compiled for birds by the Cornell Lab of Ornithology, available on a series of portals including eBird (www.ebird.org), All About Birds (www.allaboutbirds.org), and the subscription-based Birds of North America (http://bna.birds.cornell.edu). The National Science Foundation-supported eBird, an example of the power of citizen science, provides detailed information on most bird observations, allowing for an analysis of their distribution and, when combined with the almost 50 years of data from the Breeding Birds Survey, allows for detailed analysis of their distribution and trends (Sauer et al. 2014), much of the critical information needed for ecological analysis. However, many birds are strongly associated with freshwater aquatic habitats and others with marine habitats, and the available databases and sites are designed to provide information on an individual species basis without identifying their associated habitats. NatureServe and the network has developed a partnership with iNaturalist (www.inaturalist.org) to develop similar information for all amphibians, reptiles, and mammals and many groups of freshwater fish and invertebrates.

Other sources of species observation data include DataONE and the National Phenology Network. DataONE provides the distributed framework (composed of Member Nodes and Coordinating Nodes), sound management, and robust technologies that enable long-term preservation of diverse multiscale, multidiscipline, and multinational observational data (DataONE 2016). The U.S.A. National Phenology Network aims to detect and analyze trends in biodiversity by focusing on phenology in plant and animal species (USANPN 2016).

The U.S. FWS and state fish and wildlife agencies have extensive data on species, especially those that are important for hunters and fishers. Seasonal habitat use areas and migration corridors are most commonly developed for wildlife management but vary considerably in their level of development and public accessibility. Watchable wildlife areas have also been designated throughout much of the United States (Watchable Wildlife 2011), and this information may be used to document major wildlife-related recreation sites.

Information associated with the response of a given species to human alteration is found in several forms from NatureServe. A relative score (called an element occurrence or EO rank) for quality of a given location or occurrence is based on the application of ecological criteria by field biologists. These scores are A–D, where an “A” EO rank indicates a very high-quality occurrence, while a “D” rank indicates severely degraded ecological conditions and presumed limited viability. Ideally, these criteria (as opposed to the resulting score) would be of use in production functions because they could characterize the common responses of the species to human alterations that affect primary and supporting ecological processes. The criteria used to assign ranks to occurrences focus on the likelihood of long-term persistence as affected by population size (or habitat area), habitat condition, and spatial context. That is, while these factors might contribute to ecological production functions as influenced by management activities, actual production functions have not been estimated. NatureServe Conservation Status ranks use information on distribution, EO rank, and trends in threats to determine the relative extinction risk rangewide (called a global or G-rank) or within a given subnation (S-rank).

For at-risk species, an information source parallel to the NatureServe Conservation Status rank is the International Union for Conservation of Nature (IUCN) and their Red List of Threatened Species (www.iucnredlist.org). This site provides various search options to access information on common threats and protective management or policy responses.

For analysis of species, a significant need is for relatively detailed maps showing locations where species with high existence values, particularly species with regulatory requirements (listed or at risk), occur or may occur. Currently available data, such as NatureServe occurrences, remain an essential source, but their completeness and currency require ongoing investment in systematic field inventory. Also, the U.S. FWS has maps showing areas of defined critical habitat or other recovery plan areas, such as those defined as late-successional reserves (LSRs) for the northern spotted owl and marbled murrelet. For a limited number of listed or regulated species, probability-based distribution maps showing the likelihood of species’ occurrence are available.

There is a need for integrated maps that combine probability of occurrences (and/or habitat quality) with any designated critical habitat (reflecting plans for recovery). For more common vertebrates and vascular plants, integrating observations and collection data into distribution databases that showed the last observation within an area, most suitably a 12-digit hydrologic unit code (HUC), could be readily accomplished and could provide important information for species distributions and trends.
Research on trends in the distribution and status of species requires this baseline knowledge. These data can be built on over time through field monitoring and remote sensing of changing landscape conditions. This remains a substantial unmet need.

Vertebrate Models

Production function models for vertebrates assess how management or resource use affects species, so information on critical corridors and seasonal habitat need to be established and monitored. These data need to consistently characterize, map, and document the relative quality of these critical habitat components. Currently, these data are developed in limited form, often by state wildlife agencies and wildlife researchers, and so there are no established sources where these data have been consolidated.

Invertebrates, Plants, Fungi, and Other Taxa

BISON and the GBIF do a good job integrating observation and collection data; however, they are generally only searchable on a species-by-species basis. For assessing species existence in a location, a standard set of geographies used in analysis, such as watersheds, could be identified, so that species lists for these geographies could readily be generated, significantly improving agencies' ability to use the information. Natural Heritage programs commonly maintain lists of at-risk species by county or other local political jurisdiction.

Another need is to attribute these species to marine vs. freshwater vs. terrestrial ecosystems, so one can better determine how management will affect the systems in which they reside. For both, assessing species as to their relative tolerance for intensive human uses (timberlands, farmlands, rangelands, etc.) would greatly assist in ecosystem service-related analysis to help predict changes.

Natural Communities: What We Have

Natural communities provide a range of cultural, spiritual, and recreational services. Seeing a unique or colorful plant or any large native animal or walking through a majestic old-growth forest or across alpine tundra can be inspiring. Natural communities are characterized by the diversity of landscapes and regions and are chronicled most extensively for terrestrial environments of the United States. NatureServe Explorer (http://explorer.natureserve.org) and, in collaboration with the Ecological Society of America, the U.S. National Vegetation Classification (www.usnvc.org), describe vegetation-based natural communities. Maps of vegetation-based natural communities are available at national and regional scales from sources such as the USGS GAP, NatureServe, and the interagency LANDFIRE program (www.landfire.gov). In each of these efforts, natural communities are described at multiple levels of thematic detail, so that few or many map types may be displayed, depending on user needs. Both the USFS and National Park Service have active vegetation inventory programs targeted to the lands they manage.

Wetlands (i.e., swamps, bogs, marshes, riparian zones, and shallow ponds), while also included in these previously mentioned sources, are the primary focus of the National Wetlands Inventory (NWI; www.fws.gov/wetlands). NWI is an ongoing effort to map locations and trends in wetland extent nationwide. They include relatively few wetland types but do provide an extensive national map resource suitable for many applications.

Wetland condition assessments (e.g., NatureServe 2016a) aim to characterize the functional values and ecological integrity associated with a wetland, given the potential altering effects of land and water uses (U.S EPA 2016c). The U.S. EPA has supported extensive wetland and freshwater aquatic condition assessments; the latter measure the composition of aquatic species to indicate the degree to which physical or chemical alterations have affected ecological functions.

Compared with the terrestrial environment, there has been much less emphasis on freshwater natural community classification and description. Freshwater natural communities are typically described in terms of their physical characteristics (e.g., water temperature, chemistry, and dynamic flow properties) and animal species (e.g., invertebrates and fish). The Nature Conservancy (2015) has contributed much to mapping and assessing freshwater communities throughout the United States. USGS maintains maps of hydrography, depicting streams, rivers, and lakes. These data are readily available in the National Hydrological Dataset (NHD, http://nhd.usgs.gov) so that freshwater communities can be represented in generalized form, although the NHD is uneven in its development across the country and needs significant investments in many areas to provide the improvements needed to represent hydrology well enough to inform most water-related services.

Natural Communities: What We Need

As noted above, classification and description of aquatic communities are far less developed than those of terrestrial communities, although new efforts are underway (Artz 2016). Mapping the location of aquatic communities, once they are classified and described, is most advanced for surface waters. Least developed of all are natural communities, both terrestrial and aquatic, associated with caves. Natural isolation in caves is well known to result in narrow endemism of both terrestrial and aquatic species, but the classification, description, and inventory of cave ecosystems remains very limited.

Finally, the relative at-risk status of natural communities, like that for species, could provide an additional measure of irreplaceability for the existence value of biodiversity. Documenting at-risk status for natural communities lags behind efforts for species. However, recent international initiatives, with pilot efforts in the United States, include the IUCN Red List of Ecosystems. The IUCN approach documents rangewide trends in conversion and human alteration to a given ecosystem type in order to gauge its at-risk status as critically endangered, endangered, vulnerable, near threatened, or least concern. As pilot efforts are completed, new investment in documenting the at-risk status of all terrestrial and aquatic ecosystem types should provide an important contribution to ecosystem service assessments.

Predictive Models

Predictive models of species, habitats, or natural communities can be used to reflect both the existence values of important features across the landscape and the attributes that directly define services, such as carbon sequestration, flood amelioration, and pollinator availability. And most predictive models are tied to spatial data that can reflect changes over time, so that changes in service provisions based on investments, mitigation, restoration, or other activities can be measured.

Species

Predictive models for species can be generated as range maps (Hall 1981; Hurlbert and Jetz 2007), species distribution models (Scott et al. 2002; Elith and Leathwick 2009), or habitat suitability models (Hirzel et al. 2006). The latter models typically predict an index of habitat suitability, either on a scale of 0 to 1 or as "habitat/not habitat" (0/1) or in classes representing nonhabitat, poor habitat, fair habitat, and good habitat. These attributions can be assigned as a function of measured descriptors such as topography and soils (for plants) or vegetation structure and type (for animals). While these models exist, few of them are framed as production functions. For these models to be useful as production functions, it would be necessary to extend them so that changes in the predictor variables via management or other human activities would be directly reflected in changes in habitat suitability and, by inference, population size or viability (Morzillo et al. 2014). There is an older literature detailing how this might be done by linking management to wildlife habitat suitability (USDA 1980). While we increasingly have the capacity to generate such models, they are not generally available in this form, as it requires linking habitat affinities to critical vegetation attributes (Henderson et al. in press). However, these models do provide the ability to address climate-driven effects that may occur as the climate continues to change.

With respect to recreational species, fish and wildlife agencies have detailed models reflecting important habitat attributes, such as big game winter range or upland game bird breeding habitats. They also have detailed information on available wildlife numbers, allowing them to set hunting and fishing limits that maintain viable populations. However, the link between the production functions in the terrestrial and aquatic habitats or landscape and the numbers of fish and wildlife available for food and recreation is generally available locally and only for a limited number of species (salmon, deer, elk, etc.).

Natural Communities

Since patterns in vegetation or aquatic fauna reflect their environmental settings and natural disturbance processes, they form a practical focus for modeling production functions related to the existence value of these communities and a proxy for related species existence and other biodiversity-based ecosystem services. Most common forms of human alteration to natural communities are from land conversion (for agriculture, urban, and industrial land uses), degradation from overuse by forestry or grazing, displacement of native species diversity by invasive species, and disruption of natural dynamic processes like river flooding or natural wildfire. Land use and remote sensing data can track these patterns and trends across land and water (e.g., U.S. EPA 2001; Leu et al. 2008; Theobald 2013), providing a source for analysis of ecosystem service provision.

Conceptual "state and transition" models have been developed to predict and track the effects of wildfire, wildlife, forestry, or rangeland management on natural community types and landscapes. These can provide ecological production functions for assessing how ecosystem services provided by the natural community change. Models of natural wildfire regimes are available through the LANDFIRE program for all major upland vegetation types in the United States. Not only are there quantitative descriptions of fire frequency, intensity, and successional pathways, but maps are produced for fuels, topography, recent fire events, and fire regime alteration. Fire regime alteration expresses the departure from expected vegetation conditions resulting from fire suppression or effects of invasive plant species. Similarly, the NRCS maintains more-specific state and transition models connected to soil type maps for use in rangeland and forest management. These models, called "ecological site descriptions," are currently most developed in the western states, but initiatives aim to advance their development nationwide (USDA NRCS 2016).

Many federal and state agencies rely on models to evaluate how management decisions affect ecosystem outputs. Increasingly, state and transition models, such as those mentioned above, are linked to climate variables and subsequently applied using climate change projections for upcoming decades. These models may provide an indication of the magnitude and direction of change in dynamic processes (fire, species invasion, and hydrology). More complex process models, such as Landis (Landis-II 2016), are used to evaluate ecosystem outputs and tree species distributions in light of management actions and climate change. All of these can provide detailed information that can directly inform environmental outputs such as wood products, carbon sequestration, wildlife abundance, and fire risk, but currently the detailed models informing specific local or watershed outputs exist in only a few parts of the United States.

Although considerable information exists for understanding how natural communities are affected by human uses, much effort is needed to integrate existing information into predictive models and to do so across terrestrial and aquatic environments. This knowledge would be greatly enhanced by the systematic establishment of reference locations specifically aimed at measuring responses to human alteration, so that comparative analysis of field observations can better support inferences regarding the effects of land or water uses on key ecological processes. This type of information may be gleaned from Long-Term Ecological Research (LTER) sites and the developing National Ecological Observatory Networ k (NEON), but these networks aim for very intensive research in a small range of locations. The U.S. EPA (2016b) National Wetland Condition Assessment represents one broader effort to establish reference locations (currently around 1,200) for national reporting on trends in wetlands. NatureServe network programs have established as many as 60,000 locations, mostly east of the Rocky Mountains, where natural communities have been described and assessed. Much related information also exists throughout conservation lands where ecological management and restoration has been implemented and monitored. A coordinated effort to integrate and augment this information could form the foundation for modeling production functions of numerous biodiversity-related ecosystem services.

Table 2-1. Ecological data and models for ecosystem services assessments of terrestrial and freshwater biodiversity

Type	Source	Reference	Description
Data – species	NatureServe Explorer	http://explorer.natureserve.org	Provides geospatial data on at-risk and legally listed species and those with other forms of conservation significiance in North America at the county and/or HUC-8 level
	IUCN Red List of Threatened Species	www.iucnredlist.org	Provides various search options to access information on common threats and protective management or policy actions
	National Gap Analysis Program (GAP)	http://gapanalysis.usgs.gov	Downloadable spatial data showing the range and distribution of almost all vertebrate species in the United States
	EPA EnviroAtlas	http://enviroatlas.epa.gov/enviroatlas/atla.html	Uses GAP vertebrate habitat models to provide species averages and maximums at the HUC-12 watershed level

Type	Source	Reference	Description
	Biodiversity Information Serving Our Nation (BISON)	http://bison.usgs.ornl.gov/#home	Detailed specimen data from as many sources as could be identified, along with selected observations of species
	NRCS Plants	http://plants.usda.gov/java	Provides standardized information about the vascular plants, mosses, liverworts, hornworts, and lichens of the United States and its territories
	eBird	www.ebird.org/content/ebird	Detailed information of most observations on birds, allowing for an analysis of their distribution
	Breeding Birds Survey	www.pwrc.usgs.gov/bbs	Effort between the USGS's Patuxent Wildlife Research Center and Environment Canada's Canadian Wildlife Service to monitor the status and trends of North American bird populations
	Birds of North America	http://bna.birds.cornell.edu.bna	Provides comprehensive life histories for the 716+ species of birds breeding in the United States (including Hawaii) and Canada
	Global Biodiversity Information Facility (GBIF)	www.gbif.org	Free, global, open-access biodiversity data
Data – natural communities	NatureServe Explorer	http://explorer.natureserve.org	Provides descriptions of all terrestrial natural communities in the United States and their conservation status (where available)
	NatureServe	www.natureserve.org/conservation-tools/terrestrial-ecological-systems-united-states	Downloadable map of 500+ terrestrial ecosystems and land cover types at 30- to 90-meter scale for conterminous United States
	U.S. National Vegetation Classification (NVC)	http://usnvc.org/explore-classification	Provides detailed descriptions of vegetation types in the United States with ecological context and geographic ranges
	National Gap Analysis Program (GAP)	http://gapanalysis.usgs.gov	Downloadable spatial data showing the range and distribution of almost all vertebrate communities in the United States
	LANDFIRE Program	www.landfire.gov	Downloadable map of 400+ terrestrial ecosystems and land cover types at 30- to 90-meter scale for the United States; estimates canopy cover and heigh per canopy layer, successional stages, fuel types, fire regime condition classes
	National Wetlands Inventory (NWI)	www.fws.gov/wetlands	Maps the location of eight wetland and aquatic types and extent in the United States

Type	Source	Reference	Description
	National Land Cover Database (NLCD)	www.mrlc.gov	Maps of 20 land cover and forest cover types across the United States at 30-meter scale every five years
	National Ecological Observatory Network (NEON)	www.neoninc.org	Distributed network of detailed climate, vegetation, and environmental plots funded by the National Sciences Foundation (NSF)
	Long-Term Environmental Research (LTER)	www.lternet.edu	A network of 20 long-term research sites located in different biomes across the United States, with long-term environmental research supported by NSF
	National Estuarine Research Reserve (NERR)	www.nerrs.noaa.gov	A national network of research sites in estuaries across the United States, where environmental research and information gathering is funded by NOAA
	Forest Inventory and Analysis (FIA)	www.fia.fs.fed.us	National network of forest vegetation monitoring plots, collected at a regular grid in all forest landscapes in the United States; data stored at regional Forest Service Research Offices
	Natural Resources Inventory (NRI)	www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri	National network of vegetation and soil plots on agricultural and rangelands across the United States; data stored in a national data center, with private land restrictions
	Assessment, Monitoring and Inventory Program (AIM)	http://jornada.nmsu.edu/aim Toevs et al. 2011	National monitoring system of vegetation plots on all BLM lands across the country; data integrated nationally
	Natural Resources Conservation Service ecological site descriptions	www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/alphabetical/ecosite/?cid=stelprdb1049096	Used to describe common successional dynamics and effects of management on biomass production, commonly used for rangeland management
Models – natural communities	LANDFIRE Program	www.landfire.gov	Used to describe common successional dynamics at a given site based on different biophysical environment settings

An Example of Infrastructure Data from the U.S. Forest Service

Often, additional data on infrastructure that interacts with ecosystems and the flow of services will be needed for assessment. This can be useful for both the ecological assessment of ecosystem service supply and quantifying accessibility of services, which is important for understanding potential importance to people. We provide an example here from the USFS.

The USFS collects and maintains spatially referenced (geographic information system, GIS) data on the built environment (infrastructure) under its jurisdiction. Publicly available data can be found at http://data.fs.usda.gov/geodata/edw/datasets.php and include information on three types of infrastructure:

(1) National Forest System trails, (2) National Forest System roads, and (3) National Forest System recreational facilities. These GIS data are in the process of development and are not yet comprehensive. First, basic trail data are available for public use and distribution describing the characteristics of more than 5,000 USFS trails (spanning roughly 10,000 trail miles). These data may include basic trail characteristics such as trail number, trail name, trail length, trail surface (native material, imported material, snow), typical range of trail grade (in percent), trail width, and whether motorized, bicycle, or stock use of the trail is authorized.

Second, the USFS maintains publicly available data on more than 75,000 National Forest Service roads (spanning nearly 100,000 miles). For each road segment, these data include road name, road surface (paved, gravel, dirt), and suitability for various types of vehicles.

Third, the USFS collects and maintains publicly available data on selected recreational sites and facilities. These data are sparse and are currently unavailable for many recreation sites. Characteristics of the data may include the recreation area name and type.

Table 2-2. Ecological data and models for ecosystem services assessments of land use and land cover change

Type	Source	Reference	Description
Data	National Land Use Database	Theobald 2014 (doi:10.1371/journal.pone.0094628)	Comprehensive, detailed, high-resolution 79-class land use database developed through spatial analysis of nearly two dozen publicly available national spatial data sets
	National Land Cover Database (NLCD)	www.mrlc.gov/nlcd2011.php	Land cover data with a 30-meter-resolution, 16-class product developed every five years, 2011 being the most recent
	USDA Cropland Data Layer	https://nassgeodata.gmu.edu/CropScape	Crop-specific land cover data layer created annually for the continental United States using satellite imagery and extensive agricultural ground truth
	National Gap Analysis Program (GAP) land cover data	http://gapanalysis.usgs.gov/gaplandcover/data	Detailed vegetation and land use patterns for the continental United States
	EnviroAtlas	enviroatlas.epa.gov/enviroatlas/atlas.html	Provides a subset of NLCD classes aggregated at the HUC-12 watershed level
	USFS Urban Tree Canopy Assessment (UTC)	http://gis.w3.uvm.edu/utc	Data on urban forest resources, tree canopy that currently exists, and the amount that could exist
	US Interagency Landscape Fire and Resource Planning (LANDFIRE) program	www.landfire.gov	Multiple geospatial layers detailing vegetation cover and ecosystem type

Type	Source	Reference	Description
	USGS Global Ecosystems Mapping Product	http://rmgsc.cr.usgs.gov/ecosystems	A high-resolution, data-derived global ecosystems map composed of standardized global terrestrial ecosystem types
	NOAA Coastal Change Analysis Program (C-CAP)	https://coast.noaa.gov/digitalcoast/tools/lca	Available now for coastal areas at a 30-meter resolution; includes more finely resolved wetland classes than NLCD. NOAA will be producing a 1-meter product in the future.
Models	Forecasting Scenarios of Land-Use Change (FORE-SCE)	http://landcover-modeling.cr.usgs.gov/methods.php	Provides spatially explicit projections of future land use and land cover change

Pollination

Pollinators are essential to our food system and are important inputs to our farming economy (Potts et al. 2010). Roughly two-thirds of the world's most important crop plants benefit from bees and other pollinators (Klein et al. 2007). In the United States, bees are estimated to contribute 11% of agricultural gross domestic product (Lautenbach et al. 2012). Of this overall contribution, at least 20% (equivalent to $3.07 billion) is provided by wild pollinators (Losey and Vaughn 2006). Pollinators help to maintain the livelihoods of farmers who depend on them.

Pollination services can stem from wild pollinators as well as from managed colonies of insects. Many farmers use managed honeybees (*Apis mellifera*) to ensure crop pollination, but there is increasing evidence that wild bees play an important role as well (Garibaldi et al. 2013). There are roughly 4,000 species of bees in the United States, but only a relative few are important crop pollinators (Kleijn et al. 2015). Honeybees and native bees can complement each other in providing pollination to crops (Brittain et al. 2013; Greenleaf 2006), and crops appear to benefit from native bee pollination even when honeybees are abundant (Garibaldi et al. 2013). Both managed and wild populations of bees are declining in the United States due to a mix of parasites, diseases, habitat loss, and pesticides (Potts et al. 2010; Bartemeus et al. 2013; Colla et al. 2012). In the United States, the number of honeybee hives has declined steadily over the last 50 years (Ellis et al. 2010). And in 2017, the United States added its first bee (*Bombus affinis*) to the Endangered Species List.

Efforts to improve pollinator health and restore pollinator services involve three main strategies: restoring pollinator habitats, avoiding exposure to pesticides, and preventing the spread of disease. Following a White House Memorandum in 2014, a federal Pollinator Task Force developed a national strategy to promote pollinator health (Pollinator Health Task Force 2015a). The strategy is accompanied by a Research Action Plan (Pollinator Health Task Force 2015b). Federal efforts include incentives for farmers to improve or create pollinator habitats through the Pollinator Habitat Initiative from the Conservation Reserve Program (USDA Farm Service Agency). Many local efforts are also occurring nationwide.

Data Sources

The data described here pertain to insect pollinators, but data on other animal pollinators could be incorporated.

Pollinator presence can be loosely approximated on the basis of land cover type; land cover classes determined to be pollinator habitat (such as grassland, forest, or wetland) can act as a proxy for pollinator presence. This relatively simple way to account for the likely abundance of pollinators does not, however, allow for any description of population sizes or pollinator diversity. The National Land Cover Dataset (NLCD) is a widely used dataset with distinct land cover classifications that can be used to estimate the presence and amounts of pollinator habitat. (A full list of land classification datasets that could also be used as pollinator habitat proxies can be found in the "Land Use and Land Cover Change Data" section.)

There has been a recent increase in research regarding the linkages between land cover and pollinator health. For wild pollinators, important reviews include papers on loss of pollinator habitat quantity or quality (Brown and Paxton 2009; Koh et al. 2016), bee abundance and landscape composition (Viana et al. 2012; Kennedy et al. 2013), and disturbance effects on wild bees (Potts et al. 2010; Winfree et al. 2010). For honey bees, research also demonstrates a clear association between land use and honey bee colony survival (Smart et al. 2016a; Paudel et al. 2015), individual bee physiology (Smart et al. 2016b), diet (Requier et al. 2015), and large-scale habitat suitability (Gallant et al. 2014; Otto et al. 2016) (Iovanna et al. 2017).

It is important to assess pollinator services in relation to the location of crops that benefit from or require pollinators. The USDA Cropland data layers are national-scale raster coverages that distinguish among crop cover types and thus allow for identification of the location of pollinator-dependent crops. Other datasets provide lists of pollinator crops that benefit from or depend on pollinators and also indicate the fraction of production attributed to insect pollination (Calderone 2012; Klein et al. 2007).

Additional useful data sources include the USGS Pollinator Library, which documents and continually updates information on forbs that are utilized by pollinating insects across broad U.S. geographic regions (USGS 2016). Data on honey bee forage species, by region, can be found in the Bee Forage Regions database from NASA (NASA 2017). Regionally appropriate seed mixes for establishing pollinator-friendly wildflower strips are available from the USDA National Conservation Research Service (USDA National Conservation Research Service). The National Agricultural Statistics Service (NASS) houses data on honey production, prices, inventory, and sales as well data on honey bee colonies, colony sales, and colony collapse due to a variety of causes (USDA National Agricultural Statistics Service 2017).

Predictive Models

The economic value to agriculture from a change in abundance of wild pollinators depends on four factors: (1) the distance of pollinator habitats from crop fields, (2) the extent to which those crops are dependent on pollinators, (3) the response of crop yields to the additional pollination, and (4) crop price (Iovanna et al. 2017). Isolating the effect of pollinators on yields requires care, because pollination is only one of many important inputs to crops that determine yield (Iovanna et al. 2017).

The InVEST Model of Crop Pollination is a commonly used tool to predict changes in supply of native pollinators within range of a target agricultural field at a landscape scale. Data inputs include land use/land cover, relative availability of nesting and foraging resources on each land cover type, and pollinator species/guild attributes (Lonsdorf et al. 2009; Wolny 2012). The model is typically used on landscape scales, at which data can be gathered in a consistent manner (e.g., Kennedy et al. 2013; Ricketts and Lonsdorf 2013). Broader-scale assessments require much more intensive data compilation efforts, and they may require expert sources of data when consistent datasets aren't available (Koh et al. 2016). Efforts are under way to modify the InVEST landscape model to inform farm-scale decisions that reflect evaluation of integrated use of managed bees and wild bees to support crop pollination (Integrated Crop Pollination Project 2017).

The InVEST Crop Pollination model is designed to account for the diminishing impact of pollinators on crop fields with increasing distance from pollinator habitat and the diminishing change in marginal relative value with increasing pollinator abundance. In other words, where few pollinators exist, the addition of new pollinator habitat can make a large impact, but where pollinators are already plentiful, new habitat will make less of a difference (Iovanna et al. 2017). Insect pollinators are only valuable to those crops that depend in some way on pollinator services, so the InVEST Crop Pollination model accounts for the pollinator-dependence of crops in the landscape (Klein et al. 2007) (Iovanna et al. 2017). Output maps include pollinator abundance over the entire landscape, pollinator abundance on farms, and relative pollinator service value of each cell (Wolny 2012). The InVEST model provides only relative indices of pollinator abundance and value. To relate these relative indices to actual monetary values, the user must obtain prices for each pollinator-dependent crop within the area of interest. Crop prices can be found at the USDA Agricultural Marketing Service (AMS) Market News website (USDA Agricultural Marketing Service 2017), and U.S. futures market prices, at the CME Group site (CME Group 2017).

Currently, the best way to model the relationship between floral diversity and managed honeybee health is to rate the floral resources of a landscape using a managed-bee ArcGIS tool (Lonsdorf and Davis 2016). This model applies the same assumptions as the InVEST pollinator model, namely that floral resources within the foraging area are directly related to honeybee colony health. The model parameters needed to describe habitat quality can be informed by recent empirical studies (e.g., Otto et al. 2016; Smart et al. 2016a,b). Output from the model is a raster map showing the quality of floral resources at point, over the spring–fall growing season. This output can be ground truthed using honey production data. Gallant et al. (2014) developed a complex analysis for predicting conditions that might support hives using multiple sources of land cover to determine where apiaries of 100 or more colonies could be supported.

Table 2-3. Data and models for ecosystem services assessments of pollinator services

Type	Source	Reference	Description
Data	Calderone 2012	http://dx.doi.org/10.1371/journal.pone.0037235	The supplemental materials of this paper include data on crops that benefit from or require insect pollinators, including the percentage of yield due to insect pollination.
	Ricketts et al. 2008	http://dx.doi.org/10.1111/j.1461-0248.2008.01157.x	This synthesizes results from 23 studies estimating the relationship between pollination services and distance to natural habitats. Pollinator richness and visitation rates to crops exponentially decline with increasing distance from natural habitat; evidence indicates an overall decline in fruit and seed set.

Type	Source	Reference	Description
	USGS Pollinator Library	http://www.npwrc.usgs.gov/pollinator/home	This database documents and continually updates information on forbs that are utilized by honey bees and other pollinators across a broad geographic region.
	NASA Bee Forage Regions Database	https://honeybeenet.gsfc.nasa.gov/Honeybees/Forage.htm	These data on honey bee forage species are broken down by region.
	NASS Database	https://quickstats.nass.usda.gov/	This database provides data on honey production, prices, inventory, and sales as well as data on honey bee colonies, colony sales, and colony collapse due to a variety of causes.
	USDA National Cropland Data Layer (CDL)	https://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php	This 30-meter-resolution annual product provides specificity of crop types across the United States.
	Koh et al. 2016	http://www.pnas.org/content/113/1/140.full	Supplemental tables provide expert-derived estimates of floral and nesting quality for CDL classes for all of the United States.
Models	InVEST Pollinator Abundance at Landscape Scale	http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/croppollination.html	The InVEST pollination model focuses on wild bees as a key animal pollinator. It uses estimates of the availability of nest sites and floral resources and of bee flight ranges to derive an index of bee abundance nesting on each cell on a landscape (i.e., pollinator supply). It then uses flight range information to estimate an index of the abundance of bees visiting each agricultural cell. If desired, the model then calculates a simple index of the value of these bees to agricultural production, and it attributes this value back to source cells.
	InVEST Pollinator Abundance at Farm Scale	http://www.icpbees.org	This web-based tool will allow farmers to evaluate yield impacts of habitat restoration or managed bees scenarios (available August 2017).
	Managed Bee Model	http://dx.doi.org/10.3133/ofr20161006.	This model builds on the assumption that floral resources are directly related to health of a honeybee colony, and it ground truths the estimates using available honey production data.

Fresh-Water Supply

Fresh-water supply or water-quantity data describe different types of water resources: surface water that is flowing (streams, rivers) or in lakes and reservoirs, and groundwater stored in aquifers. The quantity of surface water available in a region is largely a function of climate and water-use patterns. The type of human water use defines the demand for a given quantity, quality, and timing of water. Climate, as well as hydrology and upstream water use, defines the amount and timing of water delivered into a basin. In many instances, infrastructure, such as reservoirs and canals, tunnels, and pumping stations that divert water for inter-basin transfers, has been constructed to redistribute the amount of water available over time and space. Reservoirs change the natural variation of streamflow (the amount and timing of water in a stream), which can negatively affect downstream ecosystems (e.g., Pearsall et al. 2005; Doyle et al. 2003). Some reservoirs have attempted to change their water operations to mimic a more natural flow regime while meeting societal needs (e.g., for John H. Kerr Reservoir, see Pearsall et al. 2005; for Glen Canyon Dam, see Stevens et al. 2001).

Data Sources: Status and Trends

The main source of national water-supply data is through the USGS, which manages a network of stream-gages throughout the United States (http://waterdata.usgs.gov/nwis). Stream gages collect continuous stage (height of river) and discharge (flow through the river) at a single point, which is often averaged to a daily time step. Some stream gages collect additional data including turbidity, water temperature, and other water quality parameters. Stream gages have operated over different time ranges, with some gages recording for over 100 years and others for only a few years. These data can be used directly to explore ecosystem service questions on streams where gages are located and can be extrapolated to the contributing upstream watershed by helping to calibrate hydrologic models that serve to assess ecosystem services. The USGS provides spatial delineations of river basins using a hydrologic unit code (HUC), a spatial watershed cataloging system. The smallest resolution provided is a HUC 12, which can range from less than ten to a few hundred square miles (https://water.usgs.gov/GIS/huc.html). USGS is currently developing the National Hydrology Database Plus-High Resolution (NHDPlus HR) that provides high-resolution spatial data on streams, lakes, and catchments (https://nhd.usgs.gov/Catchments can be smaller than a mile and aggregated to larger catchments that drain to an outlet point. The data include catchment characteristics, flow direction, and flow volume estimates. Although it provides high-resolution spatial data, the attribute data are static and do not capture the temporal variation in water quantity or quality. The USGS has a more limited groundwater data network that contains information regarding depth to water level and the aquifer each well is screened in or pumped from. The USGS groundwater resources program (http://water.usgs.gov/ogw/gwrp/) has studied and published reports and toolkits to assess the quantity, quality, and recharge rates of several aquifers, as well as their baseflow to streams.

Coarse-scale national assessments of water yield and availability exist (e.g., Brown et al. 2016) that may be useful for generalized assessments of larger river basins at coarse temporal scales. However, such analyses lack the spatiotemporal resolution needed for fine-grained analysis across smaller spatial and/or temporal extents.

Information on human management of streams is less consistently gathered and available. Most watersheds in the United States have reservoirs that impact the amount and timing of water available. The National Inventory of Dams provides a database of reservoirs, construction years, owners, locations, and storage volumes (http://geo.usace.army.mil/pgis/f?p=397:1:0). However, information regarding how the reservoir is operated, how decisions are made regarding how much water is stored in the reservoir, and how much is released at any given time must be gathered on an individual basis.

Finally, water-use data can help quantify demand for and use of water. USGS compiles a water-use report every five years, which aggregates state-level water-use data, describing the quantity of surface and groundwater used by different beneficiary groups (e.g., domestic, agricultural, industrial, electric power generation) at the state and country level (https://water.usgs.gov/watuse/). Additionally, Tidwell et al. (2014) developed a national database of water use and cost for western U.S. HUC-8 watersheds that could provide useful data on the economic value of water resources.

Predictive Models

Ecosystem services typically consider the multiple benefits water in streams provide to society, as direct human water use and consumption is only one benefit. Neither abundant, polluted water nor clean, scarce water is able to meet societal water-supply needs. Understanding how climate and human alterations to the landscape affect streamflow is an active area of research. Some studies have used empirical models to compare streamflow changes between nearby natural (unaltered) and human-modified basins (e.g., Vogel et al. 2011; Arrigoni et al. 2010; Hodgkins et al. 2007). Changes in streamflow in natural basins are attributed to climate and natural disturbance processes, and differences in the human-modified basins can be attributed to human influences, in terms of both direct withdrawals and indirect landscape impacts. Indirect impacts include changes in land cover, which can often have mixed impacts on water supply. For example, more forest cover can result in more evapotranspiration and less overall water supply, as well as changes in the timing of runoff, groundwater reacharge, and water quality (e.g., Kim 2012), though these are not strict relationships and they depend on watershed geology, ecology, and climate. Agricultural changes in land cover have been documented to have mixed impacts depending on type of crop, the land cover agriculture is replacing, and the drainage system used (Schilling et al. 2008). Urbanization, one of the dominant factors in altering streamflow, often results in increased streamflow after rain events due to increased impervious surface, but it can also result in an overall decrease in streamflow as groundwater recharge is reduced (Hodgkins et al. 2007; Dewalle et al. 2000).

Moving beyond a paired catchment approach, empirical analysis can be combined with physically based models (such as the Soil and Water Assessment Tool, SWAT) to determine if human activities are responsible for major changes in streamflow within a specific watershed (e.g., Kim 2012; Claessens et al. 2006). A third approach has been to quantify the relative contribution of climate and direct human modifications on mean annual streamflow using Budyko curves, which rely on the interdependence between mean annual evaporation and potential evaporation (influenced by land cover) for a watershed's precipitation regime (e.g., Patterson et al. 2013; Wang and Hejazi 2011). All three approaches can be applied and will provide different results given the location and time period of observation (i.e., trends from 1960 to 1990 may be different from trends from 1980 to 2010; McCabe and Wolock 2002). Furthermore, it is very hard to separate the effects of land use change on water supply available because watersheds are dynamic, depending on a unique combination of climate, land use, and water use that can change over time. Therefore, a given increase in urbanization may have very different relationships to changes in streamflow depending on other factors in the watershed.

Table 2-4. Selected ecological data and models for ecosystem services assessments of freshwater supply

Type	Source	Reference	Description
Data	National Water Information System (NWIS)	http://waterdata.usgs.gov/nwis	U.S.-wide U.S. Geological Survey (USGS) stream gage/monitoring site network that provides data on stream flow rate and water depth
	National Hydrography Dataset (NHDPlus)	https://nhd.usgs.gov/	Provides high-resolution spatial data of streams, lakes, and catchments
	USGS Groundwater Resources Program	http://water.usgs.gov/ogw/gwrp	Reports and toolkits to assess the quantity, quality, and recharge rates of several aquifers
	National Inventory of Dams	http://nid.usace.army.mil/cm_apex/f?p=838:12	Provides a database of reservoirs, construction years, owners, locations, and storage volumes
	Water Use in the United States	https://water.usgs.gov/watuse/	Provides water use data at the state and county level by different water users
Models	Automated Geospatial Watershed Assessment Tool (AGWA)	https://www.tucson.ars.ag.gov/agwa/	Runs SWAT and Kinematic Runoff and Erosion Model (KINEROS), making it useful across a wide range of spatial scales and climatic conditions
	ARtificial Intelligence for Ecosystem Services (ARIES)	http://aries.integratedmodelling.org/	Maps ecosystem service flows based on a catalog of data and models that are matched to the application context
	Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)	www.naturalcapitalproject.org/invest	Suite of software models used to map and value the goods and services from nature that sustain and fulfill human life; includes water yield modeling tools
	Soil and Water Assessment Tool (SWAT)	http://swat.tamu.edu	A watershed-scale model used to simulate the quality and quantity of surface and ground water and predict the impacts of land use, land management practices, and climate change
	Variable Infiltration Capacity	http://vic.readthedocs.io/en/master	Appropriate for modeling hydrology of large river basins; models water yield and stream flow

Type	Source	Reference	Description
	Water Supply Stress Index (WASSI)	https://www.fs.usda.gov/ccrc/tools/wassi	Water balance model with conservative flow routing, incorporates water demand and water stress
	Water Evaluation and Planninng (WEAP) system	http://www.weap21.org/	Water balance and quality model with conservative flow routing, incorporates water demand by different user types

Water Quality: Freshwater Recreation

Data Sources: Status and Trends

Water-based recreation—particularly swimming, fishing, and boating—requires relatively high-quality water in order for these activities to be safe and aesthetically enjoyable. Water quality for freshwater recreation is a particularly multifaceted and challenging suite of ecosystem services for which to develop nationally standardized data, models, and valuation approaches. Before water quality and its effect on associated recreational values can be valued, physical changes in water quality must be quantified; water quantity may matter as well, as it affects pollutant concentrations and the seasonality of any water-quality problems (Young 2005). Phosphorus is generally the limiting nutrient in freshwater systems, so its quantification will be particularly important; however, other pollutants may also impair water quality and affect recreational users. The U.S. EPA's Impaired Waters, Assessed Waters, and Total Maximum Daily Load (TMDL) database (http://water.epa.gov/scitech/datait/tools/waters/data/downloads.cfm) provides spatial information on water-quality impairment, including the degree of pollution and the specific pollutants of concern in a given watershed.

Water quality for freshwater recreation as an ecosystem service can be valued in at least three different ways: (1) by quantifying baseline water quality, recreational use, and value (placing value on the water resource used by recreationists, i.e., a particular river reach, lake, or reservoir, and making assumptions about potential substitutes and other considerations, such as the relationship between water quality and recreation demand); (2) by quantifying the current contribution of upstream ecosystems in improving water quality, recreational use, and associated values for downstream recreational sites (placing economic value on the upstream ecosystems that improve water quality, i.e., the value of upstream wetlands or riparian buffers in improving water quality, which requires a simulation of water quality with and without ecosystems that can filter pollutants); and/or (3) by quantifying how proposed future management changes (e.g., land use/land cover, agricultural practices) may improve or degrade downstream water quality, recreational use, and associated values (placing economic value on the water resource and/or upstream ecosystems that improve water quality, which requires a simulation of current water quality and potential future improvements or degradation brought on by land use or management changes). Each of these requires different types of information on ecosystems and the services they provide.

Many national sources of water quality data exist, including data from the U.S. Geological Survey (USGS) (http://water.usgs.gov/owq/data.html), such as the National Water-Quality Assessment (NAWQA, http://water.usgs.gov/nawqa/) and National Water Information System (NWIS, http://nwis.waterdata.usgs.gov/nwis) programs. The U.S. EPA's National Lake Assessment and National Rivers and Streams Assessment provide data on lake and stream water quality, respectively (http://water.epa.gov/type/lakes/lakessurvey_index.cfm, http://water.epa.gov/type/rsl/monitoring/riverssurvey), and their National Pollutant Discharge Elimination

(NPDES) program database provides additional data on point source pollution (https://ofmpub.epa.gov/apex/aps/f?p=GPWI:HOME::::::). The U.S. EPA's EnviroAtlas also provides a number of potential model inputs for "Clean and Plentiful Water." Results are aggregated at the HUC-12 level, which is unlikely to provide the needed spatial resolution for modeling; however, the original preaggregation data used for the EnviroAtlas can be obtained for use in modeling. The USGS's Reservoir Sedimentation Database (RESSED, http://water.usgs.gov/osw/ressed) provides data on sediment delivery to reservoirs and may be helpful for quantifying the costs of sedimentation. Emerging efforts such as the National Ecological Observatory Network (NEON) may also provide useful data on water quality that could support the quantification and valuation of this service in the coming years (www.neonscience.org).

Predictive Models

Various models have been used to quantify water quality; for a more complete review than is possible here, see Wang et al. (2013) and Olander et al. (2014). Selected models that have been used to assess water quality include dedicated hydrologic models such as the Soil and Water Assessment Tool (SWAT, Arnold and Fohrer 2005; Francesconi et al. 2016) and more generalized ecosystem service models such as Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) or ARtificial Intelligence for Ecosystem Services (ARIES, Vigerstol and Aukema 2011). The USGS Spatially Referenced Regression on Watershed attributes (SPARROW) model has been used at the national and regional scales to track nitrogen, phosphorus, suspended sediment, and organic carbon (http://water.usgs.gov/nawqa/sparrow). Another USGS model, the Load Estimator (LOADEST), can be used to quantify more diverse pollutants but is more data intensive (http://water.usgs.gov/software/loadest). The U.S. Department of Agriculture (USDA) has been working with the APEX (Agricultural Policy/Environmental eXtender)-based Nutrient Tracking Tool to evaluate the effects of agricultural (both animal and crop production) management on nitrogen, phosphorus, and sediment loadings from farms (Saleh et al. 2011).

More generalized, less data-intensive models are more likely to be useful for regional- and national-scale assessments than data-intensive models (like SWAT) whose nationwide application would be resource intensive. However, data-intensive models can be very useful for case studies and for analyzing the accuracy of more generalized models (e.g., Dennedy-Frank et al. 2016). Ecosystem service models like InVEST and ARIES use approaches including the Universal Soil Loss Equation (USLE),[1] other deterministic or probabilistic methods to quantify sediment retention as an ecosystem service, and nutrient export and retention approaches to quantify nutrient regulation (Kareiva et al. 2011; Villa et al. 2014). Such models are easier to parameterize and run when data and model coefficients are accessible and transparent; recent work to catalog model coefficients for use with InVEST sediment and nutrient models (www.naturalcapitalproject.org/database.html) and to automate data and model selection in ARIES are examples of steps forward to make these tools more useful for regional- and national-scale assessments. For most models, basic tradeoffs exist between spatial and temporal resolution data sets, and not all models are yet capable of modeling at fine (i.e., subannual) temporal resolution, as adequate calibration data may be difficult to obtain.

[1] USLE and RUSLE have several well-known limitations (Roose 1996): (1) they apply only to sheet erosion versus linear or mass erosion; (2) they have only been tested in regions with 1–20% slopes and are inappropriate for areas with steeper slopes or young mountains where greater erosion is possible; (3) energy-rainfall relationships have been best tested for the U.S. Great Plains, meaning that locally appropriate rainfall runoff erosivity factors must be carefully developed and applied; (4) data are not valid for individual storms but only for averages; a Modified USLE (Williams 1975) must be used to model sediment loads produced by a single storm; and (5) the equations simplify interactions between factors to attempt to isolate the relative effects of each.

Table 2-5. Ecological data and models for ecosystem services assessments of water quality

Type	Source	Reference	Description
Data	Environmental Protection Agency (EPA) Water Data	http://water.epa.gov/scitech/datait/tools/waters/data/downloads.cfm	Provides spatial information on water-quality impairment, including the degree of pollution and the specific pollutants of concern in a given watershed
	U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA)	http://water.usgs.gov/nawqa	Provides an understanding of water quality conditions, trends over time, and how natural features and human activities affect those conditions
	National Water Information System (NWIS)	http://waterdata.usgs.gov/nwis	USGS stream gage network throughout the United States that provides data from many sites monitoring nutrients, dissolved oxygen, sediment, and other water quality parameters of interest
	EPA National Lakes Assessment	http://water.epa.gov/type/lakes/lakessurvey_index.cfm	Provides data on lake water quality, 2012 being the most recent
	EPA Streams & Rivers Assessment	http://water.epa.gov/type/rsl/monitoring/riverssurvey	Provides data on river and stream water quality with 2008–2009 being the most recent data available
	EnviroAtlas Clean and Plentiful Waters	http://enviroatlas.epa.gov/enviroatlas/atlas.html	Multiple water-quality metrics aggregated at the Hydrologic Unit Code (HUC)-12 level; original preaggregation data can be obtained for use in modeling
	USGS Reservoir Sedimentation Database (RESSED)	http://water.usgs.gov/osw/ressed	Provides data on actual sediment delivery to reservoirs and may be helpful for quantifying the costs of sedimentation
	NSF National Ecological Observatory Network (NEON)	http://www.neoninc.org/data-resources/get-data	A continental-scale observation system for examining ecological change over time
Models	Soil and Water Assessment Tool (SWAT)	http://swat.tamu.edu	A small watershed-to-river basin-scale model used to simulate the quality and quantity of surface water and groundwater and predict the impacts of land use, land management practices, and climate change

Type	Source	Reference	Description
	USGS Spatially Referenced Regression on Watershed attributes (SPARROW)	http://water.usgs.gov/nawqa/sparrow	Used at the national and regional scales to track nitrogen, phosphorus, suspended sediment, and organic carbon delivered in watersheds
	USGS Load Estimator (LOADEST)	http://water.usgs.gov/software/loadest	Can be used to quantify more diverse pollutants than SPARROW but is data intensive
	Revised Universal Soil Loss Equation (RUSLE)	www.ars.usda.gov/Research/docs.htm?docid=5971	Online tool for modeling erosion and sediment loss using the universal soil loss equation
	Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)	www.naturalcapitalproject.org/InVEST.html	Suite of software models used to map and value the goods and services from nature that sustain and fulfill human life
	Artificial Intelligence for Ecosystem Services (ARIES)	www.ariesonline.org/about/approach.html	Maps ecosystem service flows based on a catalog of data and models that are matched to the application context

Marine and Coastal Systems: Ecological Data and Models

The potential for the ocean to provide benefits to society depends on what stressors affect marine systems and to what extent that impact can be mitigated. Each service depends on a unique suite of ecological processes, supported by biophysical structure and function. Managing for these services requires, first, an understanding of what controls these ecological processes and how they interact with one another to eventually produce services that society cares about, that is, ecosystem services production functions (Tallis et al. 2008). Only after a sufficient understanding of these processes is acquired can it then be considered how management interventions might positively affect service provision. This may include the analysis of how alternative management actions provide different types and quantities of benefits based on how they affect ecological processes, including those not initially considered significant. The ecosystem services approach provides decision-support information for managers trying to maximize the benefits of their actions given different costs, priorities, constraints, risks, and knowledge gaps.

The ocean presents a particularly challenging ecosystem to map the stock and flow of ecosystem services, "where ecosystem boundaries are fluid, habitats are often poorly spatially defined and knowledge of ecosystem function emphasizes both context dependency and complex scaling from local to global processes" (Townsend et al. 2014). International, national, regional, state, county, and local authorities share responsibilities that sometimes overlap but always involve linked ecosystem processes that cross jurisdictional boundaries (Crowder et al. 2006; Ekstrom et al. 2009). Therefore, using ecosystem services information to manage the ocean requires not only the right data and models but also having the institutional structures in place to facilitate the application of ecosystem-based management approaches.

NOAA collects a wide array of information to support its fisheries management mandates, representing one of the best sources available of marine ecosystem services-relevant data. The agency and its partners collect information on the status of fish populations not only through stock assessment surveys and by analyzing fishermen's catch data but also by collecting a wide range of physical and chemical variables such as water density, sea surface temperature, salinity, nutrients, and oxygen, as well as food habits data by analyzing wildlife stomach contents. NOAA also uses a variety of derived information sources, such as the position of currents and depth of temperature stratification in the water column. All of this information is then incorporated into ecosystem-linked stock assessments, multispecies models, and ecosystem models in order to inform NOAA's fisheries management policies. Filling data gaps (e.g., the contribution of certain marine taxa to food webs are poorly understood) and increasing survey standardization (e.g., nutrients) remain priority needs to gain a more complete picture of marine ecosystem structure and function.

In addition to supporting fisheries management, NOAA collects biophysical data for many other mission areas. These include information on marine life to support Endangered Species Act listings, marine mammals protected by the Marine Mammal Protection Act, and other species that are ecologically and/or culturally significant; ecological forecasts to help society predict and prepare for impacts from events such as harmful algal blooms and flooding from storms; the movement and location of marine debris that can harm marine life and end up on beaches; data on ocean bathymetry, currents, and tides to support ships' safe navigation; and monitoring of important ecological areas and resources, including corals and the habitats within National Marine Sanctuaries.

Predictive Models

While there are clearly myriad connections between biophysical ocean data and society's well-being, only a subset of this information is directly applicable and in a form that supports comprehensive ecosystem services assessments. Models of fisheries production function that link biophysical data, population abundance, and projected catch have been extensively used for decades to manage commercial and recreational fisheries (see Age Structured Assessment Program and A Stock Production Model Incorporating Covariates, for example, among other methods in the NOAA Fisheries Toolbox). NOAA is also currently piloting a new fisheries management model that analyzes how different management regulations (e.g., closed areas) affect fishers' welfare. Outside of fisheries, NOAA has developed ecosystem service production functions on a more limited, project-by-project basis depending on the management context. In addition, the InVEST toolkit incorporates a wide variety of data sets to assess several other marine ecosystem services (carbon sequestration, coastal protection, marine aquaculture, marine water quality, and wave energy) and is flexible to the amount and type of data available. However, other than in fisheries, there is generally a dearth of linked biophysical and socioeconomic data needed to construct production functions used in ecosystem services assessments.

Table 2-6. Ecological data and models for assessments of ecosystem services in marine and coastal systems

Type	Source	Reference	Description
Data	NOAA data	www.st.nmfs.noaa.gov/stock-assessment	Status of fish populations (stock assessment surveys and catch data)

Type	Source	Reference	Description
	NOAA data	https://ioos.noaa.gov	Physical and chemical variables related to the marine environment
	NOAA data	www.westcoast.fisheries.noaa.gov/maps_data/Species_Maps_Data.html	Biophysical data on species of concern
	NOAA data	http://oceanservice.noaa.gov/ecoforecasting	Ecological forecasts
	NOAA data	https://mdmap.orr.noaa.gov/	Location of marine debris
	NOAA data	https://tidesandcurrents.noaa.gov	Bathymetry, currents, and tides
	NOAA multi-species models	www.st.nmfs.noaa.gov/ecosystems/ebfm/ecosystem-modeling	Multispecies models linked to ecosystems used for fisheries management.
Models	NOAA ecosystem models	www.st.nmfs.noaa.gov/ecosystems/ebfm/ecosystem-modeling and http://chesapeakebay.noaa.gov/ecosystem-modeling/chesapeake-bay-regional-estuarine-ecosystem-model	Ecosystem models linked to ecosystem-based fisheries management
	Age Structured Assessment Program (ASAP)	http://nft.nefsc.noaa.gov/ASAP.html	Fisheries production function model linking biophysical data, population abundance, and projected catch
	A Stock Production Model Incorporating Covariates (ASPIC)	http://nft.nefsc.noaa.gov/ASPIC.html	Fisheries production function model linking biophysical data, population abundance, and projected catch
	Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)	www.naturalcapitalproject.org/invest	Models for marine carbon sequestration, coastal protection, marine aquaculture, marine water quality, and wave energy that are flexible to the amount and type of data available

Ecosystem Services in Cities and Urban Areas: Data Sources and Predictive Models

Urbanization and development are important drivers of land use and land cover change (Eigenbrod et al. 2011; Elmqvist et al. 2013), which in turn alter biodiversity and the delivery of urban ecosystem services critical to the health and well-being of over 80% of the U.S. population (U.S. Census Bureau, 2010; Seto et al. 2013; McPhearson et al. 2016). Many ecosystem services such as drinking water, urban heat island mitigation, noise reduction, recreation, and mental and physical health benefits of urban green space can only be locally produced within and around cities (Gómez-Baggethun et al. 2013).

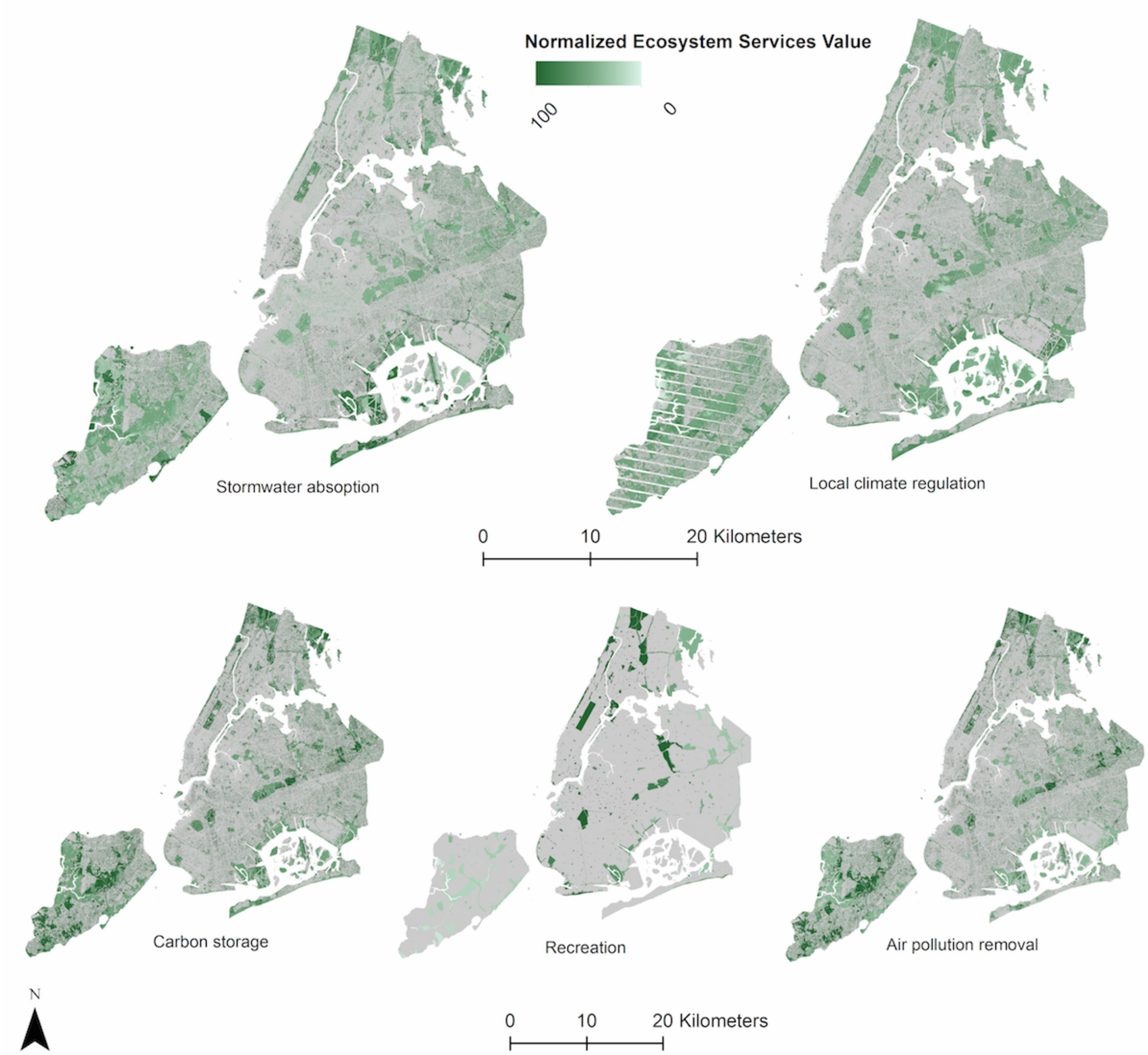
Urban ecosystem services have been most widely assessed for urban street trees and forests (Nowak et al. 2013) through the iTree modeling suite developed by the USDA Forest Service. The iTree economic valuation tool for urban ecosystem services focuses on services associated with urban trees. Recently developed urban ecosystem services assessment and nonmonetary valuation methods enable examination of tradeoffs among multiple urban ecosystem services provided not only by urban forests but also by other types of urban green infrastructure (McPhearson et al. 2013; Kremer et al. 2016) and service-providing areas (Andersson et al. 2015). Still, monetary valuation models for urban ecosystem services have not been developed explicitly for cities that allow analysis of tradeoffs and/or identify mismatches in supply and demand for multiple urban ecosystem services.

Though iTree-based studies rely on field measurements of urban trees, most urban ecosystem services assessment and valuation studies depend primarily on existing land use and land cover data available through various data portals including the NLCD. Urban areas require relatively high-resolution data (30m x 30m or less) for both social and ecological assessment and valuation since urban areas are well known to be extremely heterogeneous with social-ecological change occurring across fine spatial scales. In multiple cities 1-meter-resolution land cover data is becoming increasingly available. The EnviroAtlas Community Component provides information derived from these 1-meter land cover data summarized by census block groups for 16 cities, with 10 others currently in progress and 24 planned additions by 2019 (U.S. EPA 2016a). For example, Kremer et al. (2016) use 1-meter-resolution land cover data derived from light detection and ranging (LiDAR) and other data sources as well as land use data to assess storm-water runoff mitigation, urban heat island mitigation (cooling), carbon storage, air pollution removal, and recreation for all urban green infrastructure in New York City. Researchers were then able to examine how different valuation rankings affected the total services produced per unit area. Data at the parcel or lot scales, which is widely available for U.S. cities (Hamstead et al. 2015; McPhearson et al. 2016), can also be useful.

Table 2-7. Ecological data and models for assessments of ecosystem services in cities and urban areas

Type	Source	Reference	Description
Data			
	National Land Cover Database (NLCD)	www.mrlc.gov/nlcd2011.php	Land cover data with a 30-meter-resolution, 16-class product developed every five years, 2011 being the most recent
	EPA EnviroAtlas	http://enviroatlas.epa.gov/enviroatlas/atlas.html	Provides high-resolution (up to 1 meter) land cover data for 10 cities; used for initial community component but will be expanding
Model	iTree	www.itreetools.org	Focuses on services associated with urban trees and has been used in green infrastructure development and planning in multiple cities across the United States

Figure 2-2. Normalized ecosystem services value



Source: Kremer et al. 2016.
Note: Nonmonetary valuation of five urban ecosystem services, storm water runoff mitigation, urban heat island mitigation (cooling), carbon storage, air pollution removal, and recreation, generated by green infrastructure in New York City.

3. DATA AND MODELS FOR ECOSYSTEM SERVICES THAT REGULATE AND REDUCE RISKS

The "ecosystem services" of natural hazard protection or regulation in general depend on the presence and condition of natural systems such as mangroves or dunes but emphasize the fact that "the outcome of a natural hazard becomes a natural disaster as the result of the interaction of human or ecosystem vulnerability and the extent and severity of the damage to the human group or ecosystem receiving it" (Guenni et al. 2005).

Climate Stability through Carbon Storage and Sequestration

Data: Status and Trends

Enhancing climate stability through carbon storage and sequestration and reduced emissions of greenhouse gases are services that ecosystems can provide to people. There are several approaches for estimating vegetation-based carbon storage and sequestration capacities for the United States varying in precision and effort. Data-driven approaches rely on existing data sets that contain field measurements. The associated effort with such data sets frequently restricts their use to landscape-level assessments and can have low resolution (though some are 30-meter resolution). Examples include the Forest Inventory and Analysis (FIA) database of the USFS, soil databases such as the State Soil Geographic (STATSGO) Data Base, or remote sensing-based inventories such as LANDFIRE or the National Biomass and Carbon Dataset for the year 2000. Field measurements over time can be compared, and historic sequestration rates can be computed based on these data sets with implications to current and future developments in storage and sequestration. A subcategory of data set-based approaches relies on the use of estimation equations and lookup tables or default factors that can be applied to a given unique ecological unit (e.g., ecological sections and subsections; USDA 2007) based on typical conditions of the immediate surrounding landscape. Examples include carbon storage estimates for forest ecosystem and related human activities as provided by Smith et al. (2006).

Predictive Models

The other approach to estimating carbon storage and sequestration is model driven. General algorithms based on empirical (and data-driven) evidence are used to recreate carbon pools as well as fluxes across a system that can vary in depth and scale. For instance, the Forest Vegetation Simulator (FVS), an individual tree growth and yield model (Dixon 2002), estimates carbon storage and sequestration capacity on a stand to landscape scale including all relevant forest ecosystem pools such as aboveground and belowground live biomass, detrital pools, and organic soil carbon. Extensions of FVS can further provide estimates under various climate change assumptions as well as on carbon pools and fluxes of biomass harvests including forest product fate assumptions. FVS, coupled with fire models such as FlamMap (USDA 2016b) and advanced vegetation and fire behavior modeling, can encompass highly disruptive stochastic events in their estimates (Finney 2006). For agriculture, carbon storage and sequestration models focus on the plant-soil nutrient cycling such as the CENTURY model and the user-friendly adaptation of this tool, COMET-Farm (Finney 2006).

A variety of hybrid approaches rely more on the data- or model-driven approach. For instance, FIA data coupled with FVS modeling efforts are frequently used to estimate and monitor carbon storage and sequestration capacity of forests at a variety of scales (e.g., Nunery and Keeton 2010; MacLean et al. 2014; Gunn et al. 2014).

If the goal is to assess general greenhouse gas implications of land use scenarios, it is important to consider that a change in vegetation cover and soil dynamics is not restricted to carbon or CO_2 release.

The inclusion of non-CO_2 GHG-relevant emissions (other reactive gases and biogenic aerosols and factors such as methane or atmospheric particles), surface albedo, evapotranspiration, or complex greenhouse gas decay functions can alter model results significantly.

We identify six major fields of uncertainty in several components of current approaches to estimate carbon storage and sequestration: (i) The identification of baselines against which a given scenario can be assessed is a major step in carbon storage and sequestration estimates and frequently a focus of scientific debate. In particular, defining and predicting an alternative future in the absence of a proposed policy or practice (i.e., a counterfactual baseline) is inherently uncertain (e.g., Buchholz et al. 2014). (ii) Spatial and (iii) temporal boundaries frequently drive outcomes and can range from a stand-level to ecoregion-level analysis including wildfire dynamics or from a few decades to thousands of years. (iv) The inclusion of behavioral effects and leakage frequently extends outcome uncertainty significantly. (v) In the case of GHG impact analysis, a lack of scientific consensus on metrics complicates a comparison of study outcomes. Last, (vi) the mineral soil is one of the largest terrestrial carbon pools. The response of this slow-acting carbon pool to altered aboveground conditions is largely unknown.

Table 3-1. Data and models for assessment of ecosystem services that regulate and reduce climate risk

Type	Source	Reference	Description
Data	Forest Inventory Assessment (FIA)	www.fia.fs.fed.us	Data on status and trends in forest area and location; in the species, size, and health of trees; in total tree growth, mortality, and removals by harvest; in wood production and use rates by various products; and in forest land ownership
	Soil Survey Geographic Database (SSURGO)	http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm	Geospatial data set that provides soils data useful for estimating vegetation-based carbon storage and sequestration capacities
	Forest Carbon Xplorer	http://forestcarbonx.umn.edu	Imputed forest carbon stock estimates from FIA inventory plots to a nationally continuous coverage
	USDA CarbonScapes	www.carbonscapes.org	Tools include an Atlas for carbon pool summaries, an Explorer for data visualization, and a Data Catalog for downloading data
	LANDFIRE program	www.landfire.gov	Provides a remote sensing-based forest inventory including vegetation composition and structure as well as surface and canopy characteristics

Type	Source	Reference	Description
	National Biomass and Carbon Dataset (2010)	www.whrc.org/mapping/nbcd	High-resolution (30 m), year-2000 baseline estimate of basal area-weighted canopy height, aboveground live dry biomass, and standing carbon stock for the conterminous United States
Models	Forest Vegetation Simulator (FVS)	www.fs.fed.us/fmsc/fvs	Estimates carbon storage and sequestration capacity on a stand to landscape scale including all relevant forest ecosystem pools
	FlamMap	www.firelab.org/project/flammap	Advanced vegetation and fire behavior model that can encompass highly disruptive stochastic events in its estimates
	CENTURY model	www.nrel.colostate.edu/projects/century	Carbon storage and sequestration models that focus on plant-soil nutrient cycling
	COMET-Farm	http://cometfarm.nrel.colostate.edu	A farm and ranch GHG accounting tool that allows emissions comparisons between management scenarios
	USGS LandCarbon	www2.usgs.gov/climate_landuse/land_carbon	Current and potential carbon stocks and fluxes in major terrestrial and aquatic systems

Wildfire Risk Regulation

The vegetation of North America has been shaped by recurring fires over millions of years. Fire remains the primary natural disturbance influencing the plant and animal communities of most western forests today. The wildfire risk regulation ecosystem service varies with respect to the degree to which each ecosystem is fire adapted. In general, the frequency and mosaic patterns of intensity are shaped by the underlying terrain and climate; however, human influence has long been a factor in this relationship as well. In some forest types, new forest structures and fire regimes, shaped by past management efforts and exacerbated by climate changes, are leading to what many view as uncharacteristically severe wildfires. The consequences of these forest structures and fire regimes are most serious in forest types that were historically characterized by frequent but low-severity fire, many of which are found in low elevations and are often close to human settlements (Noss et al. 2006). Fire-adapted systems require occasional fire to remove dead and desiccant vegetation and debris, along with some live vegetation, maintaining diversity of vegetation composition, age, and size structure. These features of a constantly refreshing landscape allow it to sustain habitat, watershed protection, and other ecosystem services as well as limiting negative air quality.

Documents such as the interagency *Quadrennial Fire and Fuels Reports* (QFFR 2005, 2009, 2014) and books released in recent years such as *Mapping Wildfire Hazards and Risks* (Sampson et al. 2000) and *The Economics of Forest Disturbances* (Holmes et al. 2008) all document substantial progress in understanding and modeling the ecosystem service of wildfire regulation. Under the Millennium

Ecosystem Assessment (2005) framework, wildfire risk reduction is considered one of several regulating services that can be managed to provide several constituents of well-being, including security from disasters and access to clean air, while concurrently providing material for shelter as a byproduct of risk reduction treatments. Using this typology, the primary service that the wildland environment provides is some level of protection or resilience from damaging fire events that are regularly ignited by lightning and people (both intentionally and accidentally). These fires (1) affect people in negative ways with primary effects (e.g., burnt structures, forage, timber), secondary effects (e.g., debris flows and flooding in recently burnt areas), and indirect effects (e.g., smoke-induced health problems); (2) affect the supply of many other ecosystem services both positively and negatively (Venn and Calkin 2011); and (3) cost municipal, state, and federal taxpayers money to prevent, extinguish, and rehabilitate. All three of these types of impacts can theoretically be valued, and ideally a national picture based on a schematic (e.g., Kline, 2004, pg. 7) could be developed that adequately addresses the complexity arising from the variable intensities, scales, and frequency of fire through time in U.S. fire regimes, including:

- Benefits: maintenance and resilience of vegetation patterns and associated soil/nutrient/hydrologic flows (intermediate services) that all change through time, affecting a number of final provisioning and regulating services such as timber, forage, and wildlife (e.g., big game) availability, the quantity and quality of water (including flows and floods), scenery, recreation, and carbon sequestration;
- Damages: risk of loss of structures (private and public) and other built capital and cultural/historical sites, as well as risks to human health and safety (in part via impacts to air); and
- Expenditures (management actions): private and public funds spent on (i) prevention/hazard reduction treatments, (ii) suppression, (iii) rehabilitation/reconstruction.

Since a devastating series of forest fires swept through Idaho, Montana, and Washington in 1910, five years after the establishment of the Forest Service, the relative influence people have had on fire has grown, as attempts are made to suppress nearly all wildfires. With population growth and habitation in fire-prone areas, unmanaged wildfire causes far more unwanted consequences than desirable effects. Nationally, roughly 97% of all reported ignitions are suppressed as small fires each year, which confounds our ability to describe pure ecosystem resilience to fire. Recognition of how fire's important ecosystem role has diminished led to efforts to increase its function using prescribed burning and, in limited cases, wildfire use under its various monikers. More recently, thinning followed by burning has been proposed as a preparation mechanism to allow naturally ignited fires back onto the landscape under conditions where naturally ignited fire can restore forest health and provide more cost-effective and enduring resilience to damaging events.

Fire Modeling Considerations

Wildfires typically grow from ignitions based on interactions of the wildland fire behavior triangle (National Park Service n.d.), where dynamic weather and fuel conditions interact with topography to determine fire spread and resultant fire effects. In reality, several other social factors influence the fire behavior triangle, directly affecting not only the spatial fuel arrangements' temporal trajectory but also fire impacts through preventative mitigation (constructing homes and fences with flame-resistant materials, installing sprinklers, foaming structures), suppression actions (building fire lines, applying suppressants to fire, conducting burnouts to eliminate potential fuels), and rehabilitation efforts. Estimating the changing ecosystem service values resulting from natural trends, anthropocentric activities designed to reduce wildfire risk, or the combination of the two is best accomplished by estimating incremental avoided costs. Untangling the interaction of factors yielding avoided costs, namely preventative vegetation changes and suppression actions, is very site specific. Even at a small scale it is hard to do systematically as circumstances change as a result of fuel conditions, resource availability, and evolving perceptions of risk informed by near real-time information technology. In reality, maximization, let alone full understanding of the following production function for the subsequent ecosystem service, is nearly impossible:

$$\text{Marginal Wildfire Risk Regulation Ecosystem Services} = f(X, Y, Z, Q, P)$$

where X is wildland fire potential given dynamic climatic, vegetative, and weather processes; Y is trajectories of mitigating impacts from preventative actions by home owners; Z is trajectories of mitigating impacts from hazardous fuel treatment; Q is wildfire suppression actions; and P is rehabilitation efforts.

Although efforts like the Forest Service's Fuel Treatment Effectiveness Monitoring Program evaluate if hazardous fuel treatments affected fire behavior or facilitated suppression efforts, no data collection efforts currently aim to empirically evaluate all factors for a comprehensive analysis of the interacting components. However, given that current wildfire modeling helps demonstrate the logic representing best available science for several components and incorporation of choice modeling of social factors (e.g., Wibbenmeyer et al. 2013) in addition to the current and alternate fuel conditions, one can estimate the value of different levels of wildfire risk management. Despite the complexity of wildfire risk regulation, important subsets of ecosystem services have strong potential for which nationally standardized data, models, and valuation approaches can be developed. Before marginal impacts can be evaluated, a conceptual framework must be accepted that reconciles the mechanisms through which wildfire risk reduction affects expected values in different directions at different times; for a discussion of evolving thought on how to analyze net value change through time see Gebert et al. (2008). Mercer et al.'s (2008) work is one example of an approach to revealing the tradeoffs of fuel management, suppression, and expected damages. Specifically, the common task required in most evaluations is defining baseline wildfire risk trajectories of expected losses and expected benefits. These are best ascertained by using multiple conditional fire intensity probabilities, which can be changed to reduce the vulnerability of homes and property conditions and to transition from net negative to net positive impacts on other ecosystem components. An essential requirement of a useful conceptual model is the ability to handle the temporal aspect of risk reduction associated with various mitigation actions that can alter risk both at different times and for different durations. Incorporating fluctuating insurance coverage and dynamic property valuation into this portrayal of risk must be done carefully yet parsimoniously to realistically assess changes in fire expectations based on modeling.

Predictive Models

Ecological Fire Modeling vs. Fire Behavior Modeling

Given that fire as a disturbance interacts with both live and dead vegetation in multiple states of flammability, it can be valuable to include expected patterns of transition due to vegetative succession as well as the influence of insects and disease, windthrow, hurricanes, and other common wildland disturbances that affect fuel loading. The recent decade has demonstrated the magnitude of these interactions and makes modeling fire in the context of other ecological processes appealing. While some models are deterministic in nature in that they project change through time steps in a preprogrammed manner, other ecological process models that employ statistical probabilities of disturbances and are run multiple times to develop ranges of future conditions or probability surfaces of conditions and disturbance levels are more suited for this task. These models are used to gain an understanding of the amount of change expected but are not generally capable of suggesting how any specific part of the modeled area is likely to change. In other words, deterministic models like the Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS; www.fs.fed.us/fmsc/fvs) tend to be better at showing expectations under defined scenarios, and models like FireBGCv2 (USDA 2016a) tend to be better at showing how the composition of a landscape's fuels might change through the future.

Fire behavior models are used to determine what type of fire is expected under specified fuel and weather conditions. Most of these models are built on foundational BEHAVE (Andrews 1986) fire behavior modeling logic, with variants used to address multiple management questions. Many U.S. analysts use FARSITE to model how an ignition will likely evolve as a fire from a specified point, given the fuel and weather conditions input to the model (e.g., www.fire.org/downloads/farsite/WebHelp/usersguide/ug1_introduction.htm). FlamMap, a derivative of FARSITE, can be used to model the type of fire that would be expected were an entire area to burn under one or more specified sets of weather conditions (Finney 2006). If there are concerns about the avenues through which fire will likely spread the fastest, the minimum travel time (MTT) component of the Treatment Optimization Model (TOM) software can be used (Finney 2006). When a fire breaks out and managers want to understand the probability of spread in different directions, FSPro is used to compute a probability surface associated with a range of possible weather for a specified duration (http://wfdss.usgs.gov/wfdss_help/WFDSSHelp_FSPro_Ref.html). The Large Fire Simulator (FSim) is useful for estimating annual burn probabilities and conditional fire intensities across an entire landscape (www.firelab.org/project/wildfire-hazard-potential).

Although numerous other modeling tools have been developed, those noted above are the most commonly used wildfire behavior modeling tools in the United States, and all rely on the same inputs describing physical and fuels characteristics, with the more complicated questions requiring a move from static weather conditions to a distribution of several weather variables and ignition probabilities. One helpful development is that a coarse scale assessment process called LANDFIRE has mapped topographic and fuel conditions across the entire United States and continues to update them on a regularly scheduled basis. While many analysts choose to modify or substitute for these wall-to-wall layers, there is data available nationally. Given that some fuels information is available everywhere, the next task is to meaningfully carve the nation into modeling units at scales that show the marginal changes in hazards under unmanaged or various potential management scenarios. These should be developed thoughtfully to ensure the areas align with planning jurisdictions and common fire regimes with current Fire Planning Units or something similar.

Property Risk Models—From Types of Structures to Area-Wide Assessments

All of these fire behavior tools help address the hazard but do not completely diagnose risk. Finney (2005) describes fire risk as the combination of fire probabilities and fire effects. In the case of wildfire, the beneficiaries' perspective can be used to bound the assessment of the changes in the expected levels of ecosystem services. Perhaps the most obvious beneficiaries are those whose lives and safety are affected, which is difficult to assess. While most residents and firefighters evacuate from wildfire areas before they are injured or killed, the fuel conditions and fire line intensity do impact how fire is fought. Beyond the risk of life and injury, estimating risk to private property and other ecosystem service values that can be affected by wildfire is another substantial challenge. Jack Cohen's (1995) post-incident investigation work has been key in modeling the expected amount of destruction to property if fire interacts with residential dwellings. His Structure Ignition Assessment Model (SIAM) was built to explore how changes in structural materials (especially the choice of roofing materials) and surrounding vegetation change a structure's vulnerability to fire. Stockmann et al. (2010) demonstrated how this information could be combined with ecological fire modeling probabilities to assess property damage and risk reduction possibilities as a way to evaluate mitigation options. Spatial aspects of risk for home ignition zone modeling present unique challenges, such as capturing small-scale changes in flammability, as the SIAM model and the more contemporary Department of Homeland Security WildFIRE Wizard model (Wildfire Ignition Resistant Home Design, WIRHD) both disclose the sensitivity of radiative ignition potential at small distances and the unpredictability of long-range firebrands (embers) as ignition vectors. In the bigger picture, vegetation dynamics represented by raster-based fire models actually vary substantially within coarse pixels and change at different rates within and between fire seasons.

Expanded Risk Models—Accounting for Climate Change and Development

Whereas some policy critiques try to model the Wildlife Urban Interface (WUI) expansion mainly as a source of increased wildfire suppression expenditures (Gude et al. 2013) others take a more dynamic view. The National Science Foundation recently funded an Assessing and Adaptively Managing Wildfire Risk in the Wildland-Urban Interface for Future Climate and Land Use Changes (FIRECLIM) project. This effort combined many of the aforementioned modeling approaches to estimate expected property damages to residents from wildfire, in light of continued climate change and residential development. The metric used for this purpose is a discounted computation across five decades involving (1) simulating residential development; (2) delineating the WUI; (3) estimating and assigning conditional burn probabilities to structures on individual residential properties; (4) simulating vegetative succession for a greenhouse gas emission scenario; (5) estimating the probabilities that pixels in the WUI burn and the conditional probabilities of residential losses for each WUI property given residential parcels burn; and (6) assigning monetary values to residential properties and aesthetic property value losses due to wildfire. The intent is not only to quantify current and future financial risk but also to clarify the degree to which all involved agents (homeowners, developers, municipal zoning authorities, and land/fire management agencies) can modify this risk (Prato et al. 2014).

Wildland Fire Decision Support System efforts such as the Rapid Assessment of Values at Risk (RAVAR; Calkin et al. 2011) were attempts to determine the most sensitive human assets to wildfire. RAVAR went beyond residences and commercial structures, commonly found in state revenue department cadastral databases, to other elements of human security and well-being and is designed to enhance both real-time fire management strategy and long-term wildfire risk reduction planning. The good news is that many of the modeling efforts conducted to assess how land and fire management activities might be able to maintain or reduce wildfire risk are designed as GIS processes, where the analyst artificially modifies fuel conditions as a speculative response to hypothetical treatments to detect how much change is possible and the new trajectory of risk following treatments. For example, the ArcFuels (2016) extension in Esri ArcMap software uses a logic process that identifies valuable natural and infrastructure assets and iteratively explores how treatments could modify risk to each asset (also using some assumptions regarding suppression). Thompson et al. (2013) showed how ArcFuels and FSim can provide a before-and-after look at wildfire risk when a community has collectively provided a set of undesirable fire encounters. The USFS is currently combining this approach with the stratified cost index to compare investments in 10-year fuel treatment plans with expected suppression cost savings to analyze financial tradeoffs in the context of the multiple objectives for its landscape-level fuel treatments.

Gaps and Challenges

Financial property loss is not the only wildfire impact to people. Efforts such as STARFire (Manley et al. 2010) are attempts to plan with information regarding the suite of expected impacts, including damage to vulnerable assets and avoided costs, as well as positive impacts to other resources to compute estimated marginal net costs/benefits. A complement or possible alternative to this type of modeling is to ask people to value the suite of ecosystem services associated with wildfire risk reduction using the contingent valuation method. Loomis and Gonzalez-Caban (2008) summarize various studies that have estimated the value to specified populations of residents of reducing wildfire risk by specific amounts in clearly delineated areas. Although the contingent valuation methodology has recognized limitations and is expensive, the potential exists to borrow from representative situations and use the benefit transfer approach to apply generalized dollar values. Even if they are used only as relative values, this approach may help managers who are comfortable using these elicited value estimates in their decisions.

Despite significant advances in wildfire modeling and valuation several gaps in our knowledge remain and require attention. The primary challenge is to standardize how the counterfactual representation of wildfire events and their probability is portrayed in the absence of preventative treatments, suppression, and rehabilitation activities. The marginal difference between real outcomes and this alternate portrayal is the basis for evaluating changes in ecosystem conditions and the flow of ecosystem services. The Fire Regime Condition Class (FRCC) is one useful modeling approach that addresses this counterfactual situation, by classifying the degree of departure from expected fire regimes across the United States. Although FRCC is criticized for various reasons, it offers one way to estimate current ecosystem resilience to fire, displays how suppression has changed this resilience across the nation, and highlights the relative benefits of treatments or desirable fires and of returning to more appropriate fire regimes. Another challenge is the changing climate and its influence on fire behavior. Seasoned fire managers describe growth in the upper end of fire behavior observations, and the lack of these conditions in the historic record means there is limited predictive power outside the range of inputs used in forecasting, requiring a move from inference to extrapolation.

Like all ecosystem services, fire risk regulation is part of an interconnected web of benefits, and we currently struggle to express those relationships sufficiently to represent tradeoffs that will occur or even what we expect to come from management actions. The troubling inadequacies of legacy dogma and associated analysis systems in recognizing fire's role in maintaining ecosystem balance (which collectively provides myriad related ecosystem services) expands to be even more problematic when we consider that impacts may change from negative to positive or vice versa through time (see Kline 2004 for discussion of dynamic complexities of benefits linked to fuel treatments). In other words, short-term damage often yields long-term hazard reduction or ecosystem service enhancement in the same vicinity. As a terrestrial and aquatic example, fire often eventually leads to increased density of ungulate forage and recruitment of woody debris, as standing trees are converted to fallen logs and transported downslope into creeks, where they increase shade and reduce stream temperatures in fire-adapted ecosystems. While many scientists have addressed the string of temporal reactions in the environment such as these, a gap still exists for how to abstract from local understanding to regional or national understanding of fire's place in the web of services.

Moving from appropriate representations of this wildfire risk regulation to useful analyses of benefits will require a great deal of work. Just consider even a limited set of familiar ecosystem services such as timber, forage, or other protected provisioning values. A lack of documented information about specific public and private forest management plans for a baseline makes assessments, which are often done with poor information describing consumer and producer surpluses, extremely speculative. Expanding from this basic analysis to consider all of the confounding interactions of these additional ecosystem service variables seems to make accurate with-or-without cost-benefit analyses prohibitive. Although FIRECLIM, the newest generation of Forest Plan revision in the Sierra Nevada Mountains (Thompson et al. 2016), and other cooperative efforts seem to tackle the complexity of wildfire risk regulation, they require a large team to complete the analysis for even part of one state. While this cutting-edge approach could likely be replicated across the country to estimate a large portion of wildfire risk reduction ecosystem service values, it is likely too onerous for forest planning teams to complete on their own. This gap complicates how this type of learning can be factored into fire and land management planning, prioritizing activities such as harvesting and using prescribed fire or fire suppression strategies.

Working together, federal agencies and partners can develop and document the conceptual framework and plans to address key data and modeling gaps associated with the ecosystem service of wildfire risk regulation. Perhaps the best vehicle to solidify and communicate that vision is the next iteration of the QFFR and the upcoming Cohesive Wildfire Management Strategy revision.

Table 3-2. Data and models for regulation and reduction of wildfire risk

Type	Source	Reference	Description
Data	LANDFIRE program	www.landfire.gov	Mapped topographic and fuel conditions across the entire United States updated on a regular basis
Models	Fire and Field Extension (FFE) - Forest Vegetation Simulator (FVS)	www.fs.fed.us/fmsc/fvs	Links the dynamics of forest vegetation (primarily trees) with models of snag, fuels, and fire behavior
	FireBGCv2	www.firelab.org/project/firebgcv2-simulation-platform-and-projects	Modeling program and platform that mechanistically simulates fire, vegetation, and climate and fuels dynamics across multiple space and time scales
	FARSITE	www.firelab.org/project/farsite	Models how an ignition will likely evolve as a fire from a specified point, given input fuel and weather conditions
	FlamMap	www.firelab.org/project/flammap	Models the type of fire expected were an entire area to burn under one or more specified sets of weather conditions
	Treatment Optimization Model (TOM)	Finney 2006	Minimum travel time (MTT) component identifies avenues through which fire will likely spread the fastest

Type	Source	Reference	Description
	FSPro	http://wfdss.usgs.gov/wfdss/pdfs/FSPro.pdf	Used to compute a probability surface associated with a range of possible weather and a specified duration
	Large Fire Simulator (FSim)	www.firelab.org/project/wildfire-hazard-potential	Models estimates of annual conditional fire probability and fire line intensities across an entire landscape
	Structure Ignition Assessment Model (SIAM)	Cohen 1995	Models how changes in structural materials (especially choice of roofing materials) and surrounding vegetation change a structure's vulnerability to fire
	WildFIRE Wizard Model	www.flash.org/wfwizard	Tool designed to help people understand how landscaping, terrain, and structural features increase or decrease their home's vulnerability during a wildfire
	Wildfire Climate (FIRECLIM)	http://projects.cares.missouri.edu/fireclim-montana/Methods/Methods.html	Estimates expected property damage to residents from wildfire in light of continued climate change and residential development
	Rapid Assessment of Values at Risk (RAVAR)	www.fs.fed.us/rm/wfdss_ravar	Designed to enhance both real-time fire management strategy and long-term wildfire risk reduction planning by going beyond structures to other elements of human well-being
	Esri ArcMap - ArcFuels	www.arcfuels.org	Uses a logic process that identifies valuable natural and infrastructure assets and iteratively explores how treatments could modify risk to each asset

Flooding

Data Sources: Hydrology and Risk to People

Two main types of data are needed to evaluate the flood risk management benefits of ecosystems: (1) hydraulic data—maximum depth, arrival time, and duration across a range of flows for each structure location or damageable element in the study area—and (2) damageable elements data—value and depth damage relationships for every damageable structure or element within the study area, either individually represented with stage-damage relationships or aggregated into a single stage-damage relationship.

A comprehensive hydraulic current conditions (without-project) data set for the entire United States does not exist. However, numerous hydraulic studies have been done on a local and even regional scale, but they would have to be gathered from a patchwork of sources: reclamation districts, local flood control agencies, cities, counties, state water resource agencies, Federal Emergency Management Agency

(FEMA), USACE, and others. One of the best sources of data may be the Corps Water Management System (CWMS) National Deployment; this data set is limited to watersheds with existing corps projects.

The National Structure Inventory describes a screening-level structure inventory for the entire United States (https://data.femadata.com/FIMA/NSI_2010). This inventory contains adequate information on structures to derive damage functions, values, and populations.

Predictive Modeling

To account for flood risk reduction, it is necessary to have *with*- and *without*-project conditions. Comparison of these two project conditions allows calculation of benefits generated by the project. The with-project condition should reflect a change in the hydraulic or structure data. This requires some sort of hydraulic modeling that can account for changes to the floodplain caused by the project (levees, channel improvements, reservoirs, etc.). The damageable elements within the floodplain may also change as a result of the alternatives being analyzed (e.g., relocations and raising structures for nonstructural measures or buyouts to make room for the levee structure). With-project hydraulic data must be generated for individual projects, with the analysis tailored specifically to each project.

When assessing the hydrological and ecological impacts of a change in management, it is necessary to analyze incremental changes in ecosystems and those functions resulting from the management change, any of which can magnify or impede structural and nonstructural changes throughout the floodplain. To do this, the with-project hydraulic model must be capable of evaluating changes in vegetation, sediment loading, flow retention, and other geospatial and hydrological features as well as ecological habitat.

It is necessary to be able to evaluate the impacts that structural changes have on the survivability of ecological habitats over time. This requires the ability to incorporate a feedback loop between ecological and hydrologic models over multiple years because the changes in the ecology of an area may affect flood mitigation in a particular area downstream or upstream and may even interact directly with the structural measures' ability to provide continued flood mitigation. For example, the addition of a wetland may attenuate flood hydrographs, which in turn reduces scour, erosion, and sedimentation. This ecosystem feature may provide increasing benefits across time.

Finally, to adequately evaluate the life cycle of a project alternative in a systems context, a comprehensive modeling framework is required. One option is to research the application of the Hydrologic Engineering Center Watershed Analysis Tool (HEC-WAT) with the flood risk analysis compute option, using Hydrological Modeling System (HEC-HMS), Reservoir System Simulation (HEC-ResSim), River Analysis System (HEC-RAS), Ecosystem Functions Model (HEC-EFM or EFM-Sim), and Flood Impact Analysis (HEC-FIA).

Table 3-3. Data and models for assessing ecosystem services that regulate and reduce flooding risk

Type	Source	Reference	Description
Data	Corps Water Management System (CWMS)	www.hec.usace.army.mil/cwms/cwms.aspx	Integrated system of hardware and software that stores hydromet, watershed, and project status data; model results only in watersheds with existing corps projects

Type	Source	Reference	Description
	National Structure Inventory	https://data.femadata.com/FIMA/NSI_2010/	Provides adequate information on structures to derive damage functions, values, and populations
Models	Hydrologic Engineering Center (HEC) models		USACE hydrologic analysis software made available to the public whenever appropriate
	HEC-HMS	www.hec.usace.army.mil/software/hec-hms	Simulates the complete hydrologic processes of dendritic watershed systems
	HEC-ResSim	www.hec.usace.army.mil/software/hec-ressim	Simulates reservoir operations for flood management, low-flow augmentation, and water supply for planning studies, detailed reservoir regulation plan investigations, and real-time decision support
	HEC-RAS	www.hec.usace.army.mil/software/hec-ras	Performs one-dimensional steady flow, unsteady flow, sediment transport/mobile bed computations, and water temperature modeling
	HEC-EFM	www.hec.usace.army.mil/software/hec-efm	Models ecosystem responses to changes in the flow regime of a river or connected wetlands
	HEC-FIA	www.hec.usace.army.mil/software/hec-fia	Calculates damage to structures and contents and losses to agriculture and estimates the potential for life loss

Coastal Inundation/Storm Surge

Assessing the potential storm surge benefits provided by coastal habitats requires a combination of tools and techniques that cross several disciplines (Dietrich et al. 2011; Doyle et al. 2015; FEMA 2013). Everything from the biophysical makeup of the system (habitat) to hydrodynamics and socioeconomic conditions must be considered to effectively measure storm protection services.

As a starting point, an assessment of the hydrodynamics of the system of interest is necessary. There are a number of models, such as those cited above; the Sea, Lake, and Overland Surges from Hurricanes model (www.nhc.noaa.gov/surge/slosh.php); and the ADvanced CIRCulation (ADCIRC) model (www.adcirc.org). As an example, ADCIRC can be used to generate storm surge scenarios that can then lead to an estimation of the impact on society. ADCIRC is a physics-based hydrodynamic model that uses a computational mesh to solve shallow water equations for a number of applications, including coastal storm surge and flooding. Users are able to simulate storm event surges for a defined region. Some have found value in combining with ADCIRC the Simulating Waves Nearshore wave modeling software (http://swanmodel.sourceforge.net), which computes random short-crested, wind-generated waves in coastal regions and inland waters (Dietrich et al. 2011). Storm surge grids generated by ADCIRC can then be modified to inundation grids, which measure impact on coastal communities.

To assess the physical and economic impact of coastal flooding, FEMA developed Hazus-MH (hereafter Hazus), a geographic information system (GIS)-based modeling tool that estimates physical, economic, and social impacts of natural disasters such as floods, earthquakes, and hurricanes (www.fema.gov/hazus). Hazus uses internal databases concerning hazards, buildings, facilities, transportation systems, vehicles, lifeline utilities, hazardous materials, and agricultural products (FEMA 2013). The effect of flooding events, for example, is then measured in dollar losses of buildings, monetary losses of vehicles, and displacement of households.

It is also important to consider changes in the landscape over time. Human impacts in the form of coastal development and physical changes to the natural environment as a result of sea level rise require additional computational steps to effectively account for storm surge impacts. The USGS has recently released a report that catalogs the relevant tools to model and visualize sea level rise impacts on coastal environments (Doyle et al. 2015).

Table 3-4. Data and models for assessment of ecosystem services that regulate coastal inundation and storm surges

Type	Source	Reference	Description
Data	NOAA Shoreline Website	https://shoreline.noaa.gov	Various data sets relating to shorelines including shoreline change analysis, boundary determination, and shoreline mapping history
	Digital Elevation Model (DEM) Discovery Portal	www.ngdc.noaa.gov/mgg/dem/demportal.html	DEM with bathymetry and above-water topography
	NOAA Shoreline Data Explorer	www.ngs.noaa.gov/NSDE	Online mapping tool that allows for shoreline exploration
Models	Sea, Lake & Overland Surges from Hurricanes model	www.nhc.noaa.gov/surge/slosh.php	Assesses the hydrodynamics of a system
	Advanced CIRCulation model (ADCIRC)	www.adcirc.org	Generates storm surge scenarios and estimates impacts on society
	Simulating Waves Nearshore wave modeling	http://swanmodel.sourceforge.net	Computes random wind-generated, short-crested waves in coastal regions and inland waters; can be used in combo with ADCIRC

Type	Source	Reference	Description
	FEMA Hazus-MH	www.fema.gov/hazus	GIS-based modeling tool to estimate physical, economic, and social impacts of disasters (including coastal floods and hurricanes)

4. SOCIAL AND ECONOMIC DATA AND MODELS FOR ECOSYSTEM SERVICES

Sociocultural Context

The flow of ecosystem service benefits is always mediated by social systems. Every human use of nature has a sociocultural context: relatively enduring relationships and understandings among individuals and groups that shape both the ends and means of actions affecting ecosystems. This context can determine the nature of the ecosystem benefits received, their value, who shares these benefits, and who does not. Humans do not experience their environment as an external and objective reality. Rather, "nature is seen by humans through a screen of beliefs, knowledge, and purposes, and it is in terms of their images of nature, rather than of the actual structure of nature, that they act" (Rappaport 1979, 97). Such "images of nature" are not universal but to a great extent vary from society to society. While for many societies pigs are a valuable source of meat, for Islam and Judaism the pig is considered to be an unclean animal, not to be eaten (Douglas 1966). Given this cultural premise, for these religious communities, pigs provide no provisioning service.

The use of wood for heating and cooking might seem a simple example of a provisioning service, needing little in the way of sociocultural context to be understood, but this is not the case. In an analysis of fuel wood use in the Peruvian Andes, Keely Maxwell uses anthropological and ecological methods to describe the Andean *fuelscape* or energy landscape. "Fuelscapes are shaped by ecological characteristics, historic settlement patterns and property rights, gendered and intergenerational divisions in household labor, and state conservation policies" (Maxwell 2011, 465). Rights to fuel wood are determined by multiple factors. For fuel from planted trees, these include "community residency, house and field ownership, and the degree of human labor in tree planting and harvest—a complex mix of ownership and usufruct rights." Trees in the uncultivated *monte* are a common pool resource, with rights to fuel conveyed by membership in a nearby community (Maxwell 2011, 472).

Different situations require greater or lesser attention to the sociocultural context of ecosystem services provision and value. The analytic skills involved—understanding how social systems mediate the human experience of the environment and the consequences of environmental change—are basic to several disciplines, including environmental anthropology, environmental sociology, and human geography.

Sociodemographic Data

Ecosystem services, like other market services, are used and appreciated by different population sectors in varying rates. A prime example of this is outdoor recreation. Survey data and economic modeling efforts consistently show differential participation rates for outdoor recreation across a host of demographic variables including sex, age, race, ethnicity, income, and population density (Bockstael et al. 1987; Bowker and Leeworthy 1998; Bowker et al. 2006; FHWAR 2006, 2011). Modeling and mapping the impacts of management decisions (and actions) on ecosystem services requires an understanding of the spatially explicit supply and demand of these services. Sociodemographic factors that vary spatially provide insight into the demand side of this equation.

Demand for use services can be modeled using per capita rates of use or participation and multiplying by population present in a given spatial unit (pixel, county, watershed, etc.). While many different sociodemographic factors may influence these rates, only those sociodemographic factors that display geographic variability are relevant for spatial representation of demand. Many demographic variables such as age and sex may not vary substantially at the spatial scale of analysis, in which case average participation rates (e.g., across all ages and sexes) will serve to represent demand spatially. However, when sociodemographic factors are both determinants of participation or use levels and vary spatially, it is important to use them in assessing spatial demand.

The U.S. Census (2010) provides the most accurate demographic data available for the United States. These data are aggregated into census block spatial units to protect the privacy of census respondents. Spatial mapping of ecosystem service demand frequently requires finer-scale demographic information. The U.S. EPA developed a dasymetric population map of the continental United States for EnviroAtlas. This map combines the U.S. Census blocks with landcover data (NLCD 2011) using a simple model to allocate the summarized census block populations down to 30m x 30m gridded raster cells. The dasymetric population data can also be reaggregated into any spatial unit, a method that sometimes has a distinct advantage over using the census blocks, which vary greatly in size depending on population density. The dasymetric population map is publicly available through the EnviroAtlas website (www.epa.gov/enviroatlas).

The EnviroAtlas dasymetric population map can be combined with other types of demographic data from the U.S. Census (2010). Current work explores the application of census block-level demographic proportions to the dasymetric map to segment the market for the purpose of estimating spatially explicit demand for outdoor recreation services (Mazzotta et al. 2014). Fine-scale mapping of demographic variables in this manner can never provide 100% accuracy because it is impossible to accurately spatially allocate those demographic variables within a census unit. These methods merely provide approximated geographic representations of predictor variables on which economic models may be built. The final products derived from these methods must be maps of ecosystem service demand aggregated to a summary unit (i.e., county) where spatial errors are smoothly distributed.

Table 4-1. Sociodemographic data for ecosystem services assessments

Type	Source	Reference	Description
Data	U.S. Census	www.census.gov/en.html	Provides most accurate demographic data available for the United States; 2010 is the most recent
	EnviroAtlas Dasymetric Population Map	https://catalog.data.gov/dataset/enviroatlas-dasymetric-population-in-the-conterminous-united-states-web-service	Combines U.S. Census blocks with NLCD 2011 using a simple model to allocate the summarized census block populations down to 30m gridded raster cells

Use and Benefit Transfer Data and Models

Ecosystem services assessments require information on how many people use, appreciate, or are affected by a change in service provision. Various resources that collect some of this data are described below.

Wildlife Resource Valuation

Various types of economic value are derived from wildlife resources, including use values for wildlife-based recreation activities, as well as passive use values held for the preservation of wildlife species and their habitats. The first practical application of the contingent valuation method was implemented by Davis (1963) to monetize the value of big game hunting in Maine, and since then there have been dozens of studies valuing wildlife-based recreation activities. Many of these studies quantify per-person per-activity day values; for instance, 659 such value estimates for hunting and 324 for wildlife viewing are reported in a database of recreation use values developed at Oregon State University, which has compiled studies conducted in the United States and Canada from 1958 to 2006 (see http://recvaluation.forestry.oregonstate.edu). The Benefit Transfer Toolkit being developed by USGS includes updated databases for hunting and wildlife viewing, compiling data from new or previously overlooked valuation studies conducted in the United States through 2014 (see https://my.usgs.gov/benefit-transfer). Many of the value estimates included in these databases are based on *The National Survey of Fishing, Hunting, and Wildlife-Associated Recreation* conducted by the U.S. FWS and U.S. Census Bureau, which often includes contingent valuation questions to capture net economic values of wildlife-related recreation activities by state (see Hay 1988; Waddington et al. 1994; Boyle, Roach, et al. 1998; Aiken and la Rouche 2003). Continuing to collect these data regularly can help facilitate benefit transfers.

Meta-regression models based on this existing literature can often be used for benefit function transfers. For instance, Loomis et al. (2008) estimates such a model for recreational hunting values. USGS's Benefit Transfer Toolkit includes an updated version of this hunting model and also includes meta-regression models of per-person per-day values for wildlife viewing and fishing. It is important to note that existing benefit-per-unit estimates need to be tied to an estimate of quantity, such as hunter or viewer days. Thus, at the area of interest for applying benefit transfer values, collecting data on visitor use of public lands is an extremely important service that agencies can provide to help facilitate benefit transfers of wildlife-based recreation values.

In addition to the economic value held for wildlife-based recreation activities, many people derive passive-use values, such as existence and bequest values, from the preservation of wildlife species, particularly threatened, endangered, and rare species. Beginning in the 1980s, primary studies quantifying the total economic value held for rare and endangered species were published; Loomis and White (1996) conducted a meta-analysis of such studies. An updated summary and meta-analysis by Richardson and Loomis (2009) summarizes the results of 31 studies that have used stated preference methods to quantify the economic value of approximately 29 fish and wildlife species in the United States. In addition to the differences in the types of species these studies value, they differ in other significant ways. For instance, some studies are based on surveys of visitors at a specific site, while others survey households in a particular city or state, and still others survey households across the entire United States. A meta-regression model based on these existing studies is also provided in Richardson and Loomis (2009), who find that variables such as the type of species being valued, the change in the size of the species population being valued, whether a species is a "charismatic megafauna" or not, the year the study was conducted, and various methodological attributes of the study significantly influence willingness-to-pay values. The information provided in Richardson and Loomis (2009) can be used for unit value transfers, average value transfers by species type, and function transfers based on the meta-regression model provided. In addition to those studies conducted in the United States, many have valued rare or endangered species in other countries, such as Australia (Wilson and Tisdell 2007; Jakobsson and Dragun 2001), Sweden (Boman and Bostedt 1999; Ericsson et al. 2007), England (White et al. 1997; White et al. 2001), China (Kontoleon and Swanson 2003), Sri Lanka (Bandara and Tisdell 2005), Greece (Langford et al. 2001), and Spain (Ojea and Loureiro 2007).

The majority of existing studies quantifying total economic values for wildlife species have focused on valuing often large gains in the population of a species (e.g., a 50% gain) or the avoidance of large losses in populations. More research is needed on valuing smaller changes in populations, as many projects affect only a limited area of habitat. Transferring values or functions from the existing literature typically requires an understanding of how the population of the species being evaluated is expected to change with project impacts or a management action. Often, an agency can model how management actions will result in changes to species' habitats, but it is important to have models, data, or professional judgments that can be used to translate habitat changes into estimates of population changes that can be tied to a measure of economic value. Additionally, existing estimates of economic value are often reported on a per-household basis for a specific geographic extent, making it important to understand the possible extent of the affected market when transferring values (see Loomis 2000 for empirical analysis of this issue). It can be challenging to conduct benefit transfers of passive-use values, and the limited number of studies quantifying economic values for threatened, endangered, and rare species adds to the difficulty of identifying a representative study in the existing literature. While function transfers based on meta-regression models can alleviate some of these concerns, there is a considerable need for additional primary studies quantifying the total economic value of wildlife. Endangered species that may be affected by major management actions, such as the Florida panther, as well as unique species that spur controversial resource allocation issues, such as wild horses and burros on BLM and USFS lands, could be targeted for future research.

Table 4-2. Benefit transfer data and models for wildlife

Type	Source	Reference	Description
Value estimates	Oregon State University (OSU) recreation database	http://recvaluation.forestry.oregonstate.edu	Contains 659 value estimates for hunting and 324 for wildlife viewing compiled from studies conducted in the United States and Canada from 1958 to 2006
	USGS Benefit Transfer Toolkit	https://my.usgs.gov/benefit-transfer	Updates the OSU hunting and wildlife viewing databases with studies conducted in the United States through 2014; contains 83 value estimates for threatened, endangered, and rare species compiled from U.S. studies through 2014

Type	Source	Reference	Description
	National Survey of Fishing, Hunting, and Wildlife-Associated Recreation (FHWAR)	www.census.gov/prod/www/fishing.html	Survey that often includes contingent valuation questions to capture net economic values of wildlife-related recreation activities by state; many results captured in OSU and USGS databases
Meta-regression models	USGS Benefit Transfer Toolkit	https://my.usgs.gov/benefit-transfer	Provides meta-regression models for hunting, fishing, and wildlife viewing that can be used for benefit function transfers
	A Benefit Transfer Toolkit for Fish, Wildlife, Wetlands, and Open Space	Loomis et al. 2008, http://dare.agsci.colostate.edu/outreach/tools/#BTT	Provides a meta-regression model, based on the recreational hunting literature, that can be used for benefit function transfers
	Total Economic Value of Threatened, Endangered, and Rare Species	Richardson and Loomis 2009, doi:10.1016/j.ecolecon.2008.10.016	Summarizes the results of 31 studies that have used stated preference methods to quantify the economic value of approximately 29 fish and wildlife species in the United States and provides a meta-regression model based on these studies

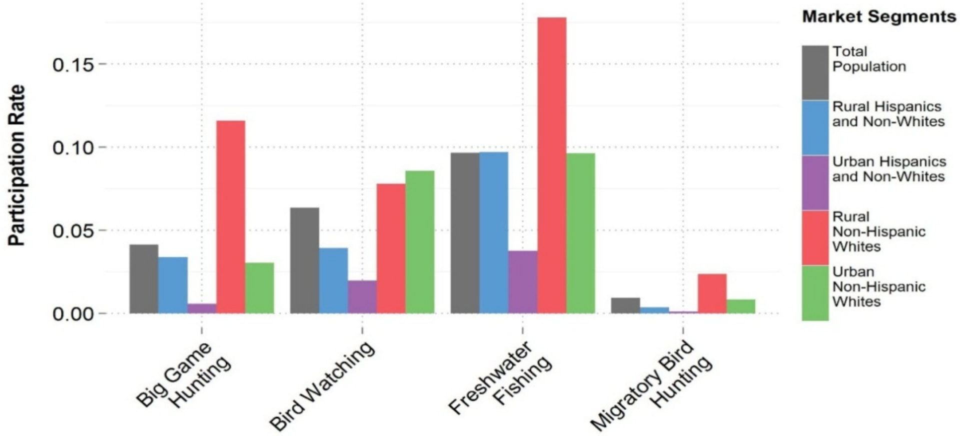
Recreational Use of Species, Natural Communities, and Biodiversity

Use Data for Outdoor Recreation

Information on hunting and fishing uses are widely gathered but currently not standardized in ways that would allow them to be used for regional or multistate analysis. Both the BLM and the USFS permit the collection of nontimber products, including mushroom collection, Christmas tree cutting, native plant collecting, and other uses that, if included in their agency databases (e.g., the Natural Resource Information System), could provide data for service-related analysis. Similarly, while watchable wildlife areas have been designated throughout much of the United States, information on the amount and kinds of uses are not standardized or readily available. It also may be possible to analyze eBird observations to spatially attribute recreational bird viewing.

The EnviroAtlas identified four types of outdoor recreation with the minimum data sets necessary to construct national maps of demand. These four types of outdoor recreation are big game hunting, freshwater fishing, migratory bird hunting, and bird watching. The base data set required to estimate recreation demand is derived from national survey data, namely the National Survey of Fishing, Hunting, and Wildlife-Associated Recreation (FHWAR). Data from the FHWAR must be aggregated into the sociodemographic groups identified as spatially heterogeneous determinants of recreation participation. We narrowed this list to two variables of interest including rural/urban status and a combination of race and ethnicity. Figure 4-1 shows the variability of participation rates across these variables.

Figure 4-1. National outdoor recreation participation rates across four market segments (EnviroAtlas, Mazzotta 2014)

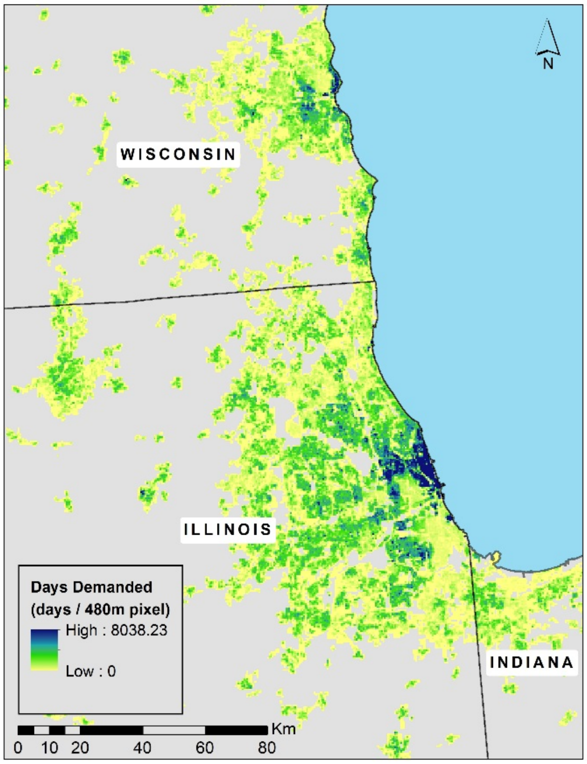


Participation rates may also vary geographically. For example, hunting participation rates tend to be higher in the northern Midwest than in New England. For this reason, the country is first divided into 10 regions based on climate and agricultural similarities (USDA 1998); the region-specific participation rates are then calculated for each of the four market segments. This gives a total of 40 unique participation rates for each type of outdoor recreation.

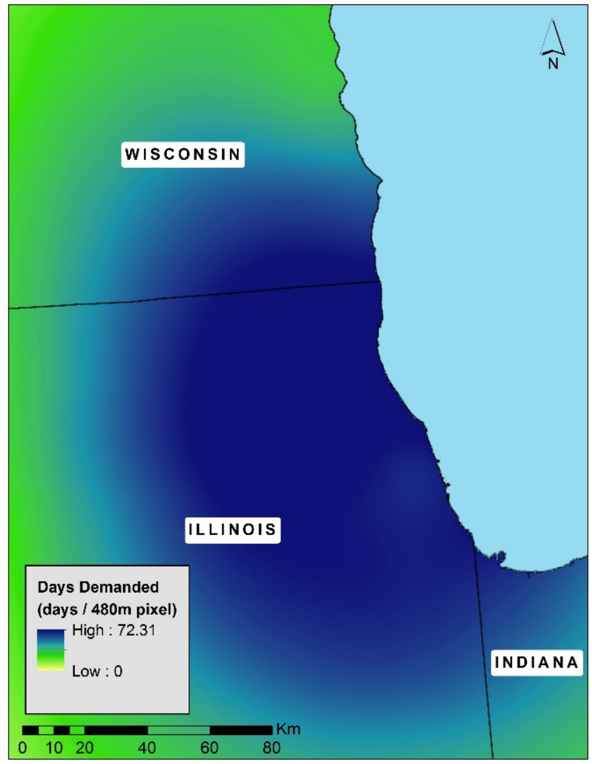
The EnviroAtlas dasymetric population map can be combined with other types of demographic data from the U.S. Census (2010) to generate maps of the market segments identified above. The four market segment maps are then divided into the 10 regions, and the regional participation rates are applied. This creates a map estimating the number of participants within a market segment. Because participants may choose to recreate in different locations throughout the year, we convert the number of participants to the number of recreational days demanded by multiplying by the weighted mean number of days of annual participation. These maps are then added together to create a surface of recreation demand. An urban example map for the Chicago area is shown in Figure 4-2A.

The issue with these maps is that they only represent demand for outdoor recreation in the locations where the participants live. The majority of outdoor recreation occurs away from the home. Much of the economics literature focusing on recreation centers on the development of complex travel distance and site selection models (Parsons, 2013). A much simpler method uses available survey data to approximate participants' willingness to travel for recreational purposes, pulling travel distance data for the four types of recreation from the National Visitor Use and Monitoring Survey (USDA, 2009) database. The data can be separated by urban versus rural status based on prior observations in differing willingness to travel across this variable (Bowker et al. 2006). A gamma probability density function (pdf) is then fit to the urban and rural data and these pdfs used to generate a two-dimensional probability surface approximating an individual's willingness to travel for a given type of recreation. The two-dimensional probability surfaces are then applied to the urban and rural maps of the days demanded. The result is a smoothed surface of recreational demand. This map better represents where recreation would likely occur if environmental conditions are amenable. Figure 4-2B shows an example of this smoothed final map for the Chicago area.

Figure 4-2. Maps of urban big game hunting demand for the Greater Chicago Area (EnviroAtlas)



A – Big game hunting days demanded *in situ*, or where hunters live.



B – Big game hunting days demanded dispersed across the landscape using the two-dimensional travel distance probability surface.

EnviroAtlas is currently working to complete these final maps of recreational demand for big game hunting, bird watching, freshwater fishing, and migratory bird hunting. A more thorough scientific manuscript is currently in progress documenting this method's specifics. The completed maps will be publicly available through the EnviroAtlas website soon (or by request at www.epa.gov/enviroatlas/forms/contact-enviroatlas).

Case Study: These methods were used in a recent study to assess the economic impact of mountaintop removal mining on recreational fisheries in West Virginia (Mazzotta et al. 2014). This study modeled the impacts of different mining scenarios on fish populations. Our maps of freshwater fishing demand were overlaid with the modeled fish maps to quantify changes in the supply of recreational fishing. A map of days of recreational fishing demanded can allow changes in fish populations in specific streams to be quantified in terms of the recreational ecosystem service provided. The Mazotta study takes this a step further by applying benefit transfer to monetize the impact of the mining scenario on the recreational fishery.

Valuation

Recreation plays an important role in public land use, and federal agencies have long expressed the need for recreation value estimates to incorporate in planning and project evaluation. Throughout the 1970s and 1980s, the U.S. Water Resources Council and USFS published administratively approved recreation value estimates based on a combination of existing studies, expert judgment, and political screening (Rosenberger and Loomis 2003). Over the following decades, four comprehensive literature reviews of studies valuing recreation were conducted for the USFS by Sorg and Loomis (1984), Walsh et al. (1988), MacNair (1993), and Loomis et al. (1999). This information was then compiled by Rosenberger and Loomis (2001), who summarized the results of 163 recreation valuation studies conducted from 1967 to 1998 in the United States and Canada. These studies comprise 760 value estimates across 21 different recreation activities, varying in geographic scale. For instance, while some focus on recreation activities at specific sites, others value recreation activities at broader geographic scales, such as at the state or national level. The information provided in Rosenberger and Loomis (2001) can be used for various types of benefit transfers, including unit value transfers, transfers of average values across recreation activities and geographic regions, and benefit function transfers based on an estimated meta-regression model. An updated report, released by Loomis (2005), compiles studies and value estimates through the year 2003, resulting in 1,239 value estimates for 30 different outdoor recreation activities on national forests and other public lands. Average per-person per-day values by recreation activity and census region are also provided in Loomis (2005). Not only do these facilitate average value transfers, but they can be used to identify major gaps in the existing literature across recreation activities and regions. For instance, only one existing valuation study was identified for recreation activities such as backpacking and horseback riding. If agencies expressed a need for value estimates for these activities, primary research could be targeted there.

A comprehensive online database of recreation use values held for a wide variety of recreation activities has been developed at Oregon State University by Randall Rosenberger (http://recvaluation.forestry.oregonstate.edu). This database provides detailed information about recreation valuation studies conducted in the United States and Canada from 1958 through 2006, resulting in 2,703 per-person per-activity day value estimates. The Benefit Transfer Toolkit being developed by USGS includes updated databases for a subset of these recreation activities, compiling value estimates from new or previously overlooked studies conducted in the United States through 2014 (https://my.usgs.gov/benefit-transfer). The Toolkit also provides average values by region. These databases are easily accessible and provide a convenient source of information for value transfers. Additional sources of data for benefit transfers include databases of value estimates for specific recreation types, such as coastal-based recreation (see www.oceaneconomics.org/nonmarket/valEstim.asp and www.marineecosystemservices.org/explore), and meta-regression models for various types of recreation (for instance, Johnston et al. 2006; Brander et al. 2007; Loomis et al. 2008; Neher et al. 2013; https://my.usgs.gov/benefit-transfer).

Benefit transfers of recreation values require knowledge of changes in recreation use, an estimate of quantity that can be tied to an appropriate measure of economic value. Due to the fact that existing studies frequently report welfare estimates in per-person per-day units, it is often necessary for resource specialists, planners, or managers to be able to estimate this quantity change, based on data or professional judgment. While this presents a challenge for agencies that do not consistently collect visitor use data, especially by recreation activity, these data are a necessary component of incorporating information on recreation values into planning efforts, making it increasingly important for agencies to continue to improve on visitor use data collection efforts.

Many federal and state agencies frequently lack the necessary resources to conduct primary valuation studies. Fortunately, recreation on public lands has been studied quite extensively in the nonmarket valuation literature by academic economists. Benefit transfer thus provides a reasonable approach to incorporating recreation use values into planning efforts and decision making. However, considerable gaps in the valuation literature do exist for certain types of recreation, such as activities involving cultural sites and those in certain geographic locations. Databases of existing value estimates will likely continue to be updated and expanded on and can be used to identify gaps in the literature where primary studies can be targeted. In addition, focusing primary research on recreation activities that spur controversial resource tradeoffs, such as off-highway vehicle use, could benefit agencies that need to evaluate competing recreation values to make informed decisions regarding resource allocation and use. It is also important for original valuation studies to report detailed information to facilitate more accurate transfers. Finally, while many agencies lack the resources to conduct primary studies, incorporating valuation questions into regularly administered visitor satisfaction surveys can provide a low-cost approach to obtaining information for use in future transfers, especially if a random sample of visitors is surveyed.

Table 4-3. Use and benefit transfer data and models for recreational use of species, natural communities, and biodiversity

Type	Source	Reference	Description
Use data	EnviroAtlas	http://enviroatlas.epa.gov/enviroatlas/atlas.html	Estimates four types of recreation demand (big game hunting, freshwater fishing, migratory bird hunting, and bird watching) derived from national survey data, namely the FHWAR
	National Visitor Use and Monitoring Survey (NVUM)	http://apps.fs.usda.gov/nrm/nvum/results	Provides statistically sound estimates of visitation to each national forest and to each site type, including visitor demographic information, reason for visiting, satisfaction level, and money spent
	NPS Visitor Use Statistics	https://irma.nps.gov/Stats	Provides data on recreation visits to each national park
Valuation data	Updated Outdoor Recreation Use Values on National Forests and Other Public Lands	Loomis 2005	Compiles studies and value estimates through the year 2003, resulting in 1,239 value estimates for 30 different outdoor recreation activities on national forests and other public lands

Type	Source	Reference	Description
	Oregon State University (OSU) Recreation Database	http://recvaluation.forestry.oregonstate.edu	Provides detailed information about recreation valuation studies conducted in the United States and Canada from 1958 through 2006, resulting in 2,703 per-person per-activity day value estimates
	USGS Benefit Transfer Toolkit	https://my.usgs.gov/benefit-transfer	Provides detailed information about recreation valuation studies conducted in the United States through 2014
	National Ocean Economics Program	www.oceaneconomics.org/nonmarket/valestim.asp	Environmental and recreational (nonmarket) value estimates for ocean and coastal resources in the United States
	Marine Ecosystem Services Partnership (MESP)	www.marineecosystemservices.org/explore	Database of value estimates for marine ecosystem services
Meta-regression models	Meta-Analysis of Recreational Fishing Values	Johnston et al. 2006	Conducted to identify systematic patterns in marginal willingness to pay (WTP) per fish among recreational anglers
	Meta-Analysis on Recreational Value of Coral Reefs	Brander et al. 2007, doi:10.1016/j.ecolecon.2006.11.002	Includes 166 coral reef valuation studies, 52 of which provided sufficient information for a statistical meta-analysis, yielding 100 separate value observations
	A Benefit Transfer Toolkit for Fish, Wildlife, Wetlands, and Open Space	Loomis 2008, http://dare.agsci.colostate.edu/outreach/tools/#BTT	Provides meta-regression models based on the recreational hunting and fishing literature that can be used for benefit function transfers
	USGS Benefit Transfer Toolkit	https://my.usgs.gov/benefit-transfer	Provides meta-regression models for fishing, hunting, trail use, and wildlife viewing that can be used for benefit function transfers
	Valuation of National Park System Visitation	Neher et al. 2013	Models were estimated using 58 different park unit survey data sets; WTP estimates for these 58 park surveys were used within a meta-regression analysis model to predict average and total WTP for NPS recreational visitation system-wide

Forest-Based Recreation

Several benefit transfer studies have been conducted to support the USFS's outdoor recreation planning efforts. These studies trace back to 1980 when the USFS began publishing recreation values (per-person per-activity day estimates) under the auspices of the Resources Planning Act (Rosenberger and Loomis 2001; Loomis 2005). Although early estimates of forest-based recreation values were derived from a limited number of empirical studies and relied on substantial expert judgment, more recent benefit transfer studies have used an expanded set of primary studies (based on travel cost, contingent valuation, and choice-based methods) to conduct statistical meta-analyses. Because hundreds of observations are available to estimate these models, they have a much stronger scientific foundation than earlier estimates. Explanatory variables used in meta-analyses of forest-based recreation in the United States include whether or not the primary study was conducted on USFS land (and, if so, the USFS region), the type of recreational site (e.g., forest, lake, river), and the primary recreational activity (e.g., hiking, snowmobiling, big game hunting; Shrestha and Loomis 2003). By including an indicator for studies conducted on USFS land, multiple-use values for various types of outdoor recreation on National Forests have been be obtained.

In addition to studies conducted in the United States, meta-analysis has been used to explain travel cost estimates of forest recreation values based on observations gathered from nine European countries (Zanderson and Tol 2009). The authors included several auxiliary variables in the analyses to consider the influence of socioeconomic variables and site-specific characteristics on forest recreation values. Site attributes and measures of national economic and population variables played a significant role in explaining forest recreation values.

Meta-analysis has also been used to explain the variation in estimates of forest values based on contingent valuation studies of forest management programs conducted around the globe (Asia, Europe, Latin America, the Middle East, the United States; Barrio and Loureiro 2010). In these studies, management to enhance forest recreation was found to provide a significant contribution to total forest value. Site and national socioeconomic characteristics were also found to be important in explaining willingness to pay for forest management programs.

Table 4-4. Use and benefit transfer data for forest-based recreation in ecosystem service assessments

Type	Source	Reference	Description
	Benefit transfer of outdoor recreation use values	Rosenberger and Loomis 2001	Annotated bibliography providing information regarding literature on outdoor recreation use valuation studies
	Updated outdoor recreation use values on national forests and other public lands	Loomis 2005	Summarizes more than 30 years of literature on net economic value of outdoor recreation on public lands

Type	Source	Reference	Description
	Meta-analytic benefit transfer of outdoor recreation economic values	Shrestha and Loomis 2003	Test of convergent validity of meta-analytic benefit transfer tested using out-of-sample studies
	A meta-analysis of forest recreation values in Europe	Zandersen and Tol 2009	Uses meta-analysis to explain variation in forest recreation values in Europe based on 26 studies in nine countries
	Meta-Analysis of Contingent Valuation Forest Studies	Barrio and Loureiro 2010	Uses meta-analysis to explain the variation in values obtained using the contingent valuation method based on 35 studies conducted across several countries and forest types

Water Supply

Use Data

The USGS collects county-level water use data across the United States every five years by different sectors: municipal, private, industry, mining, electricity, commercial, agriculture, and so on. The water use data report withdrawals (water removed from the system and returned back to the system farther downstream) and consumption (water permanently lost to the system). The USGS provides a low-resolution spatial and temporal snapshot of information, the best available at a national scale (http://water.usgs.gov/watuse).

Each state has different requirements regarding when water withdrawals must be reported (e.g., in North Carolina, agricultural users must report withdrawals of more than 1 million gallons per day, while nonagricultural users must report withdrawals exceeding 100,000 gallons per day). North Carolina is one of the few states that has a centralized database of local government-owned water utilities that report their water source and the amount of water withdrawn and discharged on a monthly basis (www.ncwater.org/water_supply_planning/Local_Water_Supply_Plan). Otherwise this data needs to be estimated based on demographic information. The USDA Forest Service's Forests to Faucets project uses GIS to model and map the continental United States land areas most important to surface drinking water and the role forests play in protecting these areas. This project uses the EPA's Safe Drinking Water Information System (SDWIS) to identify locations and number of people served by surface water intakes to develop a drinking water protection index. This index shows which areas have the highest potential to affect water quality through the input of sediments and contaminants from the land, while taking the number of water users into account (Weidner and Todd 2011). While the number of users is incorporated into the water protection index, the type of water use is not differentiated.

In the western United States, water allocation laws have created a more extensive system of tracking and allocating water use (see next section on Western Water). Each state or water management district within a state (if a state has one) manages watersheds differently and has different management priorities.

Water and demand management practices can be roughly divided between the eastern and western United States. Eastern U.S. management is based on riparianism and the assumption that there will be enough water available to meet all reasonable demands. Western U.S. management is based on the doctrine of prior appropriation and that there is not enough water available, so all water must be allocated among different users. These states have a framework for managing water supply among users. Individual states are responsible for establishing the framework for water demand and management, with wide variation in the degree of regulation (Gerlak 2005). As water shortages have been experienced in the eastern United States, more states are moving toward a form of regulated riparianism where they are starting to require water permits for withdrawals over a certain magnitude (e.g., in North Carolina, as described; MacDonnell 2009; Dellapenna 2002). Most states have different regulations for managing surface water compared to groundwater, and these rules may vary within states depending on endangered species, groundwater overwithdrawal or recharge rates, reservoir operations, and so on. Water utilities are risk averse and track the service population, water use, water supply, peak demand, and other factors to ensure they have enough supply to meet demand (Lemos 2008). This data is often available in utility annual reports, particularly for larger water utilities.

Reservoirs are owned by national, state, private, and public entities. Some reservoirs are run-of-the-river and do not have an operational component. Other reservoirs, such as federally owned flood control dams, hydroelectric dams, and water supply dams, have a water-control manual that describes how the reservoir is managed and operated. Operational rules vary between reservoirs, but once known, they can be modeled.

Ecological or environmental flows are often defined as the minimum streamflow that can maintain ecological integrity. Ecological flows have been implemented for some reservoirs (minimum release) and by some states. It is an area of current research on the best way to determine the ecological flow of streams (e.g., Richter et al. 1996; Poff et al. 2010) given limited data availability and the difficulty of determining how much the change in flow is due to climate versus human alterations. Where ecoflows are established, they can provide a boundary for assessing availability of water for different services and beneficiaries—separating availability for consumption (irrigation, drinking water, etc.) from water for ecosystem functions (recreation, etc.).

Continued research on teasing out how much water supply is changing due to climate versus human impacts and what management practices (land cover type, reservoirs, etc.) are contributing to the greatest shifts in streamflow quantity and timing requires having better data, particularly the temporal resolution, on the human side of the equation (land cover change, withdrawals, discharges). As part of the federal Clean Water Act, the EPA has put in place a permitting system (National Pollutant Discharge Elimination System) that limits the maximum discharge an individual wastewater facility plant can handle on a daily basis. The EPA collects this data, and facilities can be searched through their website (www.epa.gov/enviro). While this data is useful, more accurate models could be developed using the actual discharge (as this likely changes by season). Currently, the only way to get this information is from individual facilities or state governments that collect it. A similar situation exists for withdrawals, for which a plant's maximum capacity can be obtained but not necessarily how much of the plant's capacity is being used on a daily basis. Water utilities plan their water supply around meeting the peak, not average, daily demand.

Having a standardized collection method and management of human modification data would enable cumulative impacts to be assessed. NLCD updates every five years or so. Population, climate events, and so on change or occur on a much shorter timescale. We can model and estimate, but there is a mismatch between water supply data that is collected at a specific point (minute to minute, hourly, daily, monthly, etc.) and land cover change (every five years), water use (every five years at the county scale), and population. Regarding the last, there is a census block every 10 years and municipal/county estimates every year (this is also residential, but daily water demand might be different as people travel from suburbs to city center—which could be in a different basin). Our ability to pull apart what is human use and what is climate would be better with better use data.

Traditionally, water policy has dealt with issues of quantity and quality separately; however, these should be integrated and addressed together. Plentiful, polluted water, just as scarce, clean water, do not constitute a sufficient water supply to meet demand.

Table 4-5. Use data for water supply in ecosystem services assessments

Type	Source	Reference	Description
Use data	USGS Water Use Data through NWIS	http://waterdata.usgs.gov/nwis/wu	County-level water use estimates provided by states aggregated every five years
	USDA Forests to Faucets	www.fs.fed.us/ecosystemservices/FS_Efforts/forests2faucets.shtml	Maps land areas most important to surface drinking water, the role forests play in protecting these areas, and the extent to which these forests are threatened by development, insects and disease, and fire

Social Preference, Valuation or Benefit Transfer: An Example of Western U.S. Water

Efforts to model water use and/or demand in the western United States have been the subject of considerable interest, particularly as population growth and economic development have increasingly strained water supplies in many western regions. Data on water use and demand are a foundational part of these analyses but can be difficult to acquire at the desired spatial and temporal resolution, particularly over long time periods. While individual organizations (e.g., water utilities, irrigation districts) often have records of water use, which could then be translated into demand relationships (with varying levels of difficulty), this data can be difficult to acquire, even in the rare instances that it exists in a convenient form. Long-term and comprehensive national-level data on water use is maintained by the USGS (www.usgs.gov) but is often available only at the state level and at annual intervals. In many cases, state agencies are the most complete and accessible sources of water use data, with California's Department of Water Resources offering perhaps the most well-refined database (www.water.ca.gov/waterdatalibrary).

Turning water use data into a demand relationship often requires, at a minimum, additional information on the (marginal) price of water and the price elasticity of demand. Centralized databases with information on water prices are uncommon, but price information can often be gleaned from the websites of water utilities (urban) or irrigation districts (agricultural), although the myriad pricing schemes used (e.g., increasing block rates) can complicate estimates of demand functions. Perhaps the quickest and most straightforward manner of gaining a rough estimate of a demand function is via the "point expansion" approach that has been used by many and described clearly by Griffin (2006). A considerable body of literature has been developed for estimating water demands in various sectors, including agricultural (Howitt et al. 2012; Young and Loomis 2014), urban (Howe and Linaweaver 1967;

Nieswiadomy 1992; Whittington et al. 1990; Young and Loomis 2014), hydropower (Young and Loomis 2014), flood control (White 1964; Young and Loomis 2014), recreation (Freeman 2003), and ecosystem services (Freeman 2003; Young and Loomis 2014). And, while each situation has its idiosyncrasies, a general sense of demand behavior in each of these sectors can be gleaned from these research efforts.

There is also a long history of combining data on water use and models to develop strategies for managing water, with most of these focusing on water quantity (Harou et al. 2009), as opposed to water quality. One of the most advanced is the CALVIN model (https://watershed.ucdavis.edu/shed/lund/CALVIN) developed by researchers at the University of California, Davis, as a means of examining California-wide water resource management strategies (Jenkins et al. 2004). There is also a broad range of regional/watershed models that have been developed for investigating improved water management throughout the western United States; however, in most cases these models were developed for a specific application and, consequently, are often designed solely for the researcher who developed it. As a result, these models are often poorly documented and maintained, an issue that the water resource systems modeling community needs to address.

Water Quality: Economic Benefits of Water Quality Changes

There is an extensive literature devoted to the estimation of economic benefits of water quality change, and methods for estimating these values are well developed (Young and Loomis 2014; see Freeman et al. 2014 for a methodological summary of economic valuation methods in general). These values are often (though not always) expressed in terms of individuals' or groups' willingness to pay (WTP) for specified changes in water quality within particular areas.[2] Although methods for valuing the benefits of water quality improvements are well developed, and the literature now includes hundreds (if not thousands) of studies addressing values of water for different beneficiary groups, it is not straightforward to develop widely applicable and transferable estimates of water quality value. Water quality benefits often vary considerably across sites, even for similar or identical chemical changes. Among the primary reasons are the many ways that water quality improvements benefit different groups of users and nonusers and heterogeneity in both beneficiaries and values over different areas. Water quality has multiple characteristics that pose challenges for WTP estimation (Griffiths et al. 2012; Griffiths and Wheeler 2005). Water quality can vary spatially and temporally, for example, headwater versus downstream.

There are also many interrelated ways that water can change (e.g., pollutant concentrations, dissolved oxygen, pH, temperature, clarity, color), each with potentially distinct implications for use and nonuse benefits realized by different groups (Bergstrom et al. 2001; Van Houtven et al. 2014; Young and Loomis 2014). Moreover, water quality benefits are often realized through direct and indirect effects on other ecosystem services valued by different user/nonuser beneficiaries (Blamey et al. 2002; Boyd and Krupnick 2013; Boyd et al. 2016; Johnston and Russell 2011). Water quality changes provide different benefits (in terms of both type and quantity) for many different beneficiary groups, including but not limited to agricultural users (Ward and Michelsen 2002), nearby homeowners (Leggett and Bockstael 2000; Poor et al. 2007), the general public, including users and nonusers (Johnston et al. 2005; Johnston et al. 2003; Johnston et al. 2015; Johnston and Thomassin 2010; Van Houtven et al. 2007), recreational users (Bockstael et al. 1989; Lipton 2004; Lipton and Hicks 1999; Peters et al. 1995), and others. Hence, the estimation of water quality benefits requires one to first specify the causal chain through which

[2] For commercial entities such as farms, values are commonly expressed in terms of changes in producer surplus or profits (Young and Loomis 2014).

specific types of water quality changes benefit or harm specific beneficiary groups. These causal chains (or conceptual means-ends diagrams) specify whose benefits are being considered (i.e., the beneficiary group) and the channels through which benefits are realized. Valuation methods (and benefit transfers) must similarly adapt to these differences.

Different valuation methods are required to measure different types of ecosystem service values related to water quality improvements; no single valuation method can measure all possible values (Holland et al. 2010; Johnston et al. 2002). Stated preference methods provide the only means to measure total use and nonuse WTP for water quality change, although revealed preference methods may be capable of measuring total values of certain beneficiary groups when values are linked solely to observable uses (Freeman et al. 2014).[3] In general, the results of stated and revealed preference methods are not directly comparable, as these approaches measure different components of total value (Johnston et al. 2002). An additional challenge in comparing water quality values estimated by different stated and revealed preference studies is that different metrics may be used to quantify water quality change within different contexts. Moreover, different types of water quality measures are applicable to different types of valuation applications (Boyd et al. 2016). A common simplification in stated preference analysis is to convey policy effects using a single water quality index (WQI) that combines information on multiple physical and chemical water quality parameters (Abbasi 2012; Carson and Mitchell 1993; Vaughan 1986; Van Houtven et al. 2014). An additional simplification used along with (or instead of) WQIs is the characterization of water quality using use criteria such as swimmable or boatable (Smith et al. 1986; Viscusi et al. 2008). However, many other measures of water quality are possible (e.g., clarity, specific quality parameters such as dissolved oxygen, temperature, probability of adverse events such as harmful algal blooms), and these are not always comparable across studies. Moreover, as noted, the most relevant measures of water quality often differ across beneficiary groups (Boyd et al. 2016).

These complications aside, there have been a number of recent efforts to generalize the insights provided by the water quality valuation literature and to generate reduced form functions that could be used to predict certain types of water quality benefits (often total WTP including both use and nonuse components) across unstudied sites. For example, meta-analysis has been used to evaluate systematic influences of study, economic, resource, and population attributes on measures of nonmarket willingness to pay (WTP) for environmental quality improvements (including water quality change), and to generate parameterized functions for use in benefit transfer (Bergstrom and Taylor 2006; Boyle et al. 2013; Johnston and Rosenberger 2010; Johnston et al. 2015; Nelson and Kennedy 2009). Within meta-regression models used for such purposes, the dependent variable is most often a comparable mean or median welfare measure (e.g., WTP) drawn from existing primary valuation studies. Independent moderator variables represent observable factors hypothesized to explain variation in this welfare measure across observations. Meta-regression models have been used to estimate benefit functions for changes in both the quantity and quality of many different types of nonmarket goods, including changes in water quality (Johnston et al. 2003, 2005, 2016; Johnston and Thomassin 2010; Bergstrom et al. 2001; Van Houtven et al. 2007). Benefit transfers from these functions—typically predicting mean per household WTP—have been used to support multiple benefit cost analyses of environmental regulations affecting

[3] Stated preference methods estimate values based on responses to carefully designed survey questions. Revealed preference methods estimate values based on analyses of observable behavior, such as recreational or home purchase behavior (Holland et al. 2010).

U.S. water quality (e.g., U.S. EPA 2010, 2012, 2013, 2015). In principle, such approaches are well suited for large-scale applications, as they provide a means to tailor value forecasts to specific conditions.

Despite the potential use of meta-analysis to support benefit transfers in this area, applications also face empirical and theoretical challenges, involving such issues as selection biases in the published literature (Rosenberger and Johnston 2009), difficulties reconciling and combining the information provided by prior studies (Smith and Pattanayak 2002; Bergstrom and Taylor 2006; Johnston and Moeltner 2014), and econometric modeling (Nelson and Kennedy 2009). Moreover, any benefit transfer—including those applying meta-analysis—involves generalization errors not present when using primary studies for valuation (Rosenberger and Stanley 2006). Hence, the development of broadly applicable meta-analytic value functions for water quality (or using other means such as structural benefit transfer; Smith et al. 2002) is not a trivial undertaking. Simpler forms of benefit transfer for water quality benefits, such as single-site benefit function transfer, are only suitable when study sites (where the primary study was conducted) and policy sites (where the value is needed) are similar across all relevant dimensions (Johnston and Rosenberger 2010; Johnston et al. 2015). Discussions of the advantages and disadvantages of different types of benefit transfers are provided by Johnston et al. (2015).

In practical terms, the capacity exists to conduct meta-analytic and other types of benefit function transfers for some types of water quality improvements in water bodies and watersheds nationwide. The best-developed capacity is for transfers of total WTP (including use and nonuse values) for water quality improvements quantified using a standard WQI. Similarly robust transfers can be conducted for use thresholds that can be linked to a WQI (e.g., the value of obtaining swimmable water). While these methods are relatively well developed, transfers of this type are only suitable in cases where approximate values are required. Rosenberger (2015) finds that benefit function transfers (over all types of resources) generate errors that average 65%, with a median of 35%. Where more precise values are warranted, primary studies are required (Allen and Loomis 2008).

Other types of values, such as amenity values of water quality or clarity captured by hedonic property value models, are likely to be more context specific and difficult to transfer with accuracy. There are also fewer directly comparable studies of such values in the literature that can be used to support benefit transfers or meta-analysis. As a result, researchers have not yet developed robust meta-analyses or other benefit functions enabling these values to be forecast for different sites. Similar limitations apply to recreational benefits such as the value of clean water for different types of recreation—although the number of studies in this area could in principle be used to support development of robust meta-analyses. In general, the capacity for benefit transfers is more defensible and robust for cases in which benefits can be directly linked to standardized scales that are commonly used across the valuation literature, such as WQIs or water quality ladders, or uses that can be linked to these scales. As values become more idiosyncratic across sites or are linked to less commonly used measures of water quality, benefit transfer becomes less defensible.

Example of Economic Valuation Data and Models for Freshwater Recreation

The economic valuation of water quality for freshwater recreation can use several different methods. Cost-based approaches are often used to value avoided cost of removing sediment or nutrients from waterways, as in the case of water treatment costs for nutrient removal or reservoir dredging costs. These approaches can be valid and useful if they represent a realistic, least-cost estimate for water-quality improvement, though they lack a connection to economic welfare theory (i.e., they do not measure producer and/or consumer surplus), and are used to estimate changes in the value of water quality more generally rather than the explicit value of freshwater recreation.

Contingent valuation, travel cost, and related approaches have frequently been used to estimate both current recreational values and potential future values under scenarios for water-quality improvement or decline (e.g., Poor and Breece 2006, Johnston and Thomassin 2010). Because of the time and expense associated with conducting new primary studies, value-transfer approaches may also be useful for valuing water quality for freshwater recreation as an ecosystem service, as long as best practices for value transfer are carefully followed. Numerous attributes could theoretically influence economic values for recreation, though not all of these are likely to be statistically significant. Accounting for these attributes in valuation or value transfer approaches is important. These attributes include the type of recreational activity (e.g., fishing, boating, swimming), attributes related to ecosystem service supply (e.g., type of water body, land ownership—i.e., Forest Service, NPS, USACE), and attributes related to recreation demand (e.g., per capita income, congestion, substitute sites; Rosenberger and Loomis (2001), http://recvaluation.forestry.oregonstate.edu). Existing value transfer tools (e.g., http://dare.agsci.colostate.edu/outreach/tools; Loomis et al. 2008) and databases (http://recvaluation.forestry.oregonstate.edu, https://my.usgs.gov/benefit-transfer/) may be particularly helpful for this purpose.

Coastal and Marine Services

Use Data

The most comprehensive survey of recreational use of our coastal and marine resources is the National Survey of Fishing, Hunting, and Wildlife-Associated Recreation, which is produced by the U.S. FWS and the U.S. Census Bureau. The geographic coverage (every state; marine and terrestrial) and time series (every five years since 1991) provides consistent measurements of use and impact. However, applying it to regions smaller than the state level can be challenging. Additionally NOAA publishes recreational catch statistics through the Marine Recreational Information Program.

Valuation

Armed with only biophysical data, managers may know enough about the societal context in which they are working to conduct an ecosystem services assessment without socioeconomic values and to improve management outcomes. Alternatively, depending on the drivers, managers may primarily care about the biophysical outcome (e.g., amount of hectares restored or protected) and not necessarily the benefits humans derive from it (recreational, aesthetic, existence, etc.). Explicitly accounting for how human well-being is influenced by changes in environmental conditions helps avoid assumptions, unintended consequences, and missed opportunities to discover optimal solutions.

There are several contexts within which researchers derive marine ecosystem service values, producing different information depending on the intended use. Because NOAA, as well as regional and state fisheries management organizations, are mandated to collect market data, the value of commercial fisheries is the most readily available marine ecosystem services information. Before passing new fisheries regulations, for instance, NOAA analyzes how the changes may alter the benefits fishers receive from a given day at sea. Most marine ecosystem services values, however, are derived from passive use (e.g., existence and aesthetics), which requires the use of nonmarket valuation techniques. Unlike with commercial fisheries, there is no market that can be analyzed to derive valuation information from these services. Other economic information associated with services is collected—e.g., the economic impact of

National Marine Sanctuaries—but these may only be used as proxies for the value that society derives from healthy marine ecosystems.

Over the past two decades, NOAA has supported several dozen nonmarket valuation studies (many of which are included in an inventory of studies described here), including many through its Sea Grant College program. A majority of these studies derive values associated with either beach recreation or recreational fisheries, as both of these activities are enjoyed by millions of people annually. Other services valued include scuba diving, the continued existence of endangered species, flood protection, and water quality.

There are several approaches to capturing the value of ecosystem services using nonmarket methods (U.S. EPA 2009; NRC 2004, 2012). Besides directly valuing services (e.g., the amount people are willing to pay to scuba dive in a particular location—see Parsons and Thur 2008), some valuations focus on a particular area (e.g., a state park—see Wallmo and Edwards's 2007 Technical Memorandum, which conducts a valuation on Marine Protected Areas) so the services being valued are implied in the value of the area rather than explicitly considered. Others derive values for services based on people's preferences for the outcome of how different alternative management actions affect a resource (e.g., how wide a beach should be constructed through nourishment—see Pendleton et al. 2012). Another approach is to analyze the loss of value when a resource or service is negatively affected (e.g., through the degradation of habitat or natural resources—see Petrolia and Kim 2011).

Benefit transfer approaches are also used to derive marine ecosystem services values. Such approaches are used when an original nonmarket valuation study is not justified given the manager's informational needs and there exists a value or values from other studies that can be applied to a separate but relatively similar context. At NOAA, these approaches are most commonly used to assess damages to recreation and other ecosystem services from oil spills and other toxic discharges. In general, benefit transfer approaches are more commonly used when the primary focus is on assessing the biophysical changes driven by an environmental impact or a management action and is seen as an expeditious way of incorporating socioeconomic information. Most of NOAA's ecosystem services work, however, has focused on the socioeconomic part of the equation, so primary studies are justified. There is certainly potential to use benefit transfer in broader ocean and coastal management contexts, particularly where there are strong drivers to quickly and cost-effectively calculate valuation information. In these cases, it is nonetheless critical that best practices for using benefit transfer approaches are used (described elsewhere).

Besides those studies that explicitly support mandates—including fisheries market values, damage assessments from oil spills, and cost-benefit analyses to support National Environmental Policy Act analyses—there are two main drivers for social scientists to conduct or apply ecosystem service valuations in the marine and terrestrial environment. The first driver is to compel decision makers and the public of the importance of conservation, environmental regulations, the support of recreational activities, and so on. Rarely do these studies link to biophysical production functions because they have a communication focus and do not require such rigorous ecological data.

The second driver is to provide decision-support information by, for example, evaluating how different regulations affect the value of recreational fishing. In neither of these contexts are biophysical and socioeconomic information consistently linked to each other within a holistic analysis. Part of the reason is that many ecosystem services, particularly recreational ones, can be enhanced without changing ecological processes (e.g., more mooring buoys are provided for fishing boats). In other cases, valuations are not linked to biophysical production-functions simply because the research questions being asked by social scientists seemingly do not require this information. When social science surveys pose hypothetical alternative restoration actions, for instance, they may not be concerned with the efficacy of the restoration method. Instead, the assumption is that a certain level of restoration is achieved, and the focus is on how it affects societal outcomes. The reverse holds true for biophysical scientists who fail to draw strong linkages with human well-being. The ecological processes they are analyzing are done through the lens of assessing the change in ecological outcome. The strength of the ecosystem services approach laid out in this working paper is that biophysical and socioeconomic information are explicitly linked, providing a more complete, robust picture of the management context that includes the ultimate societal outcomes of alternative management actions.

Urban Social Preference and Value Data

Most cities have much of the required data to perform ecosystem services evaluations, especially as high-resolution land cover data become more widely available (e.g., U.S. National Agriculture Imaging Program (NAIP) data, though raw data will still need to be converted to land cover). Urban land cover and land use data make assessment and valuation of urban services possible, especially for provisioning and regulation services. For cultural services, however, social use and preference data is much less available.

Cultural ecosystem services have the potential to contribute some of the highest values in urban ecosystem valuation studies, especially when physical and mental health benefits of urban green space are included. Studies of urban systems within the field of urban ecology (Grimm et al. 2000; Pickett et al. 2011) highlight the importance of human activity, values, perceptions, and norms and how they interact with ecological processes to affect ecosystem structure, functioning, and services (e.g., Andersson et al. 2007; Grove et al. 2006). Since human decisions and preferences strongly shape urban space, preferences are not necessarily primarily decided by knowledge (McNie 2007). People bring various material, moral, spiritual, aesthetic, and other values to bear on the urban environment, and their values can affect their attitudes and actions toward ecosystems and the services they provide (Ernston 2013; Gómez-Baggethun and Barton 2013), which makes valuation challenging in urban areas without substantial social use and preference data. Still, social-demographic indicators derived from U.S. Census data and local land use data have been used to understand social need for urban ecosystem services (McPhearson, Auch, et al. 2013; McPhearson, Kremer, et al. 2013), and social networking data from Twitter, Flickr, Foursquare, and others is increasingly used to examine social preferences for green areas and services (Bertrand et al. 2013; Wood et al. 2013).

Research to develop robust decision support tools for examining tradeoffs and synergies among multiple services produced in urban and periurban areas is ongoing. However, new tool development is in process with the expectation that in the very near term modeling suites that build on but go beyond iTree will soon be available. For example, an Urban InVEST model is currently in development through a partnership with the Natural Capital Project, the New School, and Stockholm Resilience Center with prototypes for multiple services being tested in Minneapolis and New York City. Additionally, the ARIES modeling tool in development could provide similar capability for urban areas (Villa et al. 2014). The main barriers to scientifically robust metrics for monetary valuation of urban ecosystem services include both social and ecological data availability, especially at the high spatial resolution needed to advance planning and management in urban contexts. Increasing the scientific rigor of existing and newly developed models will be important, especially to take into account the built and technical infrastructure in cities. For example, reliable calculations for air pollution removal by urban green infrastructure depends on wind speed, building height, amount of vehicle traffic, and road width, all of which need to be incorporated in modeling efforts.

Still, urban ecosystem services assessment and valuation is moving forward quickly (Gómez-Baggethun and Barton 2013; Larondelle and Haase 2013; Haase et al. 2012, 2014; Kremer, Hamstead, and McPhearson 2016) especially for understanding how urban ecosystems contribute to urban heat island reduction, noise mitigation, recreation, stormwater absorption, and carbon storage and sequestration. Remaining challenges and areas for future research include gathering social preference data both from social media and through traditional social science methods. Additional research is especially needed to understand the social inequality in access to urban green spaces driven by mismatches between the spatial distribution of the supply of and the demand for ecosystem services, especially in underserved areas of the city (Haase et al. 2014; Kremer, Hamstead, Haase, et al. 2016). For example, a recent effort to map the social need for ecosystem services around vacant lots in NYC found that low-income, high-population-density areas of the city also tend to have decreased access to green space where many ecosystem services are produced (Kremer et al. 2013; McPhearson, Kremer, et al. 2013). Finally, ecosystem protection in cities will rely on increasing efforts by park and natural area managers to focus on management outcomes that seek to maximize ecosystem functioning for services, which could be an abrupt shift from existing or past management goals (Schewenius et al. 2014).

Federal mechanisms regulate and influence how cities manage some of their most important ecosystem services, including water supply and stormwater quality, among others (McPhearson et al. 2014), which demonstrates a unique opportunity for federal-level urban planning, management, and design incentives to increase socially just production of urban ecosystem services critical for the health and well-being of urban residents.

Table 4-6. Use data and models for urban social preference and value in ecosystem services assessments

Type	Source	Reference	Description
Data	U.S. National Agriculture Imaging Program (NAIP)	www.fsa.usda.gov/FSA/apfoapp?area=home&subject=prog&topic=nai	Provides aerial imagery acquired during the agricultural growing seasons in the continental United States
Models and mixed models	Urban InVEST	http://environment.umn.edu/wp-content/uploads/2016/03/NatCap_Urban_InVEST_1-pager_links.pdf	Toolbox in development with the ability to assess multiple ecosystem services and look at tradeoffs and cobenefits in the urban environment

Climate Stability

The economic valuation of climate-stabilizing (e.g., sequestration of carbon) or -destabilizing actions (greenhouse gas emissions) is determined by the severity of future climate change and its associated impacts. A large research effort has gone into establishing the causal links between atmospheric CO_2

concentrations and climate change. Through the investigations discussed previously, links can then be established between changes in the climate and the potential future damages (from sea level rise, changes in precipitation patterns, and so on) associated with a lack of climate stability. Economic models then take these damages, or the benefits associated with avoiding them, and monetize them to attempt to assign an overall economic value to the ecosystem services being affected by climate change.

A broad summary measure of this type is the social cost of carbon, or SC-CO_2 (Interagency Working Group on Social Cost of Carbon 2015). The SC-CO_2 measure developed by the Interagency Working Group (IAWG) is intended to be a comprehensive estimate covering all damages associated with climate change, although as noted in the IPCC Fifth Assessment Report (IPCC 2014), the models used to estimate the economic consequences of emissions do not include all physical, ecological, and economic impacts associated with climate change. However, the models used by the IAWG to estimate monetized damages from an incremental increase in emissions do include a range of impacts such as net changes in agricultural productivity, human health, property damages, and the value of ecosystem services (where possible).

Typically, information from the ecological data and models discussed in the foregoing are expressed as "damage functions" that can be incorporated in economic models, which overlay these ecological inputs with assumptions about human economic behavior. Several types of economic models are used to assess policy or programmatic scenarios that affect emissions and climate stabilization: sector-specific models that focus on a narrow slice of the economy, broader macroeconomic models that can cover all interactions among businesses and households within a region or globally but do not explicitly model ecosystem services and atmospheric chemistry, and integrated assessment models that combine modeling of economic behavior and its associated emissions with information on the interactions among emissions, climate change, and the physical world.

Sector-specific economic models are helpful in providing detailed estimates of potential costs of climate change within one or more sectors of the economy. For example, the Forestry and Agricultural Sector Optimization Model with Greenhouse Gases (FASOM-GHG) can estimate how changes in temperature, precipitation, and land use may interact with agricultural markets and domestic or global policies to affect U.S. food production and trade, along with the emissions associated with agricultural production (Adams et al. 2005). Similarly, the Global Timber Model (Sohngen et al. 2001) is a dynamic model of ecological change and economic change that can capture the impact of climate change on world timber markets.

Unlike detailed sector-specific models that can express relatively precise relationships between climate and economic outcomes, broader macroeconomic models express relationships among climate stability, ecosystem services, and the economy through more general damage functions derived from the results of ecological models. The models then attempt to quantify changes in the economy for a specific climate change scenario or mitigation policy. For instance, the Intertemporal General Equilibrium Model (IGEM) of the U.S. economy was used to estimate climate change impacts on agriculture, forestry, energy demand, water supplies, coastal protection, and the labor supply through changes in air quality and health (Jorgenson et al. 2004). Other work has modeled the economic effects of individual impacts of climate stabilization on ecosystem services (see, for example, Bosello et al. 2006, who use the GTAP-E model to look at human health, and Hinkel et al. 2013 on coastal flood damage and adaptation costs associated with sea-level rise).

To develop the broadest measures of the monetized impacts of climate change, such as the SC-CO_2, integrated assessment models (IAM) are typically employed. Because of their scope, they are less reliant on prespecified damage functions than the narrower macroeconomic models and can estimate some types of emissions damages directly. The Global Change Assessment Model (GCAM), developed at the Joint Global Change Research Institute and used by the U.S. EPA, among others, has representations of the economy, energy sectors, land use, and water that are linked to a climate model. The IAWG that developed the SC-CO_2 measures used by U.S. federal government agencies relied on three IAMs: DICE (Nordhaus and Boyer, 2000), PAGE (Hope, 2006), and FUND (Tol 2002a, 2002b). Similar to GCAM, these three models translate emissions into changes in atmospheric greenhouse concentrations, the atmospheric concentrations into changes in temperature, and finally the changes in temperature into economic damages. This type of structure allows the IAMs to explore climate change, mitigation policies, and interactions among the physical and economic components of the model.

Table 4-7. Models for economic valuation of climate stability risk regulation

Type	Source	Reference	Description
Sector-specific models	Forestry and Agriculture Sector Optimization Model with GHG (FASOM-GHG)	http://agecon2.tamu.edu/people/faculty/mccarl-bruce/FASOM.html	Mathematical programming model simulating future potential policy impacts on land use, markets, and GHG fluxes between and within the U.S. agricultural and forest sectors
	Global Timber Model (GTM)	http://aede.osu.edu/research/forests-and-land-use/global-timber-market-and-forestry-data-project	Dynamic mathematical programming model of ecological and economic change that simulates impacts of climate change on global timber markets
Macro-economic models	Intertemporal General Equilibrium Model (IGEM)	www.igem.insightworks.com	Econometrically estimated intertemporal general equilibrium model of the United States economy
	Global Trade Analysis Project model (GTAP)	www.gtap.agecon.purdue.edu/models	Multiregion, multisector, general equilibrium model covering all aspects of the global economy
Integrated assessment models	Global Change Assessment Model (GCAM)	www.globalchange.umd.edu/archived-models/gcam	Dynamic-recursive model with technology-rich representations of the economy, energy sector, land use, and water linked to a climate model
	Dynamic Integrated Climate and Economy model (DICE)	www.econ.yale.edu/~nordhaus/homepage/Web-DICE-2013-April.htm	IAM that combines economics and science to examine the dynamics and policy aspects of climate change

Type	Source	Reference	Description
	Climate Framework for Uncertainty, Negotiation and Distribution (FUND)	www.fund-model.org	IAM used to perform cost-benefit analyses of emissions reduction policies through linking simple models of the economy, population, sea levels, and other impacts
	Policy Analysis of the Greenhouse Effect (PAGE)	http://climatecolab.org/wiki/-/wiki/page/PAGE	IAM that projects future increases in temperature, economic costs of damages caused by climate change, costs of mitigation policies, and potential costs of adaptation measures

5. DATA AND MODELING INFRASTRUCTURE

Given the historic memo (Donovan et al. 2015) released by the Executive Offices of the President in October of 2015 and the resulting momentum within the largest resource management agencies in the United States (USDA, Department of the Interior, NOAA, USACE), there is tremendous opportunity to advance the use of ecosystem services in federal decision making. In the next two to five years it will be critical to put the data and modeling foundations in place so ecosystem services information can be put into practice. Implementing, operationalizing, and institutionalizing ecosystem services will require efforts to address remaining challenges including those around data and modeling. These include (1) missing data and models (ecological and economic), (2) uncertainty about what data and models are acceptable (good enough), (3) uncertain precision of results, and (4) the time required to assess ecosystem services. Building a robust and sustainable data and modeling infrastructure could help address all of these challenges.

Further, the rapid growth of terrestrial sensor networks, drone-based mapping and monitoring, satellite remote sensing, and crowdsourced data increasingly open the door to data mining, machine learning, and other inductive "big data" modeling approaches that have thus far seen relatively limited application in the field of ecosystem services (Hey et al. 2009, Villa et al. 2014). These methods, which use algorithms to identify patterns and relationships from data, differ from deductive ecological production function approaches but may work well in cases where data from traditional field experiments are sparse but sensor-based data are abundant or where ecological production function relationships are unknown or perform poorly. These techniques require further work on semantics and the use of data services (ideally Open Geospatial Consortium, OGC) that are seeing increasing use in environmental modeling (Peckham et al. 2013, Villa et al. 2014). They are also receiving attention from federal agencies such as USGS (www2.usgs.gov/cdi/participate.html) and the Interagency Steering Committee on Multimedia Environmental Modeling (ISCMEM, www.nrc.gov/docs/ML1328/ML13281A407.pdf). Combined with cloud-based modeling, these approaches hold promise to greatly advance the integration of data and models in service of faster, better, cheaper ecosystem service modeling in service of decision making.

Current Federal Efforts

A number of efforts are under way to develop pieces of a data and modeling infrastructure.

- **EcoINFORMA:** This data portal is part of data.gov. It is aimed at expanding the availability and interoperability of federal and nonfederal biodiversity, ecosystems, and ecosystem services information by collecting, organizing, and serving existing data. It currently includes three resource hubs: BISON, EnviroAtlas, and Multi-Resolution Land Characteristics Consortium (MRLC), which serves data from the NLCD. www.data.gov/ecosystems/ecoinforma
- **BISON:** This database and mapping interface focuses on species occurrence data collected from numerous research institutions including museums, journals, botanical gardens, herbariums, federal agencies, universities, and many others. http://bison.usgs.ornl.gov/#home
- **EnviroAtlas:** The Atlas is a geospatial mapping tool with national data (including only the continental United States at present). It currently generates maps at a HUC-12 scale for the national data but includes some high-resolution data for a growing number of cities. While the EPA has put forth a heroic effort in pulling this resource together it has a few limitations. First, at this time the national data is at a resolution too coarse for many services. Second, it only provides partial information for some services. And third, it will need a long-term home and funding as the

EPA Office of Research and Development (ORD) operates by developing research and tools but is not set up to fund and manage them long term. www.epa.gov/enviroatlas

- **Ecological Production Function Library:** This nascent effort to design a well-organized and searchable database of ecological production function models has identified a real need. This initial effort needs to be shared with other federal agencies and users to get feedback on how to align it with data and to make it credible and functional for users, so that its use will be supported by experts. A coordinated effort with capacity from multiple agencies will be needed to populate the library with a wide range of existing models that agencies, universities, and other researcher organizations have developed. Like other products by the EPA's ORD, it will need a long-term home and funding. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=241148
- **Benefit Transfer Toolkit:** A benefit transfer toolkit was developed for fish, wildlife, wetlands, and open space (Loomis et al. 2008). This version of the toolkit (available at http://dare.agsci.colostate.edu/outreach/tools) can be credibly applied by knowledgable economists and continues to be used for benefit transfers. Discussion about continuing to update and expand this type of tool led USGS to develop a new web-based version (https://my.usgs.gov/benefit-transfer). This version of the toolkit includes updated value estimates and new meta-regression models and will ultimately include additional ecosystem services and mapping features.

In addition, two other initiatives are being developed within the USGS: an Environmental Capital Dashboard (www.fort.usgs.gov/science-tasks/111148), which is collecting and developing pilot studies, and a National Capital Accounting program (http://powellcenter.usgs.gov/view-project/57741607e4b07657d1a9910c), which will collate national data to assess status and trends over time.

Although these are a good start, they lack strong approaches for gathering new economic and social data and are not sustainably resourced or well coordinated given the nature of federal funding and programs. Thus it is necessary to ramp up efforts to address remaining challenges in building and maintaining national data and modeling infrastructure and assuring the data can accurately inform social and economic outcomes.

Challenges

A number of important issues will need to be addressed in building a robust national data and modeling infrastructure.

Ecological Data and Models

Building, collecting, and maintaining the broad category of ecological models and the data that are required to allow them to operate for ecosystem services assessment provide significant challenges related to the variable spatial and temporal scale of information needed to inform decisions (Schimel et al. 1997). Most existing monitoring systems and national inventories are established to address national-scale questions and therefore are set up to provide information to feed national models and analyses (e.g., whether in the United States forests are stable or lands producing timber are increasing or decreasing; Oswalt et al. 2012). As a result, the information generated may be too coarse to be useful to apply to many of the subregional plans (regional highway plans, national forest plans, BLM district plans, watershed plans), which actually influence funding allocation for infrastructure, restoration, mitigation, or conservation, while most of the detailed monitoring, mapping, and data collection for on-the-ground projects are too detailed and expensive to practically develop at the scale of these plans. Similar scale issues exist for much of the aquatic and hydrologic data in the country.

Other problems relate to the use of ecological data that can only approximate the types of services being analyzed in the models. Land cover is often used as the only available proxy for myriad services that it can only approximate (Eigenbrod et al. 2010). Available methods allow for the development of spatial data attributes that might better inform the indicators that can feed economic or social models. An example is the use of imputed plot data for forests (Ohmann and Gregory 2002), which can provide information on forest structure and composition, rather than just informing whether some type of forest is present; this data is much more likely to be relevant to models of ecosystem service outputs. Wetlands, streams, estuaries, grasslands, and shrub-steppe ecosystems all have similar disconnects between what is measured and the services the ecosystems provide.

The final data-related challenge relates to the difficulty in keeping appropriate data up to date, to reflect current services at the time of the analysis. Data is usually collected at different times in different locations and aggregations, such as national wetlands assessments and land cover maps that get updated every five years and take a year or two more before they are publicly available. The 2011 National Land Cover Data (NLCD) was released in 2015 and will be used until the 2016 update is available, possibly in 2019 or 2020. NLCD is working to analyze change (Jin et al. 2013). Creating data that can be continuously updated and tied to ongoing inventories of water, vegetation, and species is a reachable goal and is critical to measuring ecosystem service outputs and change over time.

There are a number of ways the agencies can move forward to improve data and modeling. They can focus efforts on key data sets that underlie assessment of many services in the United States. For example, the hydrological base information (the National Hydrography Database, NHD) needs to be high resolution (Hi-RES) all over the country and needs to convey common attributes so that models of water output, availability, flow patterns, and aquatic habitat can be developed across watersheds throughout the United States. At this time there is no national support for creating even data across the country because work is done and supported on a state-by-state basis. Similarly, soils and surficial geology are data layers that could significantly improve model outputs from ecosystems to services. Developing these data layers across the country on even a moderate (1:100,000) scale would be valuable for modeling many services. The Soil Survey Geographic Database (SSURGO 1:24,000) mapping was to be completed for the conterminous United States 20 years ago. While agricultural areas continue to be updated, forested areas are incomplete, particularly in western states, in spite of the role of forest soils in erosion and soil formation (SSURGO 2015).

In addition, agencies are the primary source of research and research funding focused on resource management, which generates the data for ecological production function models that underlie ecosystem services assessments. These data, when collected from studies that range in geographic, spatial, and temporal scale, are the basis for meta-analyses and the generation of generalized functions and models that can be more widely used. Agencies can request or require that critical data from the individual studies they conduct or support be made available, setting reporting requirements and metrics. They can ask for data to be provided to a repository or made available in a standard electronic format. Such steps are necessary as individual studies often do not report or even collect all the data that would be useful for a meta-analysis.

Economic Data and Models

Currently the federal government's efforts to capture "traditional" socioeconomic data and information is significant. Examples of these are the Census (www.census.gov) and additional products such as the American Community Survey (www.census.gov/programs-surveys/acs/), American Housing Survey (www.census.gov/programs-surveys/ahs.html), and Economic Census (www.census.gov/econ/census). Price indices (www.bls.gov/ppi) and labor numbers produced by the Bureau of Labor Statistics (www.bls.gov) provide an essential foundation in the production of values for ecosystem services and, in particular, when employing a robust benefit transfer approach such as functional transfer. However, there still exist significant gaps in "nontraditional" socioeconomic data that can enhance the development and uptake of benefit transfer models.

By design, primary valuation studies are required input for benefit transfer models. These studies can be significantly more expensive and take longer than transfer valuations (Wilson and Hoehn 2006), and so there is a desire to default to benefit transfer. There exists a significant problem, especially in the coastal and marine environments, of a lack of primary valuation studies of acceptable rigor that can be used in a transfer analysis in any meaningful way, especially for policy application. With increased demand for ecosystem services valuation work to be done, how do we service that need with limited resources?
In order to meet the growing demand and support the appropriate use of benefit transfer models there is a need to build an *intellectual infrastructure* that would do the following:

Support primary valuation studies that can be used in benefit transfer analysis: There is a need to grow the number of studies (*n*), especially for underrepresented services (e.g., water quality, aesthetics) and habitats (e.g., seagrass, prairie pothole) in a manner that is useful in benefit transfer. Loomis and Rosenberger (2006) provide general criteria necessary for valid benefit transfer but, more importantly, discuss how the design and reporting out of primary studies can increase their usefulness, including:

- Policy-relevant study designs (e.g., commodity, welfare measure, and market area comparability);
- Full and consistent reporting (e.g., what was valued, market area, welfare measures);
- Information repositories.

These important suggestions, as well as others, could be institutionalized within agency studies and as requirements for grantees and contractors conducting primary valuation studies.

Primary valuation methods like contingent valuation, a stated preference approach, requires public surveys. Given federal rules, public surveys done by the agencies or with public funding require Office of Management and Budget (OMB) approval, which can at times be difficult and time-consuming to obtain (OMB 2006a, 2006b). When this occurs, primary valuation studies are not the tool of choice, pushing agencies to use benefit transfer methods when data may be poor and/or only available for a limited number of benefits. The OMB, which depends heavily on cost-benefit analyses when making decisions, currently has some concern with the use of stated-preference-type surveys, as do some federal agencies. Such surveys have been done poorly at times and can be difficult to do well but in many cases are the only option for assessing nonuse values. Concerns over stated preference have further hampered the use of such primary valuation methods for federal studies.

Development and deployment of benefit transfer tools and best practices: As demand for ecosystem services valuation increases in federal agency operations, benefit transfer analysis will be called on to fill some of this need. Given the issues identified above, along with a shortage of benefit transfer practitioners, an effort to develop robust benefit transfer tools that are transparent is warranted. A multiagency effort in this area could leverage expertise and resources within the federal family and develop buy-in early on. Additionally, the coordinated effort among the agencies would help begin to meet goals of the Office for Management and Budget and Council on Environmental Quality with regard to ecosystem services integration.

Data and Model Infrastructure

The list of questions and challenges to be addressed is long. While there are some initial conversations and efforts under way, the level of effort and resources committed to building and sustaining the necessary data and model infrastructure will likely need to be much greater. Here is a list of questions that need to be addressed.

- Is there a minimum set of data and models sufficient to support most applications (sufficiently credible)?
- National versus state/local databases? Will it be in multiple places for redundancy? How can it be made both accessible and secure? How can federal agencies address barriers created by internet security?
- How will data and models be made available? User queries via web services? Will disaggregated data be made available? If so, how can security and privacy be insured? Can the example of the U.S. Research Data Centers that manage the use of disaggregated U.S. Census data be used?
- Where will data and models be stored?
- How will data and models be curated? Who will curate the resource?
- How will data and models be quality assured? How will data and models be updated over time? How will different data sets be aligned (e.g., semantic modeling)? Will other efforts be needed to build consistency in reporting and data and model structure?
- Are there mechanisms that would allow the government to have sustained funding and sufficient expertise and capacity for this? Would it make sense to do this as a public-private partnership? Are there other data models that could be used as examples (e.g., MRLC consortium that supports the NLCD data products)?
- How will these activities be managed and funded over time?
- Do the data and models need to be freely available or can they be fee-for-service?

6. REFERENCES

1: Introduction

Bruins, R.J., L. Wainger, S. Sifleet, and T.H. Dewitt. 2012. "Development of U.S. EPA's Ecological Production Function Library." Presented at EcoSummit 2012, Columbus, OH (September 30–October 5).
Burke, M. 2013. "Why We Need More—and Not Less—Conservation Funding in the Federal Budget." *Forbes Magazine*, November 22.

Burke, T., T. Dickinson, and K. Sullivan. 2015. *Ecosystem-Service Assessment: Research Needs for Coastal Green Infrastructure*. National Science and Technology Council Report. https://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/cgies_research_agenda_final_082515.pdf.

Donovan, S., C. Goldfuss, and J. Holdren. 2015. Memorandum for Executive Departments and Agencies. M-16-01. https://www.whitehouse.gov/sites/default/files/omb/memoranda/2016/m-16-01.pdf.

Kunz, T.H., E.B. Arnett, W.P. Erickson, A.R. Hoar, G.D. Johnson, R.P. Larkin, M.D. Strickland, R.W. Thresher, and M.D. Tuttle. "Ecological Impacts of Wind Energy Development on Bats: Questions, Research Needs, and Hypotheses." *Frontiers in Ecology and the Environment* 5(6): 315–324.

Kuvlesky, W.P., L.A. Brennan, M.L. Morrison, K.K. Boydston, B.M. Ballard, and F.C. Bryant. 2007. "Wind Energy Development and Wildlife Conservation: Challenges and Opportunities." *Journal of Wildlife Management* 71(8): 2487–2498.

Lucero, C., and R. Doudrick. 2008. "USDA Announces New Office of Ecosystem Services and Markets." News Release No. 0307.08. http://www.usda.gov/wps/portal/usda/usdahome?contentidonly=true&contentid=2008/12/0307.xml.

National Ecosystem Services Partnership (NESP). 2016. *Federal Resource Management and Ecosystem Services Guidebook*. Durham: National Ecosystem Services Partnership, Duke University. http://www.nespguidebook.com.

Olander, L., R.J. Johnston, H. Tallis, J. Kagan, L. Maguire, S. Polasky, D. Urban, J. Boyd, L. Wainger, and M. Palmer. 2015. "Best Practices for Integrating Ecosystem Services into Federal Decision Making." Durham: National Ecosystem Services Partnership, Duke University. doi:10.13016/M2CH07.

President's Committee of Advisers on Science and Technology (PCAST). 1998. "Teaming with Life: Investing in Science to Understand and Use America's Living Capital." Report to the President. https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-teamingwithlife.pdf.

President's Committee of Advisers on Science and Technology (PCAST). 2011. "Sustaining Environmental Capital: Protecting Society and the Economy." Report to the President. https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_sustaining_environmental_capital_report.pdf.

U.S. Department of Agriculture Forest Service. 2012. "National Forest System Land Management Planning." *Federal Register* 77(68): 21162–21275.

U.S. Energy Information Administration (U.S. EIA). 2015. "What Are the Major Sources and Users of Energy in the United States?" *Energy in Brief*, December 29. http://www.eia.gov/energy_in_brief/article/major_energy_sources_and_users.cfm.

U.S. Environmental Protection Agency (U.S. EPA). 2016. "Superfund." https://www.epa.gov/superfund.
Van Wensem, J., P. Calow, A. Dollacker, L. Maltby, L. Olander, M. Tuvendal, and G. Van Houtven. 2016. "Identifying and Assessing the Application of Ecosystem Services Approaches in Environmental Policies and Decision-Making." *Integrated Environmental Assessment and Management*. doi:10.1002/ieam.1836.

Waage, S., and C. Kester. 2014. "Private Sector Engagement with Ecosystem Services." Business for Social Responsibility Working Paper.

White House Council on Environmental Quality. 2013. "Principles and Requirements for Federal Investments in Water Resources." https://www.whitehouse.gov/sites/default/files/final_principles_and_requirements_march_2013.pdf.

2: Ecological Data and Models for Ecosystem Services Assessments

Andersson, E., T. McPhearson, P. Kremer, E. Gómez-Baggethun, D. Haase, M. Tuvendal, and D. Wurster. 2015. "Scale and Context Dependence of Ecosystem Service Providing Units." *Ecosystem Services* 12: 157–164.

Arnold, J.G., and N. Fohrer. 2005. "SWAT2000: Curren Capabilities and Research Opportunities in Applied Watershed Modelling." *Hydrological Processes* 19(3): 563–572.

Arrigoni, A.S., M.C. Greenwood, and J.N. Moore. 2010. "Relative Impact of Anthropogenic Modifications Versus Climate Change on the Natural Flow Regimes of Rivers in the Northern Rocky Mountains, United States." *Water Resources Research* 46: W12542.

Artz, M. 2016. "New Map Sets Framework for Describing Ocean Ecology in Unprecedented Detail." *Esri Insider*, March 14. https://blogs.esri.com/esri/esri-insider/2016/03/14/new-map-sets-framework-for-describing-ocean-ecology-in-unprecedented-detail/.

Bartomeus, Ignasi, John S. Ascher, Jason Gibbs, Bryan N. Danforth, David L. Wagner, Shannon M. Hedtke, and Rachael Winfree. 2013. "Historical Changes in Northeastern US Bee Pollinators Related to Shared Ecological Traits." *Proceedings of the National Academy of Sciences* 110 (12): 4656–4660.

Brittain, Claire, Neal Williams, Claire Kremen, and Alexandra-Maria Klein. 2013. "Synergistic Effects of Non-Apis Bees and Honey Bees for Pollination Services." *Proceedings of the Royal Society of London B: Biological Sciences* 280 (1754): 20122767.

Brown, Mark J.F., and Robert J. Paxton. 2009. "The Conservation of Bees: A Global Perspective." *Apidologie* 40 (3): 410–416.

Brown, T.C., P. Froemke, W. Mahat, and J.A. Ramirez. 2016. “Mean annual renewable water supply of the Contiguous United States.” Briefing paper, Rocky Mountain Research Station, Fort Collins, CO.

Burkhard, B., F. Kroll, F. Müller, and W. Windhorst. 2009. “Landscapes’ Capacities to Provide Ecosystem Services: A Concept for Land-Cover Based Assessments.” *Landscape Online* 15: 1–22. doi:10.3097/LO.200915.

Burkhard, B., F. Kroll, S. Nedkov, and F. Muller. 2012. “Mapping Ecosystem Service Supply, Demand and Budgets.” *Ecological Indicators* 21: 17–29.

Calderone, Nicholas W. 2012. “Insect Pollinated Crops, Insect Pollinators and US Agriculture: Trend Analysis of Aggregate Data for the Period 1992–2009.” *PloS One* 7 (5): e37235.

Claessens, L., C. Hopkinson, E. Rastetter, and J. Vallino. 2006. “Effect of Historical Changes in Land Use and Climate on the Water Budget of an Urbanizing Watershed.” *Water Resources Research* 42: W03426.

CME Group. 2017. “CME Group.” Agricultural Products. http://www.cmegroup.com/trading/agricultural/.

Colla, Sheila R., Fawziah Gadallah, Leif Richardson, David Wagner, and Lawrence Gall. 2012. “Assessing Declines of North American Bumble Bees (Bombus Spp.) Using Museum Specimens.” *Biodiversity and Conservation* 21 (14): 3585–3595.

Crowder, L.B., G. Osherenko, O.R. Young, S. Airamé, E.A. Norse, N. Baron, J.C. Day, F. Douvere, C.N. Ehler, B.S. Halpern, S.J. Langdon, K.L. McLeod, J.C. Ogden, R.E. Peach, A.A. Rosenberg, and J.A. Wilson. 2006. “Resolving Mismatches in U.S. Ocean Governance.” *Science* 313: 617–618.

DataONE. 2016. DataONE: Data Observation Network for Earth (website). https://www.dataone.org/.
Dennedy-Frank, P.J., R.L. Muenich, I. Chaubey, and G. Ziv. 2016. “Comparing two tools for ecosystem service assessments regarding water resource decisions.” *Journal of Environmental Management* 177: 331-340.

DeWalle, D.R., B.R. Swistock, T.E. Johnson, and K.J. McGuire. 2000. “Potential Effects of Climate Change and Urbanization on Mean Annual Streamflow in the United States.” *Water Resources Research* 36(9): 2655–2664.

Doyle, M.W, E.H. Stanley, and J.M. Harbor. 2003. “Channel Adjustments Following Two Dam Removals in Wisconsin.” *Water Resources Research* 39, 1011.

Eigenbrod, F., P.R. Armsworth, B.J. Anderson, A. Heinemeyer, S. Gillings, D.B. Roy, C.D.Thomas, and K.J. Gaston. 2010. “The Impact of Proxy-Based Methods on Mapping the Distribution of Ecosystem Services.” *Journal of Applied Ecology* 47(2): 377–385. http://dx.doi.org/10.1111/j.1365-2664.2010.01777.x.

Eigenbrod, F., V.A. Bell, H.N. Davies, A. Heinemeyer, P.R. Armsworth, and K.J. Gaston. 2011. "The Impact of Projected Increases in Urbanization on Ecosystem Services." *Proceedings: Biological Sciences / The Royal Society* 278(1722): 3201–3208. doi:10.1098/rspb.2010.2754.

Ekstrom, J.A., O.R. Young, S.D. Gaines, M. Gordon, and B.J. McCay. 2009. "A Tool to Navigate Overlaps in Fragmented Ocean Governance." *Marine Policy* 33(3): 532–535.

Elith, J., and J.R. Leathwick. 2009. "Species Distribution Models: Ecological Explanation and Prediction across Space and Time." *Annual Review of Ecology, Evolution, and Systematics* 40: 677–697. doi:10.1146/annurev.ecolsys.110308.120159.

Ellis, James D., Jay D. Evans, and Jeff Pettis. 2010. "Colony Losses, Managed Colony Population Decline, and Colony Collapse Disorder in the United States." *Journal of Apicultural Research* 49 (1): 134–136.

Elmqvist, T., M. Fragkias, J. Goodness, B. Güneralp, P.J. Marcotullio, R.I. McDonald, S. Parnell, M. Schewnius, M. Sendstad, K.C. Seto, and C. Wilkinson, eds. 2013. *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities*. Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-7088-1.

Francesconi, W., R. Srinivasan, E. Pérez-Miñana, S.P. Willcock, and M. Quintero. 2016. "Using the Soil and Water Assessment Tool (SWAT) to Model Ecosystem Services: A Systematic Review." *Journal of Hydrology* 535: 625–636.

Gallant, Alisa L., Ned H. Euliss Jr, and Zac Browning. 2014. "Mapping Large-Area Landscape Suitability for Honey Bees to Assess the Influence of Land-Use Change on Sustainability of National Pollination Services." *PLoS One* 9 (6): e99268.

Garibaldi, Lucas A., Ingolf Steffan-Dewenter, Rachael Winfree, Marcelo A. Aizen, Riccardo Bommarco, Saul A. Cunningham, Claire Kremen, et al. 2013. "Wild Pollinators Enhance Fruit Set of Crops Regardless of Honey Bee Abundance." S*cience* 339 (6127): 1608–1611.

Gómez-Baggethun, E., Å. Gren, D.N. Barton, J.S. Langemeyer, T. McPhearson, P. O'Farrell, E. Andersson, Z. Hamstead, and P. Kremer. 2013. "Urban Ecosystem Services." In *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities*, edited by T. Elmqvist, M. Fragkias, J. Goodness, B. Güneralp, P.J. Marcotullio, R.I. McDonald, S. Parnell, M. Schewnius, M. Sendstad, K.C. Seto, and C. Wilkinson, 175–251. Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-7088-1_11.

Greenleaf, Sarah S., and Claire Kremen. 2006. "Wild Bees Enhance Honey Bees' Pollination of Hybrid Sunflower." *Proceedings of the National Academy of Sciences* 103 (37): 13890–13895.

Hall, E.R. 1981. *The Mammals of North America*. New York: John Wiley & Sons.
Hamstead, Z.A., N. Larondelle, P. Kremer, T. McPhearson, and D. Haase. 2015. "Classifications of the Heterogeneous Structure of Urban Landscapes (STURLA) as an Indicator of Landscape Function Applied to Surface Temperature in New York City." *Ecological Indicators*. http://dx.doi.org/10.1016/j.ecolind.2015.10.014.

Henderson, E.B., D.M. Bell, and M.J. Gregory. In press. "Do Univariate or Multivariate Vegetation Models Set a Stronger Foundation for Greater Sage-Grouse Habitat Mapping and Conservation Planning?"

Hirzel, A.H., G. LeLay, V. Helfer, C. Randin, and A. Guisan. "Evaluating the Ability of Habitat Suitability Models to Predict Species Presences." *Ecological Modelling* 199: 142–152. doi:10.1016/j.ecolmodel.2006.05.017

Hodgkins, G.A., R.W. Dudley, and S.S. Aichele. 2007. "Historical Changes in Precipitation and Streamflow in the U.S. Great Lakes Basin, 1915–2004." USGS Scientific Investigation Report 2007-5118.

Homer, Collin G., Jon A. Dewitz, Limin Yang, Suming Jin, Patrick Danielson, George Xian, John Coulston, Nathaniel D. Herold, J. D. Wickham, and Kevin Megown. 2015. "Completion of the 2011 National Land Cover Database for the Conterminous United States-Representing a Decade of Land Cover Change Information." *Photogrammetric Engineering and Remote Sensing* 81 (5): 345–354.

Hurlbert, A.H., and W. Jetz. 2007. "Species Richness, Hotspots, and the Scale Dependence of Range Maps in Ecology and Conservation." *Proceedings of the National Academy of Sciences* 104(33): 3384–3389. doi:10.1073/pnas.0704469104.

International Union for Conservation of Nature (IUCN). 2014. *Red List of Threatened Species*. http://www.iucnredlist.org.

Iovanna, R., A. Ando, S. Swinton, J. Kagan, D. Hellerstein, D. Mushet, and C. Otto. 2017. "Assessing Pollinator Habitat Services to Optimize Conservation Programs." Council on Food, Agriculture, and Resource Economics. http://www.cfare.org/UserFiles/file/Chapter1-AssessingPollinatorHabitatServicestoOptimizeConservationPrograms_v2.pdf.

Johnston, R.J., and P.J. Thomassin. 2010. "Willingness to Pay for Water Quality Improvements in the United States and Canada: Considering Possibilities for International Meta-Analysis and Benefit Transfer." *Agricultural and Resource Economics Review* 39(1): 114–131.

Kareiva, P., H. Tallis, T.H. Ricketts, G.C. Daily, and S. Polasky. 2011. "Natural Capital: Theory and Practice of Mapping Ecosystem Services." Oxford: Oxford University Press.

Kennedy, Christina M., Eric Lonsdorf, Maile C. Neel, Neal M. Williams, Taylor H. Ricketts, Rachael Winfree, Riccardo Bommarco, et al. 2013. "A Global Quantitative Synthesis of Local and Landscape Effects on Wild Bee Pollinators in Agroecosystems." *Ecology Letters* 16 (5): 584–599.

Kim, Y. 2012. *Water Yield Change under Climate and Landuse/Landcover Variability in the North Carolina Piedmont Area* (PhD dissertation). University of North Carolina–Chapel Hill.
Kleijn, David, Rachael Winfree, Ignasi Bartomeus, Luísa G. Carvalheiro, Mickaël Henry, Rufus Isaacs,

Alexandra-Maria Klein, et al. 2015. "Delivery of Crop Pollination Services Is an Insufficient Argument for Wild Pollinator Conservation." *Nature Communications* 6.

Klein, Alexandra-Maria, Bernard E. Vaissiere, James H. Cane, Ingolf Steffan-Dewenter, Saul A. Cunningham, Claire Kremen, and Teja Tscharntke. 2007. "Importance of Pollinators in Changing Landscapes for World Crops." *Proceedings of the Royal Society of London B: Biological Sciences* 274 (1608): 303–313.

Koh, Insu, Eric V. Lonsdorf, Neal M. Williams, Claire Brittain, Rufus Isaacs, Jason Gibbs, and Taylor H. Ricketts. 2016. "Modeling the Status, Trends, and Impacts of Wild Bee Abundance in the United States." *Proceedings of the National Academy of Sciences* 113 (1): 140–145.

Kremer, P., Z.A. Hamstead, and T. McPhearson. 2016. "The Value of Urban Ecosystem Services: A Spatially Explicit Multicriteria Analysis of Landscape Scale Valuation Scenarios in NYC." *Environmental Science and Policy* 62: 57–68.

Landis-II. 2016. Landis-II (website). http://www.landis-ii.org.
Lautenbach, Sven, Ralf Seppelt, Juliane Liebscher, and Carsten F. Dormann. 2012. "Spatial and Temporal Trends of Global Pollination Benefit." *PLoS One* 7 (4): e35954.

Leu, M., S.E. Hanser, and S.T. Knick. 2008. "The Human Footprint in the West: A Large-Scale Analysis of Anthropogenic Impacts." *Ecological Applications* 18: 1119–1139.

Lonsdorf, Eric, and Amelie Davis. 2016. "A Geographic Information System Tool to Project Managed and Wild Bees on Any Landscape: Appendix 5 of: 'The Integrated Landscape Modeling Partnership-Current Status and Future directions' (Mushet and Davis)." US Geological Survey. https://pubs.er.usgs.gov/publication/ofr20161006.

Lonsdorf, Eric, Claire Kremen, Taylor Ricketts, Rachael Winfree, Neal Williams, and Sarah Greenleaf. 2009. "Modelling Pollination Services across Agricultural Landscapes." *Annals of Botany* mcp069.

Losey, John E., and Mace Vaughan. 2006. "The Economic Value of Ecological Services Provided by Insects." *Bioscience* 56 (4): 311–323.

McCabe, G.J., and D.M. Wolock. 2002. "A Step Increase in Streamflow in the Coterminous United States." *Geophysical Research Letters* 29(24): 2185.

McPhearson, T., P. Kremer, and Z. Hamstead. 2013. "Mapping Ecosystem Services in New York City: Applying a Social-Ecological Approach in Urban Vacant Land." *Ecosystem Services* 5: 11–26. doi:10.1016/j.ecoser.2013.06.005.

McPhearson, T., S.T.A. Pickett, N. Grimm, J. Niemelä, M. Alberti, T. Elmqvist, C. Weber, D. Haase, J. Breuste, and S. Qureshi. 2016. "Advancing Urban Ecology toward a Science of Cities." *BioScience* 66(3): 198–212. doi:10.1093/biosci/biw002.

Morzillo, A.T., P. Comeleo, B. Csuti, and S. Lee. 2014. "Application of State-and-Transition Models to Evaluate Wildlife Habitat," in *Integrating Social, Economic, and Ecological Values across Large Lanscapes*, edited by J.E. Halofsky, M.K. Creutzburg, and M.A. Hemstrom (Portland, OR: U.S. Department of Agriculture, Forest Service), 129–145. http://www.fs.fed.us/pnw/pubs/pnw_gtr896.pdf.

Multi-Resolution Land Characteristics Consortium (MRLC). 2015. National Land Cover Database. http://www.mrlc.gov.

NASA. 2017. "HoneyBeeNet." Bee Forage Regions. https://honeybeenet.gsfc.nasa.gov/Honeybees/Forage.htm.

Nature Conservancy. 2015. *Freshwater Projects*. http://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/edc/reports data/freshwater/Pages/default.aspx.

NatureServe. 2016a. "Ecological Integrity Assessment—Wetlands." http://www.natureserve.org/conservation-tools/projects/ecological-integrity-assessment-wetlands.

NatureServe. 2016b. "NatureServe Surveyor: Comprehensive Screening for At-Risk Species." http://www.natureserve.org/conservation-tools/natureserve-surveyor.

Nowak, D.J., R.E. Hoehn III, A.R. Bodine, E.J. Greenfield, A. Ellis, T.A. Endreny, Y. Yang, T. Zhou, and R. Henry. 2013. "Assessing Urban Forest Effects and Values: Toronto's Urban Forest." *Resource Bulletin* NRS-79. Newtown Square, PA: Department of Agriculture, Forest Service, Northern Research Station.

Olander, L., T. Walter, P. Vadas, J. Heffernan, E. Kebreab, M. Ribaudo, T. Harter, and C. Morris. 2014. *Refining Models for Quantifying the Water Quality Benefits of Improved Animal Management for Use in Water Quality Trading*. NI R 14-03. Durham: Duke University.

Otto, Clint R.V., Cali L. Roth, Benjamin L. Carlson, and Matthew D. Smart. 2016. "Land-Use Change Reduces Habitat Suitability for Supporting Managed Honey Bee Colonies in the Northern Great Plains." *Proceedings of the National Academy of Sciences* 113 (37): 10430–10435.

Patterson, L.A., B. Lutz, and M.W. Doyle. 2013. "Climate and Direct Human Contributions to Changes in Mean Annual Streamflow in the South Atlantic, USA." *Water Resources Research* 49: 7278–7291.
Paudel, Yagya Prasad, Robert Mackereth, Rodney Hanley, and Wensheng Qin. 2015. "Honey Bees (Apis Mellifera L.) and Pollination Issues: Current Status, Impacts, and Potential Drivers of Decline." *Journal of Agricultural Science* 7 (6): 93.

Pearsall, S.H., B.J. McCrodden, and P.A. Townsend. 2005. "Adaptive Management of Flows in the Lower Roanoke River, NC, USA." *Environmental Management* 35(4): 353–367.

Pickard, B.R., J. Daniel, M. Mehaffey, L.E. Jackson, and A. Neale. 2015. "EnviroAtlas: A New Geospatial Tool to Foster Ecosystem Services Science and Resource Management." *Ecosystem Services* 14: 45–55.

Pollinator Health Task Force. 2015a. "National Strategy to Promote the Health of Honey Bees and Other Pollinators." The White House. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/Pollinator%20Health%20Strateg y%202015.pdf.

Pollinator Health Task Force. 2015b. “Pollinator Research Action Plan.” The White House. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pollinator_research_action_plan_2015.pdf.

Poor, P.J. and M. Breece. 2006. The contingent behavior of charter fishing participants on the Chesapeake Bay: Welfare estimates associated with water quality improvements. *Journal of Environmental Planning and Management* 49 (2): 265-278.

Potts, Simon G., Jacobus C. Biesmeijer, Claire Kremen, Peter Neumann, Oliver Schweiger, and William E. Kunin. 2010a. “Global Pollinator Declines: Trends, Impacts and Drivers.” *Trends in Ecology & Evolution* 25 (6): 345–353.

Requier, Fabrice, Jean-François Odoux, Thierry Tamic, Nathalie Moreau, Mickaël Henry, Axel Decourtye, and Vincent Bretagnolle. 2015. “Honey Bee Diet in Intensive Farmland Habitats Reveals an Unexpectedly High Flower Richness and a Major Role of Weeds.” *Ecological Applications* 25 (4): 881–890.

Ricketts, Taylor H., and Eric Lonsdorf. 2013. “Mapping the Margin: Comparing Marginal Values of Tropical Forest Remnants for Pollination Services.” *Ecological Applications* 23 (5): 1113–1123.

Ricketts, Taylor H., James Regetz, Ingolf Steffan-Dewenter, Saul A. Cunningham, Claire Kremen, Anne Bogdanski, Barbara Gemmill-Herren, et al. 2008. “Landscape Effects on Crop Pollination Services: Are There General Patterns?” *Ecology Letters* 11 (5): 499–515.

Roose, E. 1996. *Land Husbandry: Components and Strategy*. Rome: FAO.

Saleh, A., O. Gallego, E. Osei, H. Lal, C. Gross, S. McKinney, and H. Cover. 2011. “Nutrient Tracking Tool—A User-Friendly Tool for Calculating Nutrient Reductions for Water Quality Trading.”*Journal of Soil and Water Conservation* 66(6): 400–410.

Sauer, J. R., J.E. Hines, J.E. Fallon, K.L. Pardieck, D.J. Ziolkowski, Jr., and W.A. Link. 2014. “The North American Breeding Bird Survey, Results and Analysis 1966–2012. Version 02.19.2014.” USGS Patuxent Wildlife Research Center, Laurel, MD.

Schilling, K.E., M.K. Jha, Y.K. Zhang, P.W. Gassman, and C.F. Wolter. 2008. “Impact of Land Use and Land Cover Change on the Water Balance of a Large Agricultural Watershed: Historical Effects and Future Directions.” *Water Resources Research* 44(7). doi:10.1029/2007WR006644.

Scott, J.M., J.H. Heglund, M.L. Morrison, J.B. Haufler, M.G. Raphael, W.A. Wall, and F.B. Samson. 2002. *Predicting Species Occurrences: Issues of Accuracy and Scale*. Washington, DC: Island Press.

Seto, K.C., S. Parnell, and T. Elmqvist. 2013. “A Global Outlook on Urbanization.” In *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities*, edited by T. Elmqvist, M. Fragkias, J. Goodness, B. Güneralp, P.J. Marcotullio, R.I. McDonald, S. Parnell, M. Schewnius, M. Sendstad, K.C. Seto, and C. Wilkinson, 1–12. Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-7088-1.

Smart, Matthew D., Jeff S. Pettis, Ned Euliss, and Marla S. Spivak. 2016. "Land Use in the Northern Great Plains Region of the US Influences the Survival and Productivity of Honey Bee Colonies." *Agriculture, Ecosystems & Environment* 230: 139–149.

Smart, Matthew, Jeff Pettis, Nathan Rice, Zac Browning, and Marla Spivak. 2016. "Linking Measures of Colony and Individual Honey Bee Health to Survival among Apiaries Exposed to Varying Agricultural Land Use." *PloS One* 11 (3): e0152685.

Sohl, T.L., R. Reker, M. Bouchard, K. Sayler, J. Dornbierer, S. Wika, R. Quenzer, and A. Friesz. 2016. "Modeled Historical Land Use and Land Cover for the Conterminous United States." *Journal of Land Use Science* 11(4): 1–24.

Sohl, T.L., and K.L. Sayler. 2008. "Using the FORE-SCE Model to Project Land-Cover Change in the Southeastern United States." *Ecological Modelling* 219: 49–65.

Stevens, L.E., T.J. Ayers, J.B. Bennett, K. Christensen, M.J.C. Kearsley, V.J. Meretsky, A.M. Phillips III, R.A. Parnell, J. Spence, M.K. Sogge, A.E. Springer, and D.L. Wegner. 2001. "Planned Flooding and Colorado River Riparian Trade-Offs Downstream from Glen Canyon Dam, Arizona." *Ecological Applications* 11(3): 701–710.

Tallis, H., P. Kareiva, M. Marvier, and A. Chang. 2008. "An Ecosystem Services Framework to Support Both Practical Conservation and Economic Development." *Proceedings of the National Academy of Sciences* 105(28): 9457–9464.

The Integrated Crop Pollination Project. 2017. "The Integrated Crop Pollination Project." http://icpbees.org/.

Theobald, D.M. 2013. "A General Model for Quantifying Ecological Integrity for Landscape Assessments and US Application." *Landscape Ecology* 28: 1859–1874. doi:10.1007/s10980-013-9941-6.

Theobald, D.M. 2014. "Development and Applications of a Comprehensive Land Use Classification and Map for the US." *PLoS One* 9(4): e94628. doi:10.1371/journal.pone.0094628.

Tidwell, V.C., B.D. Moreland, K.M. Zemlick, B.L. Roberts, H.D. Passell, D. Jensen, C. Forsgren, G. Shlke, M.A. Cook, C.W. King, and S. Larsen. 2014. "Mapping water availability, projected use, and cost in the western United States." *Environmental Research Letters* 9: 064009.

Toevs, G.R., J.J. Taylor, C.S. Spurrier, W.C. MacKinnon, and M.R. Bobo. 2011. *Assessment, Inventory, and Monitoring Strategy for Integrated Renewable Resources Management*. Denver, CO: Bureau of Land Management.

Townsend, M., S.F. Thrush, A.M. Lohrer, and M. Felsing. 2014. "Overcoming the Challenges of Data Scarcity in Mapping Marine Ecosystem Service Potential." *Ecosystem Services* 8: 44–55.

U.S.A. National Phenology Network (USANPN). 2016. U.S.A. National Phenology Network (website). https://www.usanpn.org/.

U.S. Census Bureau. 2010. Census of Population and Housing. http://www.census.gov/geo/reference/ua/urban-rural-2010.html.

U.S. Department of Agriculture Agricultural Marketing Service. 2017. “USDA Market News.” http://www.cmegroup.com/trading/agricultural/.

U.S. Department of Agriculture Farm Service Agency. n.d. “Pollinator Habitat Planting: CP42.” https://www.fsa.usda.gov/Internet/FSA_File/pollinator_fact_sht.pdf.

U.S. Department of Agriculture Forest Service. 1980. *Management of Western Forests and Grasslands for Nongame Birds*. USDA Forest Service General Technical Report INT-86. http://www.fs.fed.us/rm/pubs_int/int_gtr086.pdf.

U.S. Department of Agriculture National Agricultural Statistics Service. 2017. “Quick Stats.” https://quickstats.nass.usda.gov/.

U.S. Department of Agriculture National Agricultural Statistics Service. 2012. “USDA National Agricultural Statistics Service Cropland Data Layer.” Published Crop Specific Data Layer. https://www.nass.usda.gov/Research_and_Science/Cropland/Release/index.php.

U.S. Department of Agriculture Natural Resources Conservation Service. n.d. “Plants for Pollinators.” https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/plantsanimals/pollinate/?cid=NRCS143_022326.

U.S. Department of Agriculture Natural Resources Conservation Service (USDA NRCS). 2015. *PLANTS Database*. http://plants.usda.gov/.

U.S. Department of Agriculture Natural Resources Conservation Service (USDA NRCS). 2016. *Ecological Site Descriptions*. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/alphabetical/ecosite/?cid=stelprdb1049096.

U.S. Environmental Protection Agency (U.S. EPA). 2001. Southeastern US Ecological Framework Project. http://www.geoplan.ufl.edu/epa/index.html.

U.S. Environmental Protection Agency (U.S. EPA). 2014. “EnviroAtlas.” https://www.epa.gov/enviroatlas.

U.S. Environmental Protection Agency (U.S. EPA). 2016a. “EnviroAtlas Communities.” https://www.epa.gov/enviroatlas/enviroatlas-communities.

U.S. Environmental Protection Agency (U.S. EPA). 2016b. “National Wetland Condition Assessment.” https://www.epa.gov/national-aquatic-resource-surveys/nwca.

U.S. Environmental Protection Agency (U.S. EPA). 2016c. “Wetlands Monitoring and Assessment.” https://www.epa.gov/wetlands/wetlands-monitoring-and-assessment.

U.S. Fish & Wildlife Service (USFWS). 2015. *National Wetlands Inventory*. http://www.fws.gov/wetlands/.

U.S. Geological Survey (USGS). 2013. *National Gap Analysis Program (GAP): Core Science Analytics and Synthesis*. http://gapanalysis.usgs.gov/.

U.S. Geological Survey (USGS). 2015. *Biodiversity Information Serving Our Nation (BISON): U.S. Species Occurrence Data and Maps*. http://bison.usgs.ornl.gov/#home.

U.S. Geological Survey. 2016. "Pollinator Library." https://www.npwrc.usgs.gov/pollinator/home.

U.S. National Vegetation Classification (USNVC). 2015. *The U.S. National Vegetation Classification: Your Guide to Inventorying Natural and Cultural Plant Communities*. http://usnvc.org.

Viana, Blandina F., Danilo Boscolo, Eduardo Mariano Neto, Luciano E. Lopes, Ariadna V. Lopes, Patrícia A. Ferreira, Camila M. Pigozzo, and Luis M. Primo. 2012. "How Well Do We Understand Landscape Effects on Pollinators and Pollination Services." *Journal of Pollination Ecology* 7 (5): 31–41.

Vigerstol, K.L., and J.E. Aukema. 2011. "A Comparison of Tools for Modeling Freshwater Ecosystem Services." *Journal of Environmental Management* 92: 2403–2409.

Villa, F., K.J. Bagstad, B. Voigt, G. Johnson, R. Portela, M. Honzak, and D. Batker. 2014. "A Methodology for Adaptable and Robust Ecosystem Services Assessment." *PLoS ONE* 9(3): e91101. doi:10.1371/journal.pone.0091001.

Vogel, R.M., C. Yaindl, and M. Walter. 2011. "Nonstationarity: Flood Magnification and Recurrence Reduction Factors in the United States." *Journal of American Water Resources Association* 47(3), 464–474.

Wang, D. and M. Hejazi. 2011. "Quantifying the Relative Contribution of Climate and Direct Human Impacts on Mean Annual Streamflow in the Contiguous United States." *Water Resources Research* 47: W00J12.

Wang, Q., S. Li, P. Jia, C. Qi, and F. Ding. 2013. "A Review of Surface Water Quality Models." *Scientific World Journal* 2013(2013). http://dx.doi.org/10.1155/2013/231768.

Watchable Wildlife. 2011. *Wildlife Viewing Areas*. http://www.wildlifeviewingareas.com/.
Williams, J.R. 1975. "Sediment Yield Prediction with USLE Using Runoff Energy Factor," in *ARS-S-40*, 244–252. Washington, DC: Agricultural Research Service.

Winfree, Rachael, Ramiro Aguilar, Diego P. Vázquez, Gretchen LeBuhn, and Marcelo A. Aizen. 2009. "A Meta-Analysis of Bees' Responses to Anthropogenic Disturbance." *Ecology* 90 (8): 2068–2076.

Wolny, Stacie. 2012. "InVEST Crop Pollination." presented at the Natural Capital Project. http://data.naturalcapitalproject.org/training_feb2012_stanford/Pollination_Stanford_02_2011.pdf.

Young, R.A. 2005. *Determining the Economic Value of Water*. Washington, DC: Resources for the Future.

3: Data and Models for Ecosystem Services that Regulate and Reduce Risks

Advanced Circulation (ADCIRC). 2015. The Official ADCIRC Web Site. http://adcirc.org.
Andrews, P.L. 1986. *BEHAVE: Behavior Prediction and Fuel Modeling System—BURN Subsystem, Part 1*. USDA General Technical Report INT-194.

ArcFuels. 2016. ArcFuels (website). http://www.fs.fed.us/wwetac/arcfuels/index.html.
Buchholz, T., S. Prisley, G. Marland, C. Canham, and N. Sampson. 2014. "Uncertainty in Projecting GHG Emissions from Bioenergy." *Nature Climate Change* 4(12): 1045–1047.

Calkin, D.E., M.P. Thompson, M.A. Finney, and K.D. Hyde. 2011. "A Real-Time Risk Assessment Tool Supporting Wildland Fire Decisionmaking." *Journal of Forestry* 109(5): 274–280.

Cohen, J.D. 1995. *Structure Ignition Assessment Model*. General Technical Report PSW-GTR-158. U.S. Department of Agriculture, Forest Service.

Dietrich J.C, M. Zijlema, J.J. Westerink, L.H. Holthuijsen, C. Dawsonc, R.A. Luettich Jr., R.E. Jensen, J.M. Smith, G.S. Stelling, G.W. Stone. 2011. "Modeling Hurricane Waves and Storm Surge Using Integrally-Coupled, Scalable Computations." *Coastal Engineering* 58: 45–65.

Dixon, G.E. 2002. *Essential FVS: A User's Guide to the Forest Vegetation Simulator*. Fort Collins, CO: USDA Forest Service, Forest Management Service Center.

Doyle, T.W., B. Chivoiu, N.M. Enwright. 2015. "Sea-Level Rise Modeling Handbook—Resource Guide for Coastal Land Managers, Engineers, and Scientists." U.S. Geological Survey Professional Paper 1815. http://dx.doi.org/10.3133/pp1815.

Federal Emergency Management Agency (FEMA). 2013. Hazus-MH Flood Model User Manual. http://www.fema.gov/media-library-data/20130726-1820-25045-8814/hzmh2_1_fl_um.pdf.

Federal Emergency Management Agency (FEMA). 2016. Index of /FIMA/NSI_2010. FEMA Cloud GIS Infrastructure Production Site. https://data.femadata.com/FIMA/NSI_2010/.

Finney, M.A. 2005. "The Challenge of Quantitative Risk Analysis for Wildland Fire." *Forest Ecology and Management* 211: 97–108.

Finney, M.A. 2006. "An Overview of FlamMap Fire Modeling Capabilities." *Fuels Management: How to Measure Success: Conference Proceedings, 28–30 March 2006*, 549–561. Portland, OR. Rocky Mountain Research Station RMRS-P-41.

Gebert, K.M., D.E. Calkin, R.J. Huggett, Jr., and K.B. Abt. 2008. "Economic Analysis of Federal Wildfire Management Programs." In *The Economics of Forest Disturbances: Wildfires, Storms and*

Invasive Species. Vol. 79 of *Forestry Sciences*, edited by T.P Holmes, J.P Prestemon, and K.L. Abt, 295–323. New York: Springer.

Gude, P.H., K. Jones, R. Rasker, and M. Greenwood. 2013. "Evidence for the Effect of Homes on Wildfire Suppression Costs." *International Journal of Wildland Fire* 22: 537–548.

Guenni, L.B. de, M. Cardoso, J. Goldammer, G. Hurtt, L.J. Mata, K. Ebi, J. House, and J. Valdes. 2005. "Regulation of Natural Hazards: Floods and Fires," in *Ecosystems and Human Well-Being: Current State and Trends, Volume 1*, edited by R. Hassan, R. Scholes, and N. Ash, 441–454. Washington, DC: Island Press.

Gunn, J.S., M.J. Ducey, and A.A. Whitman. 2014. "Late-Successional and Old-Growth Forest Carbon Temporal Dynamics in the Northern Forest (Northeastern USA)." *Forest Ecology and Management* 312: 40–46.

Holmes, T.P., J.P. Prestemon, and K.L. Abt, eds. 2008. *The Economics of Forest Disturbances: Wildfires, Storms and Invasive Species*. Vol. 79 of *Forestry Sciences*. New York: Springer.

Kline, J. 2004. "Issues in Evaluating the Costs and Benefits of Fuel Treatments to Reduce Wildfire in the Nation's Forests." General Technical Report PNW-RN-542. U.S. Department of Agriculture, Forest Service.

Loomis, J.B., and A. Gonzalez-Caban. 2008. "Contingent Valuation of Fuel Hazard Reduction Treatments." In *The Economics of Forest Disturbances: Wildfires, Storms and Invasive Species* vol. 79 of *Forestry Sciences*, edited by T.P. Holmes, J.P. Prestemon, and K.L. Abt, 229–244. New York: Springer.

MacLean, R.G., M.J. Ducey, and C.M. Hoover. 2014. "A Comparison of Carbon Stock Estimates and Projections for the Northeastern United States." *Forest Science* 60(2): 206–213.

Manley, J., D. Rideout, Y. Wei, and S.J. Botti. 2010. "Starfire: Decision Support for Strategic Integration of Wildland Fuels and Unplanned Ignitions." In *Proceedings of the 3rd Fire Behavior and Fuels Conference, October 25–29, 2010. Spokane Washington*. Birmingham, AL: International Association of Wildland Fire.

Mercer, D.E., R.G Haight, and J.P. Prestemon. 2008. "Analyzing Tradeoffs between Fuels Management, Suppression and Damages from Wildfire." In *The Economics of Forest Disturbances: Wildfires, Storms and Invasive Species*. Vol. 79 of *Forestry Sciences*, edited by T.P Holmes, J.P Prestemon, and K.L. Abt, 247–272. New York: Springer.

Millennium Ecosystem Assessment. 2005. Millennium Ecosystem Assessment (website). http://www.millenniumassessment.org/en/index.html.

National Park Service. n.d. "The Fire Triangle." *Fire and Aviation Management*. https://www.nps.gov/fire/wildland-fire/learning-center/fire-in-depth/fire-triangle.cfm.

Noss, R.F., J.F. Franklin, W.L. Baker, T. Schoennagel, and P.B. Moyle. 2006. "Managing Fire-Prone Forests in the Western United States." *Frontiers in Ecology and the Environment* 8: 481–487.

Nunery, J.S., and W.S. Keeton. 2010. "Forest Carbon Storage in the Northeastern United States: Net Effects of Harvesting Frequency, Post-Harvest Retention, and Wood Products." *Forest Ecology and Management* 259(8): 1363–1375.

Prato, T., T. Paveglio, Y. Barnett, R. Silverstein, M. Hardy, R. Keane, R. Loehman, A. Clark, D. Fagre, T. Venn, and K. Stockmann. 2014. "Simulating Future Residential Property Losses from Wildfire in Flathead County, Montana." In *Advances in Environmental Research*, vol. 33, edited by J.A. Daniels, 1–40. Hauppauge, NY: Nova Science Publishers.

Quadrennial Fire and Fuel Review Report (QFFR). 2005. https://www.forestsandrangelands.gov/strategy/documents/foundational/qffr_final_report_20050719.pdf.

Quadrennial Fire and Fuel Review Report (QFFR). 2009. https://www.iafc.org/files/wild_QFR2009Report.pdf.

Quadrennial Fire and Fuel Review Report (QFFR). 2014. https://www.forestsandrangelands.gov/QFR/documents/2014QFRFinalReport.pdf.

Sampson, N.R., R.D. Atkinson, and J.W. Lewis, eds. 2000. *Mapping Wildfire Hazards and Risks: Journal of Sustainable Forestry* 11(1–2).

Smith, J.E., L.S. Heath, K.E. Skog, and R.A. Birdsey. 2006."Methods for Calculating Forest Ecosystem and Harvested Carbon with Standard Estimates for Forest Types of the United States." General Technical Report NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station.

Stockmann, K, J. Burchfield, D. Calkin, and T. Venn. 2010. "Guiding Preventative Wildland Fire Mitigation Policy and Decisions with an Economic Modeling System." *Forest Policy and Economics* 12(2): 147–154.

Systems for Environmental Management. 2016. FARSITE Introduction (website). http://fire.org/downloads/farsite/WebHelp/usersguide/ug1_introduction.htm.

Thompson, M., N. Vaillant, J. Haas, K. Gebert, and K. Stockmann. 2013. "Quantifying the Potential Impacts of Fuel Treatments on Wildfire Suppression Costs: Pilot Study of Deschutes National Forest." *Journal of Forestry* 111(1): 49–58.

U.S. Department of Agriculture (USDA). 2007. Ecological Subregions: Sections and Subsections of the Coterminous United States. http://databasin.org/datasets/662c543156c14313b87d9b99b7a78221.

U.S. Department of Agriculture (USDA). 2015. "Wildfire Hazard Potential." *Fire, Fuel, and Smoke Science Program*. https://www.firelab.org/project/wildfire-hazard-potential.

U.S. Department of Agriculture (USDA). 2016a. “FireBGCv2.” *Fire, Fuel, and Smoke Science Program*. https://www.firelab.org/project/firebgcv2.

U.S. Department of Agriculture (USDA). 2016b. “Fire, Fuel, and Smoke Science Program and the Missoula Fire Sciences Laboratory.” *Fire, Fuel, and Smoke Science Program*. https://www.firelab.org.

U.S. Forest Service. 2016. *Forest Vegetation Simulator (FVS)*. http://www.fs.fed.us/fmsc/fvs/.
Wibbenmeyer, M.J., M.S. Hand, D.E. Calkin, T.J. Venn, and M.P. Thompson. “Risk Preferences in Strategic Wildfire Decision Making: A Choice Experiment with U.S. Wildfire Managers.” *Risk Analysis* 33(6): 1021–1037.

Wildland Fire Decision Support System. 2016. FSPro and Stratified Cost Index (SCI) (website). http://wfdss.usgs.gov/wfdss/WFDSS_Home.shtml.

Venn, T.J., and D.E. Calkin. 2011. “Accommodating Non-Market Values in Evaluation of Wildfire Management in the United States: Challenges and Opportunities.” *International Journal of Wildland Fire* 20: 327–339.

4: Social and Economic Data and Models for Ecosystem Services

Abbasi, T. 2012. *Water Quality Indices*. Amsterdam: Elsevier.

Adams, D., R. Alig, B. McCarl, and B. Murray. 2005. “FASOMGHG Conceptual Structure, and Specification: Documentation.” http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf.

Aiken, R., and G.P. La Rouche. 2003. *Net Economic Values for Wildlife-Related Recreation in 2001: Addendum to the 2001 National Survey of Fishing, Hunting and Wildlife-Associated Recreation*. Washington, DC: U.S. Fish and Wildlife Service.

Allen, B., and J. Loomis. 2008. “The Decision to Use Benefit Transfer or Conduct Original Valuation Research for Benefit-Cost and Policy Analysis.” *Contemporary Economic Policy* 26(1): 1–12.

Andersson, E., S. Barthel, and K. Ahrné. 2007. “Measuring Social-Ecological Dynamics behind the Generation of Ecosystem Services.” *Ecolological Applications* 17: 1267–1278.

Bandara, R., and C. Tisdell. 2005. “Changing Abundance of Elephants and Willingness to Pay for Their Conservation.” *Journal of Environmental Management* 76(1): 47–59.

Barrio, M., and M.L. Loureiro. 2010. “A Meta-Analysis of Contingent Valuation Forest Studies.” *Ecological Economics* 69(5): 1023–1030.

Bergstrom, J.C., K.J. Boyle, and G.L. Poe, eds. 2001. *The Economic Value of Water Quality*. Northampton, MA: Edward Elgar.

Bergstrom, J.C., and L.O. Taylor. 2006. "Using Meta-Analysis for Benefits Transfer: Theory and Practice." *Ecological Economics* 60(2): 351–360.

Bertrand, K.Z., M. Bialik, K. Virdee, A. Gros, and Y. Bar-Yam. 2013. "Sentiment in New York City: A High Resolution Spatial and Temporal View." arXiv:1308.5010. http://www.necsi.edu/research/social/newyork/.

Blamey, R.K., J.W. Bennett, J.J. Louviere, M.D. Morrison, and J.C. Rolfe. 2002. "Attribute Causality in Environmental Choice Modeling." *Environmental and Resource Economics* 23: 167–186.

Bockstael, N.E., W.M. Hanemann, and C.L. Kling. 1987. "Estimating the Value of Water Quality Improvements in a Recreational Demand Framework." *Water Resources Research* 23(5): 951–960.

Bockstael, N.E., K.E. McConnell, and I.E. Strand. 1989. "Measuring the Benefits of Improvements in Water Quality: The Chesapeake Bay." *Marine Resource Economics* 6(1): 1–18.

Boman, M., and G. Bostedt. 1999. "Valuing the Wolf in Sweden: Are Benefits Contingent on the Supply?" In *Topics in Environmental Economics*, edited by M. Boman, R. Brännlund, and B. Kriström, 157–174. Dordrecht: Kluwer Academic Publishers.

Bosello, F., R. Roson, and R. Tol. 2006. "Economy-Wide Estimates of the Implications of Climate Change: Human Health." *Ecological Economics* 58: 579–591.

Bowker, J.M., and V.R. Leeworthy. 1998. "Accounting for Ethnicity in Recreation Demand: A Flexible Count Data Approach." *Journal of Leisure Research* 30: 64–78.

Bowker, J.M., D. Murphy, H.K. Cordell, D.B.K. English, J.C. Bergstrom, C.M. Starbuck, C.J. Betz, and G.T. Green. 2006. "Wilderness and Primitive Area Recreation Participation and Consumption: An Examination of Demographic and Spatial Factors." *Journal of Agricultural and Applied Economics* 38: 317–326.

Boyd, J. and A. Krupnick. 2013. "Using Ecological Production Theory to Define and Select Environmental Commodities for Nonmarket Valuation." *Agricultural and Resource Economics Review* 42(1): 1–32.

Boyd, J., P. Ringold, A. Krupnik, R.J. Johnston, M.A. Weber, and K. Hall. 2016. "Ecosystem Services Indicators: Improving the Linkage Between Biphysical and Economic Analyses." *International Review of Environmental and Resource Economics* 8: 359–443.

Boyle, K.J., R. Bishop, J. Caudill, J. Charbonneau, D. Larson, M.A. Markowski, R.E. Unsworth, and R.W. Paterson. 1998. *A Meta Analysis of Sportfishing Values*. Washington, D.C.: U.S. Department of the Interior, Fish and Wildlife Service.

Boyle, K. J., C. F. Parmeter, B. B. Boehlert, and R.W. Paterson. 2013. "Due Diligence in Meta-Analyses to Support Benefit Transfers." *Environmental and Resource Economics* 55(3): 357–386.

Boyle, K.J., B. Roach, and D.G. Waddington. 1998. *1996 Net Economic Values for Bass, Trout and Walleye Fishing, Deer, Elk and moose Hunting, and Wildlife Watching: Addendum to the 1996 National Survey of Fishing, Hunting and Wildlife-Associated Recreation*. Report 96-2. Washington, DC: US Fish and Wildlife Service.

Brander, L.M., P. van Beukering, and H.S.J. Cesar. 2007. "The Recreational Value of Coral Reefs: A Meta-Analysis." *Ecological Economics* 63(1): 209–218.

Carson, R.T., and R.C. Mitchell. 1993. "The Value of Clean Water: The Public's Willingness to Pay for Boatable, Fishable, and Swimmable Quality Water." *Water Resources Research* 29(7): 2445–2454.

Davis, R.K. 1963. *The Value of Outdoor Recreation: An Economic Study of the Maine Woods* (Ph.D. dissertation). Harvard University.

Dellapenna, J.W. 2002. "The Law of Water Allocation in the Southeastern States at the Opening of the Twenty-First Century." *UALR Law Review* 25: 9–88.

Douglas, M. 1966. "The Abominations of Leviticus." In *Purity and Danger: An Analysis of Concepts of Pollution and Taboo*, 54–72. Harmondsworth, UK: Penguin Books.

Ericsson, G., J. Kindberg, and G. Bostedt. 2007. "Willingness to Pay (WTP) for Wolverine *Gulo gulo* Conservation." *Wildlife Biology* 13(Suppl. 2): 2–12.

Ernston, H. 2013. "The Social Production of Ecosystem Services: A Framework for Studying Environmental Justice and Ecological Complexity in Urbanized Landscapes." *Landscape and Urban Planning* 109: 7–17.

Freeman, A.M. 2003. *The Measurement of Environmental and Resource Values: Theory and Methods*. Washington, DC: Resources for the Future.

Freeman, A.M., J.A. Herriges, and C.L. Kling. 2014. *The Measurement of Environmental and Resource Values: Theory and Methods*, 3rd Edition. Washington, DC: RFF Press.

Gerlak, A.K. 2005. "Federalism and U.S. Water Policy: Lessons from the Twenty-First Century." *Journal of Federalism* 36(2): 231–257.

Gómez-Baggethun, E., and D.N. Barton. 2013. "Classifying and Valuing Ecosystem Services for Urban Planning." *Ecological Economics* 86: 235–245.

Griffin, R.C. 2006. *Water Resource Economics: The Analysis of Scarcity, Policies, and Projects*. Cambridge, MA: MIT Press.

Griffiths, C., H. Klemick, M. Massey, C. Moore, S. Newbold, D. Simpson, P. Walsh, and W. Wheeler. 2012. US Environmental Protection Agency Valuation of Surface Water Quality Improvements. *Review of Environmental Economics and Policy* 6(1):130–146.

Griffiths, C., and W. Wheeler. 2005. "Benefit-Cost Analysis of Regulations Affecting Surface Water Quality in the United States." In *Cost-Benefit Analysis and Water Resources Management*, edited by R. Brouwer and D. Pearce, 223–250. Cheltenham, UK: Edward Elgar.

Grimm, N.B., J.M. Grove, S.T.A Pickett, and C.L. Redman. 2000. "Integrated Approaches to Long-Term Studies of Urban Ecological Systems." *BioScience* 50(7): 571–584. doi:10.1641/0006-3568(2000)050.

Grove, J., A. Troy, J. O'Neil-Dunne, W.R. Burch, M. Cadenasso, and S.T.A Pickett. 2006. "Characterization of Households and its Implications for the Vegetation of Urban Ecosystems." *Ecosystems* 9(4): 578–597.

Haase, D., N. Larondelle, E. Andersson, M. Artmann, S. Borgström, J. Breuste, E. Gómez-Baggethun, Ǻ. Gren, Z. Hamstead, R. Hansen, N. Kabisch, P. Kremer, J. Langemeyer, E.L. Rall, T. McPhearson, S. Pauleit, S. Qureshi, N. Schwarz, A. Voigt, D. Wurster, and T. Elmqvist. 2014. "A Quantitative Review of Urban Ecosystem Services Assessments: Concepts, Models, and Implementation." *AMBIO* 43(4): 413–433. doi: 10.1007/s13280-014-0504-0.

Haase, D., N. Schwarz, M. Strohbach, F. Kroll, and R. Seppelt. 2012. "Synergies, Trade-Offs, and Losses of Ecosystem Services in Urban Regions: An Integrated Multiscale Framework Applied to the Leipzig-Halle Region, Germany." *Ecology and Society* 17(3): 22. doi:10.5751/ES-04853-170322.

Harou, J.J., M. Pulido-Velazquez, D.E. Rosenberg, J. Medellin-Azuara, J.R. Lund, and R.E. Howitt. 2009. "Hydro-Economic Models: Concepts, Design, Applications, and Future Prospects." *Journal of Hydrology* 375(3–4): 627–643.

Hay, M.J. 1988. *Net Economic Recreation Value for Deer, Elk and Waterfowl Hunting and Bass Fishing, 1985*. Report 85-1. Washington, DC: Fish and Wildlife Service, US Department of the Interior.

Hinkel, J., D. Lincke, A. Vafeidis, M. Perrette, R. Nicholls, R. Tol, B. Marzelon, X. Fettweis, C. ionescu, and A. Levermann. 2014. "Coastal Flood Damage and Adaptation Costs under 21st Century Sea-Level Rise." *Proceedings of the National Academy of Sciences* 111(9): 3292–3297.

Holland, D.S., J. Sanchirico, R.J. Johnston, and D. Joglekar. 2010. *Economic Analysis for Ecosystem-Based Management: Applications to Marine and Coastal Environments*. Washington, DC: RFF Press.

Hope, C. 2006. "The Marginal Impact of CO2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern." *The Integrated Assessment Journal* 6(1): 19–56.

Howe, C. W., and F. P. Linaweaver Jr. 1967. "The Impact of Price on Residential Water Demand and Its Relation to System Design and Price Structure." *Water Resources Research* 3(1): 13–32, doi:10.1029/WR003i001p00013.

Howitt, R.E., J. Medellín-Azuara, D. MacEwan, and J.R. Lund. 2012. "Calibrating Disaggregate Economic Models of Agricultural Production and Water Management." *Environmental Modelling & Software* 38: 244–258.

Interagency Working Group on Social Cost of Carbon. 2015. *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, 2013*, revised July 2015, United States Government. https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf.

Intergovernmental Panel on Climate Change (IPCC). 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Core Writing Team, R.K. Pachauri, and L. Meyer. Geneva: IPCC.

Jakobsson, K.M., and A.K. Dragun. 2001. "The Worth of a Possum: Valuing Species with the Contingent Valuation Method." *Environmental and Resource Economics* 19(3): 211–227.

Jenkins, M.W., J.R. Lund, R.E. Howitt, A.J. Draper, S.M. Msangi, S.K. Tanaka, R.S. Ritzema, and G.F. Marques. 2004. "Optimization of California's Water System: Results and Insights." *Journal of Water Resources Planning and Management* 130(4): 271–280.

Johnston, R.J., E.Y. Besedin, R. Iovanna, C. Miller, R. Wardwell, and M. Ranson. 2005. "Systematic Variation in Willingness to Pay for Aquatic Resource Improvements and Implications for Benefit Transfer: A Meta-Analysis." *Canadian Journal of Agricultural Economics* 53(2–3): 221–248.

Johnston, R.J., E.Y. Besdin, and R. Stapler. 2016. Enhanced Geospatial Validity for Meta-Analysis and Environmental Benefit Transfer: An Application to Water Quality Improvements. Environmental and Resource Economics. *Environmental and Resource Economics* 1–33. doi:10.1007/s10640-016-0021-7

Johnston, R.J., E.Y. Besedin, and R.F. Wardwell. 2003. "Modeling Relationships Between Use and Nonuse Values for Surface Water Quality: A Meta-Analysis." *Water Resources Research* 39(12): 1363–1371.

Johnston, R.J., T.A. Grigalunas, J.J. Opaluch, J. Diamantedes, and M. Mazzotta. 2002. "Valuing Estuarine Resource Services Using Economic and Ecological Models: The Peconic Estuary System Study." *Coastal Management* 30(1): 47–66.

Johnston, R.J., and K. Moeltner. 2014. "Meta-Modeling and Benefit Transfer: The Empirical Relevance of Source-Consistency in Welfare Measures." *Environmental and Resource Economics* 59(3): 337–361.

Johnston, R.J., M.H. Ranson, E.Y. Besedin, and E.C. Helm. 2006. "What Determines Willingness to Pay Per Fish? A Meta-Analysis of Recreational Fishing Values." *Marine Resource Economics* 21: 1–32.

Johnston, R.J., J. Rolfe, R.S. Rosenberger, and R. Brouwer, eds. 2015. *Benefit Transfer of Environmental and Resource Values: A Guide for Researchers and Practitioners*. Dordecht: Springer Netherlands.

Johnston, R.J., and R.S. Rosenberger. 2010. "Methods, Trends and Controversies in Contemporary Benefit Transfer." *Journal of Economic Surveys* 24: 479–510.

Johnston, R.J., and M. Russell. 2011. "An Operational Structure for Clarity in Ecosystem Service Values." *Ecological Economics* 70(12): 2243–2249.

Johnston, R.J., and P.J. Thomassin. 2010. "Willingness to Pay for Water Quality Improvements in the United States and Canada: Considering Possibilities for International Meta-Analysis and Benefit Transfer." *Agricultural and Resource Economics Review* 39(1): 114–131.

Jorgenson, D. R. Goettle, B. Hurd, J. Smith, and D. Mills. 2004. "U.S. Market Consquences of Global Climate Change." Pew Center on Global Climate Change. http://www.c2es.org/docUploads/Market_Consequences-report.pdf.

Kontoleon, A., and T. Swanson. 2003. "The Willingness to Pay for Property Rights for the Giant Panda: Can a Charismatic Species be an Instrument for Nature Conservation?" *Land Economics* 79(4): 483–499.

Kremer, P., Z. Hamstead, D. Haase, T. McPhearson, N. Frantzeskaki, E. Andersson, N. Kabisch, N. Larondelle, E.L. Rall, G. Avlonitis, C. Bertram, F. Baró, E. Gómez-Baggethun, A. Gren, R. Hansen, A. Kaczorowska, J.-H. Kain, J. Kronenberg, J. Langemeyer, P. Muehlmann, S. Pauleit, K. Rehdonz, M. Schewenius, C. van Ham, A. Voigt, D. Wurster, and T. Elmqvist. 2016. "Key Insights for the Future of Urban Ecosysem Services Research." *Ecology and Society* 21(2):29. http://dx.doi.org/10.5751/ES-08445-210229.

Kremer, P., Z.A. Hamstead, and T. McPhearson. 2013. "A Social-Ecological Assessment of Vacant Lots in New York City." *Landscape and Urban Planning* 2013: 218–233. http://dx.doi.org/10.1016/j.landurbplan.2013.05.003.

Kremer, P., Z.A. Hamstead, and T. McPhearson. 2016. "The Value of Urban Ecosystem Services: A Spatially Explicit Multicriteria Analysis of Landscape Scale Valuation Scenarios in NYC." *Environmental Science and Policy* 62: 57–68. http://dx.doi.org/10.1016/j.envsci.2016.04.012.

Langford, I.H., M.S. Skourtos, A. Kontogianni, R.J. Day, S. Georgiou, and I.J. Bateman. 2001. "Use and Nonuse Values for Conserving Endangered Species: The Case of the Mediterranean Monk Seal." *Environment and Planning* 33(12): 2219–2233.

Larondelle, N., and D. Haase. 2013. "Urban Ecosystem Services Assessment along a Rural–Urban Gradient: A Cross-Analysis of European Cities." *Ecological Indicators* 29: 179–190.

Leggett, C.G., and N.E. Bockstael. 2000. "Evidence of the Effects of Water Quality on Residential Land Prices." *Journal of Environmental Economics and Management* 39: 121–144.

Lemos, M.C. 2008. "What Influences Innovation Adoption by Water Managers? Climate Information Use in Brazil and the United States." *Journal of the American Water Resources Association* 44(6): 1288–1396.

Lipton, D. 2004. "The Value of Improved Water Quality to Chesapeake Bay Boaters." *Marine Resource Economics* 19(2): 265–270.

Lipton, D.W., and R. Hicks. 1999. "Linking Water Quality Improvements to Recreational Fishing Values: The Case of Chesapeake Bay Striped Bass." *Fisheries Centre Research Reports: Evaluating the Benefits of Recreational Fisheries* 7(2): 105–110.

Loomis, J.B. 2000. "Vertically Summing Public Good Demand Curves: An Empirical Comparison of Economic versus Political Jurisdictions." *Land Economics* 76(2): 312–321.

Loomis, J.B. 2005. *Updated Outdoor Recreation Use Values on National Forests and Other Public Lands*. General Technical Report PNW-GTR-658. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Loomis, J.B., T. Kroeger, L. Richardson, and F. Casey. 2008. "A Benefit Transfer Toolkit for Fish, Wildlife, Wetlands, and Open Space." *Western Economics Forum* 7(2):33–43.

Loomis, J.B., R. Rosenberger, and R. Shrestha. 1999. *Updated Estimates of Recreation Values for the RPA Program by Assessment Region and Use of Meta-Analysis for Recreation Benefit Transfer*. Fort Collins, CO: Colorado State University, Department of Agricultural and Resource Economics, Final Report RJVA 28-JV7-962.

Loomis, J.B., and D.S. White. 1996. "Economic Benefits of Rare and Endangered Species: Summary and Meta-Analysis." *Ecological Economics* 18(3): 197–206.

MacDonnell, L.J. 2009. "Return to the River: Environmental Flow Policy in the United States and Canada." *Journal of the American Water Resources Association* 45(5): 1087–1099.

MacNair, D. 1993. *1993 RPA Recreation Values Database*. Washington, DC: USDA Forest Service, RPA Program, Contract 43-4568-3-1191.

Maxwell, K. 2011. "Beyond Verticality: Fuelscape Politics and Practices in the Andes." *Human Ecology* 39: 465–478.

Mazzotta, M., L. Wainger, and S. Sifleet. 2014. *Assessing Lost Ecosystem Service Benefits Due to Mining-Induced Stream Degradation in the Appalachian Region: Economic Approaches to Valuing Recreational Fishing Impacts.* Morgantown, WV: Northeastern Agricultural and Resource Economics Association Meetings.

McNie, E.C. 2007. "Reconciling the Supply of Scientific Information with User Demands: An Analysis of the Problem and Review of the Literature." *Environmental Science & Policy* 10: 17–38. doi:10.1016/j.envsci.2006.10.004.

McPhearson, T., R. Auch, and M. Alberti. 2013. "Regional Assessment of North America: Urbanization Trends, Biodiversity Patterns, and Ecosystem Services." In *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities*, edited by T. Elmqvist, M. Fragkias, J. Goodness, B. Güneralp, P.J. Marcotullio, R.I. McDonald, S. Parnell, M. Schewnius, M. Sendstad, K.C. Seto, and C. Wilkinson, 279–286. Dordrecht: Springer Netherlands. doi:10.1007/978-94-007-7088-1.

McPhearson, T., Z. Hamstead, and P. Kremer. 2014. "Urban Ecosystem Services for Resilience Planning and Management in New York City." *AMBIO: Journal of the Human Environment* 43(4): 502–515. doi:10.1007/s13280-014-0509-8.

McPhearson, T., P. Kremer, and Z. Hamstead. 2013. "Mapping Ecosystem Services in New York City: Applying a Social-Ecological Approach in Urban Vacant Land." *Ecosystem Services* 5: 11–26. doi:10.1016/j.ecoser.2013.06.005.

National Land Cover Database (NLCD). 2011. *National Land Cover Database 2011 (NLCD 2011)*. http://www.mrlc.gov/nlcd2011.php.

National Research Council (NRC). 2004. *Valuing Ecosystem Services: Toward Better Environmental Decision-Making*.

National Research Council (NRC). 2012. *Approaches for Ecosystem Services Valuation for the Gulf of Mexico after the Deepwater Horizon Oil Spill: Interim Report*.

National Survey of Fishing, Hunting, and Wildlife-Associated Recreation (FHWAR). 2006. *2006 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation*. U.S. Department of the Interior, Fish and Wildlife Service, and U.S. Department of Commerce, U.S. Census Bureau. http://www.census.gov/prod/2008pubs/fhw06-nat.pdf.

National Survey of Fishing, Hunting, and Wildlife-Associated Recreation (FHWAR). 2011. *2011 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation*. U.S. Department of the Interior, Fish and Wildlife Service, and U.S. Department of Commerce, U.S. Census Bureau. http://www.census.gov/prod/2012pubs/fhw11-nat.pdf.

Neher, C., J. Duffield, and D. Patterson. 2013. "Valuation of National Park System Visitation: The Efficient Use of Count Data Models, Meta-Analysis, and Secondary Visitor Survey Data." *Environmental Management* 52(3): 683–698. http://link.springer.com/content/pdf/10.1007%2Fs00267-013-0080-2.pdf.

Nelson, J.P., and P.E. Kennedy. 2009. "The Use (and Abuse) of Meta-Analysis in Environmental and Resource Economics: An Assessment." *Environmental and Resource Economics* 42(3): 345–377.

Nieswiadomy, M.L. 1992. "Estimating Urban Residential Water Demand Effects of Price Structure, Conservation, and Education." *Water Resources Research* 28(3): 609–615.

Nordhaus, W., and J. Boyer. 2000. *Warming the World: Economic Models of Global Warming*. Cambridge, MA: MIT Press.

Ojea, E., and M.L. Loureiro. 2007. "Altruistic, Egoistic and Biospheric Values in Willingness-To-Pay (WTP) for Wildlife." *Ecological Economics* 63(4): 807–814.

Parsons, G.R. 2013. "Travel Cost Methods." In *Encyclopedia of Energy, Natural Resources, and Environmental Economics*, vol. 3, edited by J.F. Shogren, 349–358. Amsterdam: Elsevier.

Parsons, G.R., and S. Thur. 2008. "Valuing Changes in the Quality of Coral Reef Ecosystems: A Stated Preference Study of SCUBA Diving int he Bonaire National Marine Park." *Environmental and Resource Economics* 40(4): 593–608.

Pendleton, L., C. Mohn, R. Vaughn, P. King, and J. Zoulas. 2012. "Size Matters: The Economic Value of Beach Erosion and Nourishment in Southern California." *Contemporary Economic Policy* 30(2): 223–237.

Peters, T., W.L. Adamowicz, and P.C. Boxall. 1995. "Influence of Choice Set Considerations in Modeling the Benefits from Improved Water Quality." *Water Resources Research* 31(7): 1781–1787.

Petrolia, D., and T. Kim. 2011. "Preventing Land Loss in Coastal Louisiana: Estimates of WTP and WTA." *Journal of Enviromnmental Management* 92(3): 859–865.

Pickett, S.T.A., M.L. Cadenasso, J.M. Grove, C.G. Boone, P.M. Groffman, E. Irwin, S.S. Kaushal, V. Marshall, B.P. McGrath, C.H. Nilon, R.V. Pouyat, K. Szlavecz, A. Troy, and P. Warren. 2011. "Urban Ecological Systems: Scientific Foundations and a Decade of Progress." *Journal of Environmental Management* 92(2011): 331–362.

Poff, N.L., B.D. Richter, A.H. Arthington, S.E. Bunn, R.J. Naiman, E. Kendy, M. Acreman, C. Apse, B.P. Bledsoe, M.C. Freeman, J. Henriksen, R.B. Jacobson, J.G. Kennen, D.M. Merritt, J.H. O'Keeffe, J.D. Olden, K. Rogers, R.E. Tharme, and A. Warner. 2010. "The Ecological Limits of Hydrologic Alteration (ELOHA): A New Framework for Developing Regional Environmental Flow Standards." *Freshwater Biology* 55: 147–170.

Poor, P.J., K.L. Pessagno, and R.W. Paul. 2007. "Exploring the Hedonic Value of Ambient Water Quality: A Local Watershed-Based Study." *Ecological Economics* 60: 797–806.

Rappaport, R.A. 1979. *Ecology, Meaning, and Religion*. Richmond, CA: North Atlantic.

Richardson, L., and J. Loomis. 2009. "The Total Economic Value of Threatened, Endangered and Rare Species: An Updated Meta-Analysis." *Ecological Economics* 68: 1535–1548.

Richter, B.D., J.V. Baumgartner, J. Powell, and D.P. Braun. 1996. "A Method for Assessing Hydrologic Alteration within Ecosystems." *Conservation Biology* 10(4): 1163–1174.

Rosenberger, R.S. 2015. "Benefit Transfer Validity and Reliability." In *Benefit Transfer of Environmental and Resource Values: A Guide for Researchers and Practitioners*, edited by R.J. Johnston, J. Rolfe, R.S.

Rosenberger, and R. Brouwer, 307–326. Dordrecht: Springer Netherlands.

Rosenberger, R.S., and R.J. Johnston. 2009. "Selection Effects in Meta-Analysis and Benefit Transfer: Avoiding Unintended Consequences." *Land Economics* 85(3) 410–428.

Rosenberger, R.S., and J.B. Loomis. 2001. *Benefit Transfer of Outdoor Recreation Use Values: A Technical Document Supporting the Forest Service Strategic Plan (2000 revision)*. Gen. Tech. Rep. RMRS-GTR-72. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Rosenberger, R.S., and J.B. Loomis. 2003. "Benefit Transfer." in *A Primer on Nonmarket Valuation*, edited by P.A. Champ, K.J. Boyle, and T.C. Brown, 445–482. Boston: Kluwer.

Rosenberger, R.S., and T.D. Stanley. 2006. "Measurement, Generalization, and Publication: Sources of Error in Benefit Transfers and Their Management." *Ecological Economics* 60: 372–378.

Schewenius, M., T. McPhearson, and T. Elmqvist. 2014. "Opportunities for Increasing Resilience and Sustainability of Urban Social–Ecological Systems: Insights from the URBES and the Cities Biodiversity Outlook Projects." *AMBIO* 43(4): 434–444. doi:10.1007/s13280-014-0505-z.

Shrestha, R.K., and J.B. Loomis. 2003. "Meta-Analytic Benefit Transfer of Outdoor Recreation Economic Values: Testing Out-of-Sample Convergent Validity." *Environmental and Resource Economics* 75: 79–100.

Smith, V.K., W.H. Desvousges, and A. Fisher. 1986. "A Comparison of Direct and Indirect Methods for Estimating Environmental Benefits." *American Journal of Agricultural Economics* 68: 280–290.

Smith, V.K., and S.K. Pattanayak. 2002. "Is Meta-Analysis a Noah's Ark for Non-Market Valuation?" *Environmental and Resource Economics* 22(1–2): 271–296.

Smith, V.K., G. Van Houtven, and S.K. Pattanayak. 2002. "Benefit Transfer via Preference Calibration: 'Prudential Algebra' for Policy." *Land Economics* 78(1): 132–152.

Sohngen, B. R. Mendelsohn, and R. Sedjo. 2001. "A Global Model of Climate Change Impacts on Timber Markets." *Journal of Agricultural and Resource Economics* 26(2): 326–343.

Sorg, C.F., and J.B. Loomis. 1984. *Empirical Estimates of Amenity Forest Values: A Comparative Review*. General Technical Report RM-107. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Tol, R. 2002a. "Estimates of the Damage Costs of Climate Change. Part I: Benchmark Estimates." *Environmental and Resource Economics* 21: 47–73.

Tol, R. 2002b. "Estimates of the Damage Costs of Climate Change. Part II: Dynamic Estimates." *Environmental and Resource Economics* 21: 135–160.

U.S. Census Bureau. 2010. Census of Population and Housing. http://www.census.gov/geo/reference/ua/urban-rural-2010.html.

U.S. Department of Agriculture (USDA). 1998. *Agricultural Fact Book 1998*. http://www.usda.gov/documents/factbook1998.pdf.

U.S. Department of Agriculture (USDA). 2009. *National Visitor Use and Monitoring Survey Database*. https://apps.fs.usda.gov/nfs/nrm/nvum/results/.

U.S. Environmental Protection Agency (U.S. EPA). 2009. *Valuing the Protection of Ecological Systems and Services: A Report of the EPA Science Advisory Board*.

U.S. Environmental Protection Agency (U.S. EPA). 2010. *Economic Analysis of Final Water Quality Standards for Nutrients for Lakes and Flowing Waters in Florida*. U.S. EPA, Office of Water, Office of Science and Technology, Washington, DC.

U.S. Environmental Protection Agency (U.S. EPA). 2012. *Economic Analysis of Proposed Water Quality Standards for the State of Florida's Estuaries, Coastal Waters, and South Florida Inland Flowing Waters*. U.S. EPA, Office of Water, Office of Science and Technology, Washington, DC.

U.S. Environmental Protection Agency (U.S. EPA). 2015. *Benefit and Cost Analysis for the Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category*.

U.S. EPA, Office of Water, Office of Science and Technology, Washington, DC, 821-R-15-005.

Van Houtven, G., C. Mansfield, D.J. Phaneuf, R. von Haefen, B. Milstead, M.A. Kenney, and K.H.

Reckhow. 2014. "Combining Expert Elicitation and Stated Preference Methods to Value Ecosystem Services from Improved Lake Water Quality." *Ecological Economics* 99: 40–52.

Van Houtven, G., J. Powers, and S.K. Pattanayak. 2007. "Valuing Water Quality Improvements in the United States Using Meta-Analysis: Is the Glass Half-Full or Half-Empty for National Policy Analysis?" *Resource and Energy Economics* 9: 206–228.

Vaughan, W.J. 1986. "The RFF Water Quality Ladder. Appendix B." In *The Use of Contingent Valuation Data for Benefit/Cost Analysis in Water Pollution Control, Final Report*, edited by R.C. Mitchell and R.T. Carson. Washington: Resources for the Future.

Villa, F., K.J. Bagstad, B. Voigt, G. Johnson, R. Portela, M. Honzak, and D. Batker. 2014. "A Methodology for Adaptable and Robust Ecosystem Services Assessment." *PLoS ONE* 9(3): e91101. doi:10.1371/journal.pone.0091001.

Viscusi, K.W, J. Huber, and J. Bell. 2008. "The Economic Value of Water Quality." *Environmental and Resource Economics* 41: 169–187.

Waddington, D.G., K.J. Boyle, and J. Cooper. 1994. *1991 Net Economic Values for Bass and Trout Fishing, Deer Hunting, and Wildlife Watching*. Washington, DC: US Fish and Wildlife Service.

Wallmo, K., and S. Edwards. 2007. *Estimating Public Values for Marine Protected Areas in the Northeast United States: A Latent Class Modeling Approach*. U.S. Dep. Of Commerce, NOAA Tech. Memo. NMFS-F/SPO-84.

Walsh, R.G., D.M. Johnson, and J.R. McKean, J.R. 1988. *Review of Outdoor Recreation Economic Demand Studies with Nonmarket Benefit Estimates, 1968–1988*. Fort Collins, CO: Colorado State University, Department of Agricultural and Resource Economics, Technical Report No. 54.

Ward, F.A., and A. Michelsen. 2002. “The Economic Value of Water in Agriculture: Concepts and Policy Applications.” *Water Policy* 4: 423–446.

Weidner, E., and A. Todd. 2011. *From the Forest to the Faucet: Drinking Water and Forests in the U.S*. USDA Forest Service Methods Paper. http://www.fs.fed.us/ecosystemservices/pdf/forests2faucets/F2F_Methods_Final.pdf.

White, G.F. 1964. *Choice of Adjustment to Floods*. University of Chicago–Department of Geography Research Paper No. 93.

White, P.C.L., A.C. Bennett, and E.J.V. Hayes. 2001. “The use of willingness-to-pay approaches in mammal conservation.” Mammal Review 31(2): 151–167.

White, P.C.L., K.W. Gregory, P.J. Lindley, and G. Richards. 1997. “Economic Values of Threatened Mammals in Britain: A Case Study of the Otter *Lutra lutra* and the Water Vole *Arvicola terrestris*.” *Biological Conservation* 82: 345–354.

Whittington, D., J. Briscoe, X. Mu, and W. Barron. 1990. “Estimating the Willingness to Pay for Water Services in Developing Countries: A Case Study of the Use of Contingent Valuation Surveys in Southern Haiti.” *Economic Development and Cultural Change* 38(2): 293–311.

Wilson, C., and C. Tisdell. 2007. “How Knowledge Affects Payment to Conserve an Endangered Bird.” *Contemporary Economic Policy* 25(2): 226–237.

Wood, S.A., A.D. Guerry, J.M. Silver, and M. Lacayo. 2013. “Using Social Media to Quantify Nature-Based Tourism and Recreation.” *Scientific Reports* 3: 2976. doi:10.1038/srep02976.

Young, R.A., and J.B. Loomis. 2014. *Determining the Economic Value of Water: Concepts and Methods*. New York: RFF Press.

Zanderson, M., and R.S.J. Tol. 2009. “A Meta-Analysis of Forest Recreation Values in Europe.” *Journal of Forest Economics* 15: 109–130.

5: Data and Modeling Infrastructure

Donovan, S., C. Goldfuss, and J. Holdren. 2015. Memorandum for Executive Departments and Agencies. M-16-01. https://www.whitehouse.gov/sites/default/files/omb/memoranda/2016/m-16-01.pdf.

Eigenbrod, F., P.R. Armsworth, B.J. Anderson, A. Heinemeyer, S. Gillings, D.B. Roy, C.D. Thomas, and K.J. Gaston. 2010. “The Impact of Proxy-Based Methods on Mapping the Distribution of Ecosystem Services.” *Journal of Applied Ecology* 47: 377–385.

Hey, T., S. Tansley, and K. Tolle. 2009. *The Fourth Paradigm: Data-Intensive Scientific Discovery*. Redmond, WA: Microsoft Research.

Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, and G. Xian. 2013. "A Comprehensive Change Detection Method for Updating the National Land Cover Database to Circa 2011." *Remote Sensing of Environment* 132: 159–175.

Loomis, J.B., T. Kroeger, L. Richardson, and F. Casey. 2008. "A Benefit Transfer Toolkit for Fish, Wildlife, Wetlands, and Open Space." *Western Economics Forum* 7(2):33–43.

Loomis, J.B., and R.S. Rosenberger. 2006. "Reducing Barriers in Future Benefit Transfers: Needed Improvements in Primary Study Design and Reporting." *Ecological Economics* 60(2): 343–350.

Office of Management and Budget (OMB). 2006a. *Questions and Answers When Designing Surveys for Information Collections*. https://www.whitehouse.gov/sites/default/files/omb/inforeg/pmc_survey_guidance_2006.pdf.

Office of Management and Budget (OMB). 2006b. *Standards and Guidelines for Statistical Surveys*. https://www.whitehouse.gov/sites/default/files/omb/inforeg/statpolicy/standards_stat_surveys.pdf.

Ohmann, J.T., and M.J. Gregory. 2002. "Predictive Mapping of Forest Composition and Structure with Direct Gradient Analysis and Nearest-Neighbor Imputation in Coastal Oregon, U.S.A." *Canadian Journal of Forest Research* 32(4): 725–741.

Oswalt, S.N., W.B. Smith, P.D. Miles, and S.A Pugh. 2014. *Forest Resources of the United States, 2012: A Technical Document Supporting the Forest Service 2015 Update of the RPA Assessment*. General Technical Report WO-91. Washington, DC: U.S. Department of Agriculture, Forest Service.

Peckham, S.D., E.W.H. Hutton, and B. Norris. 2013. "A Component-Based Approach to Integrated Modeling in the Geosciences: The Design of CSDMS." *Computers & Geosciences* 53: 3–12.

Schimel, D.S., VEMAP Participants, and B.H. Brawell. 1997. "Continental Scale Variability in Ecosystem Processes: Models, Data, and the Role of Disturbance." *Ecological Monographs* 67(2): 251–271.

Soil Survey Geographic Database (SSURGO). 2015. *Availability of SSURGO Data*. http://websoilsurvey.nrcs.usda.gov/DataAvailability/SoilDataAvailabilityMap.pdf.

Villa, F., K.J. Bagstad, B. Voigt, G. Johnson, R. Portela, M. Honzak, and D. Batker. 2014. "A Methodology for Adaptable and Robust Ecosystem Services Assessment." *PLoS ONE* 9(3): e91101. doi:10.1371/journal.pone.0091001.

Wilson, M.A., and J.P. Hoehn. 2006. "Valuing Environmental Goods and Services Using Benefit Transfer: The State-of-the-Art and Science." *Ecological Economics* 60(2): 335–342.

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.

Nicholas Institute for Environmental Policy Solutions

The Nicholas Institute for Environmental Policy Solutions at Duke University is a nonpartisan institute founded in 2005 to help decision makers in government, the private sector, and the nonprofit community address critical environmental challenges. The Nicholas Institute responds to the demand for high-quality and timely data and acts as an "honest broker" in policy debates by convening and fostering open, ongoing dialogue between stakeholders on all sides of the issues and providing policy-relevant analysis based on academic research. The Nicholas Institute's leadership and staff leverage the broad expertise of Duke University as well as public and private partners worldwide. Since its inception, the Nicholas Institute has earned a distinguished reputation for its innovative approach to developing multilateral, nonpartisan, and economically viable solutions to pressing environmental challenges.

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