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Ecosystem services in the Great Lakes

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Abstract

A comprehensive inventory of ecosystem services across the entire Great Lakes basin is currently lacking and is needed to make informed management decisions. A greater appreciation and understanding of ecosystem services, including both use and non-use services, may have avoided misguided resource management decisions in the past that resulted in negative legacies inherited by future generations. Given the interest in ecosystem services and lack of a coherent approach to addressing this topic in the Great Lakes, a summit was convened involving 28 experts working on various aspects of ecosystem services in the Great Lakes. The invited attendees spanned a variety of social and natural sciences. Given the unique status of the Great Lakes as the world's largest collective repository of surface freshwater, and the numerous stressors threatening this valuable resource, timing was propitious to examine ecosystem services. Several themes and recommendations emerged from the summit. There was general consensus that: 1) a comprehensive inventory of ecosystem services throughout the Great Lakes is a desirable goal but would require considerable resources; 2) more spatially and temporally intensive data are needed to overcome our data gaps, but the arrangement of data networks and observatories must be well-coordinated; 3) trade-offs must be considered as part of ecosystem services analyses; and 4) formation of a Great Lakes Institute for Ecosystem Services, to provide a hub for research, meetings, and training is desirable. Several challenges also emerged during the summit, which are discussed.
Keywords: Ecosystem services; Laurentian Great Lakes; use and non-use values

Introduction

The Laurentian Great Lakes hold approximately 20% of the world's total surface freshwater supply, and collectively the basin supports an economy with a gross regional product (GRP) of ~$4.1 trillion USD (Campbell et al., 2015) although this number is very likely inflated given that the geographic boundaries used by the authors extend beyond the Great Lakes watershed boundaries. Krantzberg and De Boer (2008) also quantified the economic value of various sectors in and threats to, the Great Lakes, emphasizing Canada, revealing substantial (e.g., $7.4 billion for sport fishing and $2.2 billion for recreational boating) sums. As impressive as these numbers may be, they are conservative estimates of the Great Lakes' economic output because they do not account for a large number of benefits that society receives from the environment, referred to as ecosystem services (ES).

The Great Lakes provide society with a variety of ES (cf. Austin et al., 2007; Allan et al., 2015), many of which have potentially measurable economic values but have yet to be quantified and accounted for in existing markets. But even if we could place a value on these ES, adding those values to existing markets would still grossly underestimate the value of the Great Lakes because (a) many ES cannot be bought and sold in existing markets (e.g., the value of the Great Lakes for climate regulation or the amount you would pay to protect the Great Lakes so that your children could enjoy them in the future), and (b) many are not easily quantified in dollars (e.g., the value of the Great Lakes for mental and physical health). In particular, cultural ES have received limited attention (cf. Daniel et al., 2012; Hirons et al., 2016), especially with respect to spiritual and religious elements; in the Great Lakes, tribal and First Nations provide traditional knowledge but these attributes are rarely monetized. The total value of the Great Lakes is, therefore, the sum of their current market value, plus the sum of all ES that are not currently accounted for in existing markets, plus the sum of all ES that cannot be, or perhaps should not be, converted to currency. Most experts would agree this value is likely to be exceedingly high. But figuring out how to quantify, aggregate, and compare all of these differing values, and perhaps more importantly, how much that value changes under any particular change or management scenario, are major challenges in our desire to make more informed decisions on how to manage the Laurentian Great Lakes.

Increasingly, we have begun to recognize the need to fully account and carefully consider the myriad values of Earth's prominent natural features, such as the Great Lakes, so that we can minimize externalities (costs of business practices that are paid by society, such as pollution) and consider trade-offs among different end-users of natural resources (e.g., bottle water companies vs. fishers). The study of ES was popularized in the 1990s when Daily (1997) showed that their value can exceed the value of existing economic markets, and that consideration of ecosystem services, if taken into account, could alter management and business decisions. In 2000, United Nations Secretary General Kofi Annan commissioned the Millennium Ecosystem Assessment (MEA, 2005), which was the largest ever assessment of the health of Earth's ecosystems. The MEA involved >1,300 participants from 95 countries who concluded that the majority of ES in most systems on the planet were being degraded. The UN continues to facilitate the use of ES as a framework for monitoring and managing the impacts of changes in nature through the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES). national governments are embracing ecosystem services in management as well. For example, in October 2015, a (US) Presidential Executive Memorandum (M-16-01) stated that all *"federal agencies shall develop policies to promote consideration of ecosystem-services assessments within* *existing agency planning and decision frameworks, where appropriate and practicable, in accordance with their statutory authorities and consistent with their specific missions."*

Like other popularized terms in the literature on sustainability, the term 'ecosystem services' has been used in a variety of ways, and has come to mean different things to different users. Therefore, it was important to clarify its meaning and use for purposes of this working group by providing definitions and typologies prior to the summit. Following Munns et al. (2015), we defined ecosystem goods and services as "outputs of ecological processes that contribute to social welfare" (Fig.1). Ecological outputs are generated by ecological production functions (EPFs), which are defined as the "type, quantity, and interactions of natural features required to generate observable and measurable ecological outputs." Ecological outputs are considered ES only when those outputs are demanded or otherwise valued by people, which requires that the output be converted into some kind of social value.

The growing recognition of the importance of ecosystem services, the commitment by major organizations to consider them in decision-making, and appreciation that freshwater is a limiting resource nationally and globally makes it an opportune time to explore the importance of ES in the Great Lakes. Therefore, we invited 28 experts who work on ES in the Great Lakes to convene for a summit held in Ann Arbor, MI in June 2016. One of the underlying goals of this summit was to enhance collaboration among ES practitioners. Work on Great Lakes ES has been scattered among academic institutions and various government agencies, and when collaborations exist, they historically have occurred on a project-specific basis (e.g., Angradi et al., 2016). In addition to fostering a multidisciplinary network of individuals to discuss a more coordinated and cohesive strategy for valuing ES in the Great Lakes, we had three explicit goals for the summit: 1) summarize what is presently known about ES in the Great Lakes;

2) identify the challenges and opportunities in quantifying ES; and 3) set an agenda for new research needs in the coming decade.

Methodology

The summit was funded and hosted by the Cooperative Institute for Limnology and Ecosystems Research (CILER), one of 16 NOAA-sponsored Cooperative Institutes throughout the USA. CILER commissioned a 3-person steering committee (authors BJC, ADS, WRM) to develop the format and focal questions for the summit, and received input from various attendees before finalizing the agenda. The 28 invited participants were chosen to represent a variety of disciplines in the social and natural sciences, and included representatives from 3 government agencies, 9 universities, and 3 institutes (Table 1). The steering committee members were intentional in inviting both natural (e.g., ecologists) and social (e.g., economists) scientists in an effort to reach a common understanding of ES in the Great Lakes. The two day summit was held on the campus of the University of Michigan, and organized into 3 sessions that addressed the goals identified above. Participants were assigned to different breakout groups in advance to ensure diverse representation of disciplines. In addition, expectations were explicitly identified beforehand, and each breakout group identified individuals to take notes and report out on their findings. Steering committee members floated among the breakout groups to facilitate discussion and keep conversations focused and on topic. Each working group was charged with producing a one-page written summary of their findings within two weeks of the summit conclusion, which were then collated and refined by steering committee members.

Conceptual framework

The total social value of an ecosystem and the ES it provides is the sum of both use values and non-use values (Fig.2). Although use values can be subdivided into direct use (resources directly used or enjoyed by an end-user) and indirect use values (resources that are not directly used by people, but still provide measurable benefits), there was debate regarding whether some ES were a direct vs. indirect use. As a consequence, we decided to treat use values as a single entity (Fig.2), as the division was not pertinent to the larger questions we were attempting to address. Many use values of ecosystems can be quantified through widely employed non-market valuation methods. Revealed preference methods, such as hedonic price and travel cost address, respectively, environmental quality as reflected in market prices (e.g., property prices) and the price of accessing goods that equate to the combined opportunity cost of time and cost of travel. Opportunity and alternative cost methods can be used to estimate the value of ES that would have to be replaced by some other process in their absence (e.g., a water treatment system replacing a natural wetland biofilter).

In contrast to use values, a great many ES fall into the category of non-use values. Because non-use values do not have existing markets, they are most often quantified through survey methods (contingent valuation) that describe hypothetical markets to elicit an individual's preferences. These stated preference approaches are used to determine people's willingness to pay to assess the non-consumptive value of an environmental attribute or good. Perhaps the best known in this category is the option value of an ecosystem, which represents the potential use or enjoyment of a resource by the current generation or at some point in the future. Option values are essentially a form of 'insurance' – for example, the potential use of the Great Lakes for drinking water at some point in the future when freshwater has become more scarce. Other non-use values include bequest value, which is the benefit that the current generation derives from protecting a resource for use or enjoyment of their offspring (e.g., protecting cultural experiences like a mother fishing with her son) and existence value, which is the benefit people derive from simply knowing that a resource exists; related to this is the psychological or spiritual well-being one derives from simply viewing a Great Lake (cf. Daniel et al., 2012).

Results and Discussion

Question #1. What is the current state of knowledge about ES in the Great Lakes?

Background

Given the ecological, social, and economic importance of an ecosystem that contains almost 20% of the world's surface fresh water, it is perhaps surprising that no study has systematically examined ES at the geographic scale of the entire Great Lakes. Instead, the few efforts that have been performed at a basin-scale have focused on select subsets of ES - most often those where data readily exist in multiple formats, locations, and units. For example, Austin et al. (2007) estimated economic benefits associated with the restoration of the Great Lakes, as outlined in the Great Lakes Regional Collaboration (GLRC), which was the predecessor to the Great Lakes Restoration Initiative (GLRI). While not an assessment of ES *per se*, Austin et al. (2007) estimated the direct economic benefits of restoring the Great Lakes to total at least $50 billion, with another $30-50 billion in short-term multiplier effects, resulting in a healthy return on the estimated $26 billion cost to fully implement GLRC.

More recently, Allan et al. (2015) attempted to quantify the spatial distribution of five recreational activities that are associated with select cultural/recreational ES across the Laurentian Great Lakes, including sport fishing, recreational boating, birding, beach use, and park visitation. Their study showed that these ES were directly correlated to economic activity in coastal communities, which also led to the conclusion that ES are greatest in some of the most heavily populated and degraded ecosystems in the Great Lakes (e.g., Lake Erie's western basin). However, Allan et al.'s work was limited to select types of use values (cf. Fig.2) related to extractable resources (e.g., fisheries) or tourism and recreation activities that are routinely monitored and quantified. Such ES are clearly an important element of value; however, their study did not quantify other use values (e.g., flood or pollution control) or non-use value of ecosystems. When these latter values have been quantified, their value can exceed the summed value of direct use (Adamowicz et al. 1998). But unfortunately, values of many ES are often not available for data syntheses because they require more advanced methodologies of valuation and, as such, less data and fewer studies exist. The fact that such a large subset of ES has seldom been quantified for the Great Lakes cautions against drawing broad generalizations about the value of the Great Lakes, and emphasizes that most of our knowledge at present revolves around very limited types of value.

Valuing the full complement of ES across large geographic regions, whether it is at the whole planet scale (e.g., Costanza et al., 2014) or the Great Lakes basin, is fraught with logistical and analytical issues (McCauley, 2006). Nonetheless, these types of exercises clearly help stimulate discussion and can help inform policy (Fisher et al., 2008). Hence, while such a goal is something we only can aspire to at this time, there are examples of studies that have quantified the more difficult use and non-use values of Great Lakes ecosystems. For example, hedonic price analyses revealed that owner-occupied property values in the Buffalo River (NY) and Sheboygan River (WI) Areas of Concern (AOCs) were reduced by $118 million and $158 million, respectively (Braden et al., 2008 a,b), due to proximity to the AOC with greater loss of value the closer to the AOC location. Angradi et al. (2016) mapped indicators of 23 biophysical ES in the estuarine portion of the St. Louis River AOC (MN); the study did not include a valuation component, but the mapping allowed them to assess trade-offs in ES associated with different management actions by examining changes in the area of the AOC providing the services. Among use ES in the Great Lakes, recreation has received a fair amount of attention. Rabinovici et al. (2004) used a transfer cost analysis to examine the economic impact of beach closure at a Lake Michigan beach. They estimated the economic loss to the local community to range between $1274 to $37,030 per day; it is unclear whether these data will be of much use to local resource managers and decision makers, given the wide range in estimated losses. Recreational fishing has also received attention, with Kelch et al. (2006) reporting that the annual value of the tributary steelhead fishery in Lake Erie tributaries (OH) could be up to $12-14 million/year. Southwick Associates (2007), based on 2006 data, estimated economic impacts from Great Lakes fishing of slightly more than $7 billion. Given the logistical challenges in conducting a Great Lakes-wide assessment of ES, it is likely at least for the foreseeable future that valuation studies often will be site specific.

Summit Findings

The current state of knowledge regarding ES in the Great Lakes reveals the necessity for a full accounting of ES for sustainable management of Great Lakes, and that our knowledge of

ES in the Great Lakes system varies by sector and scale. There appears to be a better understanding of ES whose use values are associated with commercial and industrial activities, with much less understanding and confidence in use or non-use values of ecosystems represented by 'nonmarket' goods and services, such as recreational opportunities (de Groot et al., 2012). ES provide important societal benefits (broadly reflecting cultural, spiritual, existence and other values) and these are known to be important to GL residents (http://www.healthylakes.org/2016-poll/). Although many of the management decisions affecting ES are made at the local scale, issues such as fisheries and water levels (affecting use of water as an ES) require sustainable management at the basin scale, where coordination, valuation, and assessment may face greater logistical challenges.

Non-monetary approaches to value ES are underdeveloped in general, and this has led to decisions that have had significant environmental and economic consequences in the Great Lakes region. For example, the siting of factories and foundries on waterways, and their associated wastewater discharge, is now costing hundreds of millions of dollars to remediate (GLRI, 2015). While these past industrial activities helped power the economic growth of the Great Lakes region during the 20th century (Austin and Steinman, 2015), the costs of this development were passed on to the public today, as pollution from industrial activities has negatively impacted many ES and it is unknown to what degree their present day value has been compromised or lost. With the investment of GLRI funding to restore AOCs, and the removal of beneficial use impairments, ES are recovering but we have not systematically quantified their use or non-use values as these coastal regions reclaim their pre-industrial habitat and instill community pride. Isely et al. (2011) did estimate a 6.6:1 return on investment, largely due to enhanced value of real estate, for restoration of the Muskegon Lake AOC shoreline. ES cannot redress questionable land use or management decisions from the past, but they can play an important role in current and future decision-making processes.

Distinctions should be made between locations of ecological production (e.g., rocky reefs for fish spawning grounds) from those where ES are enjoyed (e.g., pelagic zone recreational fishing). Some types and locations of ecological production function hotspots in the Great Lakes are known, such as fish spawning grounds and nurseries (Manny et al., 2015) and coastal wetlands/rivermouths (Sierszen et al., 2012; Cooper et al., 2013; Larson et al., 2013). Prior mapping of ES in the Great Lakes has identified ecological "production hot spots" where ES are produced (Allan et al., 2013), and "delivery hot spots" where ES are consumed. Because these mapping exercises have focused heavily on the use values of ecosystems, the distribution of ES delivery hotspots are generally associated with areas where there is either a high concentration of people (Chicago, Milwaukee, Detroit) or high human interaction with the ecosystem, such as would occur with the usage of public lands (e.g., swimming, boating, coastal living) (Allan et al., 2015). But while we frequently have data to quantify human interactions with ecosystems near those density centers, we seldom have the data needed to quantify people's perceived value of more pristine, less populated habitats like many locations throughout Lake Superior. In addition, the information may not be truly representative of the Great Lakes as a whole because certain populations may not have access to these services. Filling these data gaps with better measures of use values and non-use values is essential if ES are to inform decisions regarding the management of the Great Lakes ecosystem.

Question #2. What are the current challenges and opportunities in quantifying ES?

Background

An immediate issue that emerged in our summit was what was meant by "quantifying" ES; were we adopting a strictly economic approach (e.g., Total Economic Value framework; Ledoux and Turner, 2002) or were we also including social value? We take an inclusive approach for valuing ES in this paper, although this question was never fully answered at the summit, and we acknowledge that ES practitioners may have strong opinions one way or another.

Our ability to quantify ES in the Great Lakes is limited by several challenges. Many of these challenges are common to research on all complex environmental problems; however, because management of ES in the Great Lakes involves multiple forms of natural and social science that must interact across two nations, two provinces, and eight states, the number of challenges that must be addressed simultaneously is unusually long. Here we discuss two primary challenges and the opportunities they create: 1) the need for more interdisciplinary training at the interface of natural and social sciences; and 2) key data gaps and methodologies that must be improved to quantify or describe ES. We also recognize that because the Great Lakes are binational, there is a need to transcend geopolitical boundaries, but this topic was not explicitly addressed due to the absence of appropriate expertise at the summit.

Summit Findings

Many environmental problems require interdisciplinary research and, in fact, it has become common to supplement traditional disciplinary training with exposure to another field to facilitate communication and understanding across disciplines. But the field of ES is unique in that, by definition, it represents the intersection of natural sciences that quantify ecological processes in ecosystems with disciplines in the humanities (e.g., arts, philosophy, religion), as well as social (e.g., economics, anthropology) and medical sciences (e.g., public health, epidemiology) that quantify or describe how humans socially value ecosystems. Because the study of ES involves the intersection of multiple disciplines, it is not sufficient for a practitioner to have deep training in one field but only a superficial understanding of the other.

Unfortunately, it is somewhat rare for ecologists to receive deep training in the humanities, social sciences or medicine, and vice versa. NOAA's National Ocean Service and Office for Coastal Management is providing and developing training in this area, and interest is certainly growing as evidenced by the National Ecosystem Services Partnership, hosted by Duke University with support from the US EPA. Nonetheless, the overall number of individuals who have the training needed to quantify ES is small. We believe the ability to more rigorously quantify ES will help inform critical policy decisions and prioritize public and private investments in the Great Lakes. The need for more training leads to a unique opportunity for universities and agencies in this region. Universities can be developing new classes in ES that provide quantitative training at the undergraduate and graduate levels, as well as initiating dual degree programs between fields such as ecology/economics, ecology/public health, and ecology/anthropology. NGOs and government agencies could further develop shorter-term training programs or classes that provide opportunities for the current workforce to receive training in how to value ES.

In addition to new forms of training, we need to improve on data collection and methodologies in order to better quantify and predict changes in ES for the Great Lakes. Many of the types of data that are needed to quantify ecological production functions (Fig.1) that lead to ES already are being monitored in parts of the Great Lakes. For example, monitoring of public beaches for pathogens, and the associated number of days with closed beaches, provide critical information for potential economic impact to coastal communities in the Great Lakes. In addition, as newer and more advanced monitoring approaches replace older ones, such as the use of qPCR in lieu of culture based methods, same day exceedance warnings can be posted before peak swimming times, resulting in fewer human exposures to pathogens. Of course, a key caveat is that these monitoring programs rarely cover the grain and extent needed to provide spatially-explicit predictions, and we rarely have sufficient time-series to produce reliable models. Because of this, there are numerous opportunities for researchers and funding agencies to promote the collection of high spatial and temporal resolution data for various ecological production values, and to generate more remote sensing and lake observatories.

In contrast to the data needed to generate ecological production functions, many types of information needed to produce social demand functions (Fig.1) lie deep within a range of social science method and theory, and therefore are difficult for the non-practitioner to utilize. While many of the use values of ecosystems (Fig.2) are publicly available, we lack routine monitoring programs for many use and non-use values of Great Lakes ecosystems (Fig.2). These include such straight-forward information as beach usage and recreational boating, measures of human health and well-being associated with exposure to contaminants, as well as many of the most important cultural values of ecosystems in management decisions on the Great Lakes (e.g., people's desire to protect the Great Lake for future enjoyment by their children, or citizens' strong spiritual connection or sense of self-identification with the Great Lakes). There is a terrific opportunity here for the current and future generations of social scientists to institute new survey-based monitoring programs that can quantify non-use value of ecosystems.

As ecological monitoring programs increase in spatial and temporal resolution, and as monitoring programs for social benefit expand, methods for data analyses and modeling will need to be refined to take full advantage of the information. Here we see several opportunities. First, market-derived estimates of value will need to be compared or combined with economic and social values that are less easily monetized. For example, a full accounting of benefits achieved by restoring X acres of habitat to increase wild rice production in the Lake Superior watershed will require approaches that include both the added market value of rice commerce and the enhanced cultural benefits gained by tribal communities. We recognize that the methodologies for non-market valuation, as well as their limitations, are well-established (cf. Heal, 2000). However, to the extent that ES are more than just functions convertible to dollars (e.g., human mental and physical health, bequest values, inspiration, community pride), methods need further development and may be as limiting as data gaps and current research community capacity. For example, how do we quantify human happiness vis-à-vis the Great Lakes? And once we do quantify these non-economic values, how do we integrate them into management and decision-making frameworks with economic forms of valuation?

Merging qualitative and quantitative information into a common modeling framework has precedent with methods such as Bayesian inference where qualitative information can be used as prior knowledge (essentially, an a priori hypothesis) that constrains the fit of data to a particular model. Other approaches include the fields of Artificial Intelligence and Machine Learning where the construction of algorithms can allow one to learn from and make data-driven predictions or decisions without following strictly static program instructions. There are great opportunities for future practitioners of ES in the Great Lakes to adopt and develop these emerging methodologies and their kin to merge the types of quantitative and qualitative information needed to quantify and fully describe ES.

Another methodological challenge involves quantifying synergies and trade-offs among ES. In those instances where ES co-vary positively with one-another, it may be relatively easy to find 'win-win' scenarios for multiple stakeholders who value different goods or services of ecosystems (e.g., restoring wetlands to create habitat but also act as nutrient filters; Steinman and Ogdahl, 2016). On the other hand, when ES co-vary negatively, trade-offs may occur. For example, Angradi et al. (2016) examined a restoration scenario that increased shallow water habitat to enhance wild rice at the expense of deep water habitat that would promote boating. Another trade-off example focuses on ES associated with Great Lakes river mouth ecosystems, where lotic and lentic systems meet and interact. Many Great Lakes river mouths have been channelized, armored, and dredged to enhance commercial and recreational shipping and boating, but in the process have destroyed or negatively impacted ecosystem structure (e.g., littoral biodiversity) and function (e.g., nutrient retention, primary and secondary productivity) (Larson et al., 2013). Because the former ES can be quantified through traditional markets and assigned a value, but the latter ES are not readily valued through market-based approaches and therefore their loss is difficult to weigh, our current assessment of ES values is unbalanced, and can lead to poorly informed management decisions. This suggests that practitioners must learn new techniques and tools that can optimize the multi-functionality of ecosystems.

Certain forms of social science are already well versed in methods of optimization and social equity. For example, in economics the use of 'efficiency frontiers' can find optimal portfolios that offer the highest expected return for a defined level of risk. In contrast, only a relatively small subset of natural scientists receive training in techniques used for optimization, and only recently have they developed the methods to quantify the positive and negative covariance of multiple ecological production functions simultaneously (Byrnes et al., 2014; Lefcheck et al., 2015). Because these tools are not widely adopted, there is yet another opportunity for different disciplines to translate and use their knowledge in the nascent field of ES.

Question #3. What is the future of ecosystem services in the Great Lakes?

Background

The field of ES has the potential to help inform some of the grand challenges facing the Great Lakes, including: 1) impacts of climate; 2) expected responses to major anthropogenic forces such as excess nutrients, water withdrawal, and introduction of invasive species; and 3) identifying the small to large-scale linkages and feedbacks among societal decisions, biological systems, and physicochemical dynamics. For example, addressing these challenges would benefit from the establishment of a monitoring, modeling, and forecasting system of ecosystem services. To be effective, such a system would need to identify how the data will be obtained to develop the models of ES, and once we have those data, how they should be utilized to develop more predictive models.

Summit Findings

Our current tools to acquire environmental data tend to be labor-intensive and at coarse spatial and temporal scales. If, for example, we want to predict how climate change will impact beach recreation, how many observations are needed to adequately monitor water temperature, currents, nutrient concentrations, cyanotoxins, phytoplankton species composition, and pathogens in real- or near real-time? And once we have the appropriate environmental data in hand that help predict whether a beach should close, how do we monitor travel costs for beach-goers, property values, or any other measure of the ES? While the Great Lakes Observing System (GLOS) coordinates a network of federal, state, academic and private institutions to gather and disseminate data in the Great Lakes, we lack a coordinated system or mechanism to determine the social benefit or cost associated with the type of data generated from GLOS or other data collection networks.

Given the legacies of past stress, as well as the current and future ones facing the Great Lakes (Danz et al., 2007; Allan et al., 2013), it is relevant to ask whether there is potential to restore the lost services of ecosystems, and what knowledge or information is needed to ensure these efforts are successful. Extensive ecological restoration has already occurred or is planned to occur throughout the Laurentian Great Lakes as part of the GLRI and Great Lakes Legacy Act, as well as other public and private funding sources. The GLRI began in 2010, with the intent to accelerate efforts to protect and restore the Great Lakes; between FY 2010 and FY 2015, the US Congress appropriated ~$2 billion on five focus areas: toxic substances and Areas of Concern; invasive species; nonpoint source pollution impacts on nearshore health; habitat and species; and foundations for future restoration actions; ~$351 million has been spent on habitat restoration alone (GLRI, 2015). Assuming that GLRI funding continues into the future, it is anticipated that greater emphasis will be placed on forecasting and predictive modeling of future threats (C. Davis, pers. comm.); hence, having a fuller understanding of the role of ES in the Great Lakes should help in prioritizing efforts not only for ecosystem restoration, but also areas for preservation (cf. Allan et al., 2015).

The restoration of the south shoreline of Muskegon Lake (MI), a Great Lakes AOC, illustrates how quantifying ES can inform ecosystem restoration. A $10 million restoration project was initiated in 2010 with the multiple goals of softening ~3050 m of hardened shoreline (foundry slag, mill debris, riprap), restoring ~4.4 ha of wetland habitat, and removing or improving ~20 ha of unnatural lake fill (103,215 m^3). Isely et al. (2011) revealed through a combination of hedonic analysis and travel cost estimates that this $10 million investment in restoring the Muskegon Lake AOC results in a return of investment of $66 million over a 10-year period, largely due to increased property values and a more attractive environment to recreate (Fig. 3). However, the non-market valuation did not take into account non-use ES, such as community pride and improved human health associated with utilizing a new walking and bicycle trail along the shoreline. While the project has resulted in improved habitat (Ogdahl and Steinman, 2014), the restoration design was based largely on the need to restore a certain area of habitat to remove the offending beneficial use impairment, with limited consideration of how ES approaches could inform the design or assess success. A simple conceptual model shows habitat restoration serving as an ecosystem production function, in this case to restore fish and wildlife production (Fig. 3). However, fish and wildlife *per se* do not become ES until people demand or otherwise value them. Accounting for these types of ES may have resulted in a different restoration design and undoubtedly would have generated an even greater estimate of the project's return on investment.

Muskegon Lake is just one of many Great Lakes Areas of Concern, each of which can provide a natural laboratory for documenting how and where habitat restoration benefits or fails to benefit human communities. Every AOC has a public advisory council (or equivalent) that involves stakeholders in the decision-making process. This wealth of local information can help to describe the social and cultural values that are important in identifying the appropriate locations for restoration (cf. Angradi et al., 2016). A coordinated, multidisciplinary analysis of case studies, using AOCs as a database, can identify ecological production functions and the social values (Figs. 1, 3) involved in ES determination.

Finally, given the sensitivity of the Great Lakes to a changing climate and its societal implications (Gronewold et al., 2013), it is vital to assess the role of ES in the adaptability and resiliency of human social systems in response to climate change. Viewing these potential changes to the Great Lakes through the lens of ES makes sense given their economic and cultural importance. The harmful algal bloom (HAB) issues in the western basin of Lake Erie illustrate this point. The combination of changing agricultural practices, timing of precipitation and subsequent nutrient runoff, and climatic conditions in Lake Erie (i.e., calm winds) have led to massive HABs in recent years in this region (Michalak et al., 2013). The causes and ecological implications of these blooms have been well-documented (cf., Michalak et al., 2013; Bosch et al., 2014; Obenour et al., 2014). A full accounting of ES associated with HABs, including the shutdown of a public drinking water supply, as well as others that are often ignored and can be informed by including stakeholders (McCahon Kalcic et al., 2016) can lead to more informed decision making.

Conclusions and recommendations

A workshop composed of 28 individuals with expertise in ES convened to assess the state of ES in the Great Lakes. ES analyses to date have focused on those where data currently exist – mostly measures of those use values (e.g., navigation, fishing) in and around habitats that are heavily used (e.g., AOCs, beaches), leaving significant gaps in our understanding. While these analyses provide important information, they are incomplete, resulting in management decisions based on partial information. We identify 4 recommendations to address this issue:

1) Create a network of ES practitioners in the Great Lakes, which fosters and incentivizes relationships among all relevant sectors;

2) Conduct a comprehensive analysis of ES in the Great Lakes ecosystem; we recognize this is not a trivial undertaking, but such an analysis will lead to more informed management decisions. While there is still much room for improvement in our measures of ES that involve use values, we propose that the greatest areas of need are for measures of less assessed use values and non-use values of ecosystems. These represent measures where few data presently exist. In addition, we recommend compiling baseline data to serve as point in time for future trend analysis (e.g., a “Great Lakes Natural Capital circa 2025” snapshot);

3) Establish a Great Lakes Institute of Ecosystem Services, dedicated to the study of ES in the region. Given the geographic identity and linkage to the water provided by the five Great Lakes and their connecting channels, and the increased attention and resources being focused on the region, the establishment of this institute emerged as a consensus recommendation from the workshop. This institute would have several functions: a) serve as a locus for bringing together experts from the academic, private, and public sectors to address ES issues germane to the Great Lakes; b) house a Great Lakes education and training program for ES practitioners, including

students; c) develop new tools and approaches for breaking down disciplinary barriers; d) identify funding opportunities and support for interdisciplinary projects across the Great Lakes; and e) provide cross training for students, including interdisciplinary graduate student committees, as well as postgraduate certificates or training programs for mid-career professional development for environmental NGOs, governmental agencies, and private sector practitioners; and

4) Develop a list of major research questions to be answered over the short (1-5 yr) and long (>10 yr) term revolving around ecosystem services in the Great Lakes.

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Table 1. The individuals and organizations participating in the ES summit.

Name	Institution
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Kate Brauman	University of Minnesota – Twin Cities
Muruleedhara Byappanahalli	U.S. Geological Survey
Brad Cardinale	University of Michigan
Matt Doss	Great Lakes Commission
Diane Dupont	Brock University
Annie Johns	NOAA Office of Response and Restoration
Donna Kashian	Wayne State University
Frank Lupi	Michigan State University
Peter McIntyre	University of Wisconsin – Madison
Todd Miller	University of Wisconsin – Milwaukee
Michael Moore	University of Michigan
Rebecca Logsdon Muenich	University of Michigan
Wayne Munns	U.S. EPA
Mary Ogdahl	University of Michigan
Rajendra Poudel	University of Minnesota – Duluth
James Price	U.S. EPA
Bill Provencher	University of Wisconsin – Madison
Anne Rea	U.S. EPA Safe & Sustainable Water Resources Research Program
Jennifer Read	University of Michigan
Steven Renzetti	Brock University
Brent Sohngen	Ohio State University
Alan Steinman	Grand Valley State University
Marc Tuchman	U.S. EPA Great Lakes National Program Office
Erika Washburn	University of Wisconsin Cooperative Extension - Lake Superior National Estuarine Reserve

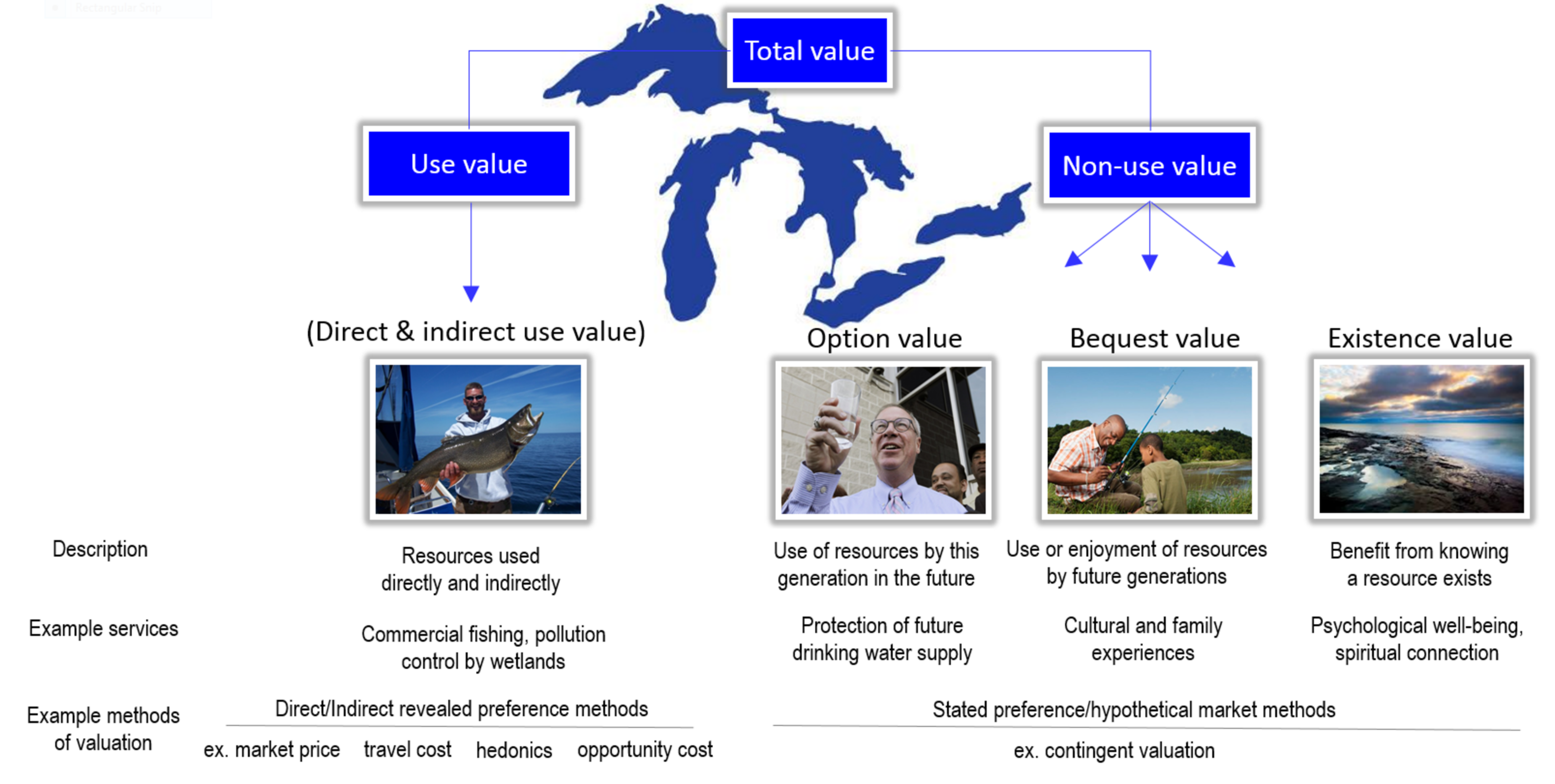
Figure Captions

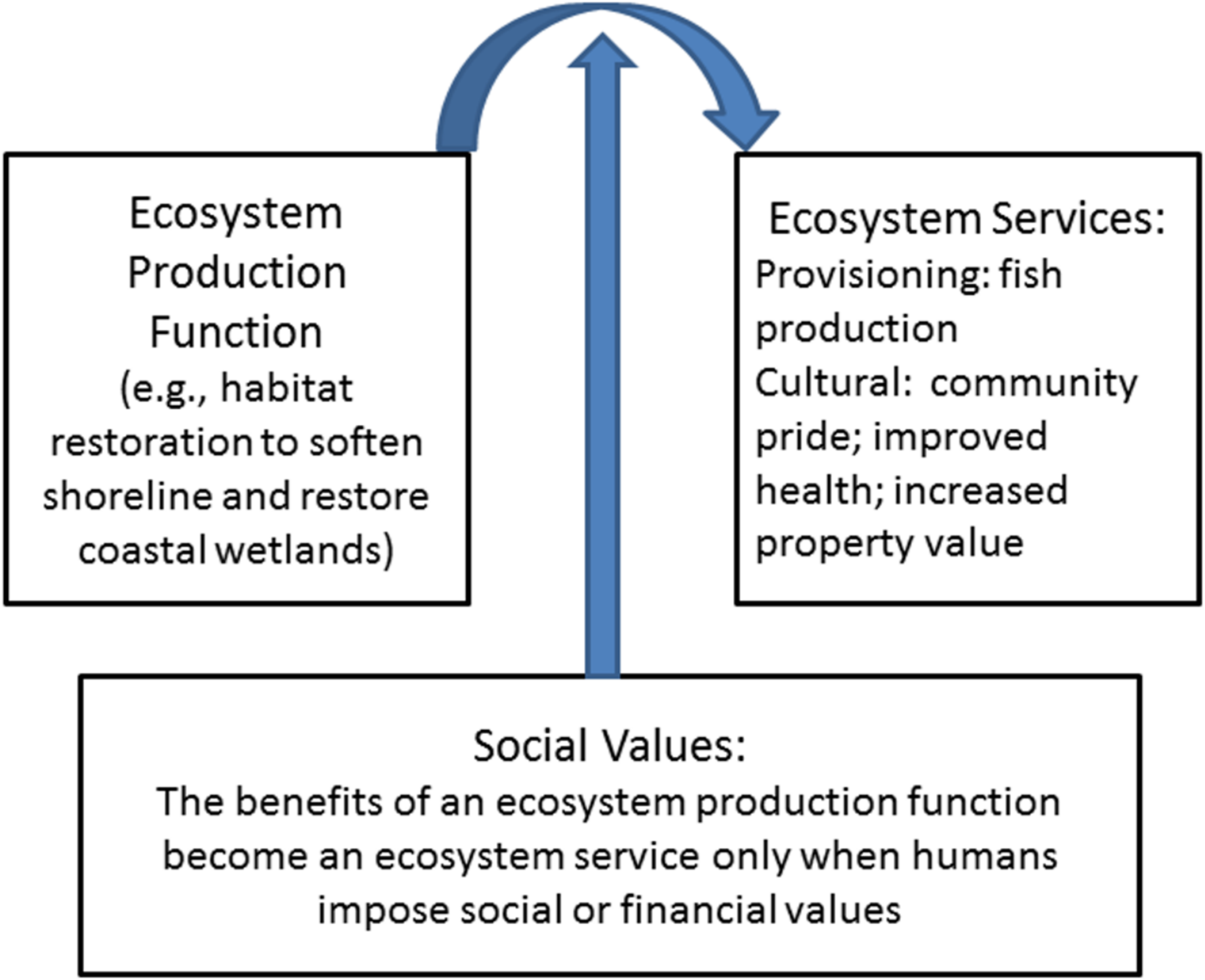
Fig. 1. Schematic of how the ecological production function and the social demand function interact to produce an ecosystem service.

Fig. 2. Flow diagram showing the components contributing to the total value of an ecosystem.

Fig.3. A simplified conceptual model that links ecosystem functions and ecosystem services (after The Quintessence Consortium, 2016).


e.g., increased fish production (catch per unit effort)
Ecological production function
Ecological output
Ecological process
e.g., restoration of coastal wetlands (hectares)
+
e.g., Friday night fish dinner ($'s paid at restaurant)
Social demand function
Social value
Ecological output
e.g., increased fish production (catch per unit effort)
=
Ecosystem service
e.g., partial value of coastal wetlands ($ per hectare)


Total value
Use value
Non-use value
(Direct & indirect use value)
Option value
Bequest value
Existence value
Description
Resources used directly and indirectly
Use of resources by this generation in the future
Use or enjoyment of resources by future generations
Benefit from knowing a resource exists
Example services
Commercial fishing, pollution control by wetlands
Protection of future drinking water supply
Cultural and family experiences
Psychological well-being, spiritual connection
Example methods of valuation
Direct/Indirect revealed preference methods
ex. market price
travel cost
hedonics
opportunity cost
Stated preference/hypothetical market methods
ex. contingent valuation


Ecosystem Production Function (e.g., habitat restoration to soften shoreline and restore coastal wetlands)
Ecosystem Services:
Provisioning: fish production
Cultural: community pride; improved health; increased property value
Social Values:
The benefits of an ecosystem production function become an ecosystem service only when humans impose social or financial values