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Ecosystem services of Lake Erie: Spatial distribution and concordance of multiple services

J. David Allan [a,*], Nathan F. Manning [a], Sigrid D.P. Smith [a,b], Caitlin E. Dickinson [a], Christine A. Joseph [a], Douglas R. Pearsall [a,c]

[a] School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI 48109, United States
[b] Department of Agriculture and Natural Resources, Delaware State University, Dover, DE 19901, United States
[c] The Nature Conservancy, 101 East Grand River Avenue, Lansing, MI 48906, United States

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ABSTRACT

The Laurentian Great Lakes provide a wide range of ecosystem services (ES) whose spatial distribution and extent are largely unquantified, thus limiting our understanding of ES co-occurrence, magnitude of ES supply, and the incorporation of ES into environmental planning. We mapped the spatial distribution of twelve ES in the Lake Erie Basin, including three supporting, three provisioning and six recreational/cultural services at three scales of analysis: sub-basins, counties and natural or urban focal areas. Whether ES are quantified by number of service sites or service delivery, the concordance of services varied among locations. Some ES were found to be spatially correlated, likely due to common function, such as sport fishing, boat launches and marinas, and other ES were co-located according to shared 'human habitat' in or near urban centers, as seen with municipal parks and municipal water supply. Most ES were spatially uncorrelated, and significant associations were almost exclusively positive. Total service delivery varied significantly among locations at both the county and focal area scales, indicating that areas of both high and low overall service delivery were common. Managers may benefit from awareness of the extent of ES delivery for different services in their area of interest, including co-benefit opportunities to improve delivery of multiple services.

Introduction

The Laurentian Great Lakes provide a wide range of human benefits, including municipal and industrial water supply, wildlife and fisheries support, and exceptional opportunities for recreation and nature enjoyment associated with the largest body of surface fresh water on earth (Pearsall et al., 2012; Allan et al., 2015; Angradi et al., 2016). Although the supply of ecosystem services (ES), defined as the benefits that people obtain from ecosystems (Millennium Ecosystem Assessment, MEA, 2005), is frequently cited as the rationale for management and restoration actions, their incorporation into environmental planning has been limited due to a lack of detailed information on their spatial distribution and extent, and of the relationship of services to one another and to environmental stressors (Allan et al., 2013, 2015). Nonetheless, a number of studies have articulated the potential of ES assessment and mapping to improve environmental management and decision-making (De Groot et al., 2010; Chan et al., 2012; Munns et al., 2015; Schaefer et al., 2016; Annis et al., 2017). Because the value of ecosystem services is determined by the location where services are provided and benefits are derived, ES information should be spatially explicit (Tallis and Polasky, 2009).

Much interest in ES has been driven by questions regarding the inter-relationships among services, including potential trade-offs as well as multiple positively correlated ES, often referred to as bundles (Bennett et al., 2009) or hotspots (van Berkel and Verburg, 2012; Queiroz et al., 2015). Trade-offs occur when the quality or quantity of an ES being used by one stakeholder is reduced as the result of other users of that or another ES (Rodríguez et al., 2006). The trade-off between agricultural production and water quality, as seen in the fertilizer-driven algal blooms of western Lake Erie, is a relevant Great Lakes example (Kerr et al., 2016), as is the harvest allocation between recreational vs. commercial fisheries (Gaden et al., 2013). On the other hand, a mix of positively correlated ES may occur together in the same place and at the same time, whether or not a causative relationship exists (Bennett et al., 2009). For example, Great Lakes wetlands provide wildlife habitat, fisheries support and water quality improvement, and potentially provide sediment and nutrient storage and carbon sequestration (Sierszen et al., 2012); thus, wetland protection can be expected to yield co-benefits.

* Corresponding author.
E-mail address: dallan@umich.edu (J.D. Allan).

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Studies of the spatial relationship among Great Lakes ES are few. Allan et al. (2015) reported that five recreational services aggregated into spatial units based on county shorelines were significantly positively correlated. Spatial correlations between pairs of 23 biophysical services in the St Louis, MN, estuary were generally low (Angradi et al., 2016). However, that study did find both positive and negative correlations that resulted from the association of particular services with shallow water (wild rice and fish spawning) vs. deep water habitats (power and sailing boats), such that management action affecting water level would generate a trade-off.

Growing interest in Great Lakes ES is evidenced in the scientific literature and in policy documents. An ISI Web of Science literature search using ecosystem services or ecological services and Great Lakes or names of individual lakes found 110 studies since 1999, initially with 0–2 papers published annually but increasing to 8–10 per year by 2010 and doubling to 16–19 annually in 2015–2016. This mirrors the growth of publications in all areas of ES studies (Boerema et al., 2016). Ecosystem services are also referred to within the 2012 Great Lakes Water Quality Agreement (https://binational.net/2012/09/05/2012-glwqa-aqegl/) and the Great Lakes Restoration Initiative's report to Congress (https://www.glri.us/pdfs/21050720-report_to_congress.pdf). Clearly, information regarding ES provisioning of individual services, and whether ES are positively or negatively correlated, can benefit managers and the public in prioritizing lake management actions.

The present study maps the spatial distribution of 12 ES throughout the Lake Erie Basin (LEB) for which location and extent of service provisioning could be estimated or approximated, including 3 supporting, 3 provisioning and 6 recreational/cultural services for both coarse and fine scales of analysis (Table 1 and Fig. 1). These ES represent three of the four commonly distinguished categories of services (MEA, 2005) but do not include regulating services which were not feasible to quantify as these are the result of highly dispersed ecosystem functions. The goals of this study were to (1) quantify the spatial distribution and delivery of 12 ES for the Lake Erie Basin, (2) evaluate spatial concordance of ES at both coarse and fine spatial scales to better understand how services may be inter-related, and (3) interpret the likely causes of spatial patterns and both positive and negative associations among ES. Lastly (4), we examine whether total service delivery varies spatially.

Table 1
Examples of Great Lakes ecosystem services, following the widely used classification of the Millennium Ecosystem Assessment (MEA) (2005), and data layers included in this study.

Service	Great Lakes examples	Included data layers
Provisioning	Commercial fishing, drinking water, water for thermo-electric plant cooling, hydro- and wind power	Commercial fishing - port landings Water withdrawals - municipal Water withdrawals - thermoelectric cooling
Cultural	Recreational experiences, nature and viewscape enjoyment, historical interests, spiritual fulfilment	Sport fishing angler effort Recreational boating Beach use Birding activity Park use – federal and state/provincial Park use – municipal
Supporting	Primary production, nutrient cycling, habitat supporting biodiversity	Coastal terrestrial biodiversity significance Coastal wetland biodiversity significance Important Bird Areas
Regulating	Climate regulation, water purification, nutrient and organic matter processing, resistance to invasion	None

Methods

The Lake Erie Basin

Lake Erie is the smallest, shallowest and most southern Great Lake (GL), and as a result is the warmest of the lakes and has the shortest water retention time. Lake Erie is bordered by New York, Pennsylvania, Ohio, Michigan and Ontario, and a small portion of the Maumee headwaters lies in Indiana. Some 11.6 million people live in the LEB, and about 11 million receive their drinking water from the lake (Pearsall et al., 2012). Lake Erie is considered to be exposed to greater stress from agriculture and urbanization than any of the other GLs (Dolan, 1993; USEPA, 1999).

Lake Erie typically is divided into three basins: a shallow western basin (WB, mean depth 7 m, maximum depth 18.9 m), a large central basin (CB, mean depth 18 m, maximum depth 25 m) deep enough to stratify during summer, and a much deeper eastern basin (EB, mean depth 25 m, maximum depth 64 m). The upper lakes drain into Lake Erie via its upstream connecting river system consisting of the St. Clair River, Lake St. Clair and the Detroit River (St. Clair-Detroit River system, SCDRS); and Lake Erie outflow connects to Lake Ontario via the Niagara River and shipping canals. Consistent with the Lake Erie Lakewide Action and Management Plan (LAMP, USEPA, 2014) this study recognizes four major units: western, central and eastern basins and the SCDRS.

We evaluate service overlap at three spatial scales (Fig. 1): (1) along the shoreline of the four largest sub-units described above (WB, CB, EB and SCDRS); (2) within shoreline polygons defined by U.S. and Ontario counties; and (3) for focal areas defined as natural or urban. Following Allan et al. (2015), shoreline polygons are delineated by the LEB's 22 county units and a 10-km buffer centered on the shoreline. Most biological resources (Vadeboncoeur et al., 2011) and human activities are concentrated along the shoreline, and nearshore influence on water quality attenuates at ~3–5 km (Kelly et al., 2015). Similarly, land-based biological resources are dependent on lake conditions to a distance of ~2–5 km (Pearsall et al., 2012; Bonter et al., 2009). As natural areas we selected national, state and provincial parks bordering Lakes Erie and St. Clair and >2 km^2 in area. We then buffered a 10-km-radius around the centroid of each and dissolved overlap to avoid double-counting of services, identifying 12 units. As urban areas we selected cities with populations >25,000, and again buffered a 10-km-radius around each and dissolved overlapping polygons, identifying 10 units.

Lake Erie ecosystem services

We obtained data from multiple sources to map service distribution (see Electronic Supporting Information [SI] Appendix A for detailed methods and data sources). The scale of available data varies and we use both down- and upscaling for purposes of comparison of individual data layers. Point data are given an approximate location such as the centroid of a beach, a marina or a port for commercial catch landings, and so are accurate at approximately the 1-km^2 scale. Some point data such as municipal water intakes or reported birding hotspots are accurate at a finer scale than 1-km^2, but these services obviously are dependent on some larger, surrounding area and not just the exact point. Management units for reporting sport-fishing activity and biodiversity services are represented by polygons of varying size. Data are representative of the 2000–2010 timeframe, with minor differences due to data availability, and water withdrawal data are more recent. Whenever possible we examined time series to determine whether a trend existed, and we averaged over time when no recent trend was obvious in that ten-year period (e.g., commercial fishing) and used the most recent years when a trend was noted (e.g., sport fishing effort is trending down). See SI for further information.

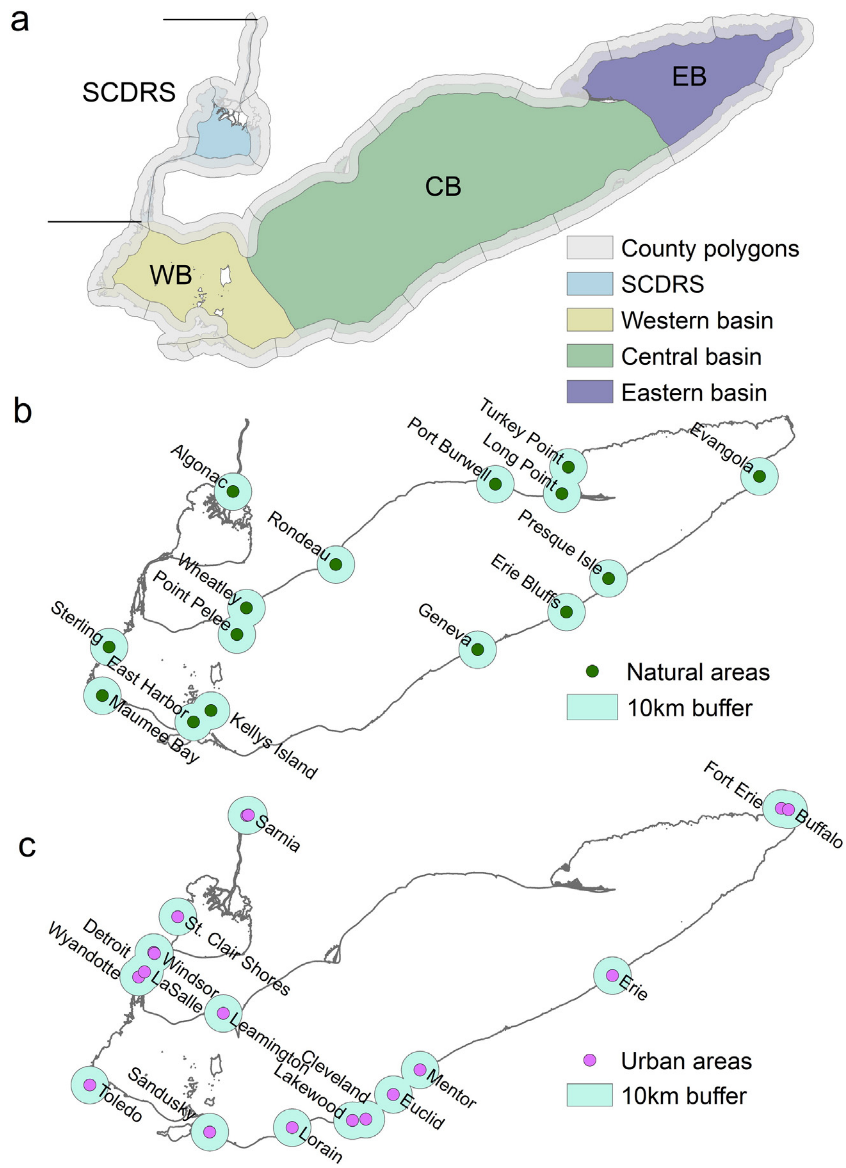

Fig. 1. Lake Erie Basin illustrating the three scales of analysis of service concordance. (a) The largest scale includes 4 units: the three sub-basins and the St. Clair Detroit River System (SCDRS). The intermediate scale consists of 22 shoreline polygons based on county boundaries and extending 5 km into land and 5 km into water. (b, c) The finest scale consists of 10 km circular buffers based on urban areas (>25,000 population within buffer) and on important natural areas. Whenever two natural or two urban areas were sufficient close that their buffers overlapped they were combined into a single unit resulting in 12 natural and ten urban areas in the analysis.

Provisioning service - commercial fishing

We reasoned that the spatial delivery of this ES was best represented by the first point of landing and obtained port landings (combined weight all species) for the years 2000–2009 from state governments, tribal authorities and the Ontario Ministry of Natural Resources.

Provisioning service - water withdrawals

While states and provinces are required to report water use information annually under the Great Lakes-St. Lawrence River Basin Water Resources Compact, there is no comprehensive database detailing withdrawal amounts by location of intake pipes. For the U.S., we compiled intake locations and annual (2013 or 2014) withdrawal amounts from individual state contacts and an intake/outfall database maintained by the Great Lakes Commission (GLC, 2014) Ontario keeps records on permits to take water (Ontario Ministry of Environment and Climate Change, 2015) but reports only locations and intake capacities, and we used a predictive relationship between capacity and withdrawal based on U.S. intakes reporting both ($y = 0.35x$; $R^2 = 0.96$, $N = 23$) to estimate public water supply withdrawals for Ontario intakes. We mapped all intake pipes drawing surface water for public water supply or thermoelectric cooling of power plants within 5 km of the shoreline. Water withdrawals for thermoelectric cooling were mapped by Allan et al. (2013).

Supporting service - coastal wetland biodiversity significance

Biodiversity significance of wetlands was estimated by the Lake Erie Biodiversity Conservation Strategy (LEBCS, Pearsall et al., 2012). Our study obtained biodiversity significance scores from the LEBCS and re-scaled data from 0 to 1 based on the observed minimum and maximum. Spatial units employed by the LEBCS extended 2 km inland from the shoreline and their lateral extent was determined by boundaries between major watersheds. Because the underlying data were not readily available for re-aggregation and we could not assess how much error would result from re-distributing these data to the county units of our analyses, we elected to leave these data in the LEBCS spatial units and thus excluded them from our county and focal area scale analyses.

Supporting service - coastal terrestrial biodiversity significance

Biodiversity significance of terrestrial ecosystems was estimated by the LEBCS (Pearsall et al., 2012). We re-scaled data from the LEBCS to 0–1 based on the observed minimum and maximum as above.

Supporting service - Important Bird Areas

An Important Bird Area (IBA) is an area recognized as being globally important habitat for the conservation of bird populations. Using data from the National Audubon Society and Bird Studies Canada, we mapped IBAs located within 5 km of the Lake Erie and SCDRS shoreline for the U.S. and Ontario. For Ontario we obtained IBA polygon data, which we represent as points at the centroid of each polygon. For all U.S. states, maps were developed from IBA latitudinal and longitudinal coordinates. IBAs are not distinguished by relative importance or value, hence are mapped and analyzed as number of locations but not as service delivery.

Recreational services - sport fishing

We divided recreational fishing into charter and private (non-charter). Recreational fishing data were obtained from annual reports by individual states and the province of Ontario, and through direct communication with data managers (Allan et al., 2015). We selected angler hours as our measure of fishing activity, under the premise that an angler derives benefit (and contributes to the local economy) whether or not fish are captured. When charter and private fishing were not distinguished in agency reports, we were informed by reporting agencies that charter fishing was minor, and we reported the combined data as private fishing effort. We averaged data from 2009 to 2011 to smooth inter-annual variation. Agency report data typically are summarized by individual reporting districts within each lake. District boundaries were taken from Smith et al. (1961) and adjusted when necessary to reflect current reporting units through consultation with agency staff. To obtain further detail on charter operators we consulted state agency listing of charter boat captains, supplemented by online lists of state and Ontario fishing associations and web searches. Locations were assigned to a specific marina when provided, or to a central location within a homeport. Private and charter fishing were omitted from finer-scale statistical analyses, since we did not have confidence in further down-scaling the delivery data beyond their original reporting districts.

Recreational services – boating

We quantified the spatial distribution and approximated the extent of recreational boating based on point locations of marinas and boat launches. Marina locations in the U.S. and Canada were identified from internet sites and confirmed using Google Earth. As a measure of marina size and boating activity we determined the number of boat slips at each marina from their websites when available or counted boat slips directly from aerial imagery (Allan et al., 2015). Boat launch locations in the U.S. and Canada were identified through tourist information publications and from marinas that reported boat launch availability, and locations were confirmed using Google Earth. We used parking spaces at boat launches as a proxy of use of launch sites, which we obtained from agency sources or Google Earth imagery. For Canadian boat launches, where poor imagery precluded counting parking spaces, we estimated the number of parking spaces using a regression for parking lot area ($R^2 = 0.92$, $N = 9$).

Recreational services – beaches

Beach locations were obtained from the U.S. EPA BEACH Act Geospatial database, and Canadian beach locations were provided by Environment Canada and supplemented with provincial park beaches identified from Canadian protected lands databases. Because comprehensive beach visitation data are lacking, we selected beaches that were: (1) monitored for contamination or (2) within national, state or provincial parks. As a proxy for beach visitation, we used the InVEST model (Natural Capital Project, 2013) to count the number of geotagged Flickr photos within a 500-m buffer of each beach location (methodology in Wood et al., 2013, see Allan et al., 2015 for further details). Action days, which include both swim advisories and beach closures, were summarized for each monitored beach using EPA annual swimming season statistics and information provided by Environment Canada from 2007 to 2009. To compare the number of action days among beaches, the summed days were normalized by the length of swim season and the percentage of swim season under action was mapped.

Recreational services – birding

We mapped the most highly used and valued birding hotspots in the GL region using data from a variety of sources. To identify actively used bird-watching locations we used the citizen-science database eBird (Sullivan et al., 2009) and selected birding locations from a database of eBird “hotspots” (eBird Basic Dataset, 2012), which are point locations for which users can upload bird observations. Hotspots can be suggested by any user, but a verification process is in place to ensure they are unique and represent publicly-accessible locations. Hotspots were included if within 5 km of the shoreline, a distance that approximates lake influence on migratory bird populations (Bonter et al., 2009; Ewert et al., 2012). Use of each hotspot was calculated by summing the logged visits to a hotspot from January 1, 1999 through December 31, 2012. We selected only those locations that had 5 or more return visits to ensure each hotspot represented a service people utilize. In addition we mapped shoreline locations of birding trails and festivals and noted hotspots from the “Top 200 Birding Hotspots in North America” (Thayer, 2011, http://www.birding.com/top200hotspots.asp).

Recreational services – state, provincial and national parks

State, provincial and national park boundaries were compiled from a variety of sources due to disparate spatial coverage (Allan et al., 2015). U.S. parks were selected from the Conservation and Recreational Lands database (CARL), maintained by Ducks Unlimited, Inc. (2008), and the Protected Areas Database (PAD-US) produced by the Conservation Biology Institute (2010). Ontario Provincial and National Parks were selected from a Protected Lands database maintained by the Ontario Ministry of Natural Resources (OMNR, 2012). Parks were selected if the polygon, or any portion of the polygon, fell within 5 km of the GL shoreline. Visitation records were compiled for the years 2005–2010 (U.S.) and 2008–2011 (CA). Ontario park visits were obtained from Ontario Parks (2008–2011). U.S. visitation records were provided by individual state agencies, and national park visitation records were accessed on the National Parks Service Visitor Use Statistics webpage (NPS, 2013).

Recreational services – municipal parks

We were unable to locate any database suitable for identifying lakeshore municipal parks and quantifying visits. As a first step toward addressing this data gap, we attempted to locate large, public urban parks along the Lake Erie and SCDRS shoreline using Google Earth. We identified 36 urban parks and were able to obtain visitation data from park managers for 9 to provide some comparison with our data for state, provincial and national parks.

Statistical analyses

We determined both the number of service locations (e.g., number of beaches or birding hotspots) and service delivery (e.g., estimated number of beach or birding visits) at each spatial scale. Because the encompassed area differed among units (e.g., CB is larger than WB, counties differed in size, as did focal areas due to the annealing of overlapping units), we examined results without normalizing by area (“unscaled”) and after area normalization (“area-adjusted”). Our analysis focuses on service delivery after area adjustment. To compare delivery of multiple services that differed in measurement units (e.g.,

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millions of gallons of water withdrawal per day vs. hours of fishing effort), we used a min-max transformation to put all services on a comparable zero-to-one scale. To explore the spatial association among individual services, these transformed values were used in pairwise correlation analysis with Pearson correlation coefficients and multivariate hierarchical cluster analysis. Hierarchical cluster analysis identifies groups, or "clusters", of ecosystem services that are representative of different locations for the spatial units analyzed. Because clusters are hierarchical, the relationships they describe can change as the spatial scale of the system changes, thus differentiating clusters that are representative of the different spatial sub-divisions of the Lake Erie Basin. We evaluated differences among spatial units in overall service delivery by two-way ANOVA of transformed values. Finally, simple linear regression is used to explore a few specific relationship with human population density. All analyses were performed in R 2.12 (R Development Core Team, 2010) and ArcGIS 10.1.

Results

Ecosystem services: spatial co-occurrence of multiple services

Results in the SI report the locations of 12 ES in the LEB and the amount of service delivery at each location. Here we examine how the mix of services varies among spatial units, both for number of locations and amount of delivery or use, at each scale. We give all services equal weight and use the min-max transformed values with and without adjustment for unequal areal size of individual spatial units. We separate charter from private fishing for these analyses because they are quantified independently, and may differ in segment of public served and investment in boats and equipment. Similarly, we include boating activity estimated by two measures, marina and boat launch capacity, which may capture different segments of the boating public.

Service comparisons across sub-basins

As seen in maps of individual services (Figs. SI-1 to SI-8), parks, beaches and birding are important services along the Ontario shoreline of Lake Erie. Water withdrawals are greatest along the U.S. shoreline, particularly in Michigan and Ohio, and over 70% of the total charter and sport fishing effort is concentrated in the WB and counties bordering Lake St. Clair. The WB has the highest values for birding, boat launches, commercial fishing, and state and provincial parks based both on number of service locations and extent of service delivery. The CB leads in numbers of municipal parks and IBAs, and has the most beach and municipal park use. The SCDRS has the greatest number of marinas and water withdrawals for both public supply and thermoelectric cooling by locations and service delivery, as well as high municipal park use. The EB has the greatest number of beaches, but generally ranks lowest in most categories. However, only unscaled service delivery differs significantly among sub-basins (Table SI-1a), due to markedly lower values for the EB.

Service comparisons across county polygons

The mix of individual services varies widely among the 22 county-level units surrounding the LEB (Fig. 2a), and services vary significantly in number of sites and amount of service delivery, regardless of area adjustment (Table SI-1b). Inspection of the data reveals that counties with the most service locations differ in rank order from those that provide the greatest amount of service delivery, whereas area adjustment resulted in only minor changes in county rank. Cuyahoga, Lorain, Ottawa (OH) and Wayne (MI) Counties in the WB all experience high service delivery. Chatham-Kent (ON), Ashtabula and Lake (OH) Counties in the CB provide an intermediate level of service delivery. Sandusky County (OH) has very low service delivery, reflecting its limited extent of Lake Erie shoreline. Lowest total service delivery is evident in counties of the EB (both U.S. and Ontario).

Hierarchical cluster analysis of county-scale service delivery, excluding IBAs for which only locations are known and the two biodiversity ES because of incompatible spatial units, indicates that some ES tend to occur together (Fig. 2b). Co-location of boat launches, marinas and private fishing reflects the expected linkage between boating and fishing as recreational activities, whereas other positive associations, such as municipal parks and public water supply, may simply be the result of their co-location in urban areas. A few associations are not easily explained, such as between charter fishing and state/provincial parks, and may represent correlated habitat conditions. A pairwise correlation analysis for area-adjusted service delivery found significant ($P < 0.05$) correlations between 7 of 55 pairs (Table SI-2a). It is noteworthy that all were positive, and no significant negative correlations were found, suggesting that trade-offs between ES were not important at this scale of analysis.

Service comparisons for focal areas

We omitted municipal parks due to frequent missing data, and both private and charter fishing because we did not have confidence in further down-scaling. State and provincial parks were over-represented and municipal parks were under-represented in natural focal areas due to the selection process itself. Service delivery (Fig. 3a) for natural areas shows substantial variation in the mix of services by location, and the number of service locations and amount of service delivery differed significantly among natural focal areas whether area-adjusted or not (Table SI-1c). Highest service totals were recorded in Presque Isle State Park, PA (beaches, state parks); Kelley's Island and East Harbor State Park, OH (boat launches and marinas); Maumee Bay State Park, OH (public water supply); Sterling State Park, MI (thermoelectric water supply); and Pt Pelee National Park and Wheatley Provincial Park, ON (birding and commercial fish landings).

Hierarchical cluster analysis of service delivery for natural focal areas (Fig. 3b) found some expected ES associations, including beaches with state/provincial parks, and boat launches with marinas. These are interdependent ES as some beaches are within parks and some boat launches are co-located with marinas. As seen with county polygons, some associations likely have no functional significance. For example, birding and commercial fishing likely group together because some highly used birding sites (Pt. Pelee and Long Point, ON) are near major ports for commercial fish landings. Pairwise correlation analysis for area-adjusted service delivery found a significant ($P < 0.05$) correlation between 3 of 28 ES pairs, and all were positive (Table SI-2b).

For urban areas, service delivery (Fig. 4a) again showed substantial variation in the mix of services. The number of locations differed significantly regardless of area adjustment, and unscaled service delivery also differed significantly (Table SI-1d). Interestingly, after area-adjustment, service delivery did not differ significantly, indicating relative similarity of area-adjusted service delivery to urban locations. Highest service totals were recorded in Erie, PA (beaches, birding, state park visits), the Detroit metro area (public water supply, boat launches), and Port Huron, MI - Sarnia, ON (commercial fishing, thermoelectric water supply).

Hierarchical cluster analysis of service delivery for urban areas found that beaches, marinas and state/provincial parks clustered together, whereas birding was an outlier relative to all other ES (Fig. 4b). At this scale, marinas and boat launches were less closely associated, possibly because urban areas often are home to large marina complexes, whereas boat launch sites are more widely distributed. Of 28 pairwise comparisons, one between beaches and state parks was significantly positive ($P < 0.05$), a second between birding and marinas was marginally negative ($P < 0.10$) (Table SI-2c).

Interestingly, the highest focal area service delivery was essentially the same for natural and urban areas due to the close proximity of

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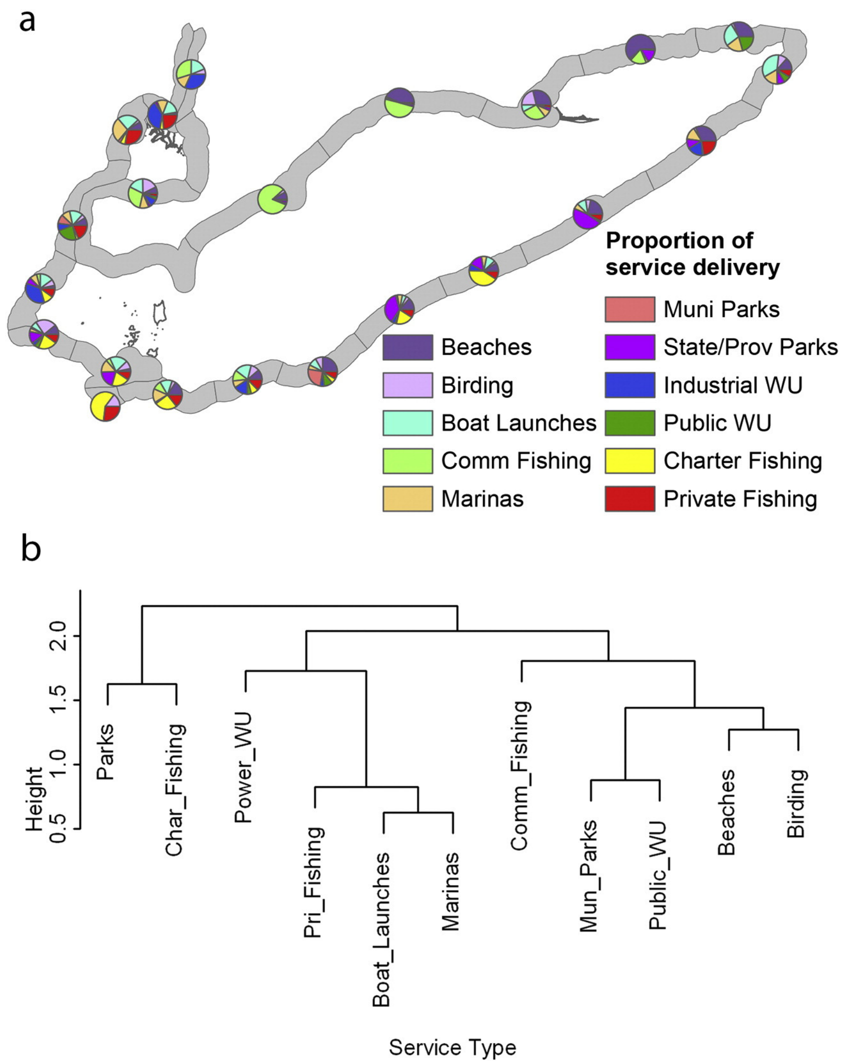

Fig. 2. (a) The relative amounts of service delivery by ES category for each of 22 counties of the LEB, illustrating how the mix of services differs among locations. (b) Hierarchical cluster analysis showing groupings of service categories based on service delivery at the county scale. Analyses use area-adjusted service delivery, re-scaled with a min-max transformation. Abbreviations: Char_Fishing = charter fishing, Comm_Fishing = commercial fishing, Pri_Fishing = private fishing, Muni-Parks = municipal parks, Parks = national, state and provincial parks, Power_WU = Power plant cooling water use, Public_WU = public water use.

Presque Isle State Park to the urban center of Erie, PA. Overall service delivery was greater in the selected urban areas when compared with the selected natural areas (T = 2.29, P = 0.03). Only a few natural areas had multiple services with scores near or above the median for individual services, whereas this was frequently the case among urban areas, which were less variable in their total service delivery.

Total area-adjusted service delivery differed significantly among spatial units at county and focal area scales but not at the sub-basin scale (Table SI-1) (Fig. 5). Because service delivery depends on human usage, we expected human population to at least partly account for this variation. Variation in ES delivery among counties was significantly related to county population ($R^2 = 0.36$, N = 21), with a few notable outliers. Ottawa County, OH, has the lowest population of any of the shoreline adjacent counties (41,428 in 2010) but the third highest fraction of service delivery (10.5% of total), presumably because of the popularity of the Bass Islands as a recreation destination with ample tourism infrastructure. In contrast, Erie County, NY, has the third highest population (919,866 in 2010) and sixth lowest fraction of service delivery (1.9% of total). Removing these outliers from the regression improved the relationship between service delivery and population ($R^2 = 0.60$), but indicated that there are still other, less easily quantifiable factors that influence the delivery of ES around Lake Erie. At the focal area scale, we found that marinas, municipal parks and both thermoelectric and public water withdrawal sites were more frequently located near urban centers, and even beaches, birding sites, boat launches and commercial fish landing locations had moderately more service delivery near population centers. Some 80% of municipal park visits and municipal water use occurred in and around population centers. The number of national, state and provincial parks located near population centers was as expected from the area represented, but two-thirds of park use occurred in those parks located near cities. Only commercial fish landings and water use for thermoelectric cooling were disproportionately lower near urban areas.

Discussion

By mapping 12 individual ES throughout the Lake Erie Basin, our results clearly show that whether quantified by number of service locations or by service delivery, spatial heterogeneity of ES is the norm. Our list of services is clearly not exhaustive, but the inclusion of three provisioning services representing commercial fishing and water supply for both public use and thermoelectric cooling, six cultural services for different recreational activities, and three services that support biodiversity ensures that many of the most frequently recognized services (e.g., Pearsall et al., 2012) are represented. However, we did not include regulating services, which may be difficult to quantify spatially.

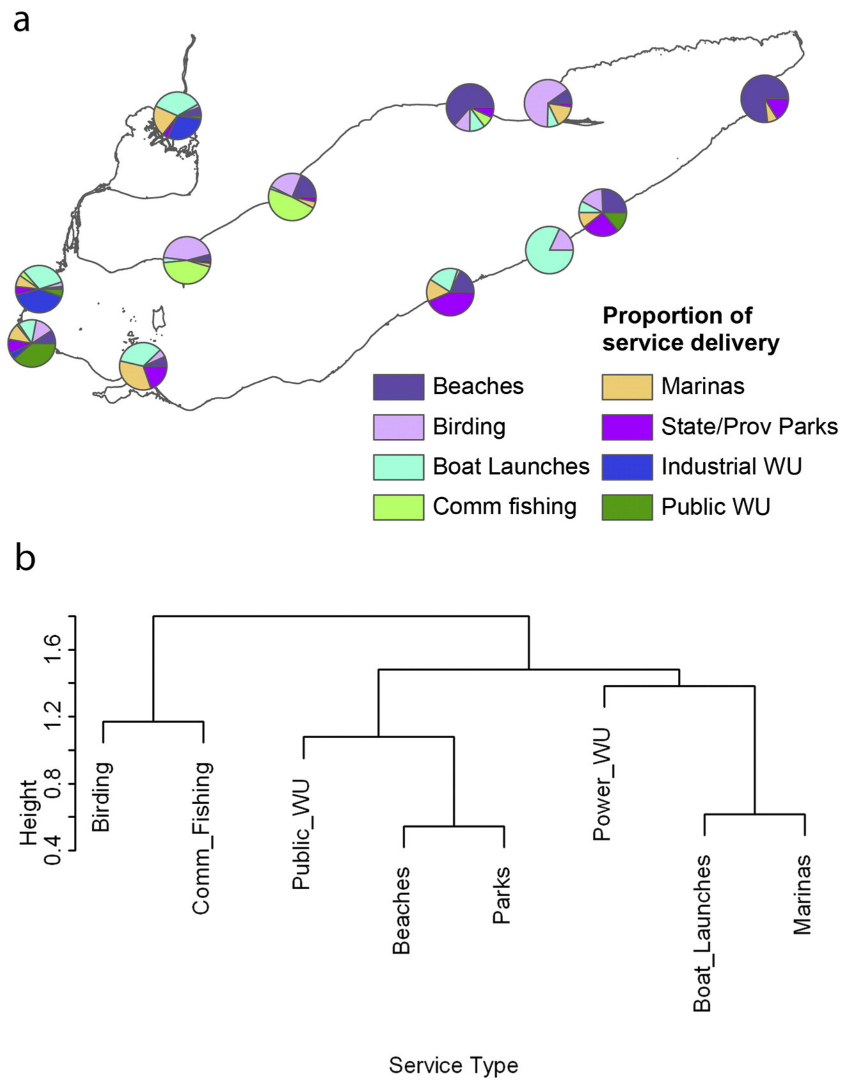

Fig. 3. (a) The relative amounts of service delivery by ES category for each of 12 natural areas of the LEB, illustrating how the mix of services differs among locations. See Fig. 1 for names of locations. (b) Hierarchical cluster analysis showing groupings of service categories based on service delivery in natural focal areas. Analyses use area-adjusted service delivery, re-scaled with a min-max transformation.

Inclusion of multiple services is relatively uncommon in ES studies (Boerema et al., 2016), and few previous GL studies have done so. Using a survey of managers, Pearsall et al. (2012) identified the ten most important ES as recreation, wildlife habitat, freshwater supply and purification, primary production, aesthetics, nutrient cycling, sense of place and climate regulation. Allan et al. (2015) mapped locations and extent of service delivery throughout the GL for five of the recreational services included here. Angradi et al. (2016) applied mapping criteria to spatially explicit biophysical data for 23 services in the St. Louis (MN) watershed and estuary, including natural views, boating, game and non-game fish and wildlife species, wild rice, parks and trails, beaches, property protection and sacred sites. While each of these studies points to the importance of various ES within the GL, it is notable that they differ in the services considered, methods used, spatial scale of analysis and additional specifics.

Current literature views ES as the final outputs from an ecosystem, still connected to the structures and processes that gave rise to them, and giving rise to the benefits that people enjoy (De Groot et al., 2010). The ES in this study occupy different positions in the ES cascade from originating ecosystem property and function to the final service, benefit or value that they produce (Boerema et al., 2016; Munns et al., 2015, Potschin and Haines-Young, 2016). The three biodiversity supporting services are ecological measures of ES supply, the three provisioning services are, in essence, end values, and the six recreational services might best be considered benefits.

We acknowledge several caveats to our analysis. Data represent a range of time intervals due to limitations of data availability. As seen in most empirical studies, the relationships we report among ES are spatial and thus temporally static. As a consequence they provide limited information regarding how one ES might change in response to a change in another ES due to some human action or management intervention (Renard et al., 2015). ES are given equal weight, although ES interdependencies may affect weighting and stakeholders may consider some to be of greater importance than others. For example, fishery quotas favor recreational over commercial fishing in U.S. waters while the opposite is the case in Canada, and quotas are re-visited annually (Gaden et al., 2013). Finally, while all services in this study are commonly identified as important (Pearsall et al., 2012), the list is not comprehensive. Additional measures of cultural values (Chan et al., 2012) would be desirable. We did not include agriculture, as our focus was on ES of the aquatic ecosystem, but conflict between agricultural land use and water quality is probably the most important trade-off in this system (Kerr et al., 2016).

By quantifying the supply of multiple ES around the LEB we sought to explore how multiple ES are spatially distributed and their extent of co-occurrence. We expected to find instances of positive and negative

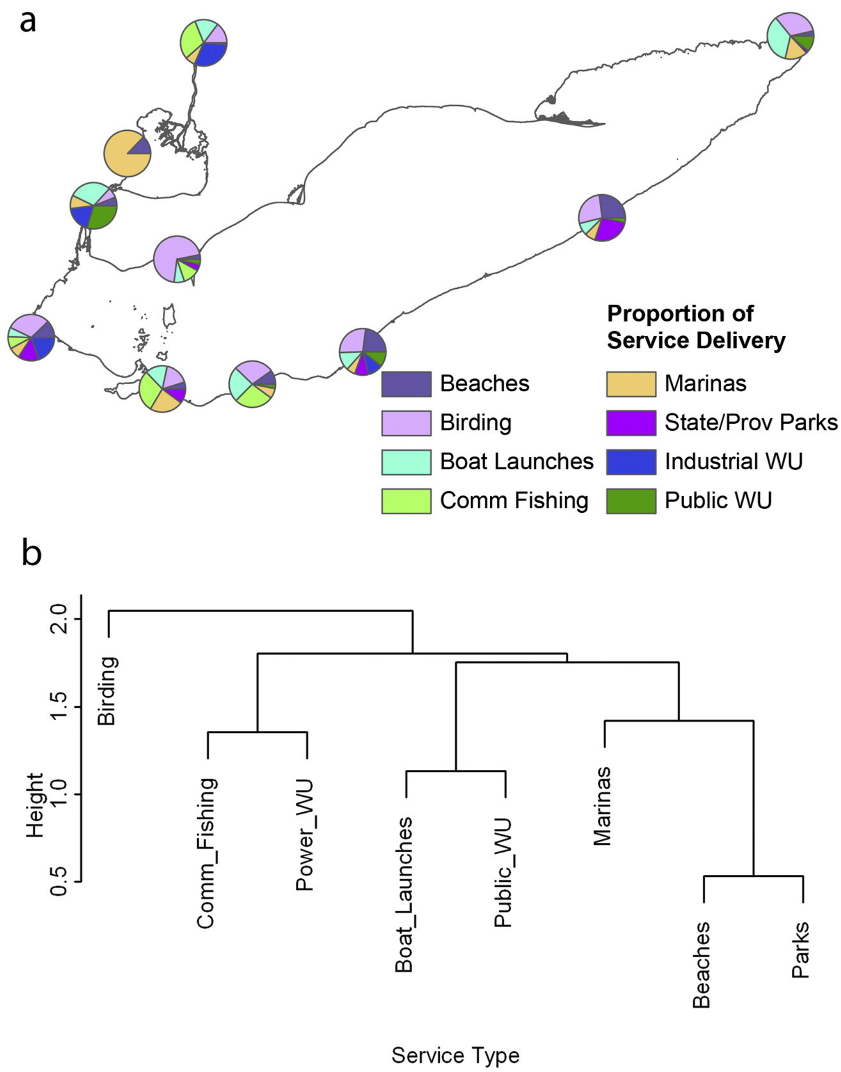

Fig. 4. (a) The relative amounts of service delivery by ES category for each of 10 urban areas of the LEB, illustrating how the mix of services differs among locations. See Fig. 1 for names of locations. (b) Hierarchical cluster analysis showing groupings of service categories based on service delivery in urban focal areas. Analyses use area-adjusted service delivery, re-scaled with a min-max transformation.

correlations, indicative of synergies and trade-offs and possibly the occurrence of some mix of positively correlated services. The finding that the included ES are at most weakly correlated and more likely to show a positive than a negative association is clearly supported by the data and analysis, but is at odds with many studies. Trade-offs have frequently been reported in the literature, and may substantially outnumber synergies. In a review of over 1300 studies (Howe et al., 2014), tradeoffs were strongly associated with provisioning services in which there was a private interest in the ecosystem service being used, such as harvest of crops or fish. In the few studies in which no provisioning service was included, the majority of interactions were synergies. The present study included three provisioning services, where one would predict tradeoffs based on that work, but the lack of tradeoffs found here may not be surprising. Water withdrawals are unlikely to conflict with other services given the volume of the Lake, and well-established management committees act to buffer conflicts between commercial and recreational fishing in most instances (Gaden et al., 2013). The recreational services included in this study are not obviously in conflict (Allan et al., 2015). Similarly, pairwise spatial correlations among mapped indicators for 23 biophysical services in the St Louis River and estuary were generally low (Angradi et al., 2016).

Although we found little evidence that the supply of one service compromises the supply of a second, the possibility exists that some future management action could have both positive and negative effects. For example, Angradi et al. (2016) predicted that a decision to manage water levels could generate a trade-off between ES that depended on shallow water (fish spawning, wetlands) and those dependent on deeper water (boating). In our study only one negative association approached significance ($P < 0.10$), between marinas and birding across urban focal areas. While one can envision marina construction affecting birding opportunities, it is at least as likely that by chance some of the ten urban areas supported large marina complexes, while other urban areas had superior nearby birding sites. One can speculate that some positive associations reflect synergistic management actions; for example, boat launches historically may have been sited to provide recreational fishing opportunities, and so private fishing now is greater near boat launches. To what degree the siting of boat launches reflects spatial variation in fishing opportunity vs. availability of public lands with suitable topography for boat launch construction, is an open question.

Hierarchical cluster analysis as well as pairwise correlations gave evidence that some ES tend to be spatially correlated due to common function. Private fishing, boat launches and marinas are closely associated in county-scale analyses, and to a lesser degree in focal area analyses. Beaches are associated with state/provincial parks within natural areas but show little association with either park category in county-

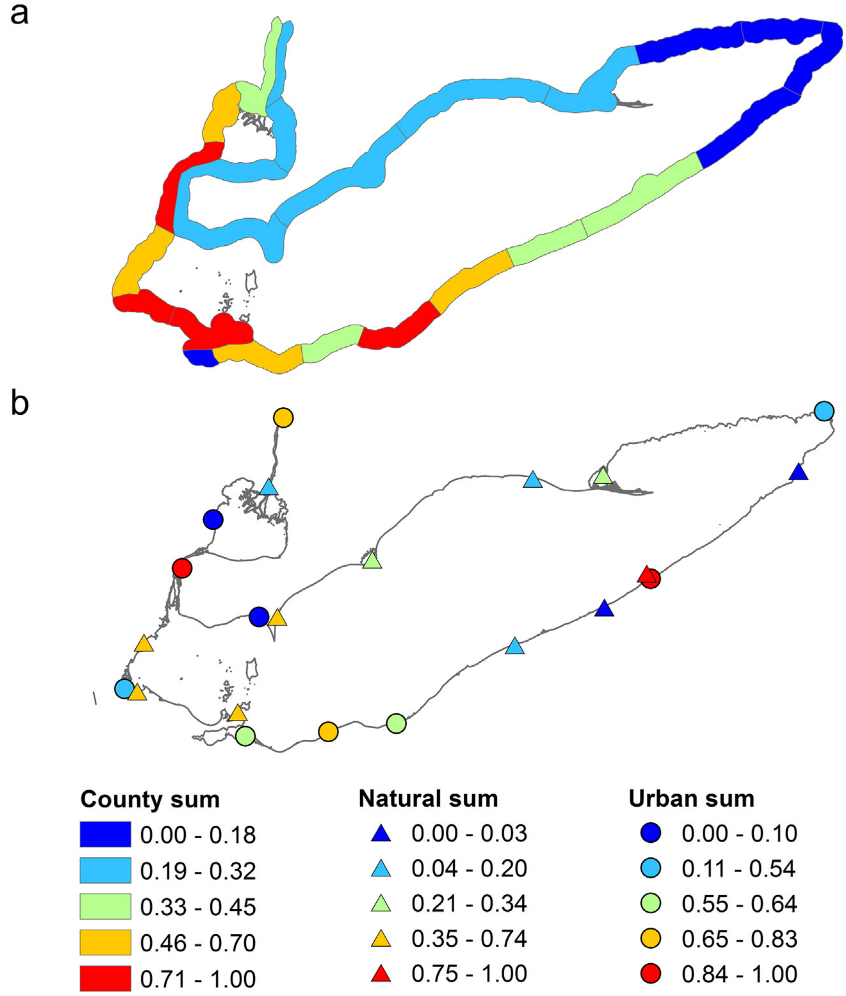

Fig. 5. (a) Total service delivery for each of 22 county units of the LEB. Total service delivery is shown as quintile shading. (b) Total service delivery for each natural area and urban area, with quintile breaks determined separately for each focal area type. Analyses use area-adjusted service delivery, re-scaled with a min-max transformation.

aggregated analysis. Some ES are co-located according to shared 'human habitat', as seen with municipal parks and municipal water supply, both located in or near population centers. Finally, some ES may simply be independent of all other services included in this study, such as birding and commercial fish landings, which correlate at some scales because fish landings are greatest at a few Ontario harbors, some of which are coincidentally near popular birding locations within parks.

We conducted our analyses at coarse and fine spatial scales to determine whether our findings were scale-dependent. While minor differences are seen in our results due partly to differences in data availability across scales (e.g., sport fishing could not be down-scaled with confidence to focal areas, municipal park data became increasingly sparse at the focal scale), and the specific service mix varied, the broad findings were consistent across the three spatial scales. Number of ES locations and especially the extent of service delivery varied among spatial units regardless of scale of measurement, underscoring the heterogeneity of ES across the LEB. The range of scales in our study also corresponds to different levels of planning. Managers focused on maintaining the supply of services to their local populations likely make decisions at scales ranging from our focal areas to counties, and coordinated planning activities such as the LAMPs may benefit from information at the sub-basin and whole basin scale.

Total ES delivery for multiple services varied considerably among locations at all spatial scales, often by as much as an order of magnitude, and significantly correlated with adjacent population. About one-third of the variance in county service delivery can be explained by county population, and this increases to 60% when two outliers are excluded. Service delivery was less variable and significantly higher in urban vs. natural areas, and the majority of state/provincial park visits were to parks with >150,000 residents within 30 km distance. Thus, even for parks usually thought of as destinations, visits were related to their accessibility to a substantial surrounding population. Total visits to the nine municipal parks with available data summed to more than the total for the 27 state/provincial parks, all of which had recorded visitor information. Similarly, the number of services increased along the St. Louis River and estuary from the less developed upriver locations toward the more highly developed St. Louis and Superior bays (Angradi et al., 2016).

The correlation of service delivery with population is an unsurprising consequence of estimating service delivery based on use by people, and is likely to provide only a partial explanation. Our study did not consider how relative benefits may vary among sites providing a particular service, and we expect that the perceived benefits of a site will importantly influence the willingness of individuals to travel greater distances and incur greater costs, as when beach-goers travel to a preferred beach or birders seek out new locations. Because ES are co-produced (Paloma et al., 2016), the recreational value of a coastal county will be largely determined by its biophysical features and socio-economic attributes including public facilities, management actions and regional demand for recreation.

Remote locations may have other, perhaps more intrinsic values or may influence ES delivery at great distance. For example, Lake Erie receives 80% of its water from the Detroit River, which transports mostly low-nutrient water from the upper Lakes, and approximately 12% from its tributaries, many of which transport a substantial nutrient and sediment load. Thus water quality in Lake Erie benefits from environmental conditions at considerable distance.

In conclusion, our analysis of multiple ES of the LEB shows that service locations and delivery generally are spatially heterogeneous and weakly correlated. The modest number of positive associations are likely a mix of common functional relationships (boating, fishing), shared habitat (municipal water supply and municipal parks) and coincidence (commercial fish landings and popular birding sites). This result is consistent with the presence of multiple cultural (recreational) services and the absence of a strong provisioning service among the ES considered (Chan et al., 2012; Howe et al., 2014).

Although not yet in widespread use, ES mapping and assessment have great potential to inform spatial planning and environmental decision-making. Whether viewed individually or combined into total delivery, ES delivery exhibits hotspots and coldspots, which may provide guidance for management investments. Illustrating this point, Annis et al. (2017) mapped optimal areas for conservation and restoration investments in coastal western Lake Erie to achieve goals for multiple ES, including many of those considered here. Because the GL are subject to multiple stressors and management actions typically focus on stressor amelioration, it will be important to better understand which individual and suites of stressors threaten the delivery of particular services in a given location (Allan et al., 2013), as well as how service delivery may change in response to management actions. As noted in Allan et al. (2015), high recreational benefits can coexist with high ecosystem stress, and while it may seem intuitive that amelioration of stress would maintain or enhance service delivery, it is also plausible that the service delivery is sufficiently resilient to be insensitive to stress reduction. This points to the need for a better understanding of the stressor-response functions between manageable anthropogenic stressors and ecological endpoints that govern service provisioning (Sierszen et al., 2012). Further research also is needed to include a wider range of ES and improve methods of quantifying ES delivery (Ouyang et al., 2016) and of the human activities that influence delivery (Paloma et al., 2016). Despite these challenges, we believe that quantification of human benefits will continue to advance and further improve environmental decision-making.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jglr.2017.06.001.

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