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Review

Researcher disciplines and the assessment techniques used to evaluate Laurentian Great Lakes coastal ecosystems

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ABSTRACT

The Laurentian Great Lakes of North America have been a focus of environmental and ecosystem research since the Great Lakes Water Quality Agreement in 1972. This study provides a review of scientific literature directed at the assessment of Laurentian Great Lakes coastal ecosystems. Our aim was to understand the methods employed to quantify disturbance and ecosystem quality within Laurentian Great Lakes coastal ecosystems within the last 20 years. We focused specifically on evidence of multidisciplinary articles, in authorship or types of assessment parameters used. We sought to uncover: 1) where Laurentian Great Lakes coastal ecosystems are investigated, 2) how patterns in the disciplines of researchers have shifted over time, 3) how measured parameters differed among disciplines, and 4) which parameters were used most often. Results indicate research was conducted almost evenly across the five Laurentian Great Lakes and that publication of coastal ecosystems studies increased dramatically ten years after the first State of the Great Lakes Ecosystem Conference in 1994. Research authored by environmental scientists and by multiple disciplines (multidisciplinary) have become more prevalent since 2003. This study supports the likelihood that communication and knowledge-sharing is happening between disciplines on some level. Multidisciplinary or environmental science articles were the most inclusive of parameters from different disciplines, but every discipline seemed to include chemical parameters less often than biota, physical, and spatial parameters. There is a need for an increased understanding of minor nutrient, toxin, and heavy metal impacts and use of spatial metrics in Laurentian Great Lakes coastal ecosystems.

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Introduction

Laurentian Great Lakes coastal ecosystems are hotspots for biological diversity and productivity. These coastal ecosystems contain diverse landforms and ecosystem types including marshes, freshwater estuaries, forested dune and swale complexes, beaches, embayments, and lake plain prairies (Albert et al., 2005). These systems are vital to many macroinvertebrate taxa (Cooper et al., 2012; Uzarski et al., 2009) and sport and prey fish communities (Jude and Pappas, 1992; Stephenson, 1990; Whillans, 1992). Additionally, coastal ecosystems, such as wetlands, provide many functions and values that benefit regional ecosystem health including carbon (Brix et al., 2001) and nutrient cycling (Mitsch and Reeder, 1991). Coastal wetlands also act as biological filters that mitigate chemical runoff, while trapping sediments (Johnston, 1991) and toxicants (Grisey et al., 2012), and preventing shoreline erosion (Fosberg, 1971).

Anthropogenic land use is affecting many coastal habitats throughout the Laurentian Great Lakes (Chow-Fraser, 2006; Danz et al., 2007). Since European settlement, a significant portion of the naturally occurring Great Lakes coastal ecosystem area has been lost (>50%), and coastlines have lost over 95% of their wetland habitat in some areas (Cwikiel, 1998; Krieger, 1992). Remaining wetlands have been further subjected to increased levels of fragmentation, degradation, and invasion of exotic plant species, greatly reducing the biodiversity and overall habitat quality of these valuable ecosystems (Cooper et al., 2012; Tulbure et al., 2007; Uzarski et al., 2009). In addition to wetlands, open water and nearshore embayment habitats (Peterson et al., 2007), rivers (Hoffman et al., 2012), and river mouths (Larson et al., 2013) of the Great Lakes have been impacted by surrounding land-use.

Scientists and managers recognize the important role that coastal ecosystems play in maintaining Laurentian Great Lakes water quality, biodiversity and productivity (Beletsky et al., 2007; Cloern, 2007; EPA, 1995; Robillard and Marsden, 2001; Schoen et al., 2016; Sierszen et al., 2012), prompting recent efforts to assess the quality of remaining habitats in the Laurentian Great Lakes basin. Recent work focused on assessing and monitoring the condition of Laurentian Great Lakes coastal ecosystems, including the development of new methods and techniques to assess coastal health. For example, Niemi et al. (2007) and Uzarski et al. (2004, 2005) have developed chemical, geographical, and biological approaches to quantify the degree of anthropogenic influence on coastal wetland habitats. These and other methods of assessment are critical for successful protection and restoration of coastal waters by allowing managers to identify, prioritize, and monitor areas in need of restoration.

Managers must be able to develop plans for restoration, protection, and monitoring on an ecosystem scale in order to be effective given their limited resources (Dalerum, 2014; Evely et al., 2010; Karlqvist, 1999; Simenstad et al., 2006). Single discipline research can be difficult to implement directly into a management plan that is developed for an entire ecosystem, because it may be limited in its perspective (Brewer, 1999; Dalerum, 2014; Evely et al., 2010; Karlqvist, 1999; Kinzig, 2001). There has been a push for more multidisciplinary research in the last 25 years to promote a more integrated approach to addressing ecosystem issues (Brewer, 1999; Klein, 1990). Conducting multidisciplinary research is an excellent goal, but successful execution is difficult, and many projects are dropped before completion (Brewer, 1999; Pooley et al., 2013). Major obstacles faced when tackling multidisciplinary research are disciplinary prejudices, insufficient or lack of interdisciplinary communication, poor data accessibility and integration, lack of shared values and priorities, and different theories of knowledge (Pooley et al., 2013).

Since 1972, the United States of America (U.S.A.) and Canadian governments have attempted to combat these obstacles for the sake of human and ecosystem health. Both countries signed and subsequently updated (in 1987) the Great Lakes Water Quality Agreement (GLWQA) to align scientists with a common goal to restore and protect the Laurentian Great Lakes (IJC, 1993). To uphold this agreement, it was decided that an understanding of atmosphere, land, biota, and human activities in the Laurentian Great Lakes and their interactions should be integral to coastal ecosystem protection and restoration (IJC, 1993). Since 1981, the reports from the International Joint Commission (IJC) praised multidisciplinary efforts in which scientists worked "across jurisdictions and disciplines to enhance learning, understanding, and the efficient use of resources" (IJC, 1993). Although the obstacle of a shared value (i.e., restore and protect Laurentian Great Lakes) had been overcome, other obstacles remained in the way of multidisciplinary research.

To combat the remaining obstacles, the first State of the Great Lakes Ecosystem Conference (SOLEC) was held in 1994 (EPA, 1995). SOLEC brought together government agencies, conservation groups, health professionals, agricultural community, industry, academia, and citizens from both Canada and U.S.A. to facilitate interdisciplinary communication to uphold objectives of the GLWQA. In subsequent years, SOLEC has also encouraged efforts to make Laurentian Great Lakes ecosystem data more readily available and abundant, addressing another multidisciplinary research obstacle. The SOLEC process and the GLWQA both promote more collaborative research, with SOLEC specifically encouraging multidisciplinary approaches to overcome disciplinary prejudices and communication, improve data accessibility, and add value to the research outcome (Environmental Law Institute, 1995; IJC, 1993; Pooley et al., 2013).

In this study, a literature search and review was performed based on published primary scientific literature directed at the assessment of Laurentian Great Lakes coastal ecosystems. Claudet and Freschetti (2010) provided a similar analysis for the Mediterranean that illustrated gaps in knowledge and pointed out disproportionate regional emphasis, which was useful for future research and management. The primary objective was to survey studies that quantify disturbance and ecosystems quality within Laurentian Great Lakes coastal ecosystems since the first 1994 SOLEC to identify trends and gaps. Additionally, this study sought to uncover evidence of multidisciplinary collaboration through the research parameters measured and/or the knowledge of its pool of contributors for articles studying Laurentian Great Lakes coastal ecosystems (Haapasaari et al., 2012; Karlqvist, 1999; Klein, 1990). This study aims to provide a synopsis of research efforts on Laurentian Great Lakes coastal systems measuring ecosystem quality concerning: 1) where Laurentian Great Lakes coastal ecosystem research is being conducted, 2) how discipline patterns of Laurentian Great Lakes researchers may have shifted over time, 3) how indicative parameters differed among scientific disciplines, and 4) which parameters were used most often.

Methods

Study area

The coastal systems of the Laurentian Great Lakes stretch approximately 17,500 km across USA and Canada (Botts and Krushelnicki, 1987). Great Lakes coastal zones include littoral habitats such as wetlands, beaches and river mouths. Coastal zones of the Great Lakes can be differentiated from offshore habitat by their warmer temperatures, shallow depths and decreased wave energy (Trebitz et al., 2009). These conditions promote sediment deposition and nutrient retention and promote the establishment of aquatic macrophytes (Parker et al., 2012). These macrophytes provide biota with structure and cover, promoting macroinvertebrate and fish richness (Randall et al., 1996). There are 275,748 acres of coastal wetlands as of 2003 in the Great Lakes Coastal Wetland Consortium inventory. In addition to coastal wetland habitat, the Great Lakes contain approximately 1500 miles of shoreline, encompassing river mouths, spawning reefs and beach and embayment habitats (Grady, 2007).

Search criteria

Articles included in this analysis were found in the Web of Science Core Collection database, which does not include government agency documents. Although much ecosystem assessment and monitoring data is housed in agency databases and reports, those data and findings that make it into the peer-reviewed literature are typically what is used to develop monitoring protocols and to determine which parameters to collect (Danz et al., 2007; Niemi et al., 2007; Uzarski et al., 2004, 2005). Accordingly, assessment of the peer-reviewed literature, can reveal trends in the advancement of hypothesis-driven scientific knowledge and understanding. Government agency documents were also excluded as they are not held to the same standards as peer-reviewed scientific journal articles. Government agency documents are not always as openly available online, through conventional search engines such as Web of Science. Lastly, government agency documents are often associated with the application of established research methods, whereas peer-reviewed journal articles available through Web of Science are more representative of current trends in environmental research.

The search criteria used in this analysis are visualized in Fig. 1. The search was restricted by study region using the following topic search terms ((“Great Lake*”) OR (“Lake$ Superior” OR “Lake$ Michigan” OR “Lake$ Huron” OR “Lake$ Ontario” Or “Lake$ Erie”). The “*” and “$” represent multiple and single wildcard characters, respectively. The results were restricted to ecosystem-relevant studies by the intersection of the search terms ((coastal OR littoral) NOT inland) and (“environment* health” OR “ecosystem health” OR anthropogen* OR “human impact*” OR disturbance* OR assess* OR integrity OR quality). The search was also restricted by the publication years 1994 to February 2015, corresponding to studies completed after the release of an influential report on the Laurentian Great Lakes by the International Joint Commission (IJC, 1993) and the first SOLEC held in 1994. The search yielded 496 search results (Fig. 1). From this list, articles were excluded that were not conducted in the Laurentian Great Lakes region (e.g., African Great Lakes, Atlantic coast) or were not of a coastal ecosystem (e.g., offshore, inland), as well as review articles and environmental policy papers. Only 234 articles fit the criteria and were used in the final analyses (Electronic Supplementary Material (ESM) Table S1). Articles published in the year 2015 were excluded from analyses that incorporated time-series data, as our article collection efforts ended part way through the 2015 year.

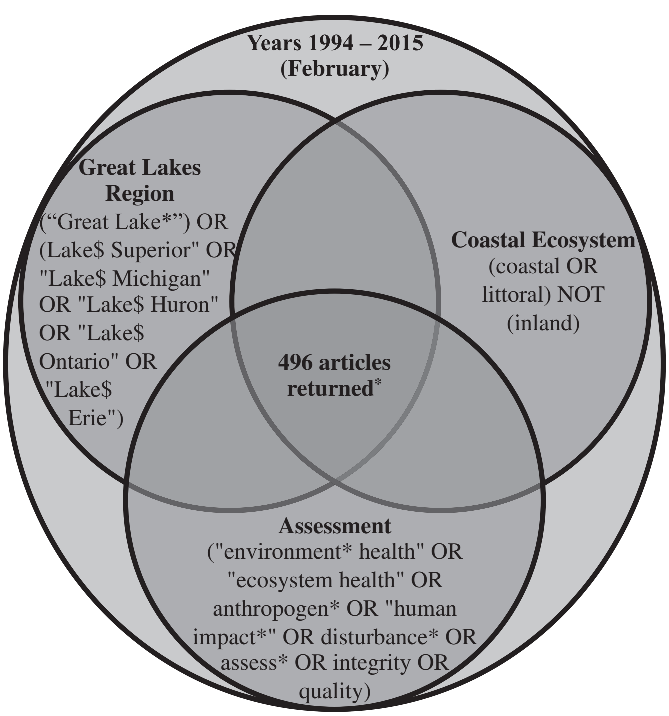

Fig. 1. Venn diagram of search criteria. Each circle represents search criteria used with peer-reviewed publications in the Web of Science Core Collection database and lists the topic search terms used. The intersection in the center displays subset of articles pertaining to the assessment of Laurentian Great Lakes coastal ecosystem quality. The * indicates that although 496 articles were returned with the search, only 234 articles were relevant upon further examination.

For each article, the country of origin (i.e., Canada, U.S.A., Both, Other), discipline(s) of the author(s), Laurentian Great Lakes(s) studied, and parameters examined were determined (Table 1; ESM Table S1). The country of origin and discipline(s) were determined based on the address of the author(s) as reported in the article and by the institution and department affiliation of the author. An article that had at least one author from neither Canada nor U.S.A. was categorized as “Other.” The discipline categories used were biology, environmental science, geography, geology, multidisciplinary, and other (e.g., chemistry, mathematics, engineering). Multidisciplinary research was defined as collaboration between two or more researchers from different fields; i.e. at least one coauthor coming from a different discipline from the first author. The articles were not rated on the degree of integration of disciplines within the study, hence the use of the term “multidisciplinary” instead of “interdisciplinary.” Environmental science is considered an inherently multidisciplinary or interdisciplinary field as it integrates different disciplinary perspectives into answering research questions (Hicks et al., 2010; Morillo et al., 2003). Authors that affiliated themselves with the environmental science discipline may have been more specialized in past research, but now consider themselves multidisciplinary. Given that “multidisciplinary” was defined as a collaboration between separate individuals and the number of authors identifying as environmental scientists, “environmental science” was considered as a separate discipline from “multidisciplinary” and the other specialized categories.

Parameters used to assess ecosystem quality were extracted and categorized into biota (e.g., taxonomic groups), chemical properties (e.g., nutrients and toxins), physical properties (e.g., temperature, pH, etc.), or spatial metrics (Table 1). In particular, spatial metrics were defined as parameters to estimate local anthropogenic impact on, or spatial characteristics of, study locations such as land use-land cover (LULC), road density, and population density (Table 1). Collectively, the parameters were used to evaluate relative level of integration of disciplines within the articles, to determine holes and knowledge gaps in coastal

Table 1
List of parameters. For each parameter category, the percentage of the studies that examined that parameter are listed, and examples of each parameter.

Parameter category	Percentage of total studies	Examples
Biota	80%	Bacteria Plants Plankton Invertebrates Fish Amphibians Reptiles Birds Mammals
Chemical properties	43%	Nutrients (e.g., carbon, nitrogen, phosphorus) Other ions (e.g., calcium, chlorine, magnesium) Toxins/heavy metals (e.g., dioxins, mercury, PCBs)
Physical properties	60%	Conductivity Temperature Turbidity Velocity Other
Spatial metrics	59%	Area (e.g., site area, watershed area) Land use/land cover (LULC) Road density Other (e.g., fetch, elevation)

ecosystem research, to assess the trends over the last 15 years, and to influence the focus of future research.

Results

Laurentian Great Lakes coastal research locations

Overall, U.S.A. researchers produced over twice as many published articles as Canadian researchers (62% and 25% respectively), with 12% of papers produced with the cooperation from both countries. Only four articles (2%) had at least one author hailing from neither the U.S.A. nor Canada (i.e., Foyle and Norton, 2007, - Germany and U.S.A.; Gal et al., 2006, - Canada, Israel, and U.S.A.; Gao et al., 2009, - China and U.S.A.; Travis et al., 2010, - Czech Republic and U.S.A.).

For articles containing a single discipline, the U.S.A. had a greater percentage of environmental science articles (35%), while Canada had a greater percentage of biology articles (62%). The distribution of articles across focal biota categories was proportionally similar between the U.S.A. and Canada. Trends over time show that only one article (Kreutzwiser and Gabriel, 2000) was produced in conjunction with both countries prior to 2005, whereas there was an average of 3 such studies per year thereafter.

Each of the Laurentian Great Lakes had similar representation among articles examining their coastal habitats (17–22%; Fig. 2). Lake Michigan represented the largest percentage of articles, while Lake Superior represented the smallest percentage (17%; Fig. 2). There were fewer articles studying Lake Superior exclusively than any of the other Great Lakes (8%; Fig. 2).

Discipline trends over time

Articles from 1994 to 2014 were examined for trends over time. The number of articles across disciplines within the Laurentian Great Lakes coastal ecosystems was <5 per year initially, peaked in 2007 at 30 articles, and decreased to 18 articles in 2014 (Fig. 3). The number of environmental science and multidisciplinary papers increased substantially after 2003, and the overall increase in Great Lakes coastal study articles is largely due to an increase in the number of environmental science and multidisciplinary studies. The number of biology articles per year appeared to be a relatively constant proportion of the total publications over time. The rise in the environmental science discipline may reflect a trend in language and naming of affiliations, not a change of approach to the research. Those concerns are addressed by further examining the types of parameters used in each study by discipline, described below.

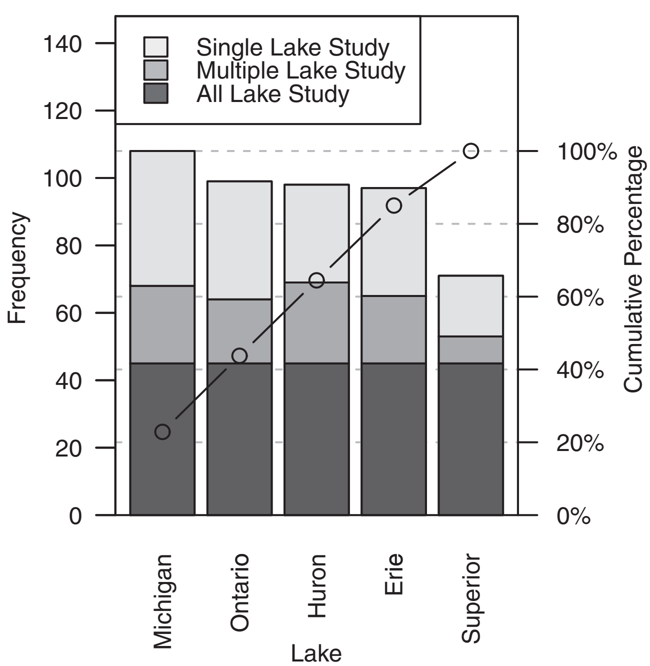

Fig. 2. Pareto chart displaying the distribution of studies in the Laurentian Great Lakes focused on the assessment of coastal ecosystems. Each bar represents one of the five Laurentian Great Lakes of the U.S.A. The left y-axis is the frequency of study and corresponds with the bars; the right y-axis is the cumulative percentage and corresponds with the black line.

Parameters used to assess Laurentian Great Lakes coastal ecosystems

Parameters by discipline

Researchers from the disciplines of biology, environmental science, and multidisciplinary teams published the majority of the articles analyzed (Fig. 4). There were few articles written by chemistry and physics researchers, thus they were included in the “other” category. While studies categorized as biological, not surprisingly, tended to emphasize biota measurements, environmental-science and multidisciplinary studies addressed biotic, chemical, physical, and spatial metrics. The parameters studied by environmental science and multidisciplinary studies were more similar in proportion to each other than to other disciplines. Within environmental science and multidisciplinary studies, biota is studied the most and chemical parameters were included the least.

Biotic parameters

Approximately 80% of the studies used a biotic parameter (e.g., plants, fish, invertebrates, bacteria, or combination thereof) to assess the ecosystem (Table 1; Fig. 5a). Studies that focused on one single biological group or population most often used plants (15%), fish (11%), bacteria (10%), plankton (7%), or invertebrates (5%) to assess the ecosystem. Studies focused on birds and herpetological communities were scarce in comparison (<3%). The largest proportion (27%) of studies assessed multiple biological groups. Of those multiple biota studies, plants (24%), fish (23%), invertebrates (19%), and plankton (18%) communities were the most highly represented (Fig. 5b). Bacterial communities were less frequently included in multi-biological group studies compared to their prevalence in single-biological group studies (Fig. 5a, b).

Chemical or physical parameters

Thirty-two percent of the studies did not measure any chemical or physical parameters (Table 1; Fig. 5c). Studies that focused on a single such parameter were represented most often by physical parameters (25%) or nutrients (6%; Fig. 5c). The majority of studies measured multiple chemical or physical parameters (Fig. 5c, d). Few studies examined toxins (2%). Other ions (e.g., calcium, magnesium, chlorine) were never examined as the only chemical or physical parameter, only in conjunction with a second chemical or physical parameter (Table 1; Fig. 5c, d).

Spatial metric parameters

Of the manuscripts reviewed in this analysis, nearly half (41%) did not consider spatial metrics in their experimental design (Fig. 5e). Of those studies that did investigate spatial relationships, 23% quantified land use-land cover (LULC) in the localized study region (Fig. 5e). The “other” categories of spatial metrics used (e.g., population mapping, color-near-infrared imagery, elevation, agricultural intensity), occurred too infrequently to elucidate further trends.

Discussion

This analysis will provide researchers and managers with an overview of how coastal ecosystems have been assessed since 1994 in the Laurentian Great Lakes. Our results identify knowledge gaps and differences among disciplines, years, countries, lakes, and types of

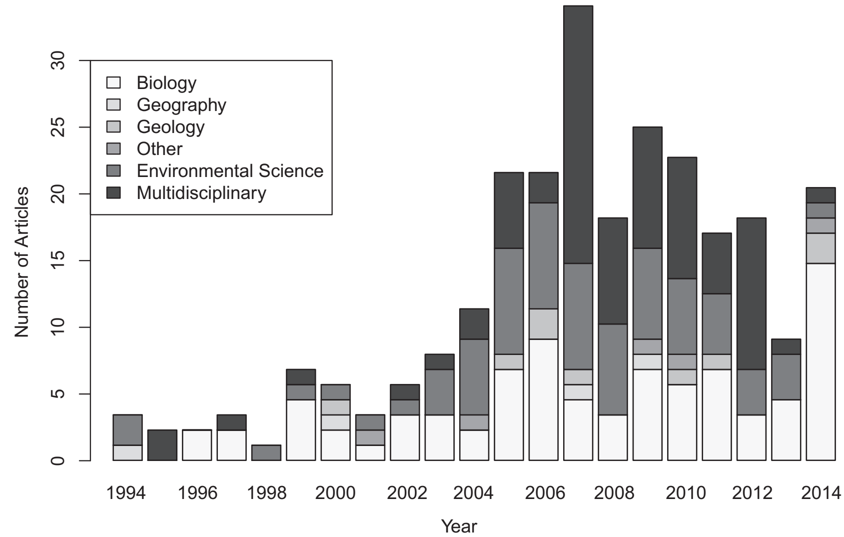

Fig. 3. Distribution of articles based on the year they were published and the discipline of the author(s). Number of articles represents units for frequency on y-axis. Each shade indicates a different discipline explained in the legend. Papers from 2015 were excluded from this figure as analyses took place during year 2015, and therefore the year 2015 was an incomplete data set.

measurements made. Successful and meaningful multidisciplinary research is difficult to achieve with cultural, political, and practical challenges to overcome (Claudet and Freschetti, 2010; Hicks et al., 2010; Marzano et al., 2006; Pettorelli et al., 2014a, 2014b; Pooley et al., 2013). Pooley et al. (2013) categorize multidisciplinary research challenges into five areas: 1) methodological (e.g., time, data integration, data accessibility), 2) value judgments, 3) theories of knowledge (e.g., qualitative, quantitative), 4) disciplinary prejudices, and 5) interdisciplinary communication. For example, remote sensing is a geographical tool that can provide many benefits to multidisciplinary research, but challenges in methodology (funding, data accessibility, technology), communication, and knowledge have impeded collaboration (Pettorelli et al., 2014a, 2014b; Roughgarden et al., 1991).

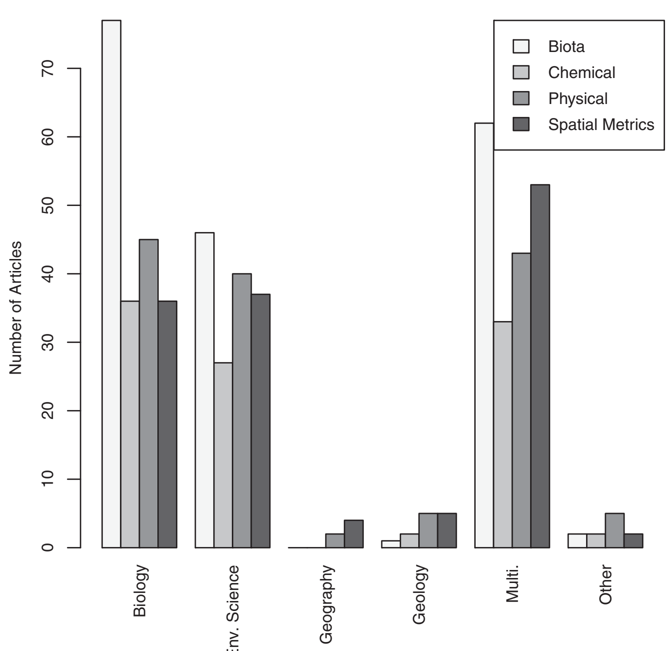

Fig. 4. The number of articles published categorized by the parameters studied (represented by the shades of each bar) and discipline of the author(s) (represented by groupings along the x-axis).

Although articles written by researchers in a single discipline (e.g. biology, geology) favored using parameters common within their discipline, occasionally research parameters were utilized beyond their given field. This implies communication and knowledge-sharing between disciplines on some level. The use of multidisciplinary techniques does not always amount to authorship collaboration across disciplines, but it does foster relationships from which future multidisciplinary efforts can be developed (Marzano et al., 2006) and is an important part in applying a holistic approach to ecosystem assessment.

The trend of increasing number of multidisciplinary manuscripts after 2005 implies that many researchers are now considering and applying multidisciplinary relationships, concepts, and tools to their projects. There is also an increasing trend of manuscripts in environmental science, an inherently multidisciplinary field (Hicks et al., 2010; Morillo et al., 2003). The establishment of these relationships, concepts, and tools early in the research is essential for a successful multidisciplinary project (Marzano et al., 2006; Pooley et al., 2013). The recent decrease in multidisciplinary and environmental science articles (2013–2014) does not span enough time to identify as a new trend.

The overall trend in published data can be attributed in part to changes in government interests and grant funding, as noted by Claudet and Freschetti (2010) and Kamalski (2010). EPA Funding initiatives (e.g., Great Lakes Ecological Indicators Project and the Great Lakes Coastal Wetland Consortium) resulted in an increase in published articles on coastal ecosystem ecological indicators. Both of these programs measure ecological indicators based on SOLEC recommendations (see www.glei.nrri.umn.edu, as well as www.glc.org). The IJC through the GLWQA fostered efforts to detail the progress of remediation within the Laurentian Great Lakes, and to eliminate toxins and organochloride discharges into the basins (Environmental Law Institute, 1995). Besides Biennial reports, the IJC produces "special reports" making recommendations concerning policy and, in turn, encouraging research in specific directions. For example, in 2011, the IJC requested more research and monitoring of "chemicals of emerging concern" (International Joint Commission Chemicals of Emerging Concern Work Group, 2011).

The somewhat lower number of articles using chemical parameters than physical or spatial parameters across all disciplines may indicate that chemists are not as involved in Laurentian Great Lakes coastal ecosystem assessment studies as other disciplines. The inclusion of more researchers with chemistry or environmental science affiliation early in the planning process for Laurentian Great Lakes coastal ecosystems may answer the call by the IJC. Among studies that measured chemical

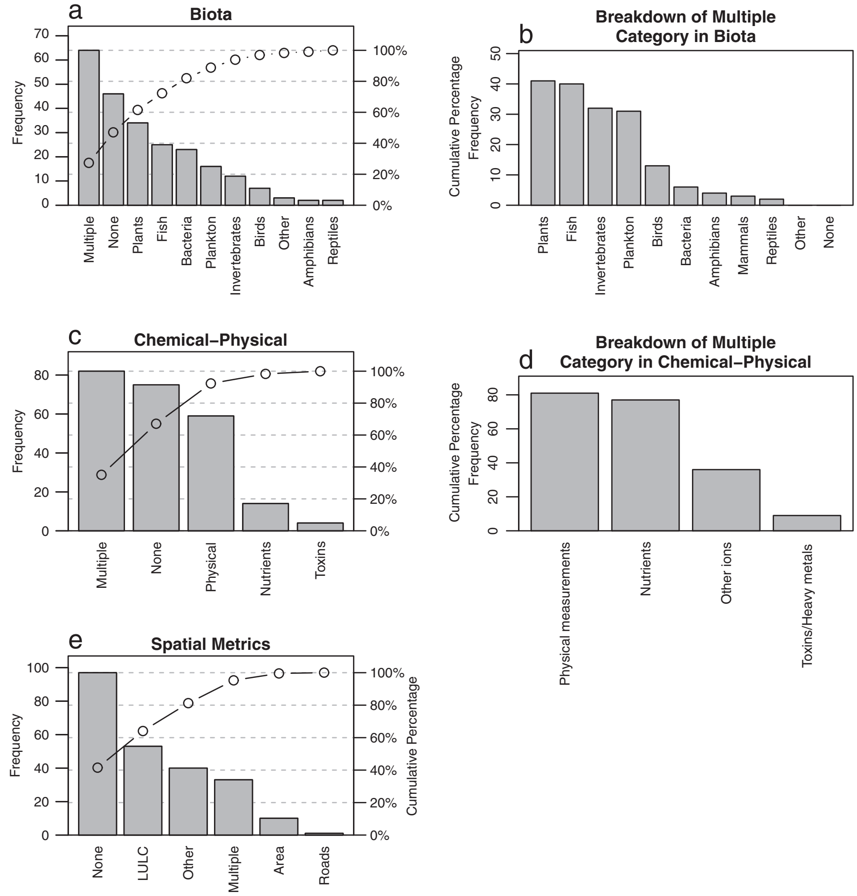

Fig. 5. Pareto charts and bar graphs showing the parameters used in Laurentian Great Lakes coastal ecosystem research from 1994 - February 2015. Figure a) is a Pareto chart showing the distribution of biological groups (biota) that were sampled; b) is a bar graph showing the breakdown of biota within studies that surveyed multiple biological groups; c) is a Pareto chart showing the distribution of chemical-physical data that were sampled; d) is a bar graph showing the breakdown of chemical-physical data that surveyed multiple categories of chemical-physical data; e) is a Pareto chart showing the distribution of spatial metrics that were collected. The spatial metrics were so variable in the multiple categories that a breakdown did not visualize well and is not included. The left y-axis of the Pareto charts (a, c, e) is the frequency of study and corresponds with the bars; the right y-axis is the cumulative percentage and corresponds with the black line.

or physical parameters, physical properties (e.g., temperature, turbidity) and major nutrients (e.g., N, P) were often measured in conjunction. A preference toward measuring these physical properties and nutrients over others is at least partially driven by the concern for anthropogenic land use effects on coastal ecosystems due to added nutrients and eutrophication. Other "minor" chemical elements (e.g., Ca, Na, K, Fe), however, were never the primary focus of any study unless other major nutrients or other physical measurements were also analyzed (Fig. 5d). Nearly a third of the studies characterizing coastal systems did not include any physical or chemical dimension, which suggests that these studies either used spatial metrics as a surrogate for direct anthropogenic influence on coastal ecosystems, or did not address such anthropogenic effect.

Toxins within coastal systems were also underrepresented in the literature reviewed for this analysis. This is surprising, as toxins and heavy metals have been found to be prevalent within coastal systems in the Great Lakes watershed. For example, heavy metals have been found in coastal wetland and estuarine sediments which consequently impacted local biotic communities (Cooper et al., 2009; Ni et al., 2015), and several Great Lakes Areas of Concern (AOCs) have been delineated as consequences of pollutant contamination (EPA; www.epa.gov/great-lakes-aocs). Wetlands have the ability to mitigate heavy metal toxins entering surface water, yet these toxins are often not included when evaluating a coastal wetland (Sheoran and Sheoran, 2006). Ecosystem assessment studies with a focus on measuring pollutants and toxins as chemical parameters are currently lacking. These studies are needed to meet the requests of the IJC to better understand the influence of pollutants and toxins on coastal environments (International Joint Commission Chemicals of Emerging Concern Work Group, 2011).

The economy also influences research. For example, fishing is critical to the Laurentian Great Lakes regional and recreational economy, contributing between $4–7 billion annually (http://www.miseagrant.umich.edu/explore/fisheries/May 2, 2016). This economic influence could be driving research on fish populations and communities, skewing research focus toward that particular taxonomic group. In these cases, the ecosystem assessment is focused on habitat quality for the fish of interest. Analysis and understanding of aquatic food webs also has attained considerable importance, especially to understand the effects of aquatic invasive species (IJC, 2012). Invertebrates and plankton represent the trophic tiers below fish in a freshwater system, which along with their role as environmental indicators (Lougheed and Chow-Fraser, 2002; Stoermer, 1978; Uzarski et al., 2004) may explain the considerable amount of research focusing on these groups. Research emphasizing particular biota may also be linked to key events, like the influx of invasive species (e.g., Asian carp) and occurrence of harmful algal blooms in Western Lake Erie. However, more research is needed to definitively affiliate these events to publications. Birds, amphibians, reptiles, and mammals were rarely examined. There is room for further study for these organisms as indicators of ecosystem integrity.

Public health interests also drive Laurentian Great Lakes research. The importance of the Laurentian Great Lakes for recreation and drinking water may explain the popularity of the bacteria parameter, but interestingly, bacteria do not appear to be studied often in conjunction with other biological communities (Fig. 5b). Several of the studies reviewed focused on fecal-associated bacteria within public beach environments in an attempt to elucidate the severity of public health concerns (e.g., Bertke, 2007; Kinzelman et al., 2008; Whitman et al., 2008), which could explain why other taxonomic groups (e.g., fish, amphibians, etc.) were not often analyzed in studies which analyzed bacteria. Outside of public health concerns, characterizing bacterial communities in synchronization with alternative taxonomic groups could elucidate broader biological community patterns (e.g., food web processes, species interactions). Furthermore, little research has explored microbial community structure and function in Great Lakes coastal ecosystems, particularly in wetlands where microbes are fundamental drivers of biogeochemical cycles.

Spatial metrics were the least used parameter type examined, with only 68% of articles including a spatial metric in their design (Fig. 5e). Spatial metrics are a fairly broad category that can be related to landscape ecology, biotic integrity, anthropogenic disturbance, or social pressures and processes (Turner, 2005). Government agencies and other property managers have called for more social and economic factors to be included in ecosystem assessments, but conceptual challenges, especially the quantification of usually qualitative data, have impeded the integration (Evely et al., 2010; Haapasaari et al., 2012; IJC, 1993; Pooley et al., 2013). Incorporating geographers into Laurentian Great Lakes research teams could quantify social and spatial parameters often overlooked in habitat studies.

Conclusion

Laurentian Great Lakes researchers have demonstrated an interest in multidisciplinary approaches through the collaborators and parameters they have included in their studies; however, there is room for incorporation of additional chemical, physical, and spatial metrics in Great Lakes coastal research. Scientific disciplines beyond biology can contribute to answering many ecosystem questions and address issues such as harmful algal blooms and invasive species. There has been an increase in multidisciplinary studies within the Laurentian Great Lakes since 1994, which would appear to be a result of encouragement from the SOLEC process and the GLWQA, and associated funding initiatives. Future cross-disciplinary meetings will encourage understanding anthropogenic interactions beyond their effect on biota and will allow managers and researchers to bring together multiple perspectives and data types to address environmental issues facing coastal ecosystems.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jglr.2016.11.008.

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