LETTER

Is limnology becoming increasingly abiotic, riverine, and global?

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Scientific Significance Statement

Has limnology had a consistent core of fundamental research topics through time, or, has the discipline’s focus shifted with advances in knowledge and technology? The temporal trends in the main research themes addressed in thousands of freshwater studies from 2004 to 2016 suggest that the field of limnology is increasingly focusing on research that is global in scope and useful for decision-making, and that this shift implies an increased reliance on abiotic data and emerging technologies and a relative decrease in the proportion of more traditional organismal themes. These global and anthropogenic shifts are not unlike what has been observed in other ecological disciplines, and we hope these results will stimulate conversation on the direction of the field of limnology and highlight the need for new techniques or networks to bring organismal studies into a more global context.

Abstract

Scientists often debate on the evolving state of their fields and future research directions, but empirical studies on research trends are rare and this limits our capacity to disentangle perceptions from facts within the mass of available data. We used ecological and paleolimnological approaches to assess how the “community” of words most commonly used in limnological studies presented at the Association for the Sciences of Limnology and Oceanography (ASLO) meetings and published in Web of Science have evolved over the last decades. We found that the field of limnology has become increasingly focused on global abiotic research themes, especially in rivers, while there was a decrease in the proportion of organismal studies. We hypothesize that this results from both major influential publications highlighting the importance of framing limnology in a global context and the methodological limitations of organismal studies that prevent data from scaling up as quickly as their abiotic counterparts.

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Lapierre et al.  Is limnology becoming abiotic, riverine, and global?

Limnology is the study of inland waters (Wetzel 2001; Kalf and Downing 2016). While this definition is widely accepted, limnologists often anecdotally debate major topics of emphasis and how trends in these topics have changed over time, as well as whether lakes and rivers are equally represented. Almost 30 yr ago, it was argued that there was a preoccupying shift in limnological research funding away from basic research toward applied and hydrology-focused, water quality research (Jumars 1990). More recently, in an expert-based evaluation of the main problems and paradigms of limnology, Downing (2014) suggested that problems such as eutrophication, invasive species, hydrological alterations, and climate change were central motivations for limnological research, but noted that there was a mismatch between the main limnological paradigms being studied, such as carbon biogeochemistry or trophodynamic food webs, and the main water quality challenges being faced by society. Interestingly, the limnologists consulted did not expect major shifts in the main problems that freshwater ecosystems were to face on a 10-yr horizon but hypothesized that the main limnological paradigms within which limnological problems are studied would shift in order to make inland waters relevant at a global scale. In an era of accelerating global change and unprecedented data availability (Durden et al. 2017), these presumed changes in paradigms should be reflected in meaningful trends in the dominant research themes in limnology.

A shift in paradigms presumably involves a change in the approaches used and scales of study, hence a shift in the conceptual frameworks that scientists use to motivate and conduct their research. There are reasons to believe that limnology, like other disciplines in the broader field of ecology (Nobis and Wohlgemuth 2004; McCallen et al. 2019), has rapidly evolved in response to (1) emerging environmental pressures operating at multiple spatial and temporal scales, (2) the development of new collaborative frameworks and analytical tools that allow scientists to generate and interpret increasingly large and complex data sets, and (3) new funding opportunities that promote interdisciplinary and applicable research. Previous studies have provided valuable insights on these issues but have mainly focused on temporal trends of individual, or combinations of keywords in the scientific literature. For example, Lewis (2005) reviewed hundreds of articles published in Limnology and Oceanography and found trends in the topics limnologists had studied from 1960 to 2004. The most noticeable trends included a relative decline in the study of phyto- and zooplankton coinciding with a relative increase in “other” groups of organisms, and an apparent slow but steady decline in the relative representation of lake studies compared to other systems. More recently, Downing (2014) hypothesized that regional and global studies should increase over time along with a greater focus on the economic valuation of freshwater resources, and themes such as global and climate change indeed appeared to occupy a greater proportion of limnological studies from 1990 to 2013. These general predictions for limnology are supported by a recent multivariate analysis of trends in empirically determined research themes in the broader field of ecology, which has shown that research at macroscales and on anthropogenic themes have increased faster than classical theoretical research (McCallen et al. 2019), but such an analysis has never been done in limnology. Hence, the following questions remain: Are there coherent research themes in the field of limnology, and if so, which have increased or decreased and what are the potential drivers and implications for future research directions?

Methods

Data sources

We used all oral and poster presentations presented at the Association for the Sciences of Limnology and Oceanography (ASLO) conferences beginning in 2004 (when digitization of these records began) as an indicator of limnological trends. We chose ASLO because it is one of the largest international scientific societies in the field of limnology that combines both basic and applied research, and it covers a balanced combination of organismal vs. ecological, as well as small- vs. large-scale studies, compared to other freshwater sciences societies (Downing 2014). Moreover, proceedings at ASLO conferences are often unpublished at the time of presentation and provide an immediate picture of the state of research with the assumption that most results are eventually published in a wide range of journals. In total, we analyzed the occurrence of words used in the 8208 “freshwater” abstracts (out of the 31,099 total abstracts submitted to ASLO meetings between 2004 and 2016; see Supporting Information Table 1 for details on the approach used to identify freshwater abstracts). The data are available in Supporting Information Table S2. Consulting with colleagues, we first identified a set of commonly used words in limnological research and then this list was expanded using an online “word cloud” (Supporting Information Fig. S1) tool to identify the most abundant words that we may have missed. We ended up with 79 topical words, and at least one of these words was found in 96.5% of the abstracts. An additional set of words was searched to characterize the type of systems (e.g., lake, river, littoral, alpine, etc.) where studies had been conducted.

We assumed that although limnological research is presented outside of ASLO meetings, research presented at ASLO meetings is representative of the field as a whole. We tested the sensitivity of our results to this assumption by comparing our approach to a literature search for the words that were the most abundant or had the strongest increasing or decreasing trends. In particular, we searched Web of Science (WOS) from 1994 to 2017 in the “limnology,” “environmental sciences,” “ecology,” “water resources,” “geosciences multidisciplinary,”

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and “marine freshwater biology” research areas. We went back 10 yr prior compared to the available ASLO data to explore if these trends began even earlier in time. We chose these research areas because they were the five subjects that returned the highest number of studies when initially searching for the words “lake” and “river.” In total, 1,826,909 articles were published in these research areas, and we calculated the absolute and percent of articles for which the searched words were found in the “Topic,” for every year. The data are available in Supporting Information Table S3. The following expression exemplifies a search for “phosphorus”:

\[ WC=\text{environmental sciences OR ecology OR water resources OR geosciences multidisciplinary OR marine freshwater biology} \text{ AND TS=phosphorus} \]

Quantifying trends in limnological research themes

We used a community ecology inspired statistical approach to characterize abstract words (e.g., presence-absence, relative occurrence) to determine the main research themes empirically emerging from the co-occurrence patterns of words used to describe limnological research, then quantified the frequency of occurrence and temporal trends for the different themes and individual words. We built a Bray-Curtis dissimilarity matrix from the square root-transformed “relative abundances” of all abstracts (species) for a given keyword (site) (Faith et al. 1987) and estimated within-theme consistency using hierarchical clustering using Ward’s Distance (Murtagh and Legendre 2014). Given that hierarchical clustering does not provide an objective means for identifying statistically significant clusters, the cutoff chosen for this study was partly subjective. We plot the cluster height vs. number of clusters and noted an inflection in the curve between 7 and 17 clusters; within this range, 11 clusters provided the groups that could be generally recognized as a coherent theme by any scientist in the field of limnology (e.g., “Plankton,” “Nutrients,” “Food webs”), whereas the 12th cluster contained words that tend to covary but do not form a coherent ensemble.

We quantified temporal trends in the identified themes by transposing the matrix to produce relative abundances of each word across all freshwater abstracts submitted to an ASLO conference in a given year. In an ecological context, words would now be “species” and abstracts would be “sites.” We then ran a stratigraphically constrained hierarchical cluster analysis on the relative abundance of all words through time (CONISS, Grimm 1987). This approach is a common tool for analyzing ecological changes in paleolimnology (e.g., Bennion et al. 2015) and allowed us to identify major shifts in word usage through time while still preserving the chronological sequence. For visualization purposes, we aggregated words into the major themes identified in the previous analysis by summing the relative abundance of all words for each year in each thematic cluster and displayed these relative proportions through time in a stratigraphic plot.

All statistical analyses were performed in the software R (R Core Team 2018). Hierarchical clustering and dendrograms were produced using the vegan (Oksanen et al. 2018), dendextend (Galili 2015), and ape (Paradis and Schliep 2019) packages. CONISS and stratigraphic plotting were performed using the rioja (Juggins 2015) package.

Results

The dominant research themes of modern limnology

Our results showed that the field of limnology has a solid biological, chemical, and physical foundation. Words like “Nutrient,” “Product,” “Species,” “Bacteria,” “Fish,” “Physics,” “Watershed,” and “Organic matter” occurred in at least 10% of the abstracts submitted to ASLO meetings in the last 15 yr (see Supporting Information Table S3 for a complete list of the words and their overall occurrence). The field of limnology also has a stoichiometry, at least in terms of rank order, that would make Alfred Redfield proud: “Carbon,”

### Table 1. Significantly increasing and declining relative occurrence of words from 2004 to 2016 in ASLO meetings. The complete list of words is found in Supporting Information Table S1.

| Keyword      | Average % occurrence 2004–2016 |
|--------------|--------------------------------|
| Product      | −0.66                          |
| Zooplankton  | −0.64                          |
| DON          | −0.57                          |
| Inorganic    | −0.55                          |
| Alga         | −0.54                          |
| Particulate  | −0.53                          |
| Omic         | 0.51                           |
| Greenhouse   | 0.52                           |
| High-freq    | 0.53                           |
| Storm        | 0.54                           |
| Automated    | 0.57                           |
| Metab        | 0.59                           |
| Methane      | 0.59                           |
| Sequencing   | 0.62                           |
| River        | 0.67                           |
| Management   | 0.71                           |
| Gas          | 0.71                           |
| Climate      | 0.75                           |
| Service      | 0.76                           |
| Global       | 0.82                           |
| Econom       | 0.82                           |
| Climate change | 0.88              |
Nitrogen, and Phosphorus are found in 21.5%, 14.2%, and 11.2% of the abstracts. Moreover, there are recurrent associations forming 12 clusters of words (11 coherent themes and a 12th cluster with weakly co-occurring words), which we interpret as dominant research themes (Fig. 1). The most consistent themes (the ones within which words were the most strongly associated among abstracts and were the first cohesive themes to separate from the other keywords) revolved around the study of organic matter and carbon (in red) and aquatic food web interactions (in purple). Other recurring themes included nutrients (green), plankton and regime shifts (black), microbial (blue), greenhouse gases and climate change (light blue and pink, respectively), social-economic (light green), anoxia (cyan), management (brown), ecotoxicology (orange), as well as miscellaneous group of loosely associated words (gray).

Fig. 1. Hierarchical clustering analysis using Ward’s D linkages of words in all ASLO abstracts from 2004 to 2016. Clusters reflect Bray-Curtis dissimilarity between all words based on their co-occurrence in ASLO abstracts. Colors correspond to the following main themes (see text): Organic matter and carbon (red), aquatic food web interactions (purple), nutrients (green), plankton and regime shifts (black), microbial (blue), greenhouse gases and climate change (light blue and pink, respectively), social-economic (light green), anoxia (cyan), management (brown), ecotoxicology (orange), as well as miscellaneous group of loosely associated words (gray).

“A shift from biotic to abiotic, the rise of rivers and global limnology

It is challenging to interpret the absolute trends in the research presented at ASLO meetings because meeting attendance greatly varies from year to year, but we found that in relative terms, certain research areas are rapidly emerging while other themes are slowly declining. Of the 79 words studied, 16 had significant increasing trends and six had significant decreasing trends (Table 1). Most of the words have remained stable through the study period, whether appearing as “frequent” (> 10%, e.g., “Carbon,” 22% average) or rare (< 3%, e.g., “Stoichiometry,” 2.9% average). The words that significantly changed over time represented both relatively frequent (e.g., “Climate,” “River”) and rare words (e.g., “Greenhouse,” “Economics”), whereas words like “Production,” “Algae,” and “DON” (DON is defined as Dissolved organic Nitrogen) have gradually decreased (Table 1). Taken together these shifts in individual words have led to a steady relative decline in plankton, nutrients and ecotox research
themes while studies on management, climate, greenhouse gases, and socio-economic research themes have relatively increased (Fig. 2). The CONISS analysis showed that the association of words used in the abstracts of 2010–2016 was more similar than those in years 2004–2009, and that there appeared to be a significant shift in the relative use of words between these two periods (Fig. 2).

Words related to study systems also showed intriguing trends. Overall, 49%, 33%, 26%, and 8% of studies mentioned lakes, rivers, streams, and wetlands, respectively, and all words but “Rivers” have remained stable. The proportion of studies mentioning rivers has shifted from between 25% and 30% in the mid-2000s to a maximum of 37.7% in 2016, and this trend was highly significant (Table 1). Most of the words that have decreased in relative occurrence represent traditional variables widely measured by limnologists (e.g., “Production,” “Algae,” “Zooplankton,” “Particulate”), whereas the words that have increased in relative occurrence mostly represent new approaches (e.g., “Omic,” “High-Frequency,” “Automated,” “Sequencing”) and contexts within which response variables are studied (e.g., “Global,” “Climate Change,” “Socio-Economical,” and “Management”).

More than an ASLO trend

There was a strong match with the trends for published articles available in WOS for most words in ASLO abstracts, including a comparable stoichiometry (i.e., about 150,000; 85,000, and 40,000 articles mention C, N, and P, respectively).

Overall, all words tended to increase within the studied period, along with the total number of studies in the five fields explored, which increased at an average rate of 3587

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**Fig. 2.** Stratigraphic diagram of all words summed by major research themes (defined in Fig. 1) through time. Dendrogram on right reflects periods of time with increasingly similar word usage as determined by constrained hierarchical clustering (CONISS). X-axis denotes the percent number of abstracts containing at least one word from this theme per year; scale changes from theme to theme. Color codes are consistent with Fig. 1, but the name of the themes have been simplified for visualization purposes.

**Fig. 3.** WOS articles vs. ASLO abstracts trends (expressed as relative change in percent occurrence) for representative words. Red dots represent words significantly increasing in both instances and blue represents “zooplankton,” which has significantly decreased in both instances. Gray dots have significantly changed in one instance but not the other, and the white dots reflect an opposite pattern for ASLO vs. WOS trends.
new papers per year. The words “Climate” and “Carbon” increased the fastest in absolute terms (687 and 532 new papers per year, respectively), but the absolute rate of increase was strongly dependent on the frequency at which words were mentioned (Supporting Information Table S3). Hence, from now on, we focus on the relative proportion of studies mentioning each word to determine the relative importance that each word occupies over the years, as this metric is more directly comparable with the analyses performed for ASLO abstracts.

We found that the relative occurrence of the words “Methane,” “Global,” “Climate,” and “Rivers” have significantly increased for both ASLO and WOS in a comparable magnitude, and that “Zooplankton” has decreased; the relative occurrence of “Lakes” has remained stable in both instances (Fig. 3). The only opposing trend was for “Productivity,” which has increased by more than 62% in WOS, but decreased by 33% in ASLO. Finally, “Phosphorus,” “Nitrogen,” and “Carbon” have increased in relative occurrence in WOS but not ASLO whereas “Algae” has decreased in ASLO but has remained stable in WOS. It should be noted however that not all studies included in the WOS search were limnological studies. Nevertheless, the agreement between the relative occurrence of words for the ASLO and WOS searches suggests that the results obtained from ASLO abstracts are representative of research conducted outside of ASLO, and both databases reveal an increasing trend for studies on globally significant themes such as climate and greenhouse gases that is not observed in organismal themes.

**Discussion**

Is limnology becoming increasingly abiotic, riverine, and global? ASLO abstract and WOS article data suggest so, at least in relative terms. Overall research output is increasing in all themes, but there have been consistent increases in the proportion of studies using words linked to themes such as climate change, economic valuation, and broad spatial extents. These findings suggest an increased focus on the role of aquatic ecosystems—rivers in particular—for the planetary carbon cycle as well as for the delivery of ecosystem services (Raymond et al. 2013; Allen and Pavelsky 2018; Dottori et al. 2018), and that this role is increasingly quantified through an anthropogenic lens.

Overall, our results suggest that limnological research is becoming more global and management focused (see Jumars 1990; Lewis 2005; Downing 2014), coherent with trends in Ecology (McCallen et al. 2019). It is difficult to identify definite reasons for these shifts, and in particular, to obtain data from funding agencies to understand where funding goes and what has motivated new funding directions. Resolving this question goes beyond the scope of our study, but we suggest that trends in limnological research stem from (1) a response from the limnological community to influential research in recent years, which may have impacted funding, and (2) an opportunism toward abiotic data that may be more widely available, scalable and coherent over broad spatial extents, or from another angle, logistical and analytical challenges that may limit the feasibility of broad-scale synthesis or harmonization of organismal data.

**Do research trends stem from influential studies?**

The recent trends in limnological research that we present here are in line with the most cited limnological studies since 2004, when ASLO abstracts started to be digitized (search conducted in July 2019 in the same research fields in WOS). Based on the WOS search, we identified the 10 limnological articles within the top 500 most cited found in the fields mentioned above. These articles focused on global synthesis of carbon and nutrients dynamics and effects on food webs (Seitzinger et al. 2006; Cole et al. 2007; Elser et al. 2007; Helms et al. 2008; Tranvik et al. 2009), global distribution of lakes and rivers (Lehner and Döll 2004; Downing et al. 2006), and eutrophication, conservation and restoration (Allan 2004; Palmer et al. 2005; Smith and Schindler 2009). While this exercise naturally favors older papers, it allowed us to identify influential studies that may have impacted recent publishing trends, and in particular the significant shift that occurred in 2009 (Fig. 2). Therefore, the research themes that have increased the most in recent years correspond to the topics of the most influential studies (as suggested by number of citations) published in the first decade of this millennium.

**Do the rising global, riverine, and abiotic studies result from data availability?**

It is unclear whether limnologists increasingly conduct global studies or rather increasingly motivate their studies in a more global context. A clear trend, however, is that the use of the world “Global” is increasing concurrently with abiotic measurements and emerging approaches to limnology, and there are no hints that novel approaches related to organismal studies may be increasingly used at a comparable pace (Table 1). Organismal studies may not scale up well because current technological limitations make measuring and identifying organisms, like phytoplankton and zooplankton, unwieldy and cost prohibitive as numbers of observations grow. Moreover, while abiotic variables tend to follow broad-scale geophysical constraints, biotic patterns respond to local and temporally variable controls and tend to be less coherent across large geographic areas (Fortin and Dale 2005; Lapierre et al. 2018). Nonetheless, biotic variables that are highly comparable among studies, such as biological rates (Elser et al. 2007), diversity metrics (Pinel-Alloul et al. 2013), or functional traits (Hébert et al. 2016), have successfully been included in broad-scale studies, but these remain rare in limnology compared to their abiotic counterparts. New technologies like flow cytometry, fluoroprobes, and eDNA are promising but have not yet matched the precision and economics of their abiotic counterparts (Harrison et al. 2016; Hering et al. 2018), for
example, portable gas chromatographs and fluorometers (Crawford et al. 2015), improved remote sensing capabilities (Olmanson et al. 2016; Toming et al. 2016) and networks of instrumented buoys (Hanson et al. 2016) that facilitate data harmonization and collaborative networks across continents. Moreover, while there are broad scale biological monitoring programs, such as the US EPAs National Aquatic Resource Surveys (e.g., NLA, NRSA; Pollard et al. 2018), a persisting challenge is to ensure consistent taxonomy and identification is applied across laboratories, especially for microscopic organisms, limiting comparison among, and even within laboratories or monitoring programs (Kahlert et al. 2016; Bishop et al. 2017). Together, these factors could explain intriguing trends, such as some abiotic words (e.g., “Methane”) increasing faster than their biotic drivers (e.g., “Microbial,” “Bacteria”). Likewise, the increasing management, climate, greenhouse, or socio-economic themes are likely not research fields per se yet, but it appears that limnologists are increasingly studying these variables or contexts as emerging central research themes rather than as consequences of their underlying abiotic drivers such as productivity, plankton, or nutrient themes; as a consequence abiotic themes have occupied an increasingly large proportion of limnological research in recent years.

McCallen et al. (2019) have argued that funding agencies should consider the shifting nature in the way scientists conduct ecological research, and here we show evidence of rapidly increasing, as well as potentially emerging themes specific to the field of limnology. We want to emphasize, however, that we do not interpret the trends reported here as a judgment on what themes are, or may become, more or less important for limnological research. Rather, these empirical trends suggest that as we know more about local aquatic ecosystem functioning, focus may be shifting to applying this knowledge in a more global context with the assistance of new informatics and analytical tools. Perhaps some more traditional study subjects such as “Zooplankton” or “Production” simply have yet to—or should urgently—be incorporated into emerging limnological problems, but we suggest that limitations in data generation and analysis that limit cross-system comparability have to be alleviated before this is realistic.

References

Allan, J. D. 2004. Landscapes and riverscapes: The influence of land use on stream ecosystems. Annu. Rev. Ecol. Evol. Syst. 35: 257–284. doi:10.1146/annurev.ecolsys.35.120202.110122

Allen, G. H., and T. Pavelsky. 2018. Global extent of rivers and streams. Science. 361: 585–588. doi:10.1126/science.aat0636

Bennion, H., T. A. Davidson, C. D. Sayer, G. L. Simpson, N. L. Rose, and J. P. Sadler. 2015. Harnessing the potential of the multi-indicator palaeoecological approach: An assessment of the nature and causes of ecological change in a eutrophic shallow lake. Freshw. Biol. 60: 1423–1442. doi:10.1111/fwb.12579

Bishop, I. W., R. M. Esposito, M. Tyree, and S. A. Spaulding. 2017. A diatom voucher flora from selected southeast rivers (USA). Phytotaxa 332: 101. doi:10.11646/phytotaxa.332.2.1

Cole, J. J., and others. 2007. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. Ecosystems 10: 171–184. doi:10.1007/s10021-006-9013-8

Crawford, J. T., L. C. Loken, N. J. Casson, C. Smith, A. G. Stone, and L. A. Winslow. 2015. High-speed limnology: Using advanced sensors to investigate spatial variability in biogeochemistry and hydrology. Environ. Sci. Technol. 49: 442–450. doi:10.1021/es504773x

Dottori, F., and others. 2018. Increased human and economic losses from river flooding with anthropogenic warming. Nat. Clim. Chang. 8: 781–786. doi:10.1038/s41558-018-0257-z

Downing, J. A. 2014. Limnology and oceanography: Two estranged twins reuniting by global change. Inland Waters 4: 215–232. doi:10.5268/IW-4.2.753

Downing, J. A., and others. 2006. The global abundance and size distribution of lakes, ponds, and impoundments. Limnol. Oceanogr. 51: 2388–2397. doi:10.4319/lo.2006.51.5.2388

Durden, J. M., J. Y. Luo, H. Alexander, A. M. Flanagan, and L. Grossmann. 2017. Integrating “big data” into aquatic ecology: Challenges and opportunities. Limnol. Oceanogr.: Bull. 26: 101–108. doi:10.1002/lob.10213

Elser, J. J., and others. 2007. Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems. Ecol. Lett. 10: 1135–1142. doi:10.1111/j.1461-0248.2007.01113.x

Faith, D. P., P. R. Minchin, and L. Belbin. 1987. Compositional dissimilarity as a robust measure of ecological distance. Vegetatio 69: 57–68. doi:10.1007/BF00038687

Fortin, M.-J., and M. R. T. Dale. 2005, Spatial analysis: A guide for ecologists. Cambridge Univ. Press.

Galili, T. 2015. dendextend: An R package for visualizing, adjusting and comparing trees of hierarchical clustering. Bioinformatics 31: 3718–3720. doi:10.1093/bioinformatics/btv428

Grimm, E. C. 1987. Constrained cluster analysis by the method of incremental sum of squares. Comput. Geosci. 13: 13–35. doi:10.1016/0098-3004(87)90022-7

Hanson, P. C., K. C. Weathers, and T. K. Kratz. 2016. Networked lake science: How the Global Lake Ecological Observatory Network (GLEON) works to understand, predict, and communicate lake ecosystem response to global change. Inland Waters 6: 543–554. doi:10.1002/iw.6.4.904

Harrison, J. W., E. T. Howell, S. B. Watson, and R. E. H. Smith. 2016. Improved estimates of phytoplankton community composition based on in situ spectral fluorescence: Use of ordination and field-derived norm spectra for the bbe FluorolProbe. Can. J. Fish. Aquat. Sci. 73: 1472–1482. doi:10.1139/cjfas-2015-0360
Hébert, M. P., B. E. Beisner, and R. Maranger. 2016. A meta-analysis of zooplankton functional traits influencing ecosystem function. Ecology. 97: 1069–1080. doi:10.1890/15-1084.1

Helms, J. R., A. Stubbins, J. D. Ritchie, E. C. Minor, D. J. Kieber, and K. Mopper. 2008. Absorption spectral slopes and slope ratios as indicators of molecular weight, source, and photobleaching of chromophoric dissolved organic matter. Limnol. Oceanogr. 53: 955–969. doi:10.4319/lo.2008.53.3.0955

Hering, D., and others. 2018. Implementation options for DNA-based identification into ecological status assessment under the European Water Framework Directive. Water Res. 138: 192–205. doi:10.1016/j.watres.2018.03.003

Juggins, S. 2015. rioja: Anlaysis of quaternary science data. R Doc. Available from https://cran.r-project.org/web/packages/rioja/index.html. Accessed November 15, 2019.

Kahlert, M., and others. 2016. Quality assurance of diatom counts in Europe: Towards harmonized datasets. Hydrobiologia. 772: 1–14. doi:10.1007/s10750-016-2651-8

Kalf, J., and J. A. Downing. 2016. Limnology: Inland water ecosystems, 2nd Edition. Bibliogenica.

Lapière, J. F., and others. 2018. Similarity in spatial structure constrains ecosystem relationships: Building a macroscale understanding of lakes. Glob. Ecol. Biogeogr. 27: 1251–1263. doi:10.1111/geb.12781

Lehner, B., and P. Döll. 2004. Development and validation of a global database of lakes, reservoirs and wetlands. J. Hydrol. 296: 1–22. doi:10.1016/j.jhydrol.2004.03.028

Lewis, W. M., Jr. 2005. Publishing in limnology, now and then. Limnol. Oceanogr.: Bull. 14: 25–30. doi:10.1002/lob.200514225

McCallen, E., J. Knott, G. Nunez-Mir, B. Taylor, I. Jo, and S. Fei. 2019. Trends in ecology: Shifts in ecological research themes over the past four decades. Front. Ecol. Environ. 17: 109–116. doi:10.1002/fee.1993

Murtagh, F., and P. Legendre. 2014. Ward’s hierarchical agglomerative clustering method: Which algorithms implement Ward’s criterion? J. Classif. 31: 274–295. doi:10.1007/s00357-014-9161-z

Nobis, M., and T. Wohlgemuth. 2004. Trend words in ecological core journals over the last 25 years (1978-2002). Oikos 106: 411–421. doi:10.1111/j.0030-1299.2004.13496.x

Oksanen, J., and others. 2018. vegan: Community ecology package. R package version 2.5–2. CRAN R.

Olmanson, L. G., P. L. Brezonik, J. C. Finlay, and M. E. Bauer. 2016. Comparison of Landsat 8 and Landsat 7 for regional measurements of CDOM and water clarity in lakes. Remote Sens. Environ. 185: 119–128. doi:10.1016/j.rse.2016.01.007

Palmer, M. A., and others. 2005. Standards for ecologically successful river restoration. J. Appl. Ecol. 42: 208–217. doi:10.1111/j.1365-2664.2005.01004.x

Paradis, E., and K. Schliep. 2019. Ape 5.0: An environment for modern phylogenetics and evolutionary analyses in R. Bioinformatics 35: 526–528. doi:10.1093/bioinformatics/bty633

Pinel-Alloul, B., A. André, P. Legendre, J. A. Cardille, K. Patalas, and A. Salki. 2013. Large-scale geographic patterns of diversity and community structure of pelagic crustacean zooplankton in Canadian lakes. Glob. Ecol. Biogeogr. 22: 784–795. doi:10.1111/geb.12041

Pollard, A. I., S. E. Hampton, and D. M. Leech. 2018. The promise and potential of continental-scale limnology using the U.S. Environmental Protection Agency’s national lakes assessment. Limnol. Oceanogr.: Bull. 27: 36–41. doi:10.1002/lob.10238

R Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

Raymond, P., and others. 2013. Global carbon dioxide emissions from inland waters. Nature 503: 355–359. doi:10.1038/nature12760

Seitzinger, S., J. A. Harrison, J. K. Böhlke, A. F. Bouwman, R. Lowrance, B. Peterson, C. Tobias, and G. Van Drecht. 2006. Denitrification across landscapes and waterscapes: A synthesis. Ecol. Appl. 16: 2064–2090. doi:10.1890/1051-0761(2006)016[2064:DALAWA]2.0.CO;2

Smith, V. H., and D. W. Schindler. 2009. Eutrophication science: Where do we go from here? Trends Ecol. Evol. 24: 201–207. doi:10.1016/j.tree.2008.11.009

Toming, K., T. Kutser, A. Laas, M. Sepp, B. Paavel, and T. Nõges. 2016. First experiences in mapping lake water quality parameters with sentinel-2 MSI imagery. Remote Sens. 8: 640. doi:10.3390/rs8080640

Tranvik, L. J., and others. 2009. Lakes and reservoirs as regulators of carbon cycling and climate. Limnol. Oceanogr. 54: 2298–2314. doi:10.4319/lo.2009.54.6_part_2.2298

Wetzel, R. G. 2001. Limnology: Lake and river ecosystems. Elsevier.

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