Historical watershed stressors for the Laurentian Great Lakes

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Abstract
This report provides a detailed set of historical stressor data for 60 watersheds comprising the Laurentian Great Lakes basin. Archival records were transcribed from public records to create quantitative data on human activities: population, mining, deforestation, and agriculture. Yearly records of stressors are provided from 1780 through 2010. These data may be used to track historical impacts on Great Lakes coastal and open water conditions. They may further be used to examine corresponding effects on response variables such as biological communities quantified during monitoring and palaeoecological programmes.

KEYWORDS
agriculture, Great Lakes, population, stressors, watershed

1 | INTRODUCTION
Targeting of remedial efforts in lakes requires quantifying anthropogenic stressors that differ spatially and in relative impact. Although historical water quality data can be sparse, human activities that affect water quality, such as mining, agriculture, and shoreline development, more commonly have long-term archives that have been maintained by government agencies. For decades, researchers have used palaeolimnology to substitute for missing information on historical impacts in aquatic systems (Smol, 2009), including a suite of studies on the Laurentian Great Lakes (Schelske and Stoermer, 1971; Schelske et al., 1983; Stoermer et al., 1985a; 1985b; 1987; Wolin et al., 1988; Stoermer et al., 1993; 1996; Shaw Chraibi et al., 2014; Reavie et al., 2017; Sgro and Reavie, 2018). While a detailed account of contemporary watershed stressors has been compiled for the Great Lakes (Danz et al., 2007), we further compiled historical stressor data to compare with palaeolimnological records. So far, we have used these data to relate historical anthropogenic activities with fossil diatom trends and geochemistry in Lake Superior (Shaw Chraibi et al., 2014) and Lake Erie (Sgro and Reavie, 2018). The sediment cores used for comparison were collected from deep, pelagic regions in the lakes, so lake-wide stressor information (i.e., from all sub-watersheds around a lake) was relevant, but there is potential to compare nearshore conditions with more localized watershed stressors. For instance, local restoration planning is often focused on maintaining ecosystem services (Bullock et al., 2011) where those services are greatest. Furthermore, having a retrospective of stress can enhance strategic targeting of restoration by indicating the most important stressors and whether conditions are improving.

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2 | METHODS

In order to provide stressor data for local watersheds, a set of 5,971 watersheds covering the US and Canadian Great Lakes basin had been delineated using ESRI ArcGIS ArcHydro extensions, as described in Hollenhorst et al. (2007) and Host et al. (2011). For this project, they were agglomerated into 60 watersheds of approximately equal size. Using the St. Lawrence Seaway as a natural break, watersheds from the original 5,971 were collected in shoreline sub-watersheds of approximately equal size. At that point, a GIS union operation was used to merge the small watersheds, and collection for the 60 new “sub-watersheds” was started. These sub-watersheds are the primary spatial units of the stressor data.

Spatial and temporal dynamics of land-use patterns were collected from governmental historical records (Supplement S1; https://doi.org/10.1594/pangaea.885879) and a database was populated with information from various Internet and GIS resources. Land use included agriculture, population, mining, and forestry (Table 1). Transcribed records combined a date (census dates, years of operation for mines), the land use in question, the level of the land use (acres, people, mines), and the spatial distribution of the land use (county boundaries, coordinates for cities, mines, and other phenomena). Historical items were placed on a timeline with annual time-steps from 1780 through 2010, though this compilation was limited by the accuracy and completeness of the historical archives. Acquiring early data for the whole basin was not possible for some parameters (pre-1790 population, pre-1850 agriculture). For years with missing data, we used linear interpolations between adjacent years with data to estimate active stress (e.g., agricultural area) for a given watershed.

The stressor value associated with each yearly record (stressor value, year) was rendered into a GIS raster grid specific to each land-use type. The value of each land use was summarized within 60 watersheds covering the basin, numbered 2 through 61 (Figure 1), each watershed capturing a major river and its upgradient catchment. (Sub-watershed 1 was a St. Lawrence River catchment and was discarded.) Although smaller watersheds would have been possible in some areas, we selected this watershed size based on the overall spatial resolution of historical data. County-based agricultural land, forested land, and population data were converted to watershed-based stressors using area-weighted averaging, while mining data were simply summarized for each watershed based on mine coordinates. Supplement S1 provides references for specific data sources in case a reader was interested in stressor data for more specific locales. We provide the full stressor dataset for all watersheds in Supplement S2 (https://doi.org/10.1594/pangaea.885879). If desired, postprocessing of these data would allow for reporting of land-use activities for a particular date and/or changes in land-use for a particular range of years. Historical land-use data could be generated for all watershed groups combined or for selected subsets of watershed groups (e.g., one lake). Figure 2 provides an example of some compiled data; all stressor data for the Great Lakes basin and data compiled for the watersheds around Lake Huron.

Additional details about the four stressor characters and how they were summarized are provided below.

2.1 | Mining (USGS, 1844–2012)

Given its importance to the economies of Great Lakes states and provinces, and its well-known association with water and atmospheric pollution, it was imperative to summarize mining-related stress. The number of active (and potentially polluting) mines at a given time was difficult to determine from historical records. However, good records were available on the establishment of new mines. The appearance of new mines, in itself, may be a satisfactory tracer of resulting stress in aquatic ecosystems. For instance, the rise of new mining facilities in the vicinity of Sault Ste. Marie was closely associated with cadmium pollution as inferred from a sediment core in Lake George, just upstream from Lake Huron (Reavie et al., 2005). In addition to summarizing new mines (i.e., the number of newly opened mine facilities in a given watershed in a given year), we calculated an additional stressor parameter that roughly estimates the prolonged impacts of mining by applying an arbitrary decay function to the new mine data, forming a “mining stress” indicator. Given the likely high variation in long-term impacts from mines, we consider this decay constant as highly uncertain, such as attributing the same stress from a cobalt mine and a limestone quarry. While we did not apply such judgements, we wanted to show how cumulative and persistent effects of mining

| Stressor variable | Unit |
|-------------------|------|
| New mines         | Number of new mines opened in a given year |
| Mining stress     | Unitless, based on cumulative effects of mines and a decay curve (Section 2.1) |
| Taconite waste discharge | Unitless, ranging from 0 (none) to 1 (maximum); Lake Superior only |
| Agriculture       | Acres of agricultural area |
| Population        | Number of human residents |
| Forestry          | Acres of forested area |
might look. The mining stress level $S$ starts at zero and changes per year according to:

$$\frac{dS}{dy} = N_y - (0.1 \times (S_{y-1} + N_y))^2,$$

where $S_y$ is the stress level in year $y$ and $N_y$ is the number of new mines in year $y$. This formula generates a unitless stressor value that may be considered the lingering effect of mining activity in a watershed. For instance, the year a mine is established it contributes 0.99 mining stress units to the total for its respective watershed. A year later its contribution is approximately 0.98 units. Etc.

An additional stressor variable characterized taconite waste discharge in Lake Superior at the Reserve Mining facility in Silver Bay (watershed 56). Approximately 500 million tonnes of taconite tailings were discharged to the lake between 1955 and 1980 (Weston, 1971), and the legacy of this contamination appears as geochemical markers in lake sediment cores (Shaw Chraïbi et al., 2014). Quantifying the volume of discharge for a given year was difficult, so we applied an arbitrary scale in which 1.0 represents maximum processing output of the facility.

2.2 | Agriculture (Canada Census Office 1880–2006, USDA 1850–2002, 2007)

Agriculture largely comprised rural land classification data generally collected as census to determine property values and necessary permits. The Census of Agriculture, taken every 5 years, is a complete count of US farms and ranches. For 156 years (1840–1996), the US Department of Commerce, Bureau of the Census was responsible for collecting data for the Census of Agriculture. In 1997, responsibility transferred to the US Department of Agriculture's National Agricultural Statistics Service (NASS). Agricultural census data for Canada was available approximately every 10 years. In many cases, data were available for farms indicating size and type, inventory, and values for crops and livestock. Unfortunately, these details were historically erratic, so we focused on documented agricultural area as the tracer for stress.
2.3 | Population (Canada Dominion Bureau of Statistics, 1871–2011, US Department of Commerce, USBC, 1850–2010)

Census data for rural and urban populations were fairly consistently available over the last two centuries. While compiling these data was time consuming, little extrapolation was required to fill data gaps.

2.4 | Forests (Supplement S1, Reavie et al., 2018)

Technically these data do not represent a “stressor” in the same way as the other parameters, but a long-term decline in forested area (deforestation) reflects watershed stress. It is well-known that deforestation results in increased runoff and, typically in association with croplands, increases nutrient supplies to aquatic systems (Hasler, 1947). These data were available from forest inventory records that characterized forest land area for each county in the United States. Periodic inventories of forested land were used to determine forest extent and removals. Without a forest inventory survey in Canada, forested area in Canada was calculated as: Total land area minus agricultural, water, and urban areas.

Urban area data were provided by the US Department of Commerce and the US Census Bureau (1850–2010) and the Canada Dominion Bureau of Statistics (1871–2011). It is our hope that these data and source summaries are useful, and we welcome discussions with interested researchers on ways to further refine or process the dataset. While maintenance is not currently funded, this land-use dataset will likely be developed and refined in the future, particularly with the addition of post-2010 data. Nonetheless, at this time, the compiled results provide a clear picture of historical activities around the Great Lakes.

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OPEN PRACTICES

This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available at https://doi.org/10.1594/PANGAEA.885879. Learn more about the Open Practices badges from the Center for Open Science: https://osf.io/tvyxz/wiki.
REFERENCES

Bullock, J.M., Aronson, J., Newton, A.C., Pywell, R.F. and Rey-Benayas, J.M. (2011) Restoration of ecosystem services and biodiversity: Conflicts and opportunities. *Trends in Ecology and Evolution*, 26, 541–549. https://doi.org/10.1016/j.tree.2011.06.011

Canada Census Office. (1880–2006) *Census of Canada Agriculture*. Ottawa, ON: S.E. Dawson.

Canada Dominion Bureau of Statistics. (1871–2011) *Census of Canada Population*. Ottawa, ON: J. O. Patenaude. Accessed October 2009. Retrieved from http://archive.org/details/1931981931m161934engfra

Danz, N.P., Niemi, G.J., Regal, R.R., Hollenhorst, T., Johnson, L.B., Hanowski, J.M., … Host, G.E. (2007) Integrated measures of anthropogenic stress in the US Great Lakes basin. *Environmental Management*, 39, 631–647. https://doi.org/10.1007/s00267-005-0293-0

Hasler, A.D. (1947) Eutrophication of lakes by domestic drainage. *Ecology*, 28, 383–395.

Hollenhorst, T.P., Brown, T.N., Johnson, L.B., Ciborowski, J.J.H. and Host, G.E. (2007) Methods for generating multi-scale watershed delineations for indicator development in Great Lake coastal ecosystems. *Journal of Great Lakes Research*, 33, 13–26. https://doi.org/10.3394/0380-1330(2007)33[13:MFGMWD]2.0.CO;2

Host, G.E., Brown, T.N., Hollenhorst, T.P., Johnon, L.B. and Ciborowski, J.J.H. (2011) High-resolution assessment and visualization of environmental stressors in the Lake Superior basin. *Aquatic Ecosystem Health and Management*, 14, 376–385. https://doi.org/10.1080/14634988.2011.625340

Reavie, E.D., Cai, M. and Brown, T.N. (2018) *Historical watershed stressors for the Laurentian Great Lakes*. PANGAEA. https://doi.org/10.1594/pangaea.885879

Reavie, E.D., Robbins, J.A., Stoermer, E.F., Douglas, M.S.V., Emmert, G.E., Morehead, N.R. et al. (2005) Paleolimnology of a fluvial lake downstream of Lake Superior and the industrialized region of Sault Saint Marie. *Canadian Journal of Fisheries and Aquatic Science*, 62, 2586–2608. https://doi.org/10.1139/f05-170

Reavie, E.D., Sgro, G.V., Estepp, L.R., Brumbaugh, A.J., Pillsbury, R.W., Shaw Chraibi, V.L. et al. (2017) Climate warming and changes in *Cyclotella sensu lato* in the Laurentian Great Lakes. *Limnology and Oceanography*, 62, 768–783.

Schelske, C.L. and Stoermer, E.F. (1971) Eutrophication, silica depletion, and predicted changes in algal quality in Lake Michigan. *Science*, 173, 423–424. https://doi.org/10.1126/science.173.3995.423

Schelske, C.L., Stoermer, E.F., Conley, D.J., Robbins, J.A. and Glover, R.M. (1983) Early eutrophication in the lower Great Lakes. *Science*, 222, 320–322.

Sgro, G.V. and Reavie, E.D. (2018) Lake Erie's ecological history reconstructed from the sedimentary record. *Journal of Great Lakes Research*, 44, 54–69. https://doi.org/10.1016/j.jglr.2017.11.002

Shaw Chraibi, V.L., Kireta, A.R., Reavie, E.D., Cai, M. and Brown, T.N. (2014) A paleolimnological assessment of human impacts on Lake Superior. *Journal of Great Lakes Research*, 40, 886–897. https://doi.org/10.1016/j.jglr.2014.09.016

Smol, J.P. (2009) *Pollution of lakes and rivers: a paleoenvironmental perspective*. New Jersey, USA: John Wiley & Sons.

Stoermer, E.F., Emmert, G., Julius, M.L. and Schelske, C.L. (1996) Paleolimnologic evidence of rapid recent change in Lake Erie's trophic status. *Canadian Journal of Fisheries and Aquatic Sciences*, 53, 1451–1458. https://doi.org/10.1139/cjfas-53-6-1451

Stoermer, E.F., Kociolek, J.P., Schelske, C.L. and Conley, D.J. (1985a) Siliceous microfossil succession in the recent history of Lake Superior. *Proceedings of the Academy of Natural Sciences of Philadelphia*, 137, 106–118.

Stoermer, E.F., Kociolek, J.P., Schelske, C.L. and Conley, D.J. (1987) Quantitative analysis of siliceous microfossils in the sediments of Lake Erie's central basin. *Diatom Research*, 2, 113–134. https://doi.org/10.1080/0269249X.1987.9704988

Stoermer, E.F., Wolin, J.A., Schelske, C.L. and Conley, D.J. (1985b) An assessment of ecological changes during the recent history of Lake Ontario based on siliceous algal microfossils preserved in the sediments. *Journal of Phycology*, 21, 257–276. https://doi.org/10.1111/j.0022-3646.1985.00257.x

Smol, J.P. (2009) *Paleolimnology of freshwater ecosystems*. New Jersey, USA: John Wiley & Sons.

US Department of Commerce. USBC (US Bureau of the Census). (1850–2010) The Census of the United States. United States Government Printing Office. Washington, DC. Accessed November 2010. Retrieved from http://www.census.gov/prod/www/decennial.html

USDA (United States Department of Agriculture). *Census of Agriculture Historical Archive*. U.S. Department of Commerce, Bureau of the Census. (1850–2002) United States Census of Agriculture. United States Government Printing Office: Washington, DC. Accessed November 2010. Retrieved from http://agcensus.ma.nnlib.cornell.edu/AgCensus/

USDA (United States Department of Agriculture). *Census of Agriculture*. U.S. Department of Commerce, Bureau of the Census. (2007) United States Census of Agriculture. United States Government Printing Office: Washington, DC. Accessed October 2010. Retrieved from https://www.agcensus.usda.gov/Publications/2007

USGS (United States Geological Survey). (1844–2012) Mineral Resources Data System. Accessed October 2010. Retrieved from http://www.mrddata.usgs.gov/mrds/

Weston, R.F. (1971) *Concept evaluation report. Taconite tailings disposal. Reserve Mining Company, Silver Bay, Minnesota*. Washington, DC: Environmental Protection Agency.

Wolin, J.A., Stoermer, E.F., Schelske, C.L. and Conley, D.J. (1988) Siliceous microfossil succession in recent Lake Huron sediments. *Archiv für Hydrobiologie*, 114, 175–198.