Record-setting algal bloom in Lake Erie Caused by agricultural and meteorological trends consistent with expected future conditions

Presented by
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Eutrophication & Algal Bloom

A massive algae bloom in 2011 turned Lake Erie into pea soup.
PHOTOGRAPH BY PETER ESSICK, NATIONAL GEOGRAPHIC
Taken in August of that year along the southeast shore of Pelee Island, Ontario. Image credit: Tom Archer
Outline

• Background
• Hypothesis
• Results & Discussions
• Future trends
2011 Algal Bloom in Lake Erie

- Record-setting magnitude
- Covered an area of 600km$^2$ in initial phase
- Peak intensity 7.3 times bigger greater than the previous 9-year average, 3.3 times greater than the previous peak observed in 2008 in duration, areal coverage and biovolume
- Cyanobacteria representing 60%-98% in western basin
2011 Algal Bloom in Lake Erie

• Mid July, Initiation of the algal bloom of microcystis
• Late August, secondary bloom of Anabaena sp.
Recall from class

• Microcystis ------ microcystin (non N-fixing, damage liver)
• Anabaena ----- anatoxin (neuron toxin, N-fixing)

• Microsystin bloom largely depleted bioavailable Nitrogen
• low N:P ratio favor non-fixing cyanobacteria species.

• Increasing nutrients allows increasing chance of HABs
• Stagnant water conditions and poor flushing may favor HABs.
Fig. 1. MODIS satellite image of Lake Erie on September 3, 2011, overlaid over map of Lake Erie tributaries. This image shows the bloom about 6 wk after its initiation in the western basin. On this date, it covers the entire western basin and is beginning to expand into the central basin, where it will continue to grow until October (Fig. S1).
Hypothesis

• Severe spring precipitation events, coupled with long-term trends in agricultural land use and practices, produced a pulse of remarkably high loading of highly bioavailable dissolved reactive phosphorus (DRP) to the western basin of Lake Erie.

• Uncommonly warm and quiescent conditions in late spring and summer and an unusually strong resuspension event immediately preceding bloom onset, are further hypothesized to have provided ideal incubation, seeding, and growth conditions for bloom development.
Trends in agricultural land use contribution

Nationally
------Corn cropland grew by 3.655 M hectares (increased 11%) between 2008 and 2011 compared to 1997-2006
------Conservation Reverse Program (CRP) declined by 2.9 M hectares (decreased 20%) since 2007

In western Lake Erie Watershed
------Downward trend in CRP area in western Lake Erie watershed, hectares declining from 128,812 in 2007 to 114,806 in 2011 (11% decrease)
------A minor upward trend annually in corn area after 2007, with hectares increasing from 944,000 in 2008 to 967,000 in 2011 (2% increase)
Fig. S2. Major agricultural land uses in western Lake Erie watershed and national corn cropland, 1997–2011.
Trends in agricultural land use contribution

- Trends in Lake Erie watershed deviate sharply from national trends
- Slightly change in both corn cropland and CRP from 2008 to 2011 in west Lake Erie basin
- Greater phosphorus runoff and loadings not expected
- Recent agricultural land use trend is not a driver
Long-term trends in agricultural nutrient management practices

• Fall fertilizer application
• Fertilizer broadcast on the surface than injected in the soil
• Conservation tillage

• Creating conditions for DRP (Dissolved Reactive Phosphorus) runoff
<table>
<thead>
<tr>
<th>Risk factor</th>
<th>Trend</th>
<th>Basis of knowledge of trend</th>
<th>Impact on nutrient loading</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall fertilizer application rather than spring</td>
<td>+</td>
<td>Impact documented by Ohio Lake Erie Phosphorus Task Force (1); trend documented in neighboring regions (2) and anecdotally confirmed by farmers and certified crop advisors.</td>
<td>++</td>
<td>Longer exposure to precipitation.</td>
</tr>
<tr>
<td>Fertilizer broadcast on surface instead of injected or incorporated</td>
<td>+</td>
<td>Anecdotal (based on discussions with farmers and certified crop advisors).</td>
<td>++</td>
<td>More direct exposure to precipitation, lack of binding to soil particles.</td>
</tr>
<tr>
<td>Conservation tillage</td>
<td>+ (primarily pre-2000)</td>
<td>Data from Conservation Tillage Information Center, Purdue University.</td>
<td>+</td>
<td>Contribution to phosphorus stratification; incentive to surface-apply nutrients.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Enhanced flow through soil matrix and reduced preferential flow lead to better contact with phosphorus-adsorption sites; enhanced water retention capacity.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Decrease contact time between phosphorus and soil matrix.</td>
</tr>
<tr>
<td>Stratification of P in soil</td>
<td>+</td>
<td>Presence documented by NCWQR, trend inferred from conservation tillage trend. Eckert and Johnson (3) showed that stratification sets up quickly (3 y) without inversion tillage.</td>
<td>++</td>
<td>Surface application; breakdown of crop residue; lack of inversion tillage leads to phosphorus concentration near soil surface where leaching is most active.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>More fertilizer, more export.</td>
</tr>
<tr>
<td>Extent and efficiency of tile drainage</td>
<td>+</td>
<td>Research of Kevin King, USDA–ARS, The Ohio State University (Columbus, OH); Jane Frankenburg, USDA–NRCS, Purdue University (W. Lafayette, IN).</td>
<td>+</td>
<td>Need for greater efficiency promotes surface application of fertilizers in the fall.</td>
</tr>
<tr>
<td>Excessive fertilizer sales</td>
<td>Unknown</td>
<td>Practice documented (4), trend unknown.</td>
<td>+</td>
<td>More nutrients from manure.</td>
</tr>
<tr>
<td>Consolidation of farms</td>
<td>+</td>
<td>Data from Census of Agriculture via National Agricultural Statistics Service.</td>
<td>+</td>
<td>More fertilizer, more export.</td>
</tr>
<tr>
<td>Animal numbers</td>
<td>+</td>
<td>Data from Census of Agriculture via National Agricultural Statistics Service.</td>
<td>+</td>
<td>Need for greater efficiency promotes surface application of fertilizers in the fall.</td>
</tr>
<tr>
<td>Soil phosphorus concentrations</td>
<td>−</td>
<td>Data obtained by NCWQR from major soil-testing laboratories in Ohio (4).</td>
<td>−</td>
<td>Higher soil concentrations correlated with higher losses in runoff.</td>
</tr>
</tbody>
</table>
Long-term trends in agricultural nutrient management practices

• Trends in agricultural nutrient management practice, are consistent with a potential for higher nutrient loading.
• 218% increase in DRP loading between 1995 to 2011 from the Maumee River, whose runoff increased by only 42%
• Maumee river contributed 5% of discharge, nearly 50% of P loading
• Detroit river had over 90% of discharge, about 50% of P loading
Fig. 51. Progression of Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images of the western basin of Lake Erie. (A) June 1, 2011. This image was taken after the peak of the late May high flow event in the Maumee River and shows the plume of suspended solids and associated nutrients from the river associated with that event. (B) July 19, 2011. This image was taken at the beginning of the Microcystis bloom. It shows that the bloom started along the western shore of the western basin, shortly after a moderate wind-driven bottom sediment resuspension event along the western shore. (C) July 31, 2011, approximately 2 wk after the bloom was first initiated. This image shows how the bloom has spread through much of the southern western basin. It also shows how the large flow from the Detroit River is keeping the bloom from spreading to the north. The Detroit River plume is also seen to be short-circuiting to the central basin through the north passage between Point Pelee and Pelee Island. (D) August 11, 2011. This image shows the bloom spreading east toward the central basin. It also shows a smaller separate bloom from Lake St. Clair beginning to be transported through the Detroit River to the western basin. (E) September 3, 2011. This image shows the bloom expanding into the central basin and a second phase of the bloom forming along the northern shore of the central basin. (F) October 9, 2011. This image shows the decline of the bloom in the western basin, as it is diluted by the Detroit River plume transporting a whiting event from Lake St. Clair (precipitation of CaCO$_3$ as pH and temperature increase) into the western basin. The bloom is still evident along both the north and south shorelines of the central basin. [Images courtesy of University of Wisconsin-Madison Space Science and Engineering Center.]
Table S2. Results of discharge and nutrient loading trend analyses, 1995–2011

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Trend, yr(^{-1})</th>
<th>% change over 1995–2011</th>
<th>P value</th>
<th>Complex regression P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge, 10(^6) m(^3)</td>
<td>9.72</td>
<td>42</td>
<td>0.12</td>
<td>—</td>
</tr>
<tr>
<td>TP load, Mg of P</td>
<td>5.01</td>
<td>58</td>
<td>0.14</td>
<td>0.56</td>
</tr>
<tr>
<td>PP load, Mg of P</td>
<td>2.28</td>
<td>31</td>
<td>0.39</td>
<td>0.003</td>
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<tr>
<td>DRP load, Mg of P</td>
<td>2.48</td>
<td>218</td>
<td>0.0004</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>TP DWMC, mg/L of P</td>
<td>4.73 (\times) 10(^{-4})</td>
<td>2.7</td>
<td>0.82</td>
<td>0.56</td>
</tr>
<tr>
<td>PP DWMC, mg/L of P</td>
<td>(-2.36 \times 10(^{-3})</td>
<td>(-16)</td>
<td>0.16</td>
<td>0.003</td>
</tr>
<tr>
<td>DRP DWMC, mg/L of P</td>
<td>2.58 (\times) 10(^{-3})</td>
<td>98</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Simple regression refers to regression against time only, complex regression refers to regression of logged parameter against ln (discharge), time, and sinusoidal seasonality factors. DWMC, discharge-weighted mean concentration (load/discharge).
Fig. 2. (A) Time series of precipitation over the Maumee watershed, with the three different fertilizer application scenarios (arrows) used in the SWAT simulations. (B) Dissolved reactive phosphorus (DRP) yield (kilograms of P per hectares) response to different precipitation intensities, fertilizer application timing, and tillage practices. All DRP yields are summed over May 21–30, 2011 (red box in A). Baseline tillage practices include a realistic combination of conventional and no-till practices. Alternate tillage practice scenarios include either all conventional or all no-till practices with fertilizer application on May 5.
Role of Precipitation

• DRP yields are sensitive to precipitation intensity, fertilizer application timing and tillage practice
• Strong influence by precipitation and least by fertilizer timing
Role of Precipitation

• Peak daily discharge in Maumee River exceeding 2,200 m$^3$/s on May. 25 to May. 27 (99.8 percentile)

• Largest total discharge and P loading for the 111-d (Feb. 17 to June.8) and 15-d (May. 25 to June. 8) since 1975

• In 2012, during March-to-June critical period for setting up algal bloom, discharge from Maumee River only 20% and DRP loading was 15% of 2011.
Fig. S4. Maumee River and Sandusky River daily discharge and cumulative DRP loading (as tons of P) for the first half of 2011. Extremely high flows occurring in February through June led to massive DRP loading. The Maumee loading to the western basin is approximately four times larger than the loading from the Sandusky to the central basin.
**Fig. S3.** Radar composite on (A) May 25, 2011 at 1730 UTC, (B) May 25, 2011 at 2300 UTC, (C) May 26, 2011 at 0600 UTC, and (D) May 26, 2011 at 2130 UTC.
Temperature & Wind Conditions

• Lake buoy----conductive to algal growth after bloom initiation, as 62% of time under warm and quiescent conditions. (daily average wind stress $\tau < 0.05$ Pa and temperature $T > 15 \, ^{\circ}C$)

• Satellite-derived lake temperatures -----3°C warmer than the 1992-2011 summer climatology.

• Unremarkable with strong wind conditions; under bloom-limiting conditions(high wind stress for resuspension, 3.5% relative to 3.3-10.3% in other years).
Lake Circulation

• Low current magnitude and increased residence time
• Residence time in the western basin from winter to summer----- 46% and 36% longer than previous year
• Residence time in the Maumee River in June 2011------ 53% higher than previous year and 77% than average in western basin
Fig. 3. Depth-averaged circulation (A) and residence times (B) in days of western basin of Lake Erie in June 2011. Red contours illustrate residence times that exceed the mean hydraulic residence time of the western basin. Histogram shows the percentage of water in the basin with residence times below 20 d, 20-40 d, 40-60 d, 60-80 d, and greater than 80 d.
Fig. 57. 2011 residence times of western basin Lake Erie water (in days) for each month. Red contours indicate residence times that exceed the estimated mean hydraulic residence time for the basin (53 d for January–October period). Histograms in the lower left corner of each plot show the percentage of water in the basin with residence times below 20 d, 20–40 d, 40–60 d, 60–80 d, and greater than 80 d.
Conclusion

• Long-term agricultural trends consistent with increasing DRP loads
• Weak circulation during summer 2011 leading to longer residence time
• Warm and quiescent lake conditions after bloom allowed Microcystis to remain on top
• Caused by a confluence of long-term trends in agricultural nutrient management and extreme meteorological events conductive to bloom formation.
Likelihood in the future

- Lower CRP acres----78% of current CRP return to crop production between 2012 to 2018
- Higher biofuel policies
- Increase in fertilizer-intensive corn acreage in the region (15% in OH, 4% in MI)
- Increase in the frequency of occurrence of large storms
- Long residence times and similar quiescent conditions
- Lower wind speed
Fig. 4. Probability of daily precipitation intensities for spring (March–April–May) averaged over the western Lake Erie basin (40°–43°N, 82°–85.5°W) as observed by the Climate Prediction Center (CPC) gridded data (black squares) for the present-day time period (1986–2005), as modeled by a 12-model multimodel average for the same present-day time period (black diamonds) and for two future time periods of 2046–2065 (red diamonds) and 2080–2099 (blue diamonds). Vertical lines represent the range of individual model predictions for those models with a nonzero probability of a given event size. Diamond size represents the number of models included in each calculation (i.e., the number of models with nonzero probabilities for a given event size), ranging from 0 to 12. Individual model members are shown in Fig. S9.
Fig. 59. Probability distribution functions of daily precipitation (millimeters day$^{-1}$) for three time periods: (A) historical (1986–2005) for CPC observations (thick red line), 12 individual model members (thin colored lines), and the present-day multimodel average (thick black line); (B) the near future (2046–2065) RCP8.5 Assessment Report 5 (AR5) individual simulations (thin colored lines) and 12-model average (thick black line); and (C) the far future (2080–2099) RCP8.5 AR5 individual model simulations (thin colored lines) and 12-model average (thick black line).
<table>
<thead>
<tr>
<th>Model name</th>
<th>Institute</th>
<th>Resolution</th>
<th>Lat/Lon Eqv.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCSM4</td>
<td>RSMAS</td>
<td>288 × 192</td>
<td>1.25° × 1°</td>
</tr>
<tr>
<td>GFDL-ESM2G</td>
<td>NOAA GFDL</td>
<td>144 × 90</td>
<td>2.5° × 2°</td>
</tr>
<tr>
<td>HadGEM2-CC</td>
<td>MOHC</td>
<td>192 × 145</td>
<td>1.875° × 1.25°</td>
</tr>
<tr>
<td>HadGEM2-ES</td>
<td>MOHC</td>
<td>192 × 145</td>
<td>1.875° × 1.25°</td>
</tr>
<tr>
<td>INMCM4</td>
<td>INM</td>
<td>180 × 120</td>
<td>2° × 1.5°</td>
</tr>
<tr>
<td>IPSL-CM5-LR</td>
<td>IPSL</td>
<td>96 × 96</td>
<td>3.75° × 1.875°</td>
</tr>
<tr>
<td>IPSL-CM5-MR</td>
<td>IPSL</td>
<td>144 × 143</td>
<td>2.5° × 1.25°</td>
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<tr>
<td>MIROC-ESM</td>
<td>MIROC</td>
<td>256 × 128</td>
<td>1.4° × 1.4°</td>
</tr>
<tr>
<td>MIROC-ESM-Chem</td>
<td>MIROC</td>
<td>128 × 64</td>
<td>2.8° × 2.8°</td>
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<tr>
<td>MIROC5</td>
<td>MIROC</td>
<td>256 × 128</td>
<td>1.4° × 1.4°</td>
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<td>MRI-CGCM3</td>
<td>MRI</td>
<td>320 × 160</td>
<td>1.25° × 1.125°</td>
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<tr>
<td>NorESM</td>
<td>NCC</td>
<td>144 × 96</td>
<td>2.5° × 1.875°</td>
</tr>
</tbody>
</table>

CCSM, Community Climate System Model; ESM, Earth System Model; HadGEM, Hadley Centre Global Environment Model; INM, Institute for Numerical Mathematics; INMCM, INM Climate Model; IPSL, Institut Pierre-Simon Laplace; MIROC, Model for Interdisciplinary Research on Climate Japan Agency for Marine-Earth Science and Technology; MOHC, Met Office Hadley Centre; MRI, Meteorological Research Institute; MRI-CGCM, MRI Coupled ocean-atmosphere General Circulation Model; NCC, Norwegian Climate Center; NOAA GFDL, National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory; NorESM, Norwegian Earth System Model; RSMAS, Rosenstiel School of Marine and Atmospheric Science, University of Miami.
Likelihood in the future

• Unremarkable with strong wind conditions; under bloom-limiting conditions (high wind stress for resuspension 3.5% relative to 3.3-10.3% in other years).

• Temperature ----- what trend it would have?
Management Practices

• What can we do to keep the HAB from happening or let it happen less frequent?
• Thanks for watching!