

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

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In 2011, Lake Erie experienced the largest harmful algal bloom in its recorded history, with a peak intensity over three times greater than any previously observed bloom. Here we show that long-term trends in agricultural practices are consistent with increasing phosphorus loading to the western basin of the lake, and that these trends, coupled with meteorological conditions in spring 2011, produced record-breaking nutrient loads. An extended period of weak lake circulation then led to abnormally long residence times that incubated the bloom, and warm and quiescent conditions after bloom onset allowed algae to remain near the top of the water column and prevented flushing of nutrients from the system. We further find that all of these factors are consistent with expected future conditions. If a scientifically guided management plan to mitigate these impacts is not implemented, we can therefore expect this bloom to be a harbinger of future blooms in Lake Erie.

extreme precipitation events | climate change | aquatic ecology | *Microcystis* sp. | *Anabaena* sp.

Eutrophication of freshwater and coastal marine ecosystems resulting from increased anthropogenic nutrient loading to receiving waters has become a global problem (1). Examples of eutrophic lakes with severe toxic cyanobacterial blooms include Lake Taihu in China (2), Lake Winnipeg in Canada (3), and Lake Nieuwe Meer in The Netherlands (4). Lake Erie, the shallowest, most productive, and most southern of the Laurentian Great Lakes, has experienced substantial eutrophication over the past half century. In the 1960s and 1970s, excess phosphorus from point and nonpoint sources produced nuisance algal blooms, poor water clarity, and extensive hypoxic areas (5). In response, the United States and Canada implemented phosphorus loading reduction strategies through the Great Lakes Water Quality Agreement (6, 7). These load reductions resulted in a rapid and profound ecological response as predicted by a range of models (8–10). Despite early success from these management actions, however, hypolimnetic oxygen depletion rates, hypoxia extent (11, 12), and algal biomass (13–15) have increased systematically since the mid-1990s. Of greatest concern is the increase in toxin-forming strains of the cyanobacteria *Microcystis* sp. and *Anabaena* sp. that produce the hepatotoxin microcystin and the neurotoxin anatoxin, respectively. Even nontoxic forms of these blooms, however, severely stress the ecological structure and functioning, as well as the aesthetics, of

the Lake Erie ecosystem. Possible causes for these more recent increases include increases in agricultural nonpoint sources of bioavailable phosphorus (16), the presence of invasive mussel species, specifically *Dreissena rostriformis bugensis* (quagga mussels) and *Dreissenid polymorpha* (zebra mussels) (17–20), and internal phosphorus loading to Lake Erie's central basin that increases in response to hypoxic conditions (21).

In 2011, Lake Erie experienced an algal bloom of record-setting magnitude (Fig. 1). Land use, agricultural practices, and meteorological conditions may all have contributed to stimulating and exacerbating the bloom. We hypothesize that 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. *Dreissenid* populations (22, 23), and phosphorus levels in lake sediments (24, 25) have been stable in recent years, and neither of these factors is therefore hypothesized to be a significant additional contributing factor. Here we test these causal hypotheses and their correspondence with long-

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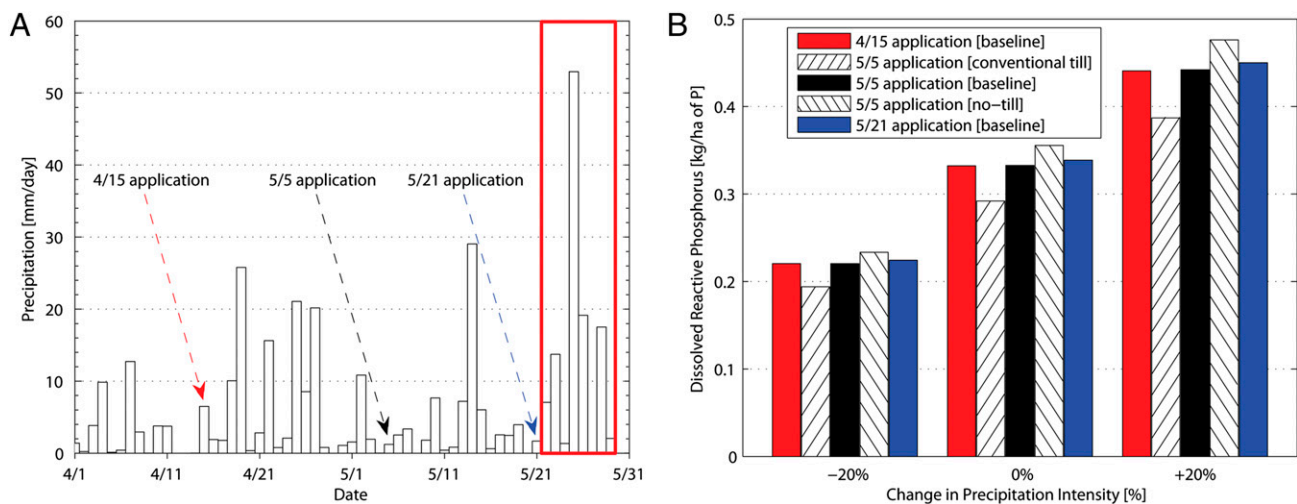


Fig. 2. (A) Time series of precipitation over the Maumee watershed, with the three different fertilizer application scenarios (arrows) used in the SWAT simulations. (B) Dissolved reactive phosphorus (DRP) yield (kilograms of P per hectares) response to different precipitation intensities, fertilizer 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.

June 8) and 15-d (May 25 to June 8) periods covering the springtime precipitation events (Fig. S4) are among the largest observed since 1975, for periods of those lengths. Similarly, total discharge and DRP loads during the March-to-June timeframe, which is the critical period for setting up algal blooms (26), were the largest since intensive monitoring began in 1975. This is in stark contrast to these months in 2012, when discharge from the Maumee was only 20% and DRP loading was 15% of 2011 values.

We use the Soil and Water Assessment Tool (SWAT) model (34, 35) to test the impact of precipitation intensity and agricultural nutrient management practices on expected nutrient loading, to determine whether these factors are likely to be responsible for the loading observed in 2011. SWAT simulations indicate that DRP yields are sensitive to precipitation intensity (higher intensity increasing yields, Fig. 2B), fertilizer application timing (proximity to storm events increasing DRP yields, Fig. 2A and B), and tillage practices (no-till increasing DRP yields, Fig. 2B), with precipitation having the strongest influence and fertilizer timing having the least influence (SI Materials and Methods and SI Results and Discussion). This supports the hypothesis that the confluence of long-term trends in agricultural nutrient management practices and extreme precipitation events was a strong contributor to the DRP yields that triggered the 2011 bloom.

We also hypothesize that temperature and wind conditions over the lake both before and during the bloom encouraged bloom growth, because warm and quiescent conditions before bloom onset led to minimal flushing of the system and reduced vertical lake mixing that allows *Microcystis* to take advantage of its buoyancy regulation. However, wind and surface water temperature data from the lake buoy indicate a lower frequency of warm and quiescent conditions during the 2011 prebloom period (defined as daily average wind stress $\tau < 0.05$ Pa and temperature $T > 15$ °C) (36) relative to other bloom years (SI Materials and Methods and SI Results and Discussion). In addition, although a particularly strong wind-driven resuspension event before the bloom onset could encourage fast initial bloom growth, wind conditions that led to the resuspension event immediately preceding bloom onset were not unusual relative to other years. After bloom initiation, on the other hand, conditions were indeed more conducive to bloom growth relative to other years, as quantified by the percent of time under warm and quiescent conditions after bloom onset (62% relative to 35–56% in other years, $P = 0.015$). These buoy-based observations are consistent

with satellite-derived lake temperatures that were 3 °C warmer than the 1992–2011 summer climatology and 1 °C warmer than 2010 temperatures (SI Materials and Methods, SI Results and Discussion, and Fig. S5).

To investigate the role of lake circulation in encouraging the bloom, we apply 3D hydrodynamic and particle transport models (SI Materials and Methods and SI Results and Discussion). Simulations show that western basin monthly circulation is characterized by a broad west–east flow that exits the basin via three channels (North, Middle, and South), with low current magnitudes correlated with increased residence times (Fig. 3). All simulated years exhibit relatively low-magnitude currents during summer months (May–August), but 2011 had an extended period with weak currents (consistent with weaker winds) from late winter through summer (February–July) (Fig. S6). The residence times in the western basin during this period were 46% and 36% longer than in the previous years (2009 and 2010, respectively). Furthermore, residence times of Maumee River water in June 2011 were 53% longer than in the previous years and 77% longer (>90 d) than the estimated mean hydraulic residence time of the western basin (Fig. S7). Simulations also show that the long residence times were accompanied by a “short circuiting” of Detroit River waters, leading to minimal mixing between the Detroit and Maumee River waters along the western and southern shores of the basin, thus diminishing dilution of nutrient-rich Maumee River waters. Although some mixing occurs near the islands between the western and central basins during April–August, Detroit and Maumee waters primarily leave the western basin through the North and Middle/South Channels, respectively (Fig. S8). Location and timing of bloom initiation is consistent with simulated advection of the elevated late spring Maumee runoff, suggesting that the water mass present at the first stages of the bloom initiation likely originated from the Maumee River close to June 1.

Of the original hypothesized causes of the monumental 2011 bloom, observations and simulations therefore confirm that long-term trends in agricultural practices are consistent with increasing DRP loads delivered to the western basin of Lake Erie, and that meteorological conditions in spring 2011 led to record-breaking nutrient loads to the lake during the late spring. This conclusion is further supported by substantially lower discharge in 2012 leading to lower DRP loading and a weaker bloom (37). Our results further show that weak circulation during summer 2011 led to

through increasing residence times and decreased mixing in the water column.

In summary, we find that trends in agricultural practices, increased precipitation, weak lake circulation, and quiescent conditions conspired to yield the record-breaking 2011 Lake Erie algal bloom. We further find that all of these factors are consistent with expected future conditions. Lacking the implementation of a scientifically guided management plan designed to mitigate these impacts, we can therefore expect this bloom to indeed be a harbinger of future blooms in Lake Erie.

Materials and Methods

Microcystis biovolume and nutrient concentrations were determined at fixed locations in western Lake Erie, and molecular fingerprints were used to analyze *Microcystis* populations. Data on land use, county-level CRP land area, and crop-level phosphate fertilizer application were obtained from the US Department of Agriculture. Additional county-level nutrient use data were obtained from the Nutrient Use Geographic Information System. Meteorological analysis used data from the University Corporation for Atmospheric Research image archive and the College of DuPage. Daily precipitation observations were obtained from National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center. Analysis of discharge and phosphorus loading were based on data from the National Center for Water Quality Research at Heidelberg University and flow data from the US Geological Survey. The SWAT model was used to model nutrient loading. Lake Erie wind and temperature data were obtained from the

NOAA National Data Buoy Center, and remote sensing lake surface temperature data were obtained from NOAA CoastWatch. Hydrodynamic modeling was conducted using the Beletsky and Schwab model and a particle tracking code was used for residence time calculations and river plume tracking. Present-day and future climate model analyses were based on the CMIP5 data archive. Detailed materials and methods, and references, are available in *SI Materials and Methods*. Information on data availability is provided in *SI Materials and Methods* and *SI Results and Discussion*.

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