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Anticipated impacts of climate change on 21st century Maumee River discharge and nutrient loads

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ABSTRACT

Climate change holds great potential to affect the Lake Erie ecosystem by altering the timing and magnitude of precipitation driven river discharge and nutrient runoff in its highly agricultural watershed. Using the SWAT hydrologic model and an ensemble of global climate models, we predicted Maumee River (Ohio) discharge during the 21st century under two Intergovernmental Panel on Climate Change (IPCC) greenhouse gas emissions scenarios: RCP4.5 (mid-range, moderate reductions) and RCP8.5 (high, "business as usual"). Annual discharge was projected to increase under both scenarios, both in the near-century (RCP4.5 = 6.5%; RCP8.5 = 2.0%) and late-century (RCP4.5 = 9.2%; RCP8.5 = 15.9%), owing to increased precipitation and reduced plant stomatal conductance. Holding fertilizer application rates at baseline levels, we found that reduced winter surface runoff and increased plant phosphorus (P) uptake led to a respective decrease in annual total P (TP) runoff in the near-century (RCP4.5 = −4.3%; RCP8.5 = −6.6%) and by the late-century (RCP4.5 = −14.6%; RCP8.5 = −7.8%). Likewise, soluble reactive P (SRP) runoff was predicted to decrease under both scenarios in the near-century (RCP4.5 = −0.5%; RCP8.5 = −3.5%) and by the late-century (RCP4.5 = −11.8%; RCP8.5 = −8.6%). By contrast, when fertilizer application was modeled to increase at the same rate as plant P uptake, TP loading increased 4.0% (0.9%) in the near-century and 9.9% (24.6%) by the late-century and SRP loading increased 10.5% (6.1%) in the near-century and 26.7% (42.0%) by the late-century under RCP4.5 (RCP8.5). Our findings suggest that changes in agricultural practices (e.g., fertilization rates) will be key determinants of Maumee River discharge during the 21st century.

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Introduction

Ecosystem services provided by Lake Erie support the health and livelihood of millions of people in the USA and Canada. The lake provides drinking water to ~11 million people in the region, accommodates one of the world's largest freshwater fisheries, and supports an $11.5 billion tourism industry (Ohio EPA, 2013). However, harmful algal blooms (HABs), which contain toxin-forming cyanobacteria such as *Microcystis* sp. and *Anabaena* sp., pose a major threat to these services (Hudnell, 2010; Michalak et al., 2013; Scavia et al., 2014; Stumpf et al., 2012). Current signs of declining ecosystem services include reduced water clarity, "No Swimming" advisories during approximately 20% of the summer, and an expanding hypoxic "dead zone" (Daloğlu et al., 2012; Ohio Lake Erie Commission, 2008). Threats to drinking water are of chief concern. In 2014, algal toxin contamination caused a three-day drinking water ban in Toledo, Ohio, leaving the city's 500,000 residents without potable water.

Excessive phosphorus (P) loading was identified as the driver of reduced water transparency, expanded bottom hypoxia, and high cyanobacteria biomass in Lake Erie during the 1960s and 1970s (Ludsin et al., 2001; Scavia et al., 2014). Beginning in 1972, regulations placed on municipal wastewater plants and commercial detergents were developed through the Great Lakes Water Quality Agreement to limit P loading into Lake Erie and its tributaries (De Pinto et al., 1986; GLWQA, 1972). These efforts led to reductions in P loading and water-column total P (TP) concentrations, improved water quality, and restored fish populations (Ludsin et al., 2001).

More recently, however, Lake Erie has become more eutrophic. Both seasonal bottom hypoxia and HABs have reemerged as water quality problems during recent decades, with nutrient loading from agricultural runoff identified as the primary driver (Scavia et al., 2014; Stumpf et al., 2012). Runoff into western Lake Erie from the Maumee River Basin (MRB), which is the largest of all the Great Lakes watersheds and consists of 74% agricultural land use (Richards et al., 2010), appears to be particularly problematic, as March–June discharge from the MRB has been shown to be highly correlated with Lake Erie HABs (Stumpf et al., 2012).

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To address the problem of excessive nutrient loading from the MRB and other Lake Erie watersheds, the Ohio EPA (2013) and the International Joint Commission (IJC, 2014) set target P loads for the MRB, requiring a 37% and 41% reductions in TP and soluble reactive P (SRP), respectively, during March–June (relative to 2007–2012 averages). Many agricultural management practices, including timing and placement of fertilizers, maintaining soil health, and utilizing methods to slow and retain runoff, have been recommended to achieve these reductions (IJC, 2014).

These recommendations, however, are based on current climate conditions, and may be insufficient to prevent HABs and maintain ecosystem services in Lake Erie as the regional climate continues to change. Annual precipitation in the USA has increased 10% since 1910, with extreme events accounting for a disproportionately large amount of this increase (Karl and Knight, 1998). This trend is relevant to P loading, as increases in large precipitation events have been shown to historically lead to greater SRP loading (Daloğlu et al., 2012). Based on climate change scenarios published by the Intergovernmental Panel on Climate Change (IPCC), precipitation is predicted to continue to increase in the Midwest USA during the 21st century (Easterling, 2000; Seager et al., 2013). Further, the effect of elevated carbon dioxide (CO_2) concentrations on plant stomatal conductance may affect watershed hydrology and nutrient loading. Wu et al. (2011) found that the effects of increased CO_2 concentrations on plant dynamics from 1986 to 2008 accounted for up to 4% of the stream flow in the Upper Mississippi River Basin (USA).

Previous Great Lakes studies suggest that continued climate change holds great potential to affect watershed hydrology and nutrient runoff in the MRB during the 21st century. Hayhoe et al. (2010), for example, predicted that climate-induced changes in temperature and precipitation can lead to a potentially lengthened growing season and increased agricultural reliance on groundwater irrigation during the summer. Likewise, in a simulation study conducted on a small (322 km^2), predominantly agricultural watershed in the Great Lakes region, Crossman et al. (2013) predicted up to a 29.2% increase in TP loading by the end of the 21st century, even with agricultural management practices such as reduced fertilizer application, buffer strips, and bank erosion controls. Within the Lake Erie basin, Bosch et al. (2014) predicted up to a 17% increase in discharge and up to a 32% increase in nutrient loading by the end of the century, with Johnson et al. (2015) predicting that annual discharge would increase by ~22% and TP loads would increase ~25% by the mid-century.

Importantly, however, the majority of existing studies that have explored the impacts of climate change on watershed hydrology within the Great Lakes Basin have not used daily climate projections from the fifth phase of the Coupled Model Intercomparison Project (CMIP5), the latest project from the World Climate Research Programme (http://cmip-pcmdi.llnl.gov/cmip5/). Further, few studies have considered the direct effects of elevated CO_2 concentrations on plant dynamics. Towards overcoming these limitations, we applied the latest suite of global climate model (GCM) projections from CMIP5 to a watershed-hydrology model of the MRB. By simulating discharge and sediment, TP, and SRP loads from the MRB into Lake Erie under two greenhouse gas emission scenarios and two fertilizer application scenarios, we seek to help agencies better understand how climate change might impact their ability to mitigate the water quality problems that Lake Erie is currently facing through agricultural management practices.

Methods

Study area

The total area drained by the MRB (Fig. 1) is approximately 16,200 km^2 and encompasses northwestern Ohio and parts of Indiana and Michigan (Calhoun et al., 2002). Much of the area comprised the historic Great Black Swamp and is characterized by a flat landscape (<0.5% slope in ~50% of the area) and poorly drained soils (Gebremariam et al., 2014). Beginning in late 1800s, ditch systems and subsurface drainage were installed to drain the swamps, which enabled productive large-scale agriculture (Kaatz, 1955). Over 90% of cropland area is currently drained by ditches and subsurface drainage (Calhoun et al., 2002; Gebremariam et al., 2014). Nearly 75% of the land cover is under row crops (primarily corn and soybeans), while urban areas occupy 10% of the land and grasslands and forests each cover 6% (Richards et al., 2010).

Conservation practices have been increasingly used in the MRB since the 1990s (Myers et al., 2000). As of 2012, conservation tillage practices, which reduce soil disturbance and allow crop residue to remain on the soil surface, are used on about 63% of croplands (NRCS, 2016). Approximately 40% of cropland uses some form of water erosion control, such as concentrated flow practices, which prevent gully formation and erosion, and edge-of-field practices, which include vegetated buffers and filters. Cover crops have been adopted in 6% of cropland. In 2012, some form of incorporation (e.g., banding, injection, tillage) was utilized on approximately 60% of cropland during every P application (NRCS, 2016).

The SWAT model

We used the Soil Water Assessment Tool (SWAT, revision 629) to model hydrology and nutrient fluxes in the MRB. SWAT is a semi-distributed, process-based hydrological model that was developed by the USDA Agricultural Research Service to simulate discharge, sediment, and chemical loads from watersheds (Neitsch et al., 2009). SWAT operates at a daily timescale, and includes processes for runoff, evapotranspiration (ET), infiltration, nutrient transport, and crop growth. Existing studies have successfully analyzed climate change scenarios with SWAT to predict impacts on loads from agricultural watersheds (Bosch et al., 2014; Ficklin et al., 2009; Mukundan et al., 2013; Wu et al., 2011). Gebremariam et al. (2014) compared multiple watershed models and found that SWAT was the most appropriate for modeling the MRB, as SWAT offered the greatest ability to represent agricultural practices, was able to run climate change scenarios, and can incorporate new processes within the modeling framework, such as dynamic fertilizer application.

Our SWAT model included the effects of CO_2 levels on plant-specific growth processes. The need to model these effects exists because plants have been shown experimentally to partially close stomata in response to elevated CO_2 conditions, leading to increased water-use efficiency and reduced transpiration (Dieleman et al., 2012; Gedney et al., 2006; Reddy et al., 2010). Elevated CO_2 concentrations have also been shown to cause increased plant photosynthetic carbon uptake and biomass production. C_3 plants, which produce a 3-carbon acid during carboxylation and include crops such as soybeans, are believed to respond to elevated CO_2 with increased rates of photosynthesis (Reddy et al., 2010). The effect of elevated CO_2 concentrations on C_4 plants, which produce a 4-carbon acid during carboxylation and include corn, are less understood; however, likely possibilities include reduced drought stress due to increased water-use efficiency and enhanced CO_2 assimilation rates in leaves (Ghannoum et al., 2000).

In our SWAT model, elevated CO_2 generally led to increased water-use efficiency and plant biomass (Arnold et al., 2012). Using the SWAT default CO_2-plant parameter values, we modeled the effects of increasing CO_2 on plants by reducing stomatal conductance 40% for all plants and increasing radiation-use efficiency by plant-specific percentages (15.4% for corn and 20.0% for soybeans) when CO_2 concentrations increased from 330 to 660 ppm. By default, CO_2 concentrations in SWAT are held constant over time. To allow for a more complete study of the effect of future emission scenarios and climate change, we (1) modified the SWAT program to allow for temporal changes in CO_2 concentrations and (2) incorporated a fertilization scheme in which nitrogen (N) and P application rates increased at the same rate as CO_2-driven increases in plant nutrient uptake. Because SWAT calculations are based on

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