Journal of Great Lakes Research 40 (2014) 581–589

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

Interacting effects of climate change and agricultural BMPs on nutrient runoff entering Lake Erie

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ARTICLE INFO

Article history:
Received 10 August 2013
Accepted 4 April 2014
Available online 19 May 2014

Communicated by Ram Yerubandi

Keywords:
SWAT
Great Lakes
Flow
Sediments
Catchment
Lake Erie

ABSTRACT

Agricultural best management practices (BMPs) have been implemented in the watersheds around Lake Erie to reduce nutrient transfer from terrestrial to aquatic ecosystems and thus protect and improve the water quality of Lake Erie. However, climate change may alter the effectiveness of these BMPs by altering runoff and other conditions. Using the Soil and Water Assessment Tool (SWAT), we simulated various climate scenarios with a range of BMPs to assess possible changes in water, sediment, and nutrient yields from four agricultural Lake Erie watersheds. Tile drain flow is expected to increase as is the amount of sediment that washes from land into streams. Predicted increases in tributary water flow (up to 17%), sediment yields (up to 32%), and nutrient yields (up to 23%) indicate a stronger influence of climate on sediment compared to other properties. Our simulations found much greater yield increases associated with scenarios of more pronounced climate change, indicating that above some threshold climate change may markedly accelerate sediment and nutrient export. Our results indicate that agricultural BMPs become more necessary but less effective under future climates; nonetheless, higher BMP implementation rates still could substantially offset anticipated increases in sediment and nutrient yields. Individual watersheds differ in their responsiveness to future climate scenarios, indicating the importance of targeting specific management strategies for individual watersheds.

Introduction

Export of nutrients from agricultural watersheds and the resultant decline in water quality are of widespread concern, potentially affecting drinking water supplies and recreational values as well as ecosystem health (Carpenter et al., 1998). Nowhere is this more apparent than in Lake Erie where blooms of toxin-forming cyanobacteria of unprecedented extent have recently occurred in its western basin (Bridgeman and Penamon, 2010; Conroy et al., 2005; Michalak et al., 2013; Stumpf et al., 2012) while bottom water hypoxia has affected substantial areas of its central basin (Edwards et al., 2005; Rucinski et al., 2010; Zhou et al., 2013). Because Lake Erie tributaries deliver very high sediment and nutrient loads, particularly from the agricultural watersheds that dominate inputs to its western basin (Richards et al., 2009), extensive efforts have been made to promote adoption of agricultural Best Management Practices (BMPs) to reduce nutrient inputs (Ohio EPA, 2010). While evidence of declining concentrations of particulate phosphorus in Lake Erie tributaries (Richards et al., 2009) indicates that changes in agricultural practices are having some success, it is clear that high runoff years result in very high nutrient loads, and wetter years may become more frequent under future climates (Michalak et al., 2013).

The Great Lakes are already experiencing long-term trends in climate consistent with human-induced climate change. Annual average temperatures are rising, snow and ice cover are declining, the growing season is longer, and intense rainfall events are more frequent (Hayhoe et al., 2010). Expected future changes for the region include increases in winter, summer, and annual average temperatures, with summer temperatures increasing as much as 7 °C by the end of the century; greater spring precipitation; and fewer snow days, with a higher percentage of winter precipitation falling as rain (Hayhoe et al., 2010; Kling et al., 2003). Annual precipitation changes over the Great Lakes region are projected to fall within the range of natural variability, but show larger shifts at the sub-annual scale. Winter and spring precipitation is projected to rise by as much as 20–30%, with larger changes expected under higher emissions, by end-of-century, and in southern Great Lake states.

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http://dx.doi.org/10.1016/j.jglr.2014.04.011
0380-1330/

Climate change is likely to influence the quantity and quality of water discharged from watersheds, potentially offsetting runoff reductions achieved from BMP implementation. Altered precipitation, temperature, and atmospheric CO_2 levels are likely to affect nutrient delivery through changes to hydrologic processes including land surface runoff and in-stream flow; and by influencing temperature and biological processes, including length of growing season. Change in the magnitude and variability of precipitation are expected to have the greatest influence on watershed hydrology, resulting in shifts in seasonal timing and greater water yields (e.g., Daloglu et al., 2012; Jha et al., 2006; Stone et al., 2003). Increased land surface runoff in turn will increase sediment loads and affect timing of sediment loss, which may experience both increases and decreases depending on season (Chaplot, 2007; Marshall and Randhir, 2008). Because losses of TP and sediments are highly correlated (Richards et al., 2009), P yields to streams also may increase. Although changes in the amount, timing, and magnitude of precipitation and surface runoff are likely to have the greatest effect on water quality, temperature change will affect the growing season and may alter the hydrologic cycle via increases in evapotranspiration (Marshall and Randhir, 2008). Changes in atmospheric CO_2 may also affect plant assimilation and soil fixation of N, thereby altering nitrate availability (Ficklin et al., 2010).

The Soil and Water Assessment Tool (SWAT) is used widely to evaluate BMP impacts on nutrient loads in streams at watershed scales (Gassman et al., 2007) and to target the locations where BMP implementation will most efficiently reduce nutrient transport rates (Bosch et al., 2013; Jha et al., 2010; Walter et al., 2007). Recent applications of SWAT suggest that BMP effectiveness varies with climate variability, and may offset expected gains from improved farm practices. Tests of a large number of BMPs and weather scenarios for a pasture-dominated watershed revealed differences in pollutant load reduction among various BMP combinations and the potential for certain weather conditions to counteract BMP effectiveness (Chaubey et al., 2010). A SWAT model for the Upper Mississippi River basin reported a 36 percent increase in average annual stream flow in response to doubling of CO_2, as well as large variability in runoff within specific months in response to different climate change scenarios (Jha et al., 2006). In a row crop and pasture watershed in Kansas and Nebraska, sediment, TP and TN yields all increased in future climate scenarios, with greatest response to the scenario resulting from the largest change in climatological variables (Woznicki and Nejadhashemi, 2012).

A number of agricultural BMPs can be employed by farmers and implemented in SWAT to explore their effectiveness in reducing sediment and nutrient loss. Reduced tillage or no-till practices can lessen erosion by leaving plant material on the soil surface and by maintaining intact root systems which trap soil particles until the next planting. Planting cover crops after harvest provides similar benefits to no-till, including rain interception and soil stabilization. Filter strips of intact vegetation along field edges slow runoff, allowing infiltration, sedimentation, and nutrient removal. Despite the advantages of these conservation practices and their increasingly wide use (Richards et al., 2002, 2009), their adoption remains incomplete due to implementation costs, the timing of available labor, and the desire to maximize land under active cultivation.

Mitigation strategies intended to offset the effects of climate change on water quality include many of the same BMPs that have been developed to reduce nutrient runoff, suggesting that future climates may compromise the ability of existing BMPs to maintain or lower nutrient runoff from agricultural landscapes. To better understand how climate change will affect nutrient and sediment transport to aquatic ecosystems, and whether BMP effectiveness will be compromised, we use SWAT to explore the impact of potential climate change on water, sediment, and nutrient discharge from the four dominant agricultural watersheds that drain into Lake Erie. In addition, we test the effectiveness of three structural BMPs under the present and two future climate scenarios.

Methods

Study area

The Raisin, Maumee, Sandusky, and Grand watersheds cover parts of Michigan, Indiana, and Ohio, draining into the western and central basins of Lake Erie (Fig. 1). The Raisin, Maumee, and Sandusky watersheds are dominated by agricultural land (Table 1). The Grand watershed also has substantial agriculture land, but is mostly forested. Area and precipitation also vary across these four watersheds, with the Maumee being larger than the other watersheds combined, and the Grand watershed receiving about 27% more rainfall than the driest watershed, the Raisin.

Model parameterization and calibration

Model parameterization and calibration methods have been detailed previously (Bosch et al., 2011), and the models have been used to explore the effectiveness of BMP alternatives under current climate conditions (Bosch et al., 2013). The four models were parameterized with the following input data using ArcSWAT (version 2.1.5): elevation, stream network, land cover, soil type, weather, point source discharges, impoundment characteristics (reservoir, lake, or pond), atmospheric N deposition, and land management practices (see Electronic Supplemental Material (ESM) Table S1 for typical example). Tile drainage was implemented in the four watershed models following the approach of Green et al. (2006). Tile drainage was assumed to be present in row-crop and hay agricultural lands with soil types included in the C and D hydrology group categories, known as poorly drained soils (see ESM Table S2 for complete list of soils).

Models were run for 1995–2005, including three years for model spin-up (1995–1997), four years for calibration (1998–2001), and four years for confirmation (2002–2005). Calibration and confirmation included stream flow discharge, sediment loads, and nutrient loads (TP, SRP, TN, nitrate). Observed daily mean stream discharge was obtained from USGS gage stations near the river mouth of each watershed. Daily sediment, TP, SRP, TN, and nitrate loads for the watersheds were obtained from the National Center for Water Quality Research at Heidelberg University. Model calibration and confirmation results showed that SWAT accurately predicted hydrology, sediment, and nutrient loads such that future use of these four SWAT models for various scenario testing was reasonable and warranted (Bosch et al., 2011; Moriasi et al., 2007).

Climate change conditions

Climate change scenarios were developed based on the projections made by Hayhoe et al. (2010) for the western Lake Erie region. These projections were representative of high to low greenhouse gas emission scenarios, using the Special Report on Emission Scenarios (SRES) A1F1 and the B1 scenarios, and projected seasonal climate deviations for three, 30-year time periods between 2010 and 2099. Climate projections were constructed based on results from three atmosphere–ocean general circulation models (US National Atmospheric and Oceanic Administration's Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1, the United Kingdom Meteorological Office's Hadley Centre Climate Model, version 3 (HadCM3), and the National Center for Atmospheric Research's Parallel Climate Model (PCM)) and statistical downscaling based on historical weather records (ESM Figure S1) (see Hayhoe et al., 2010 for details). Based on these projections, we selected two cases that span this expected range for multiple time horizons and call these "moderate" and "pronounced" scenarios (ESM Table S3) (e.g., our moderate scenario uses a temperature change that reflects the higher end of expected change for 2010–2039 and lower end of expected change for 2040–2069, see ESM).

These climate conditions were simulated within the four SWAT models through parameter value changes in the Subbasin input table

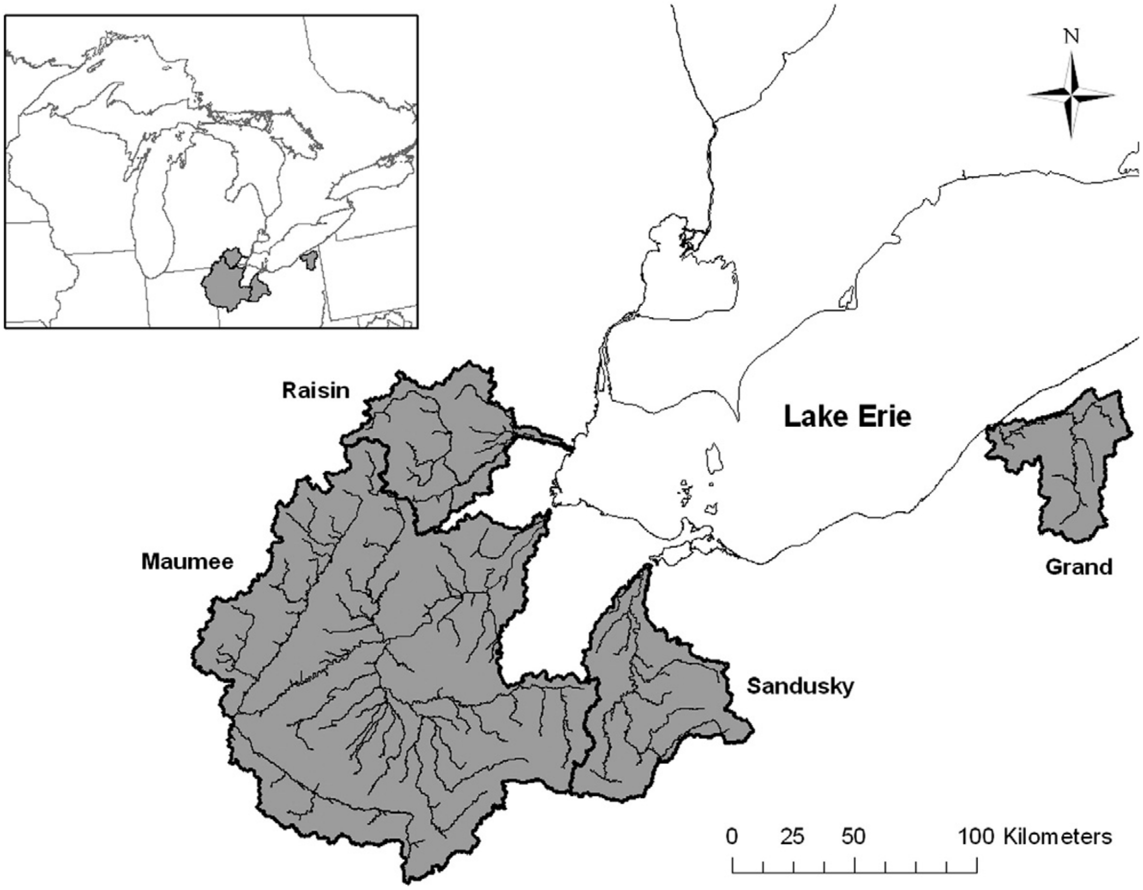

Fig. 1. The Raisin, Maumee, Sandusky, and Grand watersheds draining into western and central Lake Erie as delineated in SWAT models.

of the ArcSWAT interface. The parameter TMPINC was used to increase the observed daily minimum and maximum temperatures by the desired number of degrees for selected months of the year. The parameter RFINC was used to change the observed daily precipitation values by the percentage indicated for selected months (increases as positive % changes, decreases as negative % changes, ESM Table S3). This method changes precipitation amount only on days with measured precipitation. All climate change simulations were run from 1995 to 2005, and model output from 1998 to 2005 was used in results. Precipitation and temperature over the 1998–2005 time period were typical of the 30-year base time period of 1970–2009 (ESM Figures S2–4).

Agricultural BMPs

Three common structural BMPs, no-till, cover crops, and filter strips, were selected for evaluation under various climate scenarios. For the baseline case (Table 2a), currently employed BMP conditions were simulated without additional implementation, including no-till already implemented for soybean and winter wheat crops in the Maumee, Sandusky, and Grand watersheds. Modest expansion of a combination of the three common agricultural BMPs (Mod BMP, Table 2a) was simulated across all four watersheds under different climate conditions and compared to current BMP implementation. This modest implementation of BMP extent was limited to the amount considered feasible through consultation with local agricultural experts (see Acknowledgments), and thus was less than the maximum conceivable extent. We implemented the no-till agriculture assuming cessation of tillage for all corn and soybean crops across a randomly selected 25% of row-crop land. This was simulated in SWAT by decreasing the intensity of surface runoff and omitting tillage actions (ESM Table S4) (Arabi et al., 2008; Bosch et al., 2013). We increased the extent of cover crops to the same 25% of row-crop land that included a rye grass cover crop planted immediately after soybean harvest and removed immediately before corn planting the following year (ESM Table S4). We increased the extent of filter strips by simulating a 10-m wide edge-of-field vegetative strip (Arabi et al., 2008) with a 25% trapping efficiency (Syversen and Borch, 2005) (ESM Table S4). Filter strips were applied across a randomly selected 20% of row-crop land such that this land had all three BMPs applied; the remaining 5% of the total area under the combination scenario had only no-till and cover crop applied. Finally, to explore the

Table 1
Characteristics of the Raisin, Maumee, Sandusky, and Grand watersheds for the modeled areas, determined by the watershed outlet location. Precipitation averaged over 1998–2005 and land cover data from 2001.

	Watershed size (km^2)	Precipitation (mm/y)	Land cover (%)			
			Row-crop	Hay	Urban	Forested
Raisin	2784	861	53	19	11	16
Maumee	17,030	934	76	5	11	8
Sandusky	3455	962	80	3	9	8
Grand	1896	1093	27	10	10	52

Table 2
SWAT scenario descriptions for testing with all four watersheds (a) and only the Maumee (b).

	Scenario name	Scenario description
a)	No BMP + No C	Actual BMP conditions simulated under current climate conditions
	No BMP + Mod C	Actual BMP conditions simulated under moderate climate change conditions
	No BMP + Pro C	Actual BMP conditions simulated under pronounced climate change conditions
	Mod BMP + No C	Combination of three BMPs on some row-crop agricultural land under current climate conditions
	Mod BMP + Mod C	Combination of three BMPs on some row-crop agricultural land under moderate climate change conditions
	Mod BMP + Pro C	Combination of three BMPs on some row-crop agricultural land under pronounced climate change conditions
b)	High BMP + No C	Combination of three BMPs on 100% of Maumee row-crop agricultural land under current climate conditions
	High BMP + Mod C	Combination of three BMPs on 100% of Maumee row-crop agricultural land under moderate climate change conditions
	High BMP + Pro C	Combination of three BMPs on 100% of Maumee row-crop agricultural land under pronounced climate change conditions

maximum potential of BMP effectiveness, we tested the combination of all three BMPs at a 100% implementation level in the Maumee watershed in all row-crop land (High BMP, Table 2b). All BMP simulations were run from 1995 to 2005, and model output from 1998 to 2005 was used in results.

Results

Climate influence on water and sediment runoff

Under both climate change scenarios, we confirm precipitation increase and snowfall decrease in the SWAT model simulation relative to current climate (Table 3). Annual precipitation increased by 6% across all four watersheds under the pronounced climate scenario, while snowfall decreased substantially under both moderate (14%) and pronounced (35%) scenarios. Thus, snowfall, as a percentage of total precipitation, decreased from an average of 11% under the present climate to 7% under the pronounced climate scenario. The Grand watershed showed the greatest decrease in snowfall as a fraction of total precipitation (from 15% to 9%).

Despite modest differences in annual precipitation among watersheds (Table 1), the surface runoff increase ranged from only 1–4% among watersheds (Fig. 2A). Surface runoff in the Maumee increased by 1 mm while the Grand increased by 4 mm. Tile drainage increased by 14 mm in the Grand and 30 mm in the Sandusky. Surface runoff differed little between the two climate futures. In contrast, tile flows increased in proportion to climate change severity. Under the pronounced climate change scenario, tile flow increased by 25% in the Sandusky to 47% in the Raisin relative to current conditions.

Watershed sediment yields increased by 6–18% (mean 13%) under the moderate climate scenario; but it changed substantially more under the pronounced climate change scenario, ranging from 20% to 49% across the four watersheds with an average increase of 39%.

Climate influence on watershed discharge of water, sediment, and nutrients

Without additional BMP implementation, our SWAT models showed that watershed sediment and nutrient yields generally increased under both future climate scenarios, with the exception of slight decreases in SRP yields in the Raisin and Grand under the moderate scenario (Table 4). These decreases are somewhat surprising because water discharge increased consistently with increasing climate change severity. Total annual stream flow increased 4–9% (mean 6%) across the four watersheds under the moderate climate change scenario and 9–17% (mean 12%) for the pronounced scenario.

Predicted in-stream sediment yields increased by an average of 9% for the moderate climate scenario and 23% under the pronounced climate scenario, even though comparable water yields increased by only 6% and 12%.

The two climate scenarios resulted in modest increases in nutrient yields (Table 4). SRP yield decreased slightly (2% on average) under the moderate climate scenario and increased slightly (3%) in response to the pronounced scenario. TP yields increased more than did SRP yields, showing a 4% average increase under the moderate climate scenario and 6% under the pronounced scenario (Fig. 2D). TN and nitrate responses were consistent with flow and sediments, with smaller increases under moderate climate change (6% and 8%, respectively) compared to under a pronounced change (16% and 18%, respectively).

The four Lake Erie watersheds exhibited considerable variation in their tributary sediment and nutrient yields in response to alternative climate scenarios (Fig. 2 and Table 4). In the Raisin and Grand watersheds, tributary SRP yields decreased under both moderate and pronounced climate scenarios, but SRP yields increased for the Maumee and Sandusky watersheds (Table 4). All four watersheds showed consistent increases in sediment yield under both climate scenarios, and increases were greater under the pronounced scenario. In the Maumee and Sandusky watersheds, all constituents increased under both climate scenarios, and the Sandusky watershed changed most compared to the other three watersheds. Modeled P yields for the Raisin differed from all other watersheds, with yield declines for SRP under future climates.

Influence of climate scenarios and BMP implementation on watershed exports

When the additional BMPs considered most feasible by agricultural specialists are modeled in these four watersheds, alternative future climates result in runoff responses similar to those seen with today's climate and BMP extent (Table 5). In other words, future climates largely negate the gains under modest BMP implementation. Stream flow exhibits the most consistent increases in response to future climate scenarios, by 4 to 17% across the four watersheds. Sediment yields again exhibit the greatest overall increase, by up to 33%, increasing most under the pronounced climate scenario. Nutrient yields generally increase under future climate scenarios, but their response is variable (up to 23%). These modest additional BMPs offset some but not all of the climate change effect.

Table 3
Average annual precipitation for each watershed simulated by SWAT under each climate change condition. Snowfall is a portion of total precipitation.

Watershed	No change		Moderate change		Pronounced change	
	Total precipitation (mm)	Snowfall (mm)	Total precipitation (mm)	Snowfall (mm)	Total precipitation (mm)	Snowfall (mm)
Raisin	861	98	887	88	913	70
Maumee	934	88	962	75	987	56
Sandusky	962	85	991	69	1019	47
Grand	1093	159	1126	138	1159	109

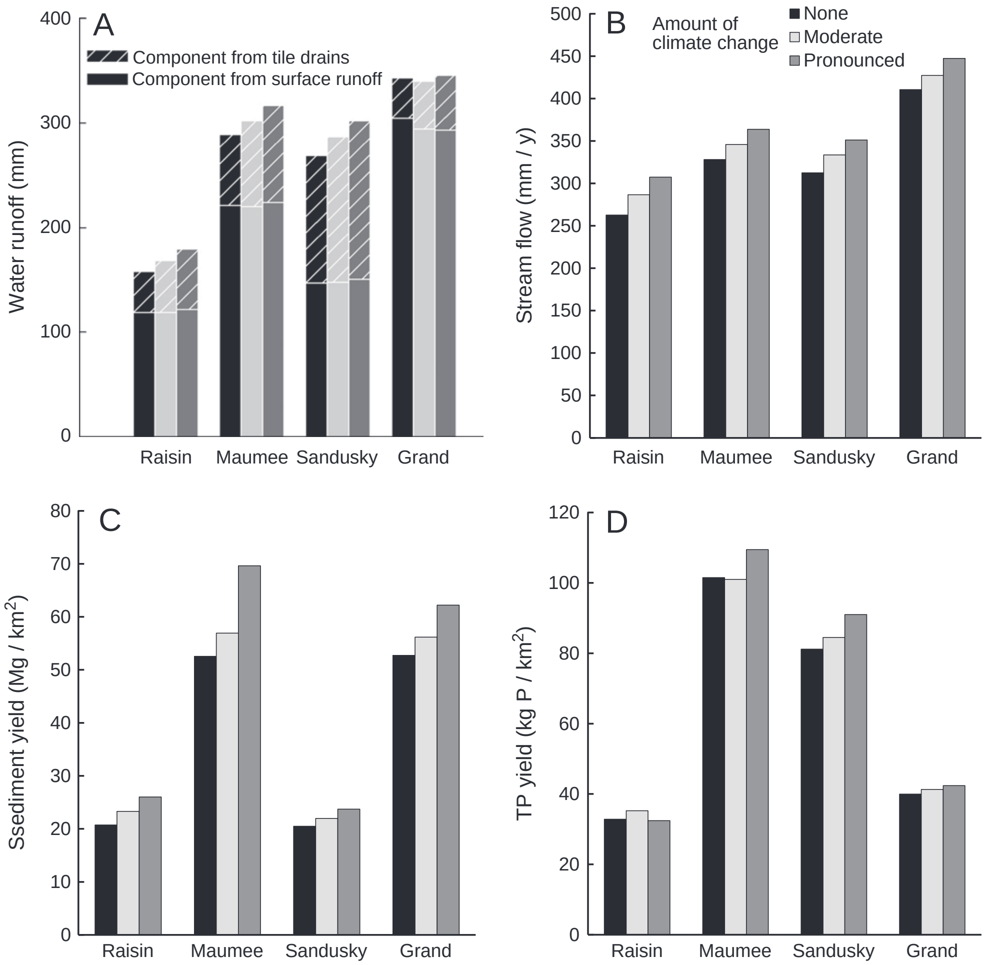

Fig. 2. Average annual (A) water runoff (mm) from land to stream channel, (B) stream flow (mm), (C) sediment yield (Mg/km^2), and (D) TP yield (kg P/km^2) for each watershed under various climate change conditions. Note that only tile drainage and surface runoff are included in panel A because they more directly influence stream water quality. Thus, total bar height should not be taken as total water yield.

Though BMPs were less effective overall under the climate projections (Fig. 3), our models suggest that, under higher implementation rates, BMPs should be able to offset the expected increased discharges (Fig. 4, Table S5). Because the Maumee watershed has received much of the attention in nutrient and sediment studies, we tested 100% implementation scenarios of the three selected BMPs in that watershed. These model predictions of sediment and nutrient discharge fell well below baseline yields under both climate scenarios (Fig. 4, Tables 4 and S5). Even under full BMP implementation, however, water discharge was predicted to increase under both future climates. Our simulations suggest that, other than in the Maumee watershed, BMP effectiveness in reducing TP is limited under the more pronounced future climate change (Fig. 3).

Discussion

Joint simulation of various BMP and alternative climate scenarios in four Lake Erie watersheds demonstrates that future climates are likely to substantially affect land surface runoff and tributary export of water, sediments, and nutrients. In general, these watersheds are

Table 4
Average annual riverine yields for the four modeled watersheds for various climate change conditions. Nutrients include total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), and nitrate. See Table 3 for scenario descriptions.

		Flow (mm/y)	Sediment (Mg/km^2)	TP (kg P/km^2)	SRP (kg P/km^2)	TN (kg N/km^2)	Nitrate (kg N/km^2)
Raisin	No BMP + No C	263	20.7	32.8	12.2	1656	1346
	No BMP + Mod C	287	23.3	35.3	11.2	1734	1440
	No BMP + Pro C	307	26.0	32.4	11.3	1898	1628
Maumee	No BMP + No C	328	52.6	101.5	26.0	2377	1995
	No BMP + Mod C	346	56.9	101.0	26.3	2441	2081
	No BMP + Pro C	364	69.6	109.5	27.4	2590	2201
Sandusky	No BMP + No C	313	20.5	81.2	25.1	2593	2405
	No BMP + Mod C	334	22.0	84.5	27.2	2786	2611
	No BMP + Pro C	351	23.7	91.0	30.1	3043	2863
Grand	No BMP + No C	411	52.7	40.0	5.0	669	374
	No BMP + Mod C	427	56.2	41.3	4.6	729	413
	No BMP + Pro C	447	62.2	42.4	4.7	815	460

Table 5
Average annual riverine yields for the four modeled watersheds under modest implementation of BMP combination and various climate change conditions. Nutrient parameters include total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), and nitrate.

		Flow (mm/y)	Sediment (Mg/km^2)	TP (kg P/km^2)	SRP (kg P/km^2)	TN (kg N/km^2)	Nitrate (kg N/km^2)
Raisin	Mod BMP + No C	261	18.4	31.7	11.8	1592	1300
	Mod BMP + Mod C	278	20.1	34.4	11.4	1640	1371
	Mod BMP + Pro C	306	23.1	32.1	11.1	1808	1550
Maumee	Mod BMP + No C	322	47.1	99.2	24.4	2239	1875
	Mod BMP + Mod C	339	51.2	95.1	24.9	2283	1950
	Mod BMP + Pro C	358	62.7	102.4	25.8	2423	2067
Sandusky	Mod BMP + No C	307	19.8	73.5	22.9	2377	2210
	Mod BMP + Mod C	328	21.3	76.6	24.4	2567	2403
	Mod BMP + Pro C	347	23.1	83.1	27.4	2828	2668
Grand	Mod BMP + No C	409	52.1	38.8	4.8	646	368
	Mod BMP + Mod C	426	55.7	40.5	4.4	711	407
	Mod BMP + Pro C	446	61.7	41.6	4.6	794	453

expected to receive more annual precipitation, and less of it in the form of snowfall. Anticipated future climates are found to increase tile drain flow and result in greater export of sediments to streams. Tributary water discharge, sediment, and nutrient yields are predicted to increase in most watersheds, with sediments showing the greatest response. Our pronounced climate change scenario had a much larger impact on sediment and nutrient yields relative to the moderate scenario, indicating a possible threshold in watershed response to changing climate conditions. Because of these projected increases in sediment and nutrient yields under climate change, agricultural BMPs become more critical not only to achieve current management goals for nutrient load reductions (Ohio EPA, 2010) but also to even maintain the status quo of loading into the future. With more pronounced climate change, these BMPs appear to become less effective at reducing the export of water, sediments, and nutrients in most watersheds. Nonetheless, expanded implementation of BMPs, in spatial extent and in combinations beyond what is currently considered feasible, can offset the anticipated increases.

These four Lake Erie watersheds responded differently to common BMP implementations and climate change, pointing to the need for considering the specific conditions of individual watersheds. This finding is consistent with studies showing differences in landscape susceptibility to sediment and nutrient loss across a wide range of scales including

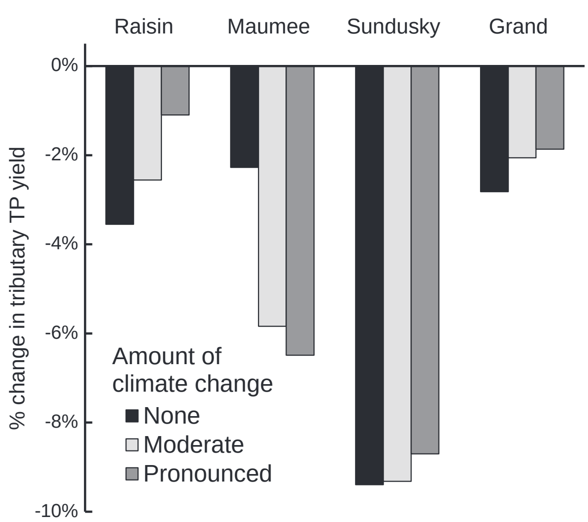

Fig. 3. Average annual changes of tributary TP yields with modest BMP implementation reported as a percentage of the yield with no additional BMP implementation for each climate scenario. Negative values indicate % yield reductions due to BMP implementation with larger negative values indicating that the BMPs are more effective in this scenario. Positive values would indicate that the tested BMPs increased nutrient transport in a given scenario.

field and sub-watershed up to continental scales (Panagopoulos et al., 2011; Qiu et al., 2007). The watersheds vary in both land use (Table 1) and hydrology (Fig. 2). The hydrologic differences are likely due to surficial geology characteristics from more infiltration with sand and gravel transitioning to clay across the Raisin watershed, to more surface runoff and tile drainage with more clay in the Maumee, Sandusky, and Grand (Federal Water Pollution Control Administration, 1968). Land use differences may likewise underlie unexpected increases in SRP yields in the more forested Raisin and Grand watersheds under climate change, while decreases in SRP yields were found in the Maumee and Sandusky watersheds which are dominated by row-crop agriculture. This has implications for public policy as new incentives are created for farmers to adopt BMPs and tighter regulations are placed on how the land can be used. For example, this study predicts that while climate change may have less impact on nutrient and sediment yields from the Raisin, Maumee, and Grand Rivers, the Sandusky River may experience more substantial increases (Table 4).

Furthermore, as observed elsewhere (Jha et al., 2010; Woznicki and Nejadhashemi, 2012), averaging over the entire watershed to focus on nutrient loading to the lake could underestimate the BMP effectiveness at the field scale. For example, our results for the effectiveness of moderate BMP implementation average over land with and without BMPs. For a manager focused on reducing fertilizer loss from a field to maintain field fertility, the effectiveness of the BMPs likely is higher than reported here.

Our observed changes in watershed hydrology and tributary exports of water, sediments and nutrients under the climate scenarios were consistent with other reports (Jha et al., 2006; Woznicki and Nejadhashemi, 2012). With the climate change conditions selected for this study (Table 2), precipitation and temperature increased, leading to high annual rainfall totals and less snowfall. Though our model predicted an increase in tile drain flow, it did not show an equivalent drop in surface runoff. This seems to be the result of higher annual precipitation especially during spring, which, after a milder winter with increased infiltration and saturated ground, would likely promote surface runoff. This explanation is supported by the model predictions which show April and May surface runoff increasing with climate change. For example, surface runoff in the Maumee watershed was predicted to increase by 69 and 70% for April and May, respectively, under the pronounced climate scenario.

Warmer temperatures may result in prolonged infiltration of water into the soil profile into the winter months, thus increasing annual tile drainage and nutrient loss through tile drains. The current model confirmed this; for example, the Maumee watershed model showed a 71% increase in tile drain flow during December–February under the pronounced climate scenario. Recent work has contradicted prior thought and shown that tile drains are a significant loss path for dissolved phosphorous (Frankenberger et al., 2012), and a recent implementation of a higher-resolution SWAT model for the Sandusky watershed (Daloglu

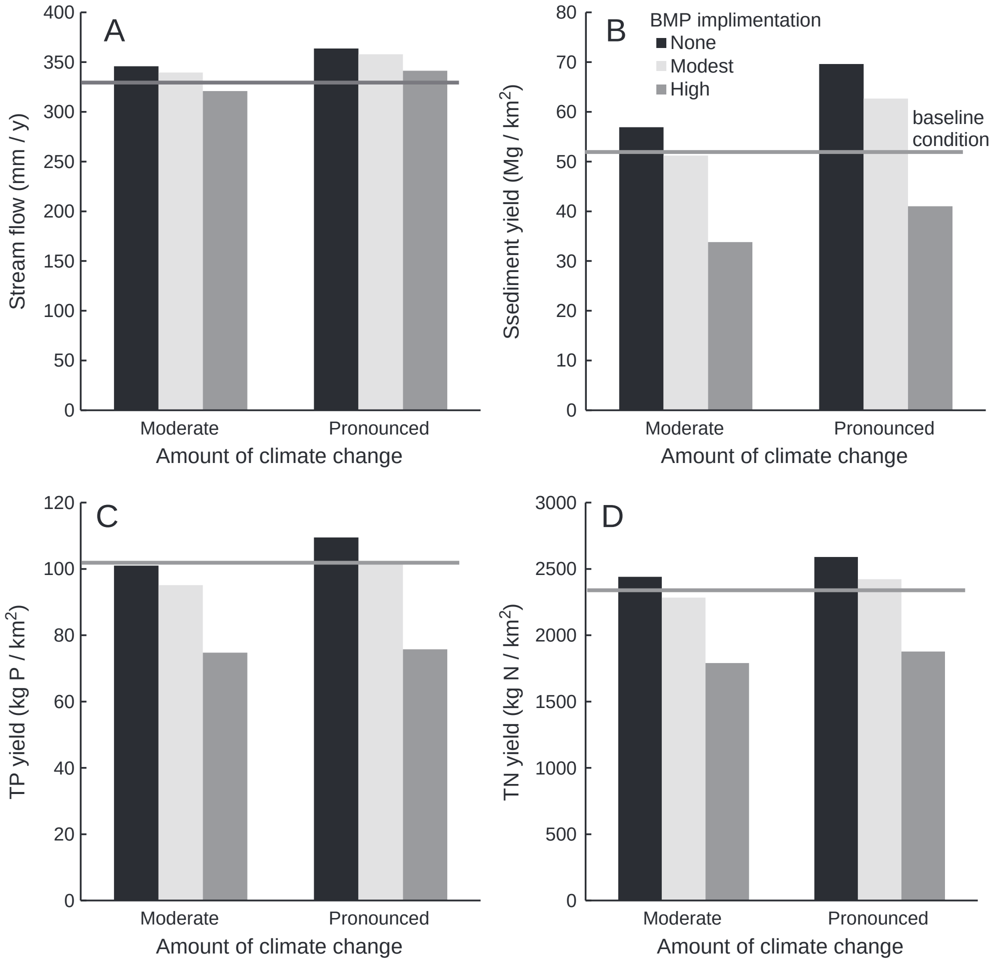

Fig. 4. Average annual (A) stream flow (mm), (B) sediment yield (Mg/km^2), (C) TP yield (kg P/km^2), and (D) TN yield (kg N/km^2) for the Maumee watershed under various climate change and BMP conditions. In each panel, a horizontal line marks the baseline (no climate change and no BMPs) condition for flow or yield.

et al., 2012) demonstrated a strong relationship between increased spring precipitation under current management practices and increased SRP loads. They suggest that no-till practices resulting in a build-up of soil P in surface layers and fall fertilizer broadcast application resulted in greater loss of SRP than previously was the case. A relationship between no-till and increases in SRP runoff has been shown in previous efforts as well (Sharpley et al., 2009, 2011). Modest changes in SRP predicted in our models may not reflect this phenomenon. Improvements in phosphorus dynamics in newer versions of the SWAT model and more focused efforts on this aspect of watershed simulation in future work will bring more clarity to this inquiry.

As springtime rain events become more intense under future climates we should anticipate increases in annual stream flow and sediment and nutrient loads, as seen in our models and the work of others (Chaplot, 2007; Daloglu et al., 2012; Marshall and Randhir, 2008). Indeed, over the past two decades, interannual variation in tributary water discharge has been the primary driver of fluctuations in nutrient export by Lake Erie tributaries (Dolan and McGunagle, 2005; Joosse and Baker, 2011), and in the annual extent of nuisance algal blooms (Stumpf et al., 2012). Sediment yields experienced the most abrupt increases under future climate scenarios, as would be expected from agricultural tillage during spring as rain events were more intense. This is consistent with model predictions of generally higher sediment yields in the more agricultural watersheds (Table 4).

Our results indicate that agricultural BMPs will be rendered less effective at reducing in-stream sediment and nutrient yields under anticipated future climates (Fig. 4). This finding may be related to the three particular BMPs that were chosen for this study. In general, cover crops and no-till management are both most effective at reducing loss of sediments and nutrients from agricultural fields from runoff during the winter and early spring months. Cover crops hold the soil and nutrients in place by absorbing nutrients into their plant tissue, retaining soil in place through their plant root structures, and by slowing runoff water as it comes in contact with above-ground plant parts (Frankenberger et al., 2012). Likewise, no-till maintains plant residue from the previous crop and keeps the soil profile intact and cohesive rather than being exposed to precipitation runoff events; the crop residue also slows water flow across the ground surface and dissipates the energy of rain that might dislodge soil particles (Frankenberger et al., 2012). In total, these BMPs decrease the speed and sediment load of surface runoff. However, potential future climates with warmer winters allow for more infiltration of water into the soil profile, thus strengthening the subsurface runoff and tile drain pathways for nutrient runoff and weakening the surface runoff pathway. This decreases the effectiveness of no-till and cover crop BMPs, which target the surface pathway. The third BMP modeled in this study was filter strips. With stronger springtime precipitation events included in the climate change conditions, these filter strips are likely to be inundated with runoff carrying sediment and nutrients, reducing their effectiveness. The filter strips implemented in the model were only 10 m wide with a conservative trapping efficiency of 25%.

Chaubey et al. (2010) also found variable BMP effectiveness under different climate change scenarios. Under their base scenario (conventional tillage), sediment, TP, and TN yields increased in future climate scenarios, with greatest change under the scenario resulting in the largest change in climatological variables. The majority of agricultural BMPs tested by Woznicki and Nejadhashemi (2012) showed significant sensitivity to climate change, with native grass and filter strips among the most sensitive, whereas no-tillage and conservation tillage were less so. The sensitivity of BMP effectiveness to climate change can also be scale dependent with greater retention noted at the field and subwatershed scale than at the watershed scale (Tuppad et al., 2010; Woznicki et al., 2011). This may be due to substantial terrestrial load reductions seen at the field scale, while the additional in-stream component at the watershed scale can dampen the response. Modest implementation of BMPs, as defined in our study to be those that are currently viewed as feasible to local farmers, was not sufficient to compensate for climate change-driven increases in sediment and nutrient loading. However, 100% implementation of these three BMPs in the Maumee watershed did compensate for those climate-related yield increases. This contrasts with the finding of Chaubey et al. (2010), who found that under certain future weather conditions, no BMP combination was adequate to maintain pollutant loads at baseline conditions. Ours is an encouraging result, but it also shows the need for much stronger BMP implementation rates than are currently seen as feasible.

While our analysis suggests that enhanced BMP implementation could compensate for the climate-driven increases in yields, it is important to note that simply holding the baseline will not reduce algal blooms or hypoxic extent. Rucinski et al. (in press) suggested that a reduction in TP load of 46% below the 2003–2011 baseline (or a 78% reduction in SRP load from 2005 to 2011 baseline) is needed to cut the Lake Erie central basin hypoxic extent in half. In addition, the Ohio EPA (2013) recommendation of a maximum spring TP load from the Maumee watershed to reduce the impacts of toxic cyanobacteria blooms in the western basin represents a 31% reduction from the 2005–2011 baseline. These reductions are much greater than what appears possible with BMPs considered feasible under current policies. In fact, Bosch et al. (2013) showed that a mixture of BMPs required almost 100% implementation across the Maumee watershed to approach 25–30% yield reductions. New strategies such as revising the U.S. Farm Bill or other incentive or regulatory mechanisms will need to be explored to minimize the potential negative impacts of climate change on Lake Erie and other lakes subject to agricultural runoff through directed and targeted increases in support for the most appropriate BMPs in individual watersheds.

Acknowledgments

We are grateful to Steve Davis, Joe DePinto, Les Ober, Michael Winchell, and Tom VanWagner for their insights into farm management practices and model implementation related to this work. Comments by reviewers on an earlier draft substantially improved the manuscript. This is publication 12-006 of the EcoFore Lake Erie project, funded by the NOAA Center for Sponsored Coastal Ocean Research under award NA07OAR4320006, and by the International Joint Commission under award P1300078.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jglr.2014.04.011.

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