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Climate change will pose challenges to water quality management in the st. Croix River basin★

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ABSTRACT

Responses of streamflow and nutrient export to changing climate conditions should be investigated for effective water quality management and pollution control. Using downscaled climate projections and the Soil and Water Assessment Tool (SWAT), we projected future streamflow, sediment export, and riverine nutrient export in the St. Croix River Basin (SCRB) during 2020–2099. Results show substantial increases in riverine water, sediment, and nutrient load under future climate conditions, particularly under the high greenhouse gas emission scenario. Intensified water cycling and enhanced nutrient export will pose challenges to water quality management and affect multiple Best Management Practices (BMPs) efforts, which are aimed at reducing nutrient loads in SCRB. In addition to the physical impacts of climate change on terrestrial hydrology, our analyses demonstrate significant reductions in ET under elevated atmospheric CO_2 concentrations. Changes in plant physiology induced by climate change may markedly affect water cycling and associated sediment and nutrient export. Results of this study highlight the importance of examining climate change impacts on water and nutrient delivery for effective watershed management.

1. Introduction

Water quality management and pollution control are critical for the wellbeing of human society (Cosgrove and Rijsberman, 2000). Maintaining sustainable water supply for growing water needs by food and energy production, human and ecosystems consumption, as well as other societal and industrial water consumption, is one of the most pressing environmental problems in the 21st century (Hajkowicz and Collins, 2007; Valipour et al., 2015). Changing climate and intensifying anthropogenic activities have challenged our ability in securing water resource sustainability (Lettenmaier et al., 1999; Pielke et al., 2007; Yang et al., 2015a, 2016). Effective management of water resources requires a sound understanding of factors and processes regulating water cycling and associated nutrient cycling. Climate change has been identified as a key uncertainty source in future water quantity and quality management (Ragab and Prudhomme, 2002; Taylor et al., 2013). Potential impacts of climate change on water quantity and quality should be explicitly investigated to inform the formulation of effective mitigation and adaptation strategies (Caldwell et al., 2012; Ahmadi et al., 2014; Yang et al., 2015b; Michalak, 2016).

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Climatic factors have direct influences on evapotranspiration (ET) and runoff, which are two key components of terrestrial water cycling (Jung et al., 2010; Labat et al., 2004). Precipitation determines the amount of water input into terrestrial ecosystems, while temperature controls water fluxes from the biosphere to the atmosphere through ET (Goyal, 2004). In addition to temperature and precipitation, elevated atmospheric CO_2 concentration also regulates ET (Bernacchi et al., 2007). Negative correlations between ET and CO_2 concentrations have been reported in controlled experiments for different plant species (Baker et al., 1990; Medlyn et al., 2001; Shams et al., 2012). To better understand hydrological consequences of climate change, it is necessary to explore the complex interplays among increasing temperatures, altered precipitation patterns, and elevated CO_2 concentrations, in changing terrestrial water cycling.

In addition to the impacts on water cycling, climatic factors also regulate nutrient export through affecting water availability for nutrient delivery from land to rivers, and nutrient phase changes along the transport pathways (Ahmadi et al., 2014; Filippelli and Souch, 1999; Whitehead et al., 2009). For example, riverine nitrogen export tends to increase in wet years but decrease in dry years, indicating that soil water movement could be a limiting factor for lateral transport of nitrogen (Goolsby et al., 2000). Changes in temperature and precipitation play important roles in nutrient mineralization, immobilization, and emission to the atmosphere (Schmidt et al., 1999; Yang et al., 2017, 2015b).

Effective water quality management calls for solid understanding of climate change impacts on water and nutrient export (Murdoch et al., 2000). In river basins with high resource values but facing water quality impairments, such as the St. Croix River Basin (SCRB), great effects have been devoted to reducing nutrient export from land to rivers. However, most nutrient management activities were developed based on the existing knowledge on water and nutrient cycling. Future climate changes may alter the magnitude, temporal variability, and spatial patterns water and nutrient export, and may undermine efforts in watershed management. As a result, there is a pressing need to evaluate how changing climate factors would alter watershed hydrology and biogeochemistry.

Using the SCRB as a test bed, we investigated impacts of future changes in atmospheric CO_2 concentrations, temperature, and precipitation on riverine water, sediment, and nutrient fluxes during 2020–2099 with the Soil and Water Assessment Tool (SWAT) model. In this study, we primarily focused on the climate change impacts on non-point source pollution since nutrient from cropland is the primary reason for water impairments in the basin. This modeling study unraveled potential hydrological and biogeochemical changes in the remaining of the 21st century in the SCRB. Results of this study will contribute to effective water and nutrient management in the SCRB. Objectives of this study are to: (1) investigate potential changes in riverine water, sediment, and nutrient fluxes in the SCRB in response to future climate change; (2) discuss implications for water quality management and pollution control under a changing climate in basins like the SCRB.

2. Methods

2.1. Study area

As a tributary to the Mississippi River, the SCRB drains a catchment of about 20,000 km^2 that spans the border between Minnesota and Wisconsin (Fig. 1). The SCRB has a typical continental climate, with an annual precipitation of 808 mm, and mean temperature of $-12.9\,^{\circ}C$ and $20.6\,^{\circ}C$ in January and July, respectively (Almendinger et al., 2015). Primary land use types in this basin include forest, surface waters, cropland, and developed area. Forests cover ca. 46.6% in northern and central parts of the SCRB (Fry et al., 2011).

Because of its high resource value, the St. Croix River was among the first eight rivers to receive federal recognition by the 1968 Wild and Scenic Rivers Act (Waters, 1977). Unfortunately, the lowermost 40 km of the river, which is the naturally impounded Lake St. Croix, has been declared impaired by eutrophication from excessive input loads of phosphorus, with an implementation plan in place to reduce these loads by 27% through a combination of Best Management Practices (BMPs) (Almendinger, 2016; Almendinger and Ulrich, 2017).

2.2. Model setup, calibration, and evaluation

Input datasets for SWAT simulations at the SCRB were derived from multiple sources. We used the 30m digital elevation model (DEM) dataset from the United States Geological Survey (USGS) to characterize topographic and hydrologic features of the basin. We compiled a stream network provided by the Minnesota Department of Natural Resources (MDNR) and Wisconsin Department of Natural Resources (WDNR) to create a continuously connected flow network in river basin delineation. The SWAT delineation method created 419 subbasins and 3110 hydrologic response units (HRUs) for the study area.

The State Soil Geographic Database (STATSGO) was used to derive soil properties of the SCRB. We used the Crop Data Layer (CDL) to derive crop rotation and the National Land Cover Dataset (NLCD) layers to obtain unmanaged land cover types. Historical (1980–2010) climate data, including precipitation and temperature, were obtained from 25 weather stations located in the basin (Almendinger et al., 2015). These climate data were used to drive model simulations during 1980–2008 for parameter calibration (Tables S1–S3).

To derive future climate change information, we compiled daily temperature and precipitation data from four Coupled Model Intercomparison Project (CMIP5) climate models, namely GFDL-ESM2M, HadGEM-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM (Table S4), which have been used in climate change studies (Heuzé et al., 2013; Lee and Wang, 2014). Future climate change projections were bias-corrected against observed climate data using the bias-correction and spatial-downscaling approach (Wood et al., 2004). To evaluate uncertainties associated with climate projections, we chose two Representative Concentration Pathways (RCPs) scenarios (RCP 4.5 and RCP 8.5) to cover range of potential climate changes. These RCP scenarios represent future changes in greenhouse gas (GHG) emissions in the 21st century. Under the RCP 4.5 scenario, GHG emissions will peak around 2040 and then stabilize in the remaining of the 21st century; under the RCP 8.5 scenario, GHG emissions will continue to rise throughout the 21st century. The corresponding future atmospheric CO_2 concentration data under the two scenarios were derived from van Vuuren et al. (2011). SWAT simulations with the derived climate forcing data were conducted for 1950–2099. To quantify changes in future riverine fluxes, we compared averaged streamflow, sediment export, and nutrient export during 2020–2099 with corresponding average fluxes of the baseline period (1960–1990). We also analyzed changes in the sediment and nutrient concentrations under future climate conditions. We employed *T*-test to evaluate whether differences in riverine fluxes between the two periods were statistically significant (Table S5).

This study employed the Penman-Monteith algorithm for ET simulations in SWAT. In the algorithm, impacts of elevated CO_2 concentrations on stomatal conductance are simulated with a linear function, which suggests that stomatal conductance will be reduced by 40% if atmospheric CO_2 concentration doubles (Neitsch et al., 2009):

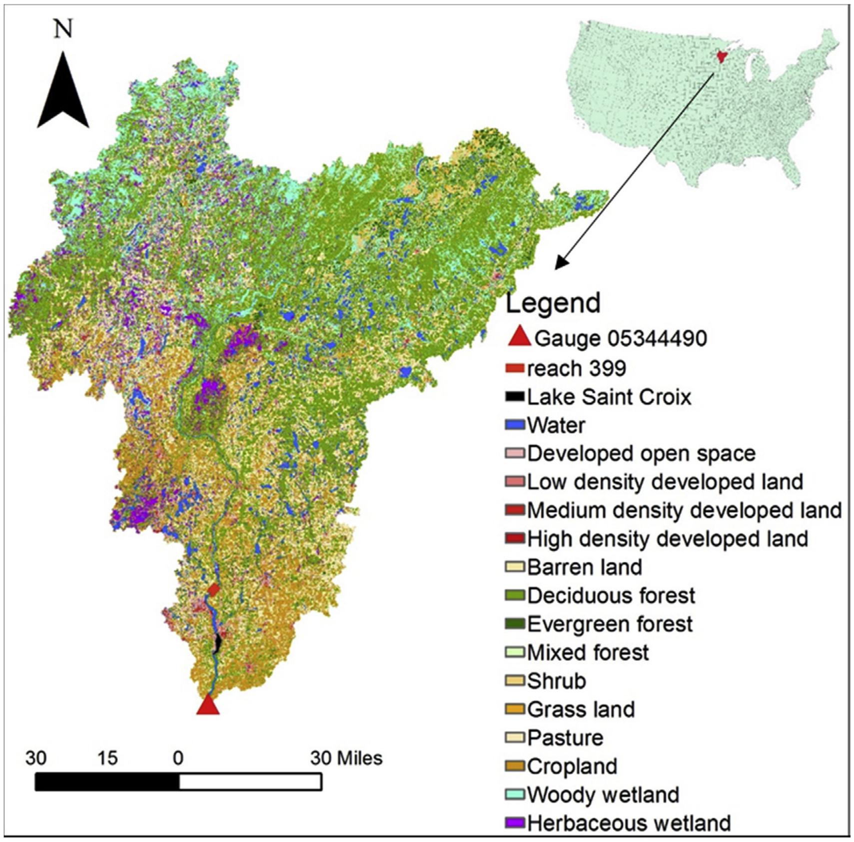

Fig. 1. Location and land use/land cover of the St. Croix River Basin.

$$g_{co2} = g_{max} \times (1.4 - 0.4 \times \frac{C_{co2}}{330})$$

where g_{co2} is the leaf conductance calculated by considering CO_2 effects ($m\ s^{-1}$); g_{max} is the maximum leaf conductance of a single leaf ($m\ s^{-1}$); C_{co2} is the air CO_2 concentration (ppm).

Parameters regulating water (Fig. S1), sediment (Fig. S2), and nutrient (Fig. S2) transport were calibrated with the riverine fluxes data during 2000–2007 from Environmental Services (Metropolitan Council Environmental Services, 2011) at Stillwater (reach ID: 399) (Almendinger et al., 2015; Yang et al., 2018). The MCES data was developed based on the U.S. Army Corps of Engineers' Flux32 software. This software quantifies riverine loads based on streamflow observations and water quality data. We employed the SWAT-CUP program to adjusted parameter values to improve model performances (Abbaspour, 2014). Specifically, we feed the SWAT model with 2000 randomly selected parameter combinations and run the model 2000 times, to find parameters producing best model performances (Tables S1–S3). During model calibration, changes in model simulations in response to changes in parameters were measured with the Nash–Sutcliffe efficiency coefficient.

Model simulations with calibrated parameters for the historical period (1980–2010) were evaluated against observed data. Streamflow data from the USGS station 05344490 during 2007–2008 were compiled for streamflow evaluation (Fig. S1). This station is the most downstream gauge with available streamflow observations in the SCRB, and observations at this station were not used for parameter calibration. According to the comparison, model simulations reasonably reproduced seasonal patterns of streamflow. The coefficient of determination (R^2) between model estimates and gauge records reached 0.56 and 0.93 at the daily and monthly scales, respectively. The comparison indicated reasonable representations of streamflow by the SWAT model and calibrated parameters.

Monthly riverine sediment, nitrogen, and phosphorus fluxes estimated by the Metropolitan Council Environmental Services (Metropolitan Council Environmental Services, 2011) at Stillwater (reach ID: 399) during 1990–1999 were used to evaluate model performances (Fig. S2). At the monthly scale, SWAT simulations explained 45% variability of the riverine sediment of the data by MCES, and reasonably reproduced high and low sediment export events ($R^2 = 0.45$). The model was able to explain 65% ($R^2 = 0.65$) and 66% ($R^2 = 0.66$) of the MCES estimated total phosphorus (TP) and total nitrogen (TN) fluxes, respectively. In addition to the temporal changes, our simulations also reconstructed well the magnitudes of nutrient fluxes (Fig. S2).

To further investigate impacts of climate change on terrestrial water cycling, we compared model estimates of future ET and water yield during 2070–2090 with those of the baseline period (1960–1990).

3. Results

3.1. Future climate change in the SCRB

According to the CMIP5 climate projections, the SCRB would experience dramatic changes in atmospheric CO_2 concentrations, precipitation, and temperature during 2020–2099, particularly under the high emission scenario (RCP 8.5). Under the RCP 4.5 scenario, future CO_2 concentrations would increase to 538 ppm by

2099, whereas the high emission scenario would experience a higher CO_2 concentration of 927 ppm by the end of the 21st century (Fig. S3).

Increases in GHG emissions will induce significant changes in precipitation and temperature (Fig. S4). We compared averaged precipitation and temperature during 2020–2099 with the corresponding averages in the baseline period (1960–1990) to show changes in future climate (Table S5). Future changes in precipitation ranged from insignificant changes projected by the IPSL-CM5A-LR and HadGEM-ES models under the RCP 4.5 scenario, to an increase of 12.1% by the GFDL-ESM2M model under the RCP 8.5 scenario. On average, precipitation increase under the low emission scenario (6.3%) was 1.5% lower than that of the high emission scenario (7.9%). Projected precipitation showed substantial temporal variability (Fig. S4). In the 2090s, three of the four models showed precipitation increases of 5.4%–15.0% relative to the baseline period.

Temperature would increase significantly in the coming decades under both climate change scenarios (Fig. S4). Under the RCP 4.5 scenario, the future temperature would increase by 3.5 °C, whereas under the RCP 8.5 scenario, it would increase by 4.8 °C during 2020–2099. During the 2070s-2090s, the warming climate would increase temperature by 4.2 °C and 6.9 °C under the RCP 4.5 and RCP 8.5 scenarios, respectively. In addition to the increasing trend, the future temperature would demonstrate significant temporal variability.

3.2. *Future streamflow, ET, and water yield in the SCRB*

In response to climate change, future streamflow at the basin outlet would increase in the 21st century relative to the baseline period of 1960–1990 (Fig. 2). The simulations driven by four selected climate projections agreed well in the long-term increasing trend of streamflow. Under the low emission scenario (RCP 4.5), average streamflow during 2020–2099 would increase by 29%. Simulation driven by the IPSL-CM5A-LR climate data had the lowest increase of 16.9%, whereas simulations based on the GFDL-ESM2M climate data resulted in the highest increase of 53.6% among all simulations. Streamflow simulations under the high emission scenario (RCP 8.5) would be substantially higher than those of the RCP 4.5 scenario. On average, future streamflow under the RCP 8.5 scenario would increase by 45.8% during 2020–2099, with the highest increase (68.4%) from the GFDL-ESM2M climate-driven simulation, and the lowest increase (27.7%) induced by the IPSL-CM5A-LR climate data.

Decadal changes in streamflow further highlight the increasing trend in future streamflow under both scenarios. Specifically, streamflow would be higher under the high emission scenario (RCP 8.5) than that of the low emission scenario in each decade in the remaining of the 21st century. In the last two decades of the 21st century, streamflow would increase by 60%–100% under the RCP 8.5 scenario relative to the baseline period. Flow duration curves (FDCs) for historical (1960–2010) and future (2020–2099) streamflow simulations further demonstrated significant increases in river discharge under future climate conditions (Fig. S5). In the FDCs, future streamflow would be higher than the historical flow for all the exceedance percentages. The increases would be more significant for high streamflow. Flow rates exceeding 10% would increase by 22% and 47% relative to historical rates under the RCP 4.5 and RCP 8.5 scenarios, respectively.

Both increased and decreased ET would occur in different parts of the basin under the RCP 4.5 scenario (Fig. 3). Our simulations found decreased ET in 1167 of the 3110 HRUs under the low emission scenario. HRUs with decreased ET were mainly located in the central and northern parts of the study area. Reductions in ET

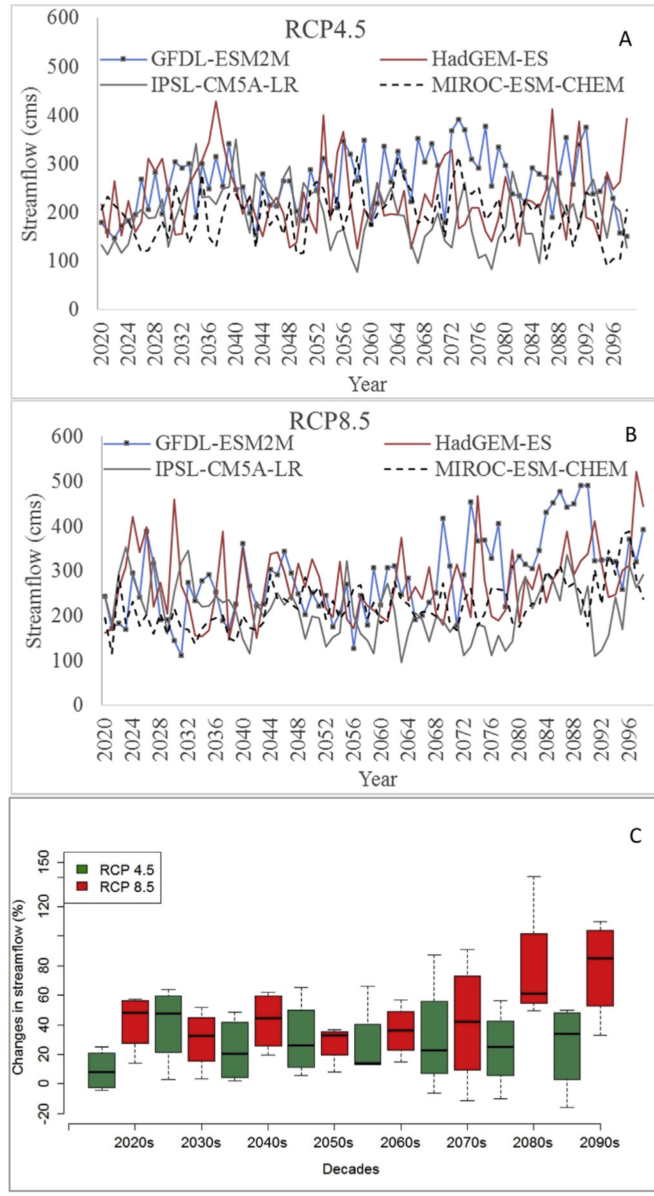

Fig. 2. Projected average streamflow at the basin outlet during 2020–2099 under the (A) RCP 4.5 and (B) RCP 8.5 scenarios, and (C) changes relative to historical streamflow during 1960–1990. A and B show annual streamflow, and C shows relative differences at the decadal scale.

would be more significant and occur to more HRUs under the RCP 8.5 scenario than the low emission scenario. We found decreased ET in 2591 of the 3010 HRUs, where annual ET would decrease by more than 30 mm/year, under the RCP 8.5 scenario. Reductions in ET would occur coincidently with increases in streamflow, particularly under the RCP 8.5 scenario, suggesting that decreases in water losses through ET would contribute to the increases in streamflow.

Water yield, defined as the net water fluxes from land to the reach of each HRU, would differ significantly under the two scenarios (Fig. S6). Under the RCP 4.5 scenario, most HRUs would undergo enhanced water yield by 10–80 mm/year. Increases in annual water yield greater than 80 mm/year would mainly occur in the central parts of the study area, consistent with the spatial patterns of ET reductions (Fig. 3). Under the high emission scenario

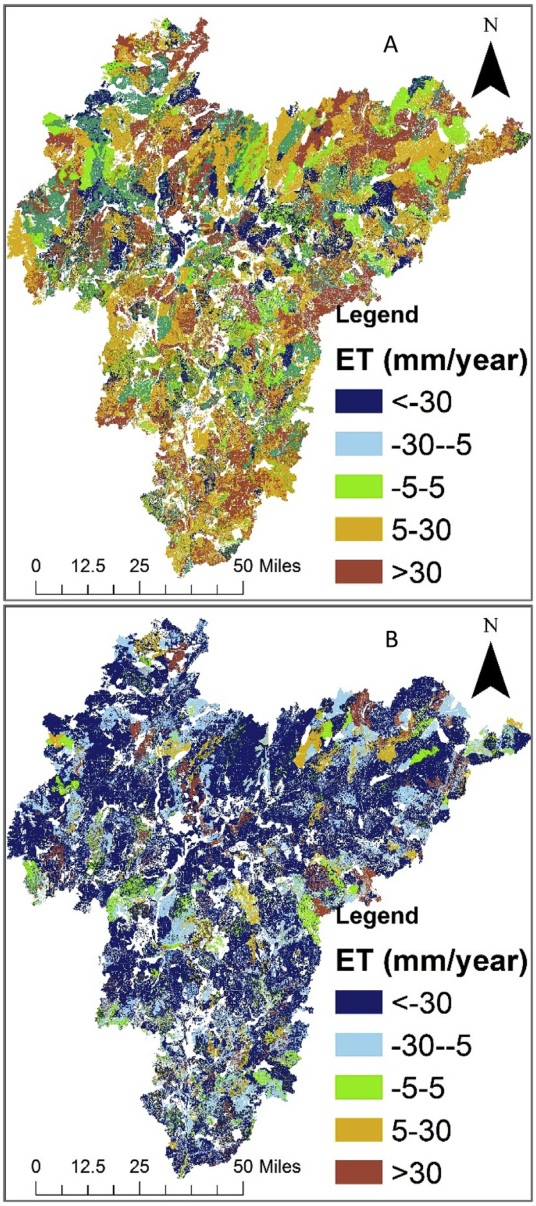

Fig. 3. Changes of projected Evapotranspiration (ET) during 2070–2099 under the (A) RCP 4.5 and (B) RCP 8.5 scenarios relative to historical ET during 1960–1990.

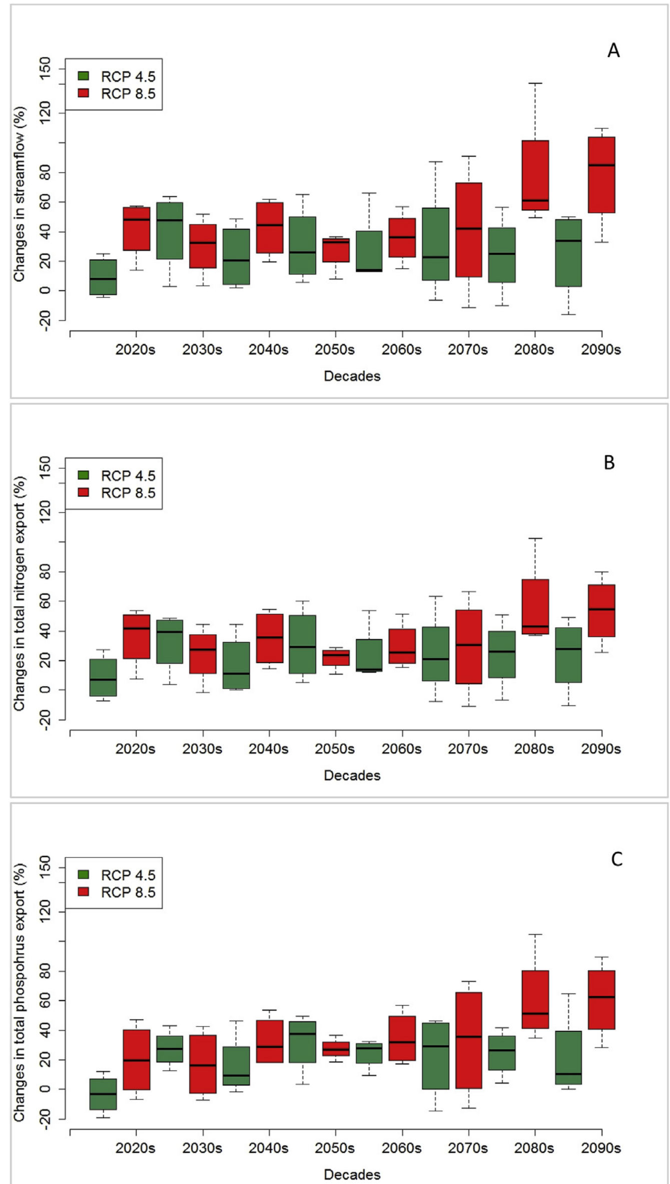

Fig. 4. Projected decadal changes in the load of riverine (A) sediment, (B) total nitrogen, and (C) total phosphorus export at the basin outlet during 2020–2099 relative to historical levels during 1960–1990.

(RCP 8.5), model simulations demonstrated more significant increases in water yield by more than 80 mm/year in most HRUs.

3.3. Future sediment export from the SCRB

Future sediment export would demonstrate long-term increasing trends, but vary substantially at the annual scale (Fig. 4 and Fig. S7). Under the low emission scenario (RCP 4.5), average increases in sediment export during 2020–2099 would reach 29.7% relative to the baseline period of 1960–1990. Due to increases in streamflow, future sediment export under the RCP 8.5 scenario would increase by 46.9%. The largest increase (69.9%) would occur under the GFDL-ESM2M climate projections, and the lowest increase (28.9%) would be induced by the IPSL-CM5A-LR climate data. In the last two decades of the 21st century, sediment export would increase significantly by 50%–140% relative to the baseline period, under the high emission scenario (RCP 8.5). In response to the significant increase in streamflow in the 2080s and 2090s under the RCP 8.5 scenario, increases in sediment loads in these two decades would also be much higher (ca.40%) than the low emission scenario (RCP 4.5).

3.4. Future nutrient export from the SCRB

Future climate change would also alter nutrient cycling, leading to enhanced nutrient export from the SCRB. Both TN and TP fluxes driven by different climate projections would vary markedly at the interannual scale (Figs. S8–S9). Projected climate conditions would generally result in increasing nutrient export. Under the RCP 4.5 scenario, average TN and TP export would increase by 24.8% and 18.1%, respectively, with the highest export estimates (43.1% for TN and 29.1% for TP) induced by the GFDL-ESM2M and HadGEM-ES data for TN and TP, respectively (Figs. S8–S12).

Under the high emission scenario, nutrient export would be further enhanced. Average increases for TN and TP under the RCP 8.5 scenario would be 35.8% and 35.7%, respectively. For TN export, the GFDL-ESM2M climate data would result in the most significant increase of 55.4%; For TP, the highest increases were induced by the HadGEM-ES model. The MIROC-ESM-CHEM climate projections would lead to the lowest increases of 22.1% and 18.6% for TN and TP under the RCP 8.5 scenario, respectively. At the decadal scale, TN and TP would demonstrate significant increases in the 2080s and the 2090s compared with other decades under the high emission scenario (Fig. 4).

Temporal patterns of sediment, TN, and TP concentrations were divergent among the three variables. Overall the concentrations would not have significant changes in the remaining of the 21st century. Sediment concentration would increase slightly under both climate scenarios. Concentrations of TN would vary over time. Fig. S13 suggested that TN concentration would decline by ca.10% under the RCP 4.5 scenario till the end of this century, but changes under the RCP 8.5 scenario would not be significant. Concentration of TP would not have statistically significant trend, and the temporal patterns under the two scenarios would be consistent. Differences between RCP 4.5 and RCP 8.5 scenarios would be more significant for TN than TP.

4. Discussion

4.1. Future riverine fluxes and implications for water quality management in the SCRB

Our simulations suggested that warming temperatures, increasing precipitation, and elevated atmospheric CO_2 concentrations would generally result in increases in riverine water, sediment, and nutrient export in the SCRB. These results are in line with previous studies which reported that climate change might lead to hydrological intensification as a result of warming-triggered increases in evaporation and precipitation (Huntington, 2006; Zhang et al., 2017). The increased streamflow projected in this study agreed with studies reporting enhanced streamflow and reduced ET under future climate scenarios in Midwest U.S. (Mishra et al., 2010). However, our simulations under the RCP 8.5 scenario, particularly reductions in ET and increases in streamflow, were different from general circulation model (GCM) simulations which predicted decreases in runoff in the Midwest U.S. (Wuebbles and Hayhoe, 2004). The inconsistencies could be attributed to different model representations of hydrological cycling in GCMs and SWAT. In addition, we considered impacts of CO_2 concentration elevation on plant physiology and evapotranspiration, which may also be responsible for differences between this investigation and other modeling studies which were primarily focused on impacts of precipitation and temperature changes on water cycling (Kergoat et al., 2002).

Our simulations suggested that climate change would have profound impacts on watershed biogeochemistry, which are consistent with previous investigations (Bernal et al., 2012; Kane et al., 2008; Neal et al., 2005). In addition to enhanced water cycling, sediment, and nutrient export from the SCRB would both increase under future climate scenarios, and thus challenge water quality management efforts in the basin.

As noted earlier, the lowermost reach of the St. Croix River was declared impaired from eutrophication driven by excessive phosphorus inputs, according to section 303(d) of the Clean Water Act. To remediate the problem, the Total Daily Maximum Load (TMDL) for phosphorus has been set at 27% below the mean phosphorus load calculated for the 1990s, in order to re-set the river back to its condition in the 1940s (Triplett et al., 2009). Watershed modeling has indicated that this load reduction might be achieved by adopting conservation cropping practices (Almendinger, 2016), with the full compliance of all farmers in the basin. Unfortunately, our simulations here suggested that climate change could make the problem worse by driving phosphorus loads up by about 18–36% under current agricultural practices. In the face climate change, resource managers in the SCRB will be further challenged in reducing nutrient load to maintain the ecological integrity of the St. Croix National Scenic and Recreational Riverway.

To mitigate impacts of climate change on water, sediment, and nutrient delivery in basins like the SCRB, effective cropland management practices, such as adding vegetated filter strips to croplands (Almendinger and Ulrich, 2017), restoring degraded wetlands (Cui et al., 2009), and cover cropping (Kaye and Quemada, 2017), could effectively trap nutrients and sediment thus reduce lateral transport. Considering the potential impacts of climate change in the SCRB, are needed for limiting climate-caused increases in sediment and nutrient fluxes. Combinations of these BMPs are expected to reduce nutrient delivery by 10%–30% (Almendinger and Ulrich, 2017; Meals et al., 2010), and effectively protect soil from erosion (Dabney et al., 2001).

4.2. Climate change impacts on water cycling

Understanding mechanisms regulating interactions of hydrological cycle in response to climate change is key for management of water quantity and quality. Changing precipitation patterns, warming temperatures, and elevated atmospheric CO_2 concentrations could affect many processes in water cycling. Our investigations further highlighted the importance of considering interactions among the climate factors in understanding hydrological consequences of climate change (Najjar et al., 2010).

Increased ET under the RCP 4.5 scenario demonstrated the joint impacts of warming temperatures and increased precipitation on ET, as a result of changes in water availability and vapor pressure deficit (Nagler et al., 2007; Will et al., 2013). In addition to temperature and precipitation, elevated CO_2 concentration is another factor that was proven to influence ET (Law et al., 2002). Free-air CO_2 enrichment experiments reported a 22% reduction in stomatal conductance when air CO_2 increased by 57% (Ainsworth and Rogers, 2007). As a result, inhibited stomatal conductance under elevated CO_2 may reduce water loss through transpiration, particular if soil moisture becomes limited (Engel et al., 2004). Although temperature and precipitation changes tended to enhance ET, CO_2 elevation offset their impacts, and resulted in ET reductions. This is the primary reason for ET reductions and streamflow increases under the RCP 8.5 scenario.

Results of this study are consistent with Qian et al., 2007 study that climate change may play the dominant role in variations of runoff (Qian et al., 2007). However, we found that mechanisms leading to water yield increase were different between the two scenarios. Although ET was projected to increase in many HRUs (Fig. 3) under the low emission scenario (RCP 4.5), water yield still increased in the basin (Fig. S6). As a result, these increases could be attributed to increases in precipitation from the water balance perspective.

Mechanisms resulted in significant water yield increases under the high emission scenario (RCP 8.5) were more complex. Under the RCP 8.5 scenario, high atmospheric CO_2 concentrations would generally reduce stomatal conductance and ET. Consequently, significant reductions in ET occurred in most HRUs would lead to enhanced water yield across the basin (Fig. S6). As a result, water yield increases caused by higher precipitation under this scenario would be further amplified by CO_2 elevation. Impacts of CO_2 on water yield as demonstrated in our simulations were in line with the increasing trend of continental runoff during 1960–1994 as a result of plant transpiration reduction following CO_2-induced stomatal closure (Gedney et al., 2006).

Impacts of atmospheric CO_2 on ET and water yield demonstrated that plant physiology changes under a changing climate might have substantial impacts on watershed hydrology. Water cycling is closely coupled with biotic processes in terrestrial ecosystems (Domec et al., 2012). Model simulations in this study further confirmed that responses of plant physiology to changing climate conditions may play important roles in future hydrological changes (Seghieri et al., 1995). Since forest and grassland cover more than 50% of the study area, responses of plant growth or physiological activities to the changing climate and their potential feedback to water cycling are worth further investigations for better water resource management in the basin.

4.3. Processes regulating sediment and nutrient export under a changing climate

Riverine sediment and nutrient fluxes are controlled either by runoff which transports leachate from land to rivers (Raymond et al., 2008), or by leachate supply (Currie and Aber, 1997). To mitigate the impacts of climate change on water quality, processes linking hydrological cycling and sediment/nutrient export should be examined for better control of excessive nutrient load in basins like the SCEB.

Soil erosion mobilizes large amounts of carbon and nutrient in soils, and act as an important pathway for soil carbon and nutrient redistribution from upland regions to depositional sites (Boynton et al., 1995; Quinton et al., 2010). Climate change affects sediment transport through influencing soil erosion and subsequent transport along river channels. Soil erosion is a critical process regulating sediment transport through streams and rivers (Berhe et al., 2014). Rainfall provides energy to detach fine soil particles from erosion sites (Mohamadi and Kavian, 2015), especially during high intensity and long duration precipitation events (Gomez et al., 2003; Nearing et al., 2005). Runoff carries the mobilized soil particles during transport and directly regulates the amount of sediment (Jiang et al., 2017). Streamflow increase is another reason for enhanced sediment transport under future climate changes (Neitsch et al., 2009). Both sediment mobilization and transport are sensitive to changes in precipitation and streamflow, and resulted in increased sediment loads in the sediment projections (Figs. 4 and S10). To mitigate the potential impacts of climate change on sediment transport, conservation practices, such as no-till cropping and detention ponds or wetlands, will be needed in future control of soil erosion and sediment transport (Almendinger and Ulrich, 2017; Bradford and Huang, 1994).

For the export of nitrogen and phosphorus, hydrological processes also have significant impacts. Net Anthropogenic Nitrogen or Phosphorus Inputs (NANI or NAPI) investigations reported that ca. 25% of nitrogen (Boyer et al., 2002) and 10% of phosphorus (Russell et al., 2008) were transported by streamflow out of lands receiving the nutrients. The remaining nutrients either accumulate in watersheds, or left watersheds through gas emissions. Low transport to input fractions indicated that nutrient transport may be limited by runoff, instead of supply. In this study, although sources of nutrients were set at the historical levels in our projections, future climate changes would still lead to enhanced export of sediment and nutrients, indicating that transport limit is an important mechanism regulating nutrient delivery in the study area. In addition to the BMPs discussed in section 4.1, water quality management practices, such as using wetlands to increase the retention time of water fluxes in the watershed, are also needed to reduce nutrient delivery to downstream waters (Jordan et al., 2003).

Although water yield and sediment/nutrient leaching are regulated by different processes, increasing trends in both streamflow and sediment/nutrient fluxes, particularly the coincident increases in the 2080s and 2090s under the RCP 8.5 scenario, further suggested that climate change-induced changes in water cycling could significantly affect sediment and nutrient export. Meanwhile, differences in spatial patterns of water yield and sediment/nutrient loads (Figs. S10, S11, and S12), and different temporal patterns of concentrations of these variables, suggested that additional processes other than transport, should also be considered to fully understand climate change impacts on watershed biogeochemistry.

Specifically, increases in concentrations of sediment are consistent with the trends in streamflow, further confirmed the predominant role of water cycling in sediment transport. Under extreme rainfalls, frequency and magnitude of soil erosion could be enhanced, and thus lead to the elevated sediment transport (Berhe et al., 2014). We observed both increases and decreases in future TN and TP concentrations. The variability could be either explained by the dilution effects as a result of increases in streamflow, or could be attributable to additional nutrient sources which were historically isolated, but become available under a wetter climate (Murdoch et al., 2000).

In addition to transport-related impacts, climate change may affect nutrient transport by regulating transformation of nitrogen and phosphorus along the land-river continuum. Unlike water cycling in which abiotic processes play the fundamental role, biotic processes, such as plant growth, litter production, and organic matter decomposition, have significant impacts on nutrient cycling (Thornton et al., 2009). With increases in plant growth in response to the warming climate and increased precipitation, large amounts of nitrogen and phosphorus were immobilized and incorporated into plant biomass and soil organic matter (Nidzgorski and Hobbie, 2016), which are more resistant to leaching than inorganic nutrients (Luo et al., 2006). In addition, warming temperatures may also stimulate soil nitrogen losses through N_2O emission (Yang et al., 2017), which may explain the more significant differences in concentrations between the two scenarios for TN than that for TP (Fig. S13). Further analyses on nutrient stocks in soils and plant biomass in response to warming temperatures and changing precipitation patterns will be needed to better understand how climate change would change specific process in nutrient accumulation, transformation, leaching, and retention (Bouwman et al., 2013; Perring et al., 2008).

4.4. Uncertainties and future work

Uncertainties associated with the input datasets and simplified model representation of plant growth in SWAT should be considered to better interpret water and nutrient fluxes projections and limitations of this study. First, climate projections have direct impacts on water cycling simulations (Murray et al., 2012). Although we selected climate data from four climate models for this study, inclusion of a larger number of climate projections will further constrain uncertainties associated with climate data. Second, model simulations highlighted sensitive responses of plant transpiration to climate change. However, lacking process-based algorithms in SWAT forest module may have introduced extra uncertainties in SWAT simulations (Yang and Zhang, 2016). As introduced in Wu and Liu (2012), default SWAT algorithms may simplify plant transpiration responses to elevated atmospheric CO_2. By adopting the suggested modifications in Wu and Liu (2012), we found that plant type-specific parameterization for describing CO_2 elevation impacts may reduce our estimates by 15.2%, 17.4%, 21.5%, and 20.8%, for streamflow, sediment export, nitrogen export, and phosphorus export, respectively. These results highlighted the importance of adding more mechanistic features to the SWAT plant module. In addition, we did not consider contributions of point source pollutants in this study. Future work needs to evaluate how future population growth and urbanization would further affect nutrient export to better understand future changes in water quality. Finally, we admit that climate change could have complex impacts on storage of nutrients in terrestrial and aquatic ecosystems, chemical transformation of N and P in multiple pools, as well as the leaching and transport along the land-river interfaces. Future modeling studies should be closely connected with field investigations to explicitly examine dynamics of nutrient pools and fluxes along the land-river transport pathway, to enhance understanding of climate change impacts on watershed biogeochemistry.

5. Conclusions

In this study, we used the SWAT model to project future water quality and nutrient export in the SCRB in response to climate change during 2020–2099. Future river discharge and sediment/nutrient export in the basin were projected to increase significantly, especially under the high emission scenario (RCP 8.5). Reducing nutrient load has been set as a goal for water resource management in the SCRB. However, pollution control practices were designed based on historical climate conditions, and did not have sufficient consideration of future climate change impacts on water quality. Our projections suggest that climate change-induced increases in water, sediment, and nutrient export would pose further challenges to water management and pollution control in the basin. Results of this study could be potentially used for the formulation of pollution control plans in basins like the SCRB.

This study also highlighted the importance of considering plant physiology changes in process-based hydrological models in projecting riverine water and nutrient fluxes under a changing climate. Plant growth is sensitive to climate changes, and may have indirect influences on water and nutrient export through regulating transpiration, water consumption, throughfall, and nutrient uptake. In addition to the influence of warming temperatures and altered precipitation, atmospheric CO_2 increases may greatly enhance streamflow and associated sediment and nutrient export through affecting plant transpiration. Future investigations should include explicit analyses on responses of plant growth to changes in climatic factors to better understand hydrological and biogeochemical consequences of climate change.

Finally, divergent spatial and temporal patterns in the load and concentration of sediment and nutrients suggested complex and interacting impacts of multiple climate variables on riverine fluxes. We conclude that future modeling investigations should be integrated with field investigations to gain better knowledge on the dynamics of nutrient pools and transformations along the terrestrial-aquatic pathway to improve our understanding of watershed biogeochemistry under a changing climate.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.04.129.

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