

Improving the SWAT forest module for enhancing water resource projections: A case study in the St. Croix River Basin

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Abstract

Insufficiently calibrated forest parameters of the Soil and Water Assessment Tool (SWAT) may introduce uncertainties to water resource projections in forested watersheds. In this study, we improved SWAT forest parameterization and phosphorus cycling representations to better simulate forest ecosystems in the St. Croix River Basin (SCRB) and further examined how those improvements affected model projections of streamflow, sediment, and nitrogen export under future climate conditions. Simulations with improved forest parameters substantially reduced model estimates of water, sediment, and nitrogen fluxes relative to those based on default parameters. Differences between improved and default projections can be attributed to the enhanced representation of forest water consumption, nutrient uptake, and protection of soil from erosion. Better representation of forest ecosystems in SWAT contributes to constraining uncertainties in water resource projections. Results of this study highlight the importance of improving SWAT forest ecosystem representations in projecting delivery of water, sediment, and nutrients from land to rivers in response to climate change, particularly for watersheds with large areas of forests. Improved forest parameters and the phosphorus weathering algorithms developed in this study are expected to help enhance future applications of SWAT to investigate hydrological and biogeochemical consequences of climate change.

Keywords: Forest; Climate change; Water resource projection; SWAT; Uncertainties; Streamflow; Sediment; Nutrients

1. Introduction

Maintaining sustainable water resources is one of the most urgent environmental challenges facing global society (Thomas & Durham, 2003). Increasing water demand by agriculture, drinking water supply, and industrial manufacturing exerts high pressures on water quantity and quality management (Demissie, Yan, & Wu, 2012; Sun, McNulty, Myers, & Cohen, 2008), particularly under a changing climate (Uniyal, Jha, & Verma, 2015). Climate change has been recognized as a key disturbance to global hydrological cycle (Delpla, Jung, Baures, Clement, & Thomas, 2009; Murray, Foster, & Prentice, 2012; Verma et al., 2015). Warming temperatures, altered precipitation patterns, and elevated atmospheric CO₂ concentrations are changing terrestrial water cycling through affecting water and energy fluxes among land, vegetation, and the atmosphere (Goyal, 2004; Oki & Kanae, 2006). Increasing efforts have been devoted to investigating hydrological consequences of climate change (Labat, Godd, Probst, & Guyot, 2004; Piao et al., 2007). Improved understanding of processes and mechanisms regulating water and nutrient cycling in the context of climate change is needed for constraining uncertainties in water resource projections based on mathematical models.

Previous investigations have reported significant impacts of climate change on physical processes of terrestrial water cycling (Luo, Ficklin, Liu, & Zhang, 2013; Snyder et al., 2011; Taylor et al., 2013). Altered precipitation patterns were found to be mainly responsible for

temporal variability of streamflow (Garbrecht, Van Liew, & Brown, 2004; Yang, Tian, Friedrichs, Liu, et al., 2015). Warming temperatures have been identified as a key factor for changes in evapotranspiration (ET) (Goyal, 2004). Stimulated plant growth in response to climate warming could also result in increased water consumption by plants through transpiration, and significantly affect soil moisture dynamics (Butterfield, Bradford, Armas, Prieto, & Pugnaire, 2016) and runoff generation (Brown, Zhang, McMahon, Western, & Vertessy, 2005). In addition, plants tend to increase stomatal resistance under elevated CO₂ concentrations, thus suppress transpiration and stimulate runoff generation (Gedney et al., 2006). The role of plant growth and development in hydrological responses to climate change should be considered to better understand water cycling under future climate conditions.

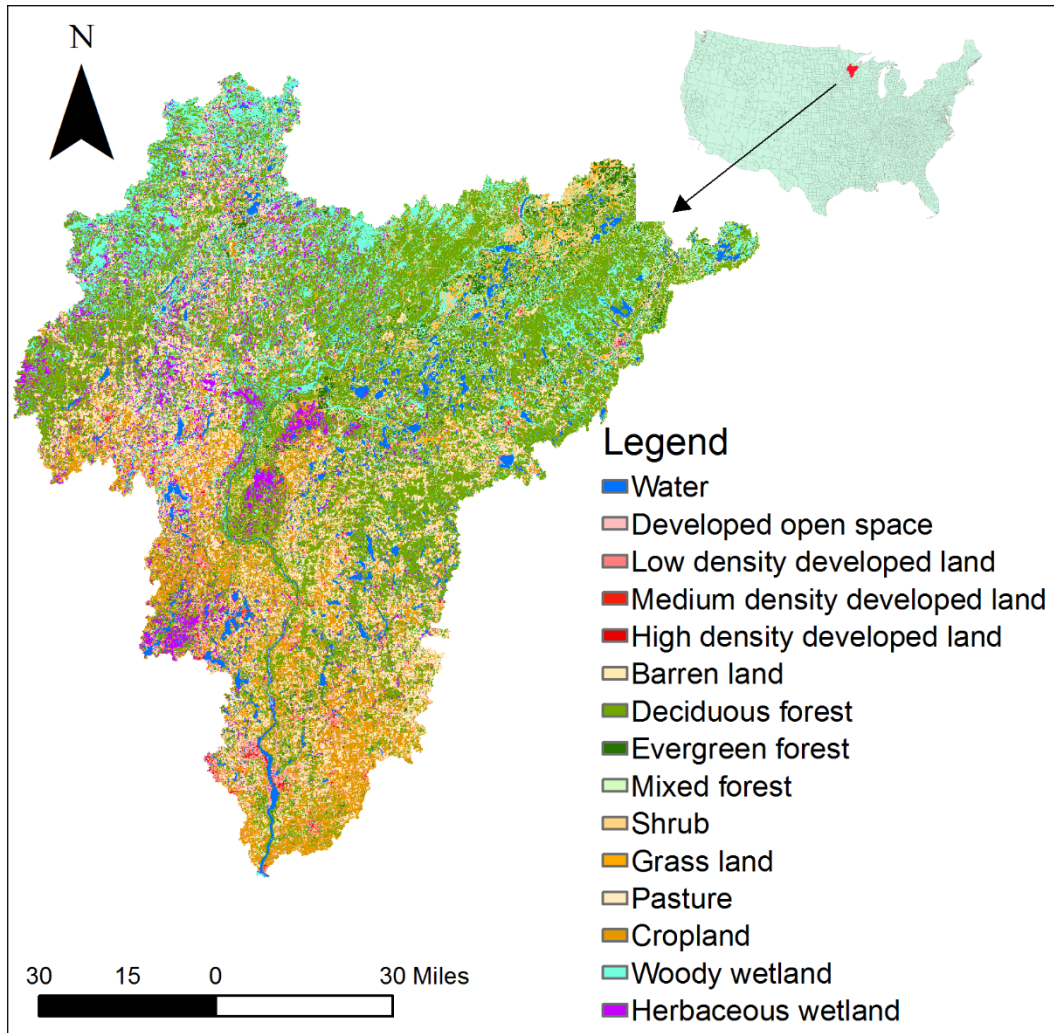
The Soil and Water Assessment Tool (SWAT, Arnold et al., 1998) model has been extensively applied to investigate impacts of climate change on hydrological dynamics (Uniyal et al., 2015; Zhang, Srinivasan, & Hao, 2007) and biogeochemical cycling (Verma et al., 2015). Forest play important roles in regional carbon, water, and nutrient cycling (Ferraz, Lima, & Rodrigues, 2012; England & Rosemond, 2004; Price, 2011). Most previous investigations adopted default parameterization of the SWAT forest module, and did not perform a detailed evaluation of SWAT performances in simulating forest ecosystems. Recent investigations improved SWAT simulation of forest ecosystems (Yang and Zhang 2016; Yang et al., 2018). In Yang and Zhang (2016), we identified limitations in default SWAT in simulating forest carbon cycling, and improved SWAT forest parameterization through model data intercomparison. We

further evaluated SWAT performances in simulating forest ecosystems at the watershed scale, and highlighted importance of forest representation in understanding watershed hydrology (Yang et al., 2018). However, implications of these improvements for watershed scale hydrology and biogeochemistry simulations under a changing climate have not been examined yet.

In recognition of the research need, we examined how improvements in forest ecosystem simulations affect projections of water resources in the St.Croix River basin (SCRB). We simulated and compared future streamflow, sediment, and nitrogen export in the basin with both default and improved forest parameters. Specific objectives of this study were to: (1) investigate future water resources in the SCRB under two climate scenarios; (2) examine how improved SWAT forest and phosphorous modules would affect streamflow, sediment, and nitrogen transport projections; (3) discuss implications for future SWAT applications in investigating hydrological impacts of climate change.

2. Methods

2.1. Study area



[FIGURE 1 Location and land use/land cover of the St. Croix River Basin]

The SCRIB is located across the Wisconsin and Minnesota borders (Figure 1). As a tributary of the Mississippi River, the St. Croix River flows 250 km from its headwaters to its outlet, with a catchment area of 20000 km² (Figure 1). Because of its scenic and recreational values, the St. Croix River was designated as a National Scenic and Recreational Riverway in 1968 (Almendinger et al., 2015; Waters, 1977).

The SCRB has a typical continental climate, with humid and warm summers, and cold dry winters. Mean temperature in January is -12.9 °C, and the mean temperature in July is 20.6 °C, according to meteorological records in Grantsburg, WI, near the basin centroid. Annual precipitation is 808 mm, with 42% of the rainfall occurring in summer (Almendinger et al., 2015). Primary land use types in this basin include forest, surface waters, cropland, and developed area. As the dominant land cover, forests cover ca. 46.6% of the basin, and are mainly distributed in central and northern parts of the SCRB (Figure 1).

2.2. Model setup and input dataset for model simulations

We compiled a comprehensive input dataset for SWAT simulations in the SCRB. Specifically, we used the digital elevation model (DEM) dataset from the United States Geological Survey (USGS) to obtain topographic and hydrologic information of the basin. A high-density flow network from the Minnesota Department of Natural Resources (MDNR) and a stream network from the Wisconsin Department of Natural Resources (WDNR) were combined to create a basin-wide continuously connected flow network. Using these data, the delineation routine from ArcSWAT created 419 sub-basins and 3110 hydrologic response units (HRUs) in the SCRB.

The State Soil Geographic Database (STATSGO) was used to derive soil property information for the SCRB. The Crop Data Layer (CDL) was used to obtain crop rotation data, and the National Land Cover Dataset (NLCD) for unmanaged land cover types. Historical (1980-

2010) climate data, including precipitation and temperature, were collected from 25 weather stations located in the basin (Almendinger et al., 2015).

Future climate data including daily temperature and precipitation under two Representative Concentration Pathway (RCP) scenarios (i.e. RCP 4.5 and 8.5) were obtained from four Coupled Model Intercomparison Project-5 (CMIP5) climate models, including GFDL-ESM2M, HadGEM-ES, IPSL-CM5A-LR, and MIROC-ESM-CHEM (Table S1). Climate simulations from these models were bias-corrected against observed climate data using the bias-correction and spatial-downscaling approach of Wood et al. (2004). These data were then used in SWAT model simulations for the 1950-2099 period. We applied the *T-Test* to discern changes in climate data during 2020-2099 relative to the historical levels (1960-1990) (Table S2). Our analyses were mainly focused on the 2020-2099 period.

Climate projections showed that the SCRB would undergo dramatic changes in atmospheric CO₂ concentrations, precipitation, and temperature in the 21st century (Figures S1-S3), particularly under the high emission scenario (RCP 8.5). Atmospheric CO₂ concentration is projected to increase significantly in the future. Under the RCP 4.5 scenario, the future CO₂ concentration would reach 538 ppm by 2099, whereas the high emission scenario (RCP 8.5) would have higher CO₂ concentrations of greater than 925 ppm by the end of the 21st century.

Future changes in precipitation would range from insignificant changes under the RCP 4.5 scenario to an increase of 12.1% under the RCP 8.5 scenario in the remaining of the 21st century relative to the baseline period (1960-1990). Temperature would increase significantly in

the coming decades. Under the RCP 4.5 scenario, future temperature would increase by 3.5 °C, whereas the RCP 8.5 scenario would have an increase of 4.8 °C in the remaining of the 21st century relative to the baseline period (Table S2).

2.3. The SWAT forest module improvement

We adjusted parameters controlling photosynthesis for deciduous and evergreen forests to better simulate Net Primary Productivity (NPP) and plant biomass (Table S3). Calibrated radiation use efficiency (*BIO_E*) values were in the range reported by previous studies (Gower, Kucharik, & Norman, 1999). Temperature is another important factor controlling forest growth and development. Base temperature (*T-Base*) for plant growth varies over different plant species and site conditions, and needs to be calibrated properly to better simulate plant phenology and associated carbon and water fluxes (Farr & Harris, 1979). We adjusted *T-Base* from 0 degree to 8 degree to better simulate timing of plant growth and associated carbon and water fluxes in cold seasons (Yang & Zhang, 2016). The default value of 0.3 for the leaf to biomass fraction (*BIO_LEAF*) in SWAT is much higher than field observations (Yang & Zhang, 2016). We decreased this parameter to 0.08 for deciduous and evergreen forests in the study area based on observational data (Yang, et al., 2018).

In addition to the above improvements in forest parameters, we also revised the phosphorus cycling module in SWAT (Yang & Zhang, 2016). In default SWAT, phosphorus supply through parent material weathering in soil is not simulated. We developed a new algorithm to account for this source of phosphorus based on the Century model (Parton, Ojima,

Cole, & Schimel, 1994). Specifically, new phosphorus produced through weathering is simulated as a function of temperature, soil moisture, and content of parent phosphorus in soils (supplementary material).

2.4. Model simulations, performance evaluation, and parameter sensitivity

In this study, we primarily focused on riverine flux uncertainties resulted from SWAT representation of forest ecosystems. We conducted two sets of SWAT simulations to discern how the improvement of key forest parameters and a newly-developed phosphorus supply module affect model simulations under future climate conditions. First, we simulated future riverine fluxes with default SWAT forest parameters (denoted as default SWAT simulations). Then, we conducted another set of simulations (denoted as improved SWAT simulations) with improved forest parameters and algorithms simulating soil phosphorus supply from weathering of parent materials, as described in Yang and Zhang (2016). In these two sets of simulations, hydrologic parameters calibrated during the historical period (2000-2009) were kept unchanged. To show changes in projected riverine fluxes, we compared average streamflow, sediment export, and nutrient export during 2020-2099, with the corresponding averages of these riverine fluxes in a baseline period of 1960-1990 (Table S2).

In this study, we use the coefficient of determination (R^2) and Nash–Sutcliffe Efficiency coefficient (NSE) to evaluate model performances (Figures S9 and S10). The coefficients of are calculated using the following equations:

$$R^2 = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - O_{avg})^2}$$

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - O_{avg})^2}$$

where O_i is the observed data, P_i is the simulated value of the independent variable in a linear correlation, and O_{avg} is the mean value of observed data, and S_i is SWAT simulated riverine flux.

We collected NPP and ET products developed based on the Moderate Resolution Imaging Spectrometer (MODIS) remote sensing data (Mu, Zhao, & Running, 2011; Zhao, Heinsch, Nemani, & Running, 2005) to evaluate SWAT simulations of forest ecosystems. Comparison with field data indicated that the MODIS NPP data compared well with field observations with a mean bias error of ca. 6% at the annual scale (Pan, Brdsey, Hom, McCullough, & Clark, 2006). Comparison against fluxtower observations suggested that MODIS ET data reproduced annual ET well, with mean bias errors ranging from 2% to 22% during 2000-2007 (Velpuri, Senay, Singh, Bohms, & Verdin, 2013). Default SWAT forest simulations substantially underestimated MODIS-based forest NPP during 2000-2008 (Figure S4). Average annual NPP estimated by SWAT based on the default parameters was 372.2 ± 66 g C/m²/year (Average \pm one Standard Deviation) during 2000-2008, or ca. 20% lower than the MODIS NPP of 459 ± 65 g C/m²/year. The average NPP based on improved SWAT forest parameters

increased to 447.5 ± 93 g C/m²/year, which was more comparable with MODIS NPP data (Figure S4). Improvements in NPP simulations resulted from the new phosphorus supply module and the calibrated parameters (Table S3)

The forest ET estimates based on default SWAT forest parameters were lower than the MODIS ET estimates (Figure S5). Average ET simulated by default SWAT simulations for the 2000-2008 period was 418.9 ± 51 mm/year, which was 25.4% lower than the average MODIS ET data (562.3 ± 14 mm /year). The improved forest parameterization increased ET estimates by 22.3% relative to the default simulations (Figure S5). Increases in ET resulted from forest parameter calibration and the new phosphorus supply algorithms, which enhanced SWAT simulation of forest growth and water consumption. Specifically, the new phosphorus enhanced NPP and ET by 6.4% and 5.5% relative to the default simulation, respectively.

We used the U.S. Department of Agriculture (USDA) Forest Service forest biomass product (Blackard et al., 2008) to evaluate SWAT simulations of tree biomass. The biomass product could explain 46% of the observed variability in Northcentral U.S., and differences between regional forest biomass estimates and plot-based estimates were less than 10% for the study area (Blackard et al., 2008). With the default forest parameters, forest biomass was markedly underestimated in the SCRB (Figure S6). Average annual forest biomass simulated with the default forest parameters was 10.8 ± 2.5 t/ha during 2000-2008, which was much lower than the USDA reported average of 72 ± 18 t/ha. By improving the forest parameters and phosphorus supply from weathering, the estimated average forest biomass from SWAT was 82.3

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± 18 t/ha during 2000-2008, which was comparable to the USDA forest biomass data. Improved biomass estimates resulted from reasonable NPP estimates and the substantial decrease in calibrated *BIO_LEAF* relative to default values.

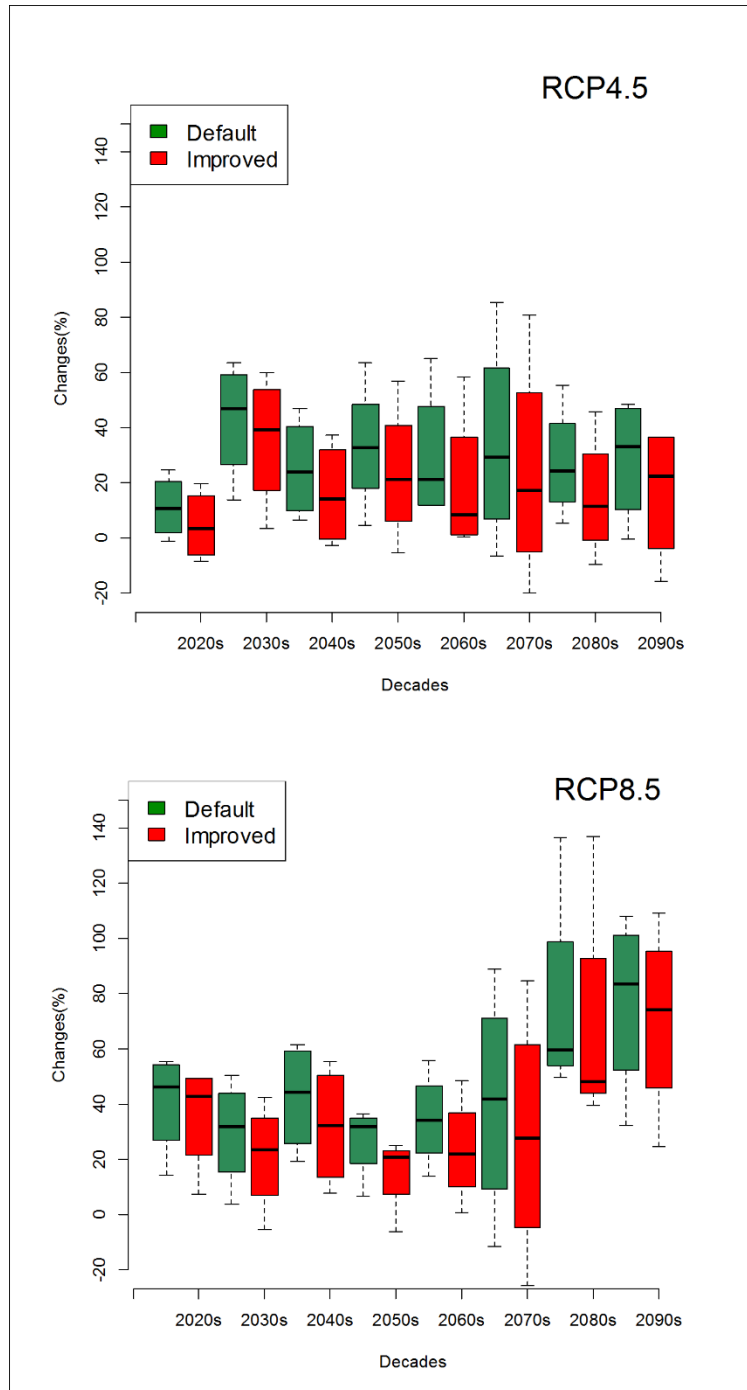
Observed climate data were used to drive model simulation during 1980-2008 for calibrating and validating hydrology and nutrient cycling-related parameters (Tables S4-S6). Model calibration was conducted using the Sequential Uncertainty Fitting version 2 (SUF2) method in SWAT-CUP (Abbaspour, 2014). We conducted parameter sensitivity analysis to identify key parameters by running the model 1000 times for simulations during 1980-2008 (Table S7). We also calculated uncertainty ranges of model simulations resulted from parameterization for the historical period (Figures S7 and S8).

To evaluate how improvements in forest parameterization would affect streamflow estimates, we compared SWAT simulations against daily gauge records from the USGS station 05344490 during 2007-2008 which were not used in calibration of hydrologic parameters (Tables S4-S7). The USGS gauge data have been widely used for model calibration and performance evaluation in hydrological studies because of the high accuracy of 90-95% compared with the actual flow (Hirsch & Costa, 2004). The improved SWAT simulations captured the temporal variability of observed streamflow well (Figure S9), with a coefficient of determination of 0.56, and the estimated average of 162 ± 105 m³/s was more comparable to the observed average of 148 ± 118 m³/s than the default simulation (191 ± 93 m³/s).

Monthly riverine sediment and nitrogen fluxes obtained from the Metropolitan Council Environmental Services (Metropolitan Council, 2016) at Stillwater (reach ID: 399) during 1990-1999 were used to evaluate model performances (Figure S10). This dataset was developed based on the U.S. Army Corps of Engineers' Flux32 software, which estimates riverine loads based on USGS streamflow records and observed water quality data. The Metropolitan Council load data have been quality-checked to eliminate bias in data development (Metropolitan Council, 2011). Simulations with improved forest parameters explained ca. 30% variability of the riverine sediment flux estimated by MCES. The SWAT estimates were able to explain ca. 71% of the Metropolitan Council-estimated total nitrogen (TN) fluxes.

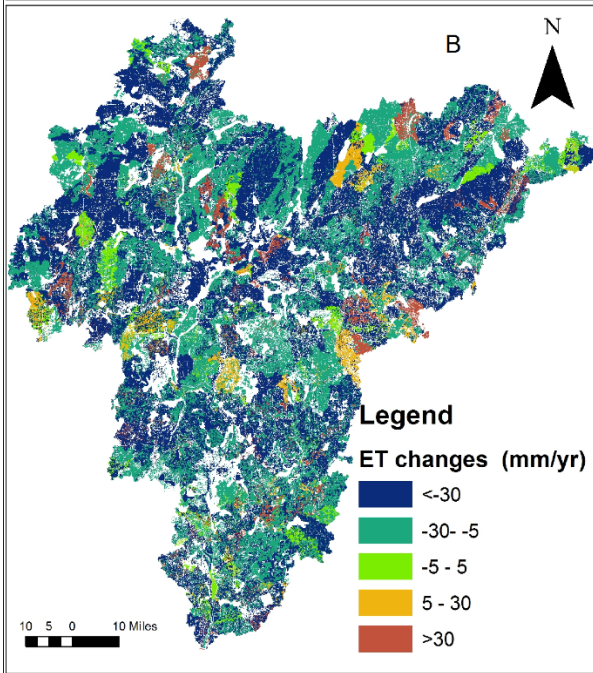
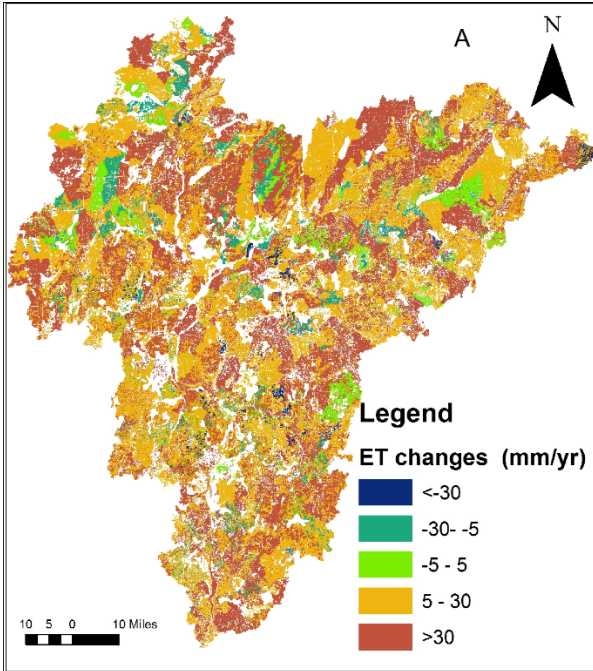
3. Results

3.1. Future streamflow, ET, and water yield in the SCRB



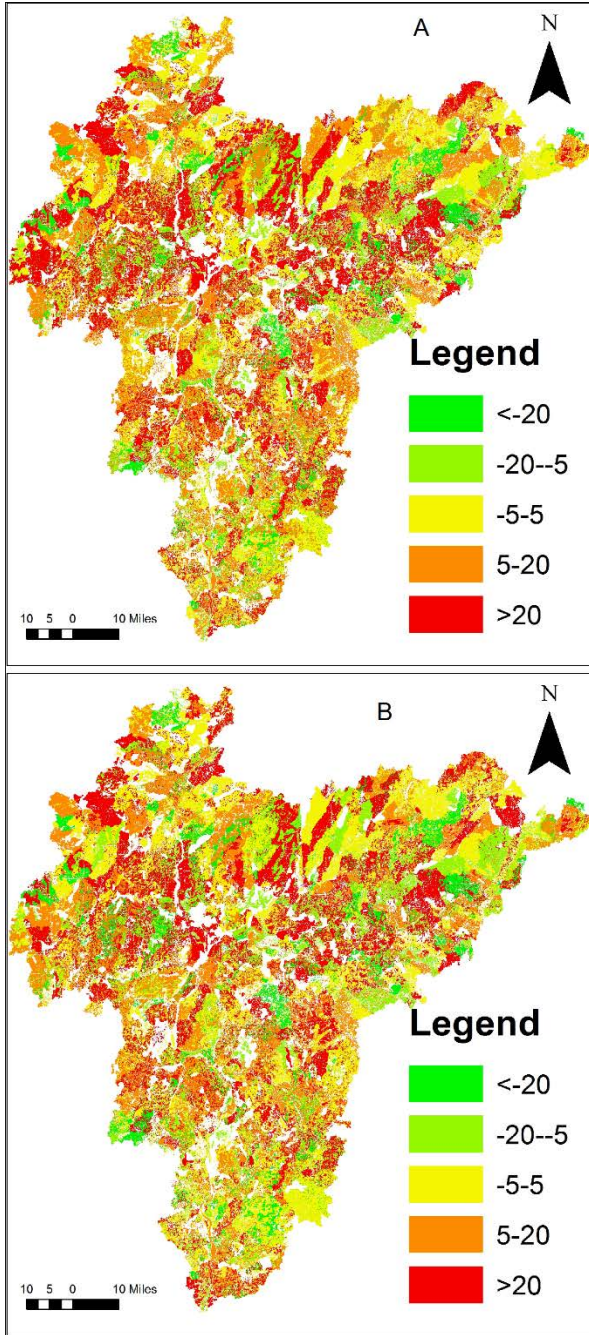
[**FIGURE 2** Changes in streamflow projections based on the default and improved simulations during 2020-2099 relative to `baseline period (1960-1990), under RCP 4.5 and RCP 8.5 scenarios. Boxplot shows variability of simulations driven by different climate models]

Default simulations suggested that streamflow would increase by 29% and 45.8% during 2020-2099 compared with that of 1960-1990 under the RCP 4.5 and RCP 8.5 scenarios, respectively (Figure 2). The projected streamflow in the improved SWAT simulations also demonstrated increasing trends, under both RCP scenarios, but magnitudes of these increases were generally lower than those in the default simulations (Figure 2). Specifically, the improved simulations projected an average increase of 19.1% under the low emission scenario, which was ca. 34% lower than that of the default simulations. For the improved simulations, we found that the GFDL-ESM2M climate data would lead to the highest increase of 46.9% in streamflow under the RCP 4.5 scenario (Figure S11). Under the RCP 8.5 scenario, the projected streamflow from the simulations would increase by 36.7%, which was ca. 20% lower than that from the default simulations, with the highest increase (63.7%) induced by the GFDL-ESM2M climate data, and the lowest increase (17.6%) induced by the IPSL-CM5A-LR climate data.

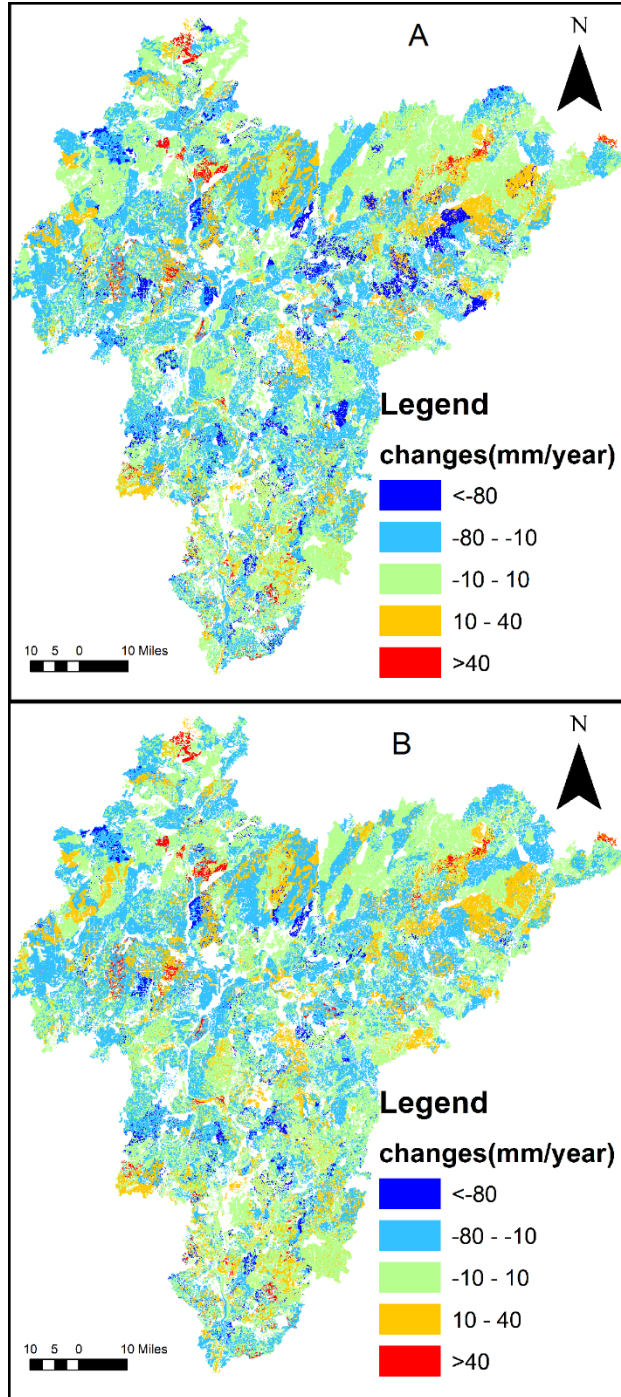


[FIGURE 3 Changes in ET from baseline period (1966-1990) to the future period (2020-2099) based on the improved SWAT forest parameterization under (A) RCP 4.5 and (B) RCP 8.5 scenarios. Here average ET during the two periods of each HRU was used to calculate ET changes]

The improved simulations showed that ET would generally increase under the RCP 4.5 scenario, but decrease under the RCP 8.5 scenario (Figure 3). Specifically, our simulations showed increased ET in 1942 of the 3110 HRUs (73% of the study area) under the low emission scenario (RCP 4.5), whereas decreases in ET occurred to 2756 HRUs (92% of the study area) under the RCP 8.5 scenario. Although climate change generally enhanced ET under the RCP 4.5 scenario, we observed decreased ET in a few HRUs, which was caused by variability in future precipitation in the basin (Figure S2). Different responses in ET under the two scenarios were caused by the complex impacts of future temperature, precipitation, and atmospheric CO₂. Detailed explanations could be found in section 4.1. Significant changes in ET, particularly decreases under the high emission scenario (RCP 8.5), is expected to induce significant changes in streamflow.



[**FIGURE 4** Differences in projected Evapotranspiration (ET: mm/year) during 2020-2099 between the improved and default simulations under the (A) RCP 4.5 and (B) RCP 8.5 scenarios]



[FIGURE 5 Differences in projected water yield (mm/year) during 2020-2099 between the improved and default simulations under the (A) RCP 4.5 and (B) RCP 8.5 scenarios]

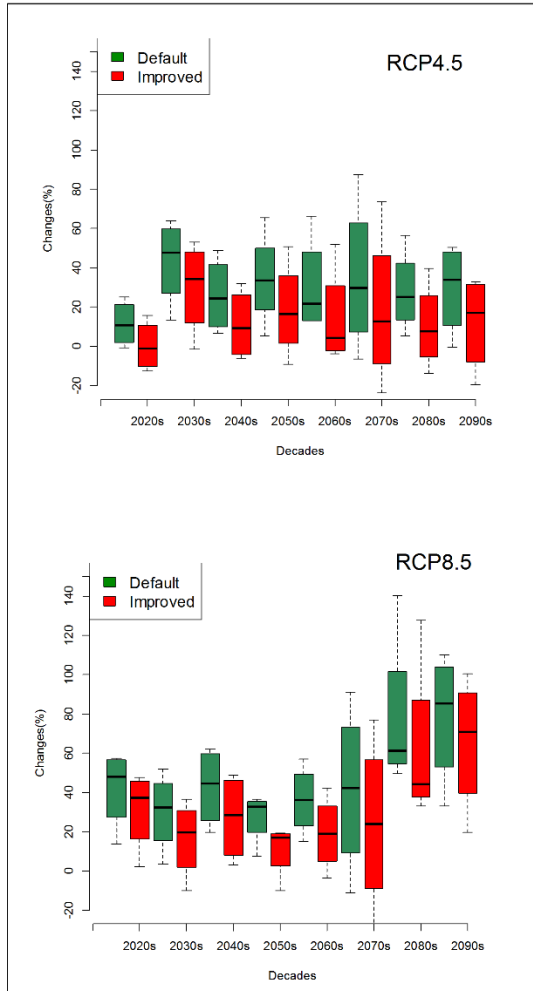
Differences in ET based on the default and improved simulations were significant, particularly for HRUs in northern and central parts of the SCRB, where forest is the dominant land cover type (Figures 4 and 5). Under the RCP 4.5 scenario, the improved simulations projected enhanced ET relative to the default simulations in 2132 (86% of the study area) of the 3110 HRUs; under the RCP 8.5 scenario, increased ET was found in 2039 (84% of the study area) HRUs, and these increases mainly occurred to forested HRUs (Figure 4B). Decreases in ET in improved simulations occurred to a few crop HRUs where crop growth is significantly stimulated by the new phosphorus supply. Increases in soil cover index in these HRUs reduced water fluxes from soil to the atmosphere.

We also compared model estimates of water yield during 2020-2099 in the default and improved simulations (Figure 5). Here water yield is defined as the net water fluxes from land to the reach of each HRU. Water yield was significantly reduced in most HRUs of the SCRB. Specifically, water yield was reduced by ca. 10-80 mm/year in the central parts of the SCRB. Spatial patterns of water yield reduction were consistent with those of ET increases (Figures 4 and 5). Under the low emission scenario (RCP 4.5), reductions in water yield occurred to 2153 HRUs; under the high emission scenario (RCP 8.5), reduced water yield occurred to 2055 HRUs.

In summary, future climate conditions would have significant impacts on water cycling in the SCRB. Our simulations demonstrated substantial increases in streamflow in both the default

and improved SWAT simulations. A comparison between the two sets of simulations demonstrated significant changes in model estimates of water cycling with improved representation of forest ecosystems. We found that uncertainties in streamflow projections were constrained in the improved simulations, and the increases in streamflow estimates were reduced by 20%-34% relative to the default simulations. These changes could be explained by increased ET in forest HRUs.

3.2. Future sediment export in the SCRB



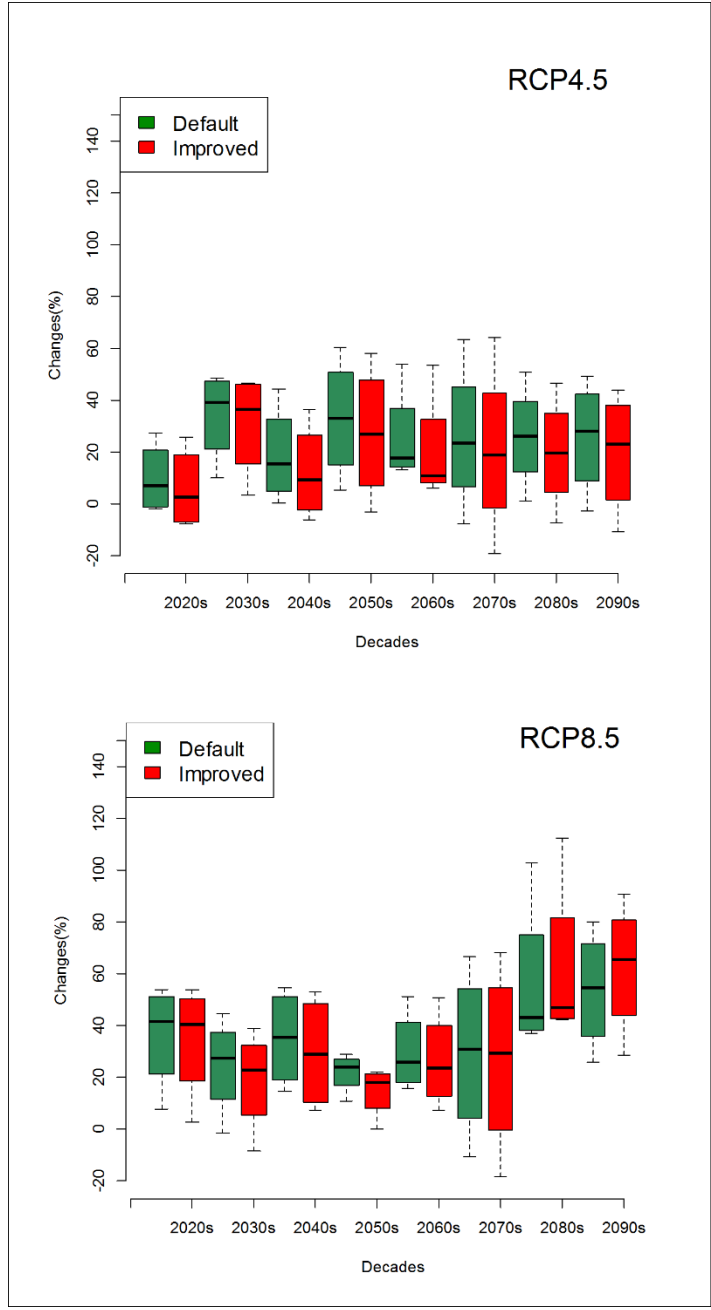
[FIGURE 6 Changes in future sediment export projections by the default and improved simulations during 2020-2099 relative to the baseline period (1960-1990), under RCP 4.5 and RCP 8.5 scenarios. Boxplot shows variability among simulations driven by the climate models]

Future sediment export under the two climate scenarios demonstrated increasing trends in the 21st century (Figure 6). In the default simulations, the average increase in sediment export

would reach 29.7% relative to the baseline period of 1960-1990 under the RCP 4.5 scenario. Climate change under the high emission scenario (RCP 8.5) would future stimulate sediment export by 46.9% relative to the baseline period in the default simulations (Figure 6).

The improved simulations also showed increasing trends in sediment export (Figure 6). However, sediment export in the improved SWAT simulations was generally lower than the default estimates in each coming decade of the 21st century. Specifically, sediment export would increase by 14.3% in the improved SWAT simulations under the RCP 4.5 scenario, and this increase was ca. 52% lower than that of the default simulations. Under the RCP 8.5 scenario, the improved SWAT simulations resulted in an average increase of 31.9% in sediment export, which was ca.32% lower than that of the default simulations (Figure S12).

3.3. Future nitrogen export in the SCRB



[**FIGURE 7** Changes in future total nitrogen projections by the default and improved simulations during 2020-2099 relative to the baseline period (1960-1990) under the RCP 4.5 and RCP 8.5 scenarios. Boxplot shows variability of simulations driven by the climate models]

Our simulations suggested that future climate change would also alter nitrogen export (Figure 7). Changes in climatic factors and atmospheric CO₂ concentrations would induce higher nitrogen export in most decades during 2020-2099 relative to the baseline period of 1960-1990, according to default SWAT simulations. TN export in the default SWAT simulations would increase by 24.8% under RCP 4.5 scenario; whereas the RCP 8.5 scenario predicted an increased TN export of 35.8%, relative to the period of 1960-1990.

In the improved SWAT simulations, TN export was generally lower than those of the default simulations (Figure S13). Specifically, the improved simulations projected an increase of 19.5% for TN export under the RCP 4.5 scenario, and this was ca. 35% lower than that of the default simulations (Figure 7). Under the RCP 8.5 scenario, the improved SWAT simulations suggested an increase of 34.4% in TN, which was ca. 4% lower than that of the default simulations.

4. Discussion

4.1. Climate change impacts on hydrological cycle in forested basins

Although the default and improved simulations demonstrated differences in magnitudes of estimated riverine fluxes, they were generally consistent in the increasing trends in future

water, sediment, and nitrogen fluxes under two climate change scenarios, suggesting substantial impacts of future climate conditions on water resources at the watershed scale. Climate change affects multiple key processes of terrestrial water cycling (Murray et al., 2012). The SWAT projections in this study demonstrated the combined effects of temperature, precipitation, and atmospheric CO₂ concentrations on ET. Our simulations suggest that ET would be stimulated under the low emission (RCP 4.5) scenario by increased precipitation and temperature, and the increases would have been more significant if CO₂ concentration elevation was not considered (Figure S14A). Under the high emission (RCP 8.5) scenario, reduction of ET induced by the elevated CO₂ on plant stomatal conductance and transpiration would cancel out the effects of temperature and precipitation, and result in decreased ET (Figure S14) and increased streamflow (Figure S15).

Due to the large leaf area index and long growing seasons, forests tend to have high ET (Yang et al., 2014). Paired-catchment experiments indicated that forest consumes large amounts of water through transpiration, and plays important roles in regional water cycling (Bosch & Hewlett, 1982). Reliable simulation of forest ET is critically important for robust analysis of water cycling and associated biogeochemical cycling in watersheds with large areas of forests (Earls & Dixon, 2008; Wu & Johnston, 2007). In this study, improved forest representations resulted in better ET simulations, and thus laid a solid foundation for modeling riverine water, sediment, and nitrogen fluxes in the SCRB.

Hydrological processes play a fundamental role in regulating sediment and nutrient delivery from land to rivers (Ferreira et al., 2016). With the enhanced representations of forest ecosystems, underestimated ET from the default simulations was corrected in the improved simulations, and the forest parameter calibration and new phosphorus algorithms reduced estimates of streamflow (Figure S16). More reliable ET estimates help reduce uncertainties in model simulations of water yield from forests, and led to better streamflow estimates. Consequently, the decreased runoff resulted in less available water for sediment and nitrogen transport (Casalí et al., 2010), and partially explained the lower sediment and nitrogen fluxes in the improved SWAT simulations as compared with the default simulations.

4.2 Importance of forest module improvement for water resource projection

Forests usually cover large areas of a basin, and play important roles in hydrological and biogeochemical cycling (Cleveland et al., 2011; Laudon et al., 2016; Yang et al., 2014; Yang, Tian, Friedrichs, Hopkinson, et al., 2015; Yang, Tian, Friedrichs, Liu, et al., 2015). Proper representation of forest ecosystems in models such as SWAT is essential for simulating complex hydrological and biogeochemical processes, and their interactions (Mickler, Earnhardt, & Moore, 2002; Wallman, Svensson, Sverdrup, & Belyazid, 2005). As a watershed model, SWAT has been widely used and tested in agricultural ecosystems (Xuesong Zhang et al., 2015; Xuesong Zhang, Izaurrealde, Arnold, Williams, & Srinivasan, 2013). SWAT simulations of forest carbon and

water fluxes with default settings demonstrated inconsistencies with benchmark data, and introduced uncertainties in water resource projections in forested basins, such as the SCRB.

Through improving plant growth representations, the improved simulations produced reasonable estimates of water (ET and streamflow) and riverine sediment and nutrient export, in comparison with independent datasets for the historical period. Results of this basin-scale study clearly demonstrated the necessity for such improvement to better simulate water, nutrients, and export at the watershed scale. Improvements in riverine flux simulations further confirmed the critical role of forests in watershed biogeochemistry (Heimann & Reichstein, 2008). In addition to the water cycle, the improved forest ecosystem representation also affected projections of future sediment and nitrogen exports. The improved forest parameters and new phosphorus algorithms provided significantly better estimates of forest biomass as compared with the default simulations, and affected riverine sediment and nitrogen fluxes through controlling soil erosion and soil nutrient contents. Increased forest biomass could better protect soil from erosion during rainfall events (Durán Zuazo & Rodríguez Pleguezuelo, 2008). Forest with higher biomass tends to uptake more nitrogen from soils to support plant growth and development (Nidzgorski & Hobbie, 2016). These inorganic nutrients are then transformed into organic forms in plant biomass and soil organic matter, which was more resistant to leaching than inorganic nutrients in soils (Luo, Hui, Zhang, & von Randow, 2006). Increases in plant biomass nutrient pools reduced soil nutrient availability for leaching, and thus resulted in reductions in nitrogen export in the improved simulations.

Agreements between simulated forest carbon and water fluxes and benchmark data demonstrated SWAT's capability in modeling forest growth and development through parameter calibration. More importantly, reductions in projected water, sediment, and nitrogen export based on the improved forest representations showed that the default SWAT simulations might overestimate riverine fluxes under future climate change scenarios. Improved representations of forest ecosystems and phosphorus cycling in SWAT make it more suitable for simulating water and nutrient cycling at watershed/basin scales, especially in investigations of climate impacts on water resources. The resulting information and knowledge are highly beneficial for improving future applications of SWAT to watersheds with large areas of forests.

4.3. Implications for future water resource management supported by watershed models

Excessive nutrient inputs and water eutrophication have challenged water resource management in the SCRB (Almendinger and Ulrich, 2017). To maintain scenic and recreational values of this nationally designated riverway, reducing excessive phosphorus by 27% below the mean phosphorus load of the 1990s has been set as a management goal to return lakes in the basin to the 1940 conditions (Almendinger et al., 2015; Triplett et al., 2009). Water resource projections derived from this study suggested that future climate conditions would substantially alter water cycling and associated nutrient export in the SCRB. These changes are expected to affect growth and species composition of algae in the river (Michalak et al., 2013), thus may challenge ongoing efforts for maintaining ecological integrity of the SCRB and riverine

ecosystems. As a result, future water resource management practices should take into account the climate change impacts, for effective water quantity and quality management of the St. Croix River.

Watershed models such as SWAT are valuable tools for assessing impacts of management practices and climate changes on water and nutrient cycling (Surendran, Sushanth, Mammen, & Joseph, 2017; Vadas, Bolster, & Good, 2013). Realistic model simulations depend on proper model configuration and representation of key processes and associated parameters which characterize hydrological cycling and its responses to changing driving forces. Presence of forest ecosystems in basins/watershed serves as a buffer to ameliorate the adverse impacts of climate changes on water and nutrient export from land to rivers (Currie & Aber, 1997; Raymond, Oh, Turner, & Broussard, 2008). The comparison of simulated water, sediment and nitrogen fluxes by the SWAT model with benchmark data revealed that using the default representation of forest ecosystems and phosphorous cycling resulted in poor model performances in the SCRB. SWAT projections of future riverine fluxes were improved with calibrated forest parameters and new phosphorus cycling algorithms. This study highlighted the importance of considering climate change impacts on upland ecosystem processes in projections of riverine fluxes for effective water resource management.

4.4 Uncertainties in water resource projection with SWAT

Although we evaluated uncertainties in model simulations associated with parameters, other uncertainty sources, such as evaluation of model projections, climate projections, and

model representations of plant growth responses to climate change in SWAT, should also be considered to better understand water resource projections. First, although we believe future riverine fluxes in the improved simulations were more reasonable than those of the default simulations because of the better representation of forest ecosystems, further evaluation of model projections should be conducted. Due to the lack of observation data for model projection evaluation, comparison with other modeling studies will be necessary for validating future riverine fluxes. Second, this study primarily focused on the climate change impacts on future water resources, and ignored influence from other environmental changes, such as land use change. The inclusion of other driving forces in future investigations may provide more accurate predictions of riverine fluxes. Third, projected climate data have significant controls on water resource simulations. Although we selected four climate models to account for uncertainties in climate projections, using more climate projections in the future will help further constrain uncertainties associated with climate change. Fourth, current algorithms in the SWAT forest module may have introduced uncertainties in simulating forest growth responses to climate change (Yang & Zhang, 2016; Wu & Liu, 2012). Adding more mechanistic features to the SWAT plant module will help better simulate forest ecosystem dynamics in response to climate change and associated impacts on water and nutrient cycling. In addition, how the new phosphorus supply algorithms affect crop growth and associated water and nutrient cycling should also be examined in the future.

5. Conclusions

Forest ecosystems play important roles in water and nutrient cycling. However, most hydrological models, including the widely-used SWAT model, have limited assessment of model performances in simulating forest ecosystems at the basin scale. We observed large discrepancies between model simulations with the default forest parameters and benchmark data, suggesting that inadequate representation of forest ecosystems and key soil nutrient cycling processes (e.g., phosphorous) may introduce significant uncertainties in water resource projections. Our analyses highlight the importance of addressing these deficiencies to better simulate hydrological and biogeochemical cycling with the SWAT model.

In recognition of this need, we improved SWAT simulations of forest carbon and water cycling at the SCRB. We then evaluated the impacts of such improvements on projections of water, sediment and nutrient exports under two climate scenarios for the remaining of the 21st century. The simulated water, sediment, and nitrogen fluxes by the improved SWAT were generally lower than default simulations. Default SWAT simulations may overestimate riverine fluxes due to the unreasonably modeled plant growth, ET, and forest biomass. Improved representation of forest ecosystem and phosphorous cycling contributed to constraining uncertainties in water resource projections. Results of this study provide valuable information for improving SWAT to investigate and assess hydrological and biogeochemical cycles under future climate conditions.

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Supplementary Material

TABLE S1 The CMIP5 climate models used in this study.

TABLE S2 *T*-Test results (*P* values) for changes in future (2020-2099) climatic factors and simulated riverine fluxes relative to the baseline period (1960-1990) in the improved simulations. Note ** indicates significant difference at the 99% confidence intervals, and * indicates significant difference at the 95% intervals.

TABLE S3 Forest parameters used in the default and improved SWAT simulations.

TABLE S4 Hydrologic parameters used in default and improved simulations of the Soil Water Assessment Tool (SWAT) model.

TABLE S5 Sediment parameters used in default and improved simulations of Soil Water Assessment Tool (SWAT) model.

TABLE S6 Nitrogen parameters used in default and improved simulations of the Soil Water Assessment Tool (SWAT) model.

TABLE S7 Ranking of parameter sensitivity

FIGURE S1 Atmospheric CO₂ concentrations under the Representative Concentration Pathways (RCPs) 4.5 and 8.5 scenarios.

FIGURE S2 Projected precipitation in the St Croix River Basin by the four climate models under (A) RCP 4.5 and (B) RCP 8.5 scenarios.

FIGURE S3 Projected temperature in the St Croix River Basin by the four climate models under (A) RCP 4.5 and (B) RCP 8.5 scenarios.

FIGURE S4 A comparison of simulated annual forest Net Primary Productivity (NPP) for St Croix River Basin with the MODIS NPP during 2000-2008.

FIGURE S5 A comparison of simulated annual forest evapotranspiration (ET) in the St Croix River Basin with the MODIS ET observations during 2000-2008.

FIGURE S6 A comparison of simulated forest biomass for St Croix River Basin in the default and improved simulations with USDA forest biomass estimates for the 2000-2008 period.

FIGURE S7 Uncertainty range (95%) of monthly streamflow simulations during 1990-2007 for reach 399 (unit is m³/month).

FIGURE S8 Uncertainty range (95%) of monthly sediment export simulations during 1990-2007 for reach 399 (unit is ton/month).

FIGURE S9 A comparison of SWAT simulated daily streamflow with default and improved forest parameters with daily observations at the USGS gauge station 05344490, during 2007-2008 period.

FIGURE S10 A comparison of sediment and total nitrogen export estimates in default and improved simulations with against fluxes data from the Metropolitan Council Environmental Services (MCES) during the 1990-1999 period.

FIGURE S11 Projected streamflow during 2020-2099 in the improved simulations

FIGURE S12 Projected sediment export simulations during 2020-2099 based on the improved SWAT model parametrization.

FIGURE S13 Projected total nitrogen export during 2020-2099 in the improved simulations

FIGURE S14. Changes in ET under RCP 4.5 (A) and RCP 8.5 (B) scenarios in the simulation which assume that future atmospheric CO₂ concentration will not change.

FIGURE S15. Changes in streamflow under the RCP 4.5 (A) and RCP 8.5 (B) scenarios in simulations which assume future atmospheric CO₂ concentration will not change.

FIGURE S16. Reduction in streamflow by forest parameter calibration and the newly added phosphorus supply algorithms in the improved simulation relative to the default simulation during 2020-2099. Contribution of each parameter was isolated through model experiments which allowed calibration of a single parameter, while using default values for other parameters.

Phosphorus supply module

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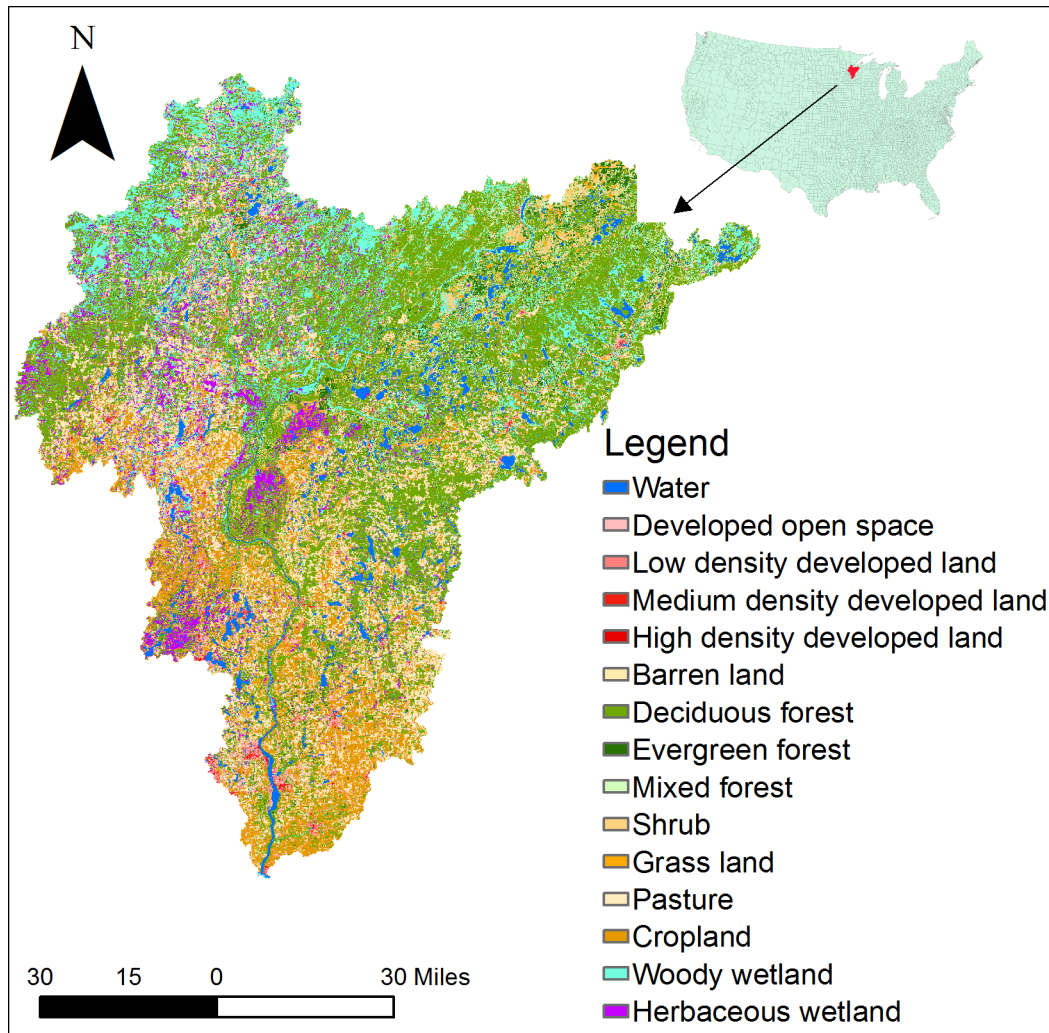
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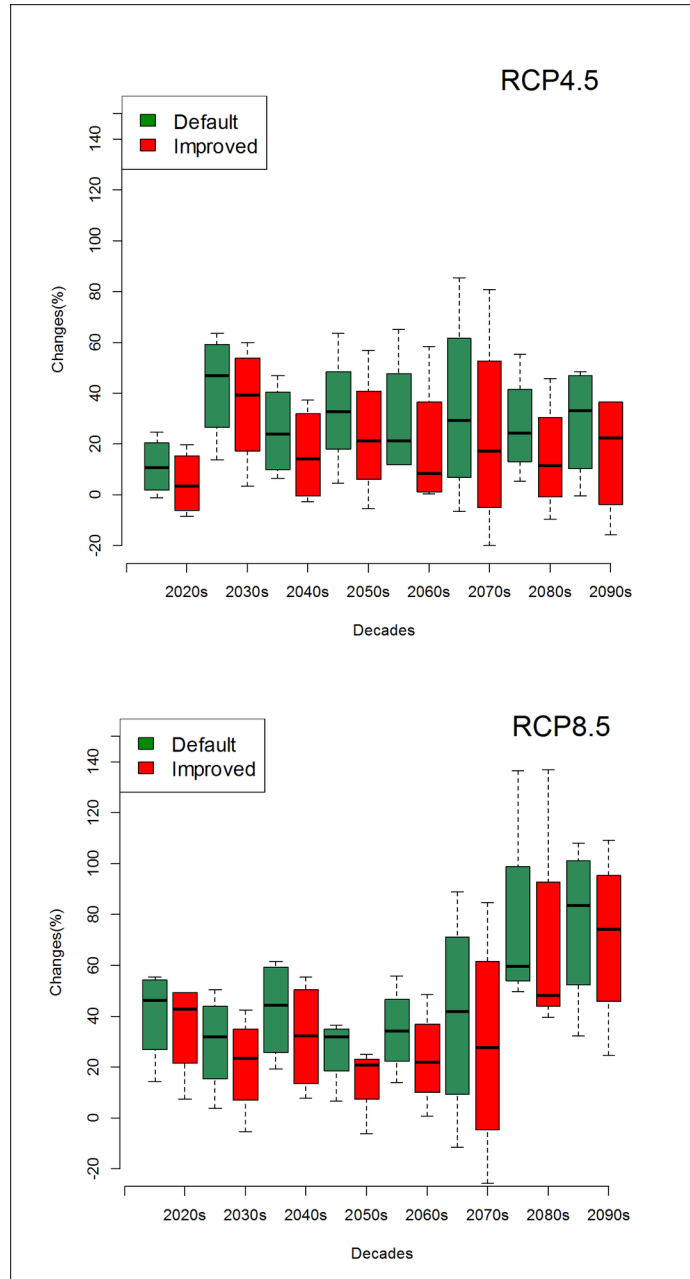
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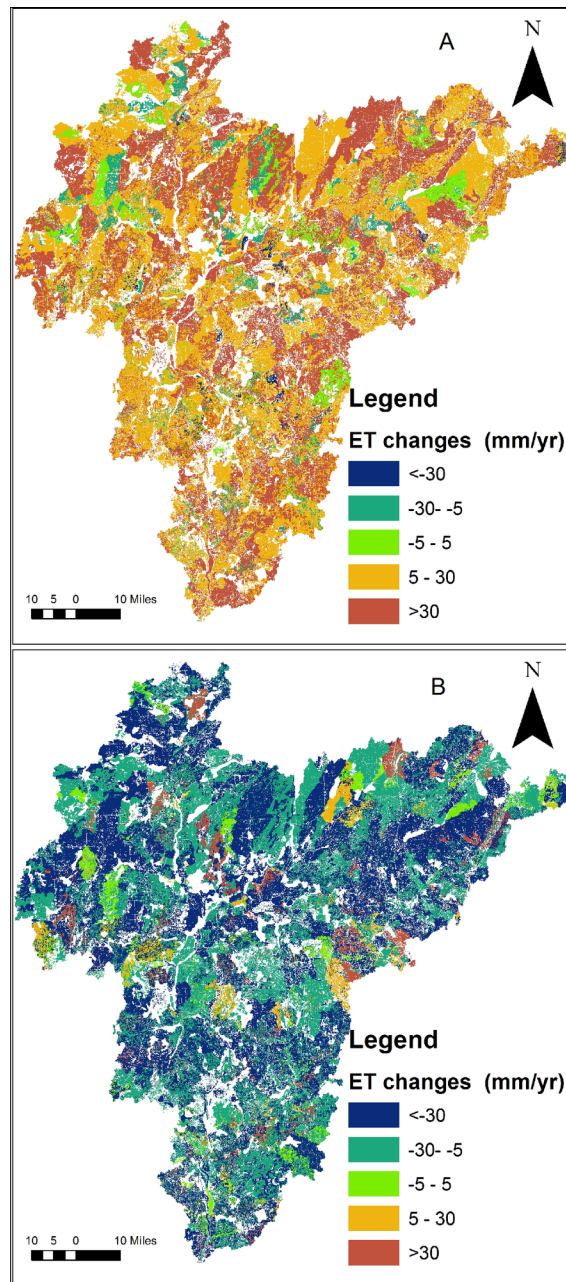
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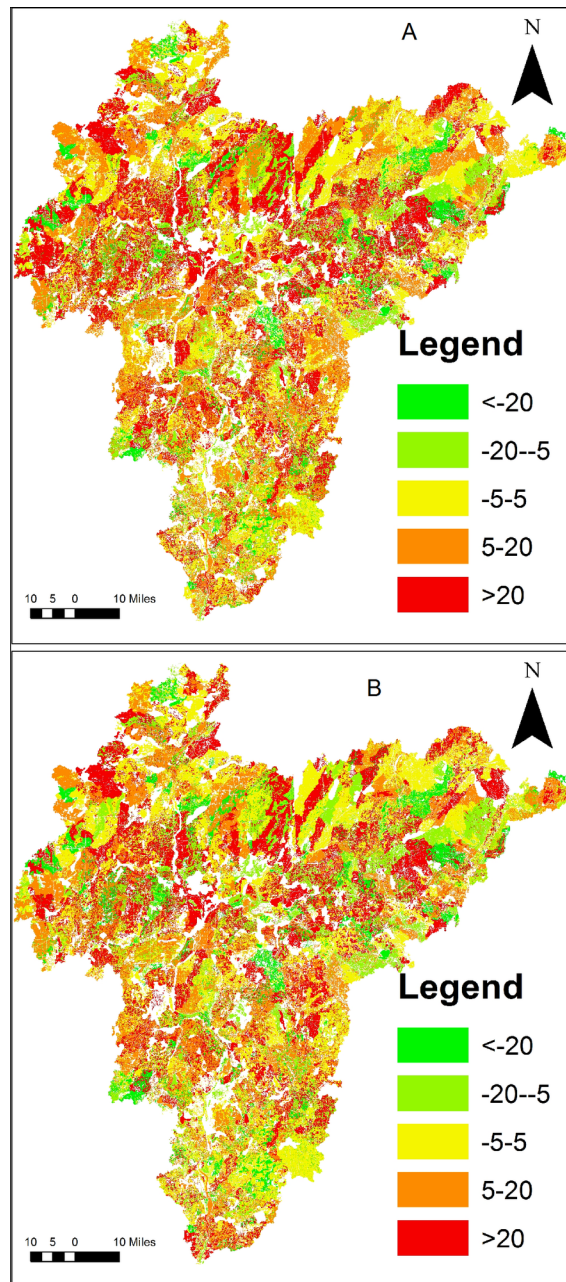
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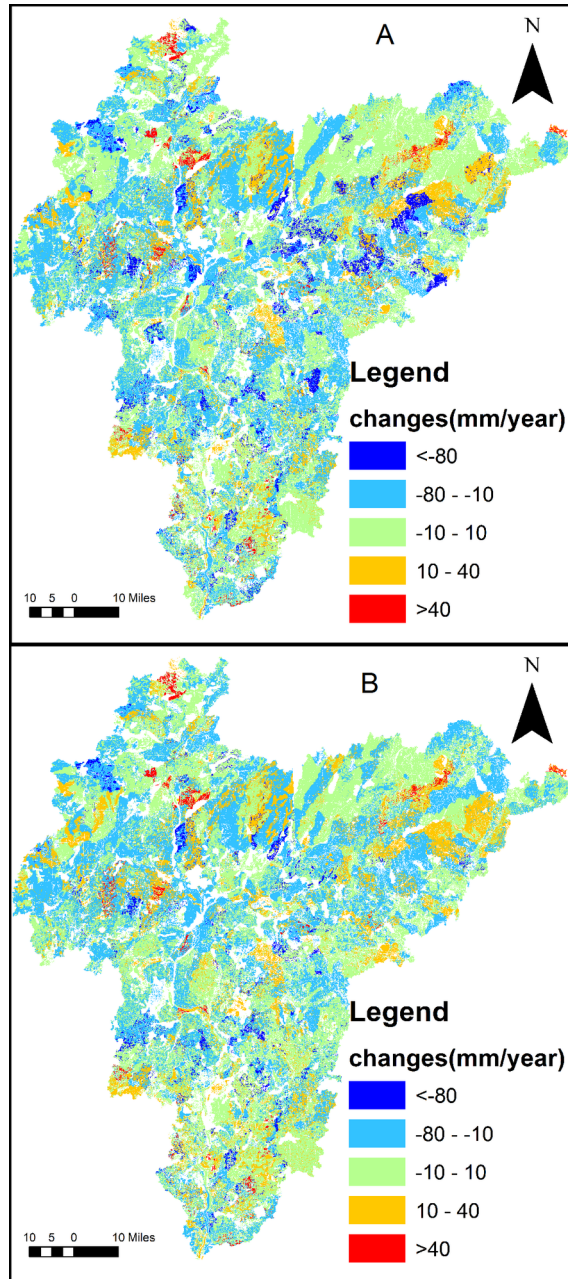
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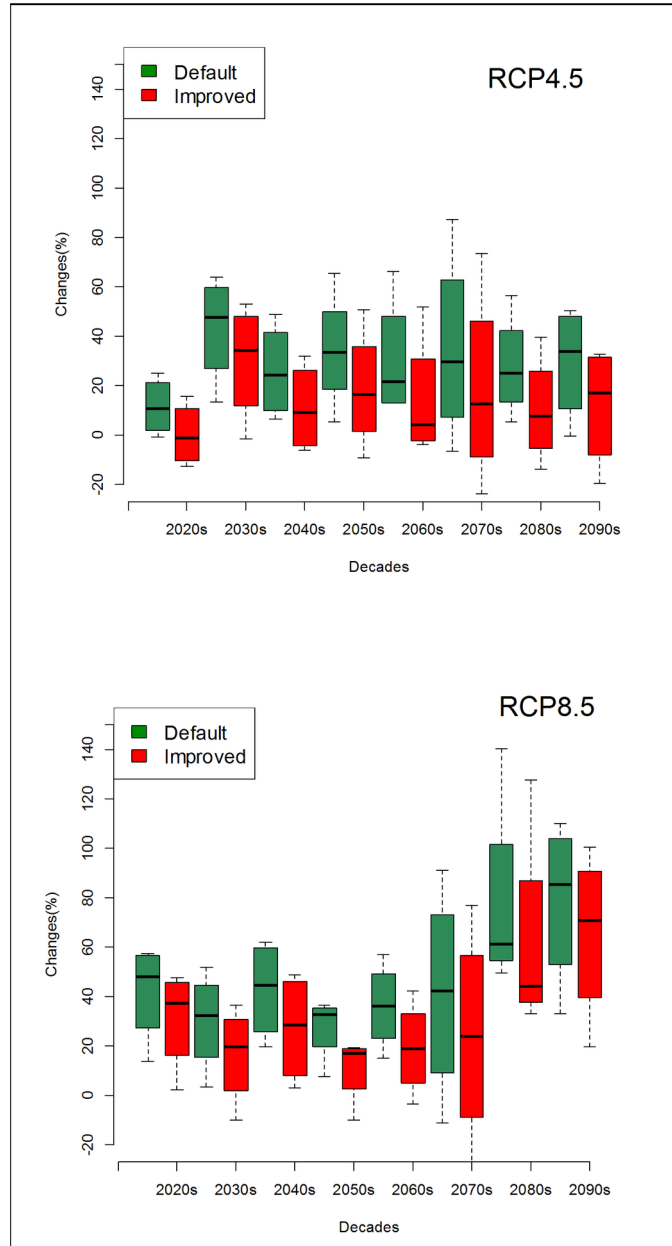
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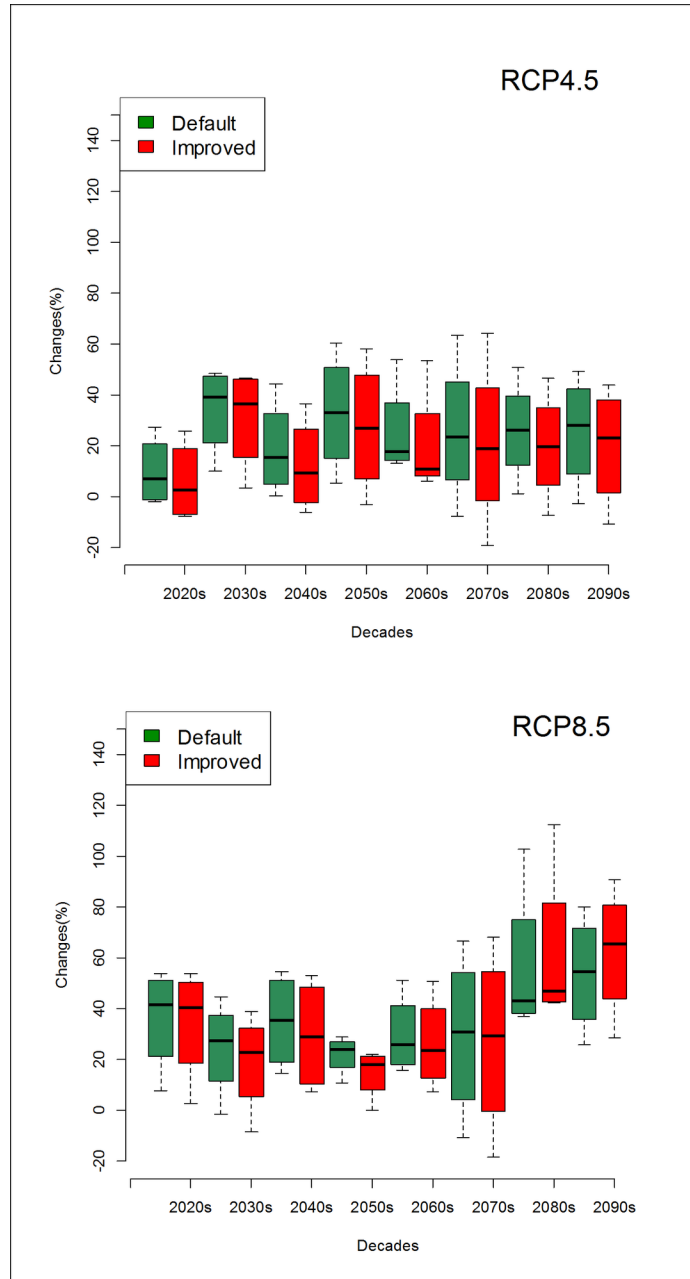
HYP_13370_FIGURE4.tif



HYP_13370_FIGURE5.tif



HYP_13370_FIGURE6.tif



HYP_13370_FIGURE7.tif