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Spatial evaluation of switchgrass productivity under historical and future climate scenarios in Michigan

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Abstract

Switchgrass (*Panicum virgatum*) productivity on marginal and fertile lands has not been thoroughly evaluated in a systematic manner that includes soil–crop–weather–management interactions and to quantify the risk of failure or success in growing the crop. We used the Systems Approach to Land Use Sustainability (SALUS) model to identify areas with low risk of failing to having more than 8000 kg ha^{-1} yr^{-1} switchgrass aboveground net primary productivity (ANPP) under rainfed and unfertilized conditions. In addition, we diagnosed constraining factors for switchgrass growth, and tested the effect of nitrogen fertilizer application on plant productivity across Michigan for 30 years under three climate scenarios (baseline climate in 1981–2010, future climate with emissions using RCP 2.6 and RCP 6.0). We determined that <16% of land in Michigan may have at least 8 Mg ha^{-1} yr^{-1} ANPP under rainfed and unfertilized management with a low risk of failure. Of the productive low-risk land, about 25% was marginal land, with more than 80% of which was affected by limited water availability due to low soil water-holding capacity and shallow depth. About 80% of the marginal land was N limited under baseline conditions, but that percentage decreased to 58.5% and 42.1% under RCP 2.6 and RCP 6.0 climate scenarios, respectively, partly due to shorter growing season, smaller plants and less N demand. We also found that the majority of Michigan's land could have high switchgrass ANPP and low risk of failure with no more than 60 kgN ha^{-1} fertilizer input. We believe that the methodology used in this study works at different spatial scales, as well as for other biofuel crops.

Keywords: climate change, constraining factors, management, marginal land, modeling, net primary productivity, switchgrass, yield

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Introduction

US's Billion Ton project requires an increase in unconventional bioenergy production, produced from cellulosic crops (DOE 2011; Langholtz *et al*., 2016). The policy, nonetheless, has led to cropland expansion in the United States. The increase in cropland area was primarily due to conversion of marginal lands (Lark *et al*., 2015). Growing bioenergy feedstock on marginal land reduces competition with crop production for the use of fertile agriculture land. However, extensive evaluation of cellulosic bioenergy crop productivity on marginal land has yet to be completed (Gelfand *et al*., 2013).

The biomass yield of switchgrass (*Panicum virgatum*), a cellulosic bioenergy feedstock, has been tested in past decades under a range of climate zones at different locations in the United States. Previous studies focused on the yield response of switchgrass to management factors, specifically nitrogen (N) fertilizer input, harvest frequency and stand age (e.g., Sanderson *et al*., 1999; Thomason *et al*., 2005; Wang *et al*., 2010; Wullschleger *et al*., 2010; Arundale *et al*., 2013a,b). The reported switchgrass aboveground biomass in the United States ranged widely, from 0 to 28 Mg ha^{-1} for lowland switchgrass cultivars and 0 to 40 Mg ha^{-1} for upland cultivars (Wullschleger *et al*., 2010). The underlying factors that control the switchgrass productivity variations are, however, unknown.

Cultivation of switchgrass for bioenergy is not much different from row crop production, which requires inputs to enhance productivity (Robertson *et al*., 2011). Following the lead of food crop yield gap research, gaps between low yield and high potential yield can be closed by management and cultivar choices. Studies have shown that differences in water and nutrient availability have caused yield variability for major cereal crops and that irrigation and fertilizer application can reduce the gap between actual and potential yield (Licker *et al*., 2010; Mueller *et al*., 2012).

Switchgrass aboveground net primary productivity (ANPP), and management to improve its ANPP, has yet

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to be investigated in a systems approach, where switchgrass, climate, soil and management interactions are taken into account (Robertson *et al*., 2011). The systems approach is critical to large-scale switchgrass cultivation for bioenergy, in light of climate change projections. The Midwest of United States is where future switchgrass production will partly take place and where cropland is currently the major land cover. This area has experienced climatic challenges in the last century that have included increasing temperatures, shifts in precipitation patterns and more frequent extreme weather (Rosenzweig *et al*., 2001; Pryor *et al*., 2009; Kunkel *et al*., 2013). Projections from different climate models that incorporate different greenhouse gas concentration pathways are not uniform or certain; however, rising temperatures and changes in precipitation patterns are likely to occur (Wuebbles & Hayhoe, 2004; Pryor *et al*., 2014). Therefore, the need to investigate the impact of these changes on switchgrass ANPP is even more critical.

The assessment of switchgrass ANPP and the risks associated with its cultivation across agricultural and marginal lands in Michigan (located in the northern Midwest of United States) is valuable information for the bioenergy sector. The objectives of this study were (1) to identify areas in Michigan where high switchgrass biomass productivity is achievable; (2) to determine the probability that N or water would constrain switchgrass from attaining its potential ANPP in a given location; and (3) to evaluate the response of switchgrass ANPP to fertilizer management. Each of these objectives was evaluated under three climate scenarios (baseline climate in 1981–2010 and two future climate scenarios using representative concentration pathway (RCP) 2.6 and RCP 6.0, where the radiative forcing would be raised to 2.6 and 6.0 W m^{-2}, respectively).

Materials and methods

Study site

We chose to conduct this research in Michigan, a northern state in the US Midwest, because of its unique niche in US agricultural production. The dominant land cover in Michigan is agriculture, which includes crops, fruit and vegetable production as well as pasture land (Boryan *et al*., 2011). Identification of marginal land in the literature is based on the land capability class (LCC) system developed by the US Department of Agriculture. Lark *et al.* (2015) defined marginal land as LCCs III-IV; LCCs I-II were identified as prime agricultural land and LCCs V-VIII were considered unsuitable for agriculture. Gelfand *et al.* (2013) defined LCCs I-IV as agricultural land and LCCs V-VIII as marginal land. We adapted these definitions for this study: LCCs III-VIII were considered marginal land and LCCs I and II were fertile agriculture land (Fig. 1a). The climate in Michigan commonly features cold and wet winters and warm and wet summers. The average annual temperature is 7.9 °C and annual precipitation is 795.4 mm in 1981–2010 (Fig. 1b).

Switchgrass cultivar choices for biomass production in Michigan

Upland switchgrass cultivar Cave-in-Rock was simulated in this study because the winter kill in the state of Michigan cannot accommodate lowland switchgrass growth. Because a significant proportion of switchgrass biomass is produced at its establishment stage, as opposed to the first a few years at the initialization stage, we calibrated switchgrass coefficients in a crop simulation model to represent an established switchgrass stand (Parrish & Fike, 2005). Although the lowland switchgrass cultivars, which are currently adapted to warm and drought-prone environment in the southern United States, may survive in Michigan due to the increasing temperature under climate change scenarios, we did not analyze the possibility of lowland switchgrass productivity in Michigan (Casler *et al*., 2007; Casler, 2012).

Overview of Systems Approach to Land Use Sustainability (SALUS) model

We used the SALUS model to quantify switchgrass ANPP potential and minimum attainable ANPP. SALUS is a process-based model designed to simulate the interactions between climate, soil, crop genotypes and management on crop growth, water and nutrient cycles over multiple growing seasons (Fig. 2). The model was derived from the well-established CERES model with modifications in the nitrogen cycle, water balance and tillage (Basso *et al*., 2006; Albarenque *et al*., 2016) and can be used in simple or complex form to simulate crop development and growth. Similar to CERES, the SALUS model uses leaf development coefficients to represent specific cultivars. The simple approach of the SALUS model uses the predefined leaf area development curve for the simulation (Dzotsi *et al*., 2013). We used the SALUS in the simple form in this study because there are no detailed switchgrass leaf area development data to parameterize the coefficients required by the complex form of the model. Both the simple and complex approaches of SALUS use daily weather parameters, soil parameters by layer, crop coefficients and management decisions as inputs to calculate crop growth, nutrient cycle and water balance at daily step. Weather parameters include incoming solar radiation, minimum and maximum temperature and precipitation. Soil attributes include silt, clay and sand content, pH, bulk density and organic matter content. Crop development and growth simulation procedures in the simple approach of the SALUS model are similar to those in the ALMANAC model (Kiniry *et al*., 1996, 1997; Dzotsi *et al*., 2013).

The SALUS model predicts crop germination and duration based on thermal time to germination and duration in the crop coefficient database, respectively. Leaf area change over a growing season is calculated based on the sigmoid curve which has two critical points: relative leaf area index near emergence and near flowering. Radiation-use efficiency, provided by the crop coefficient database, and leaf area index (LAI), calculated

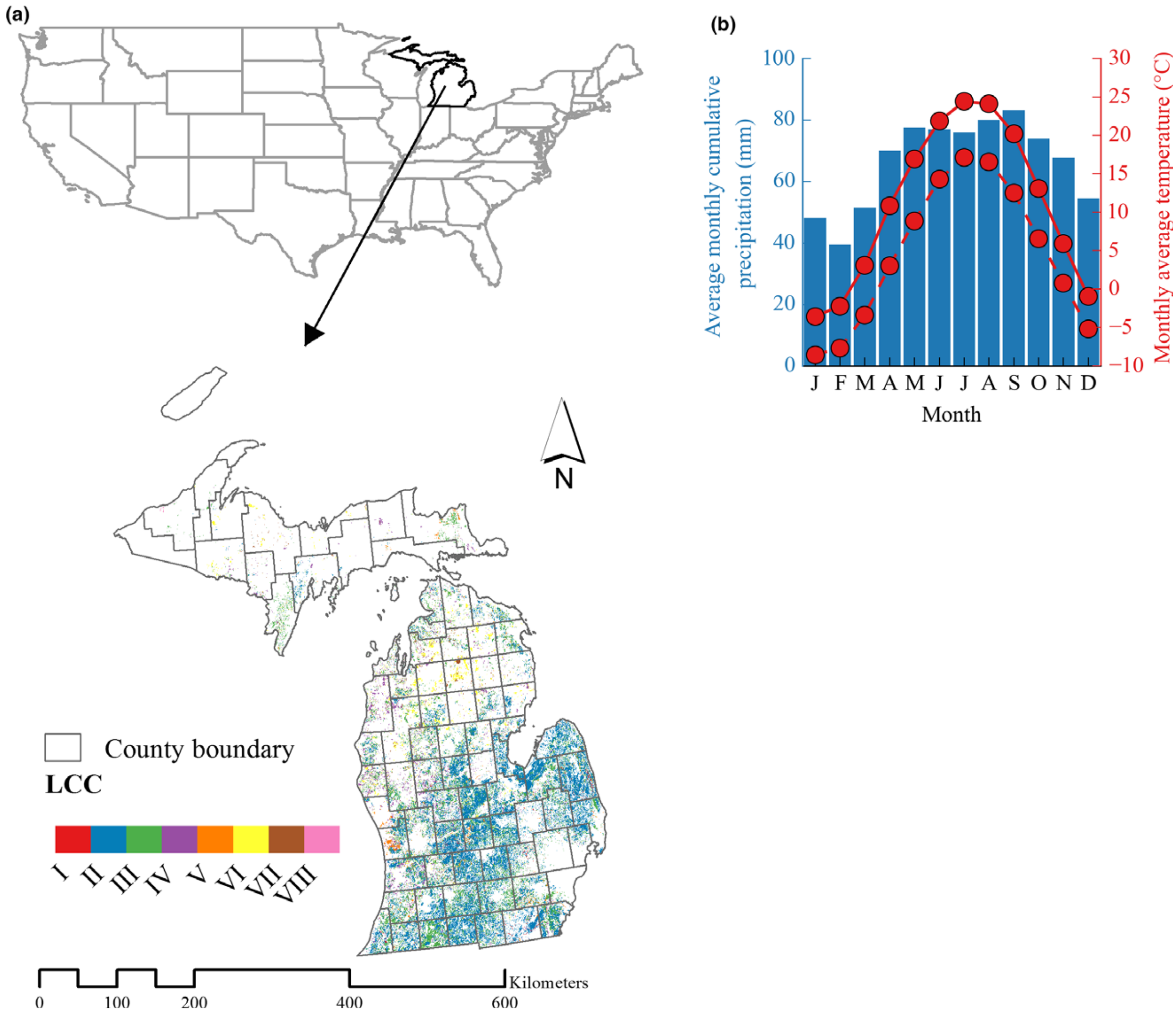

Fig. 1 Study region: Michigan, United States. (a) Land capability class (LCC) distribution, (b) average monthly temperature and precipitation distribution in 1981–2010.

by multiplying the relative LAI by the predefined maximum LAI, are then used to calculate biomass accumulation at a daily basis (Dzotsi *et al*., 2013; Table 1).

The SALUS model has been tested for cereal crop phenology and yield (Basso *et al*., 2011, 2012), nutrient cycling (Senthilkumar *et al*., 2009; Giola *et al*., 2012; Basso & Ritchie, 2015) and soil water balance (Basso *et al*., 2010). It has also been used to model switchgrass evapotranspiration (Hamilton *et al*., 2015). To verify the SALUS model in simulating switchgrass growth, the simulated switchgrass (cultivar Cave-in-Rock) yield was compared to the observed switchgrass yield in 2010–2013 at the W.K. Kellogg Biological Station (KBS) in southwest Michigan (42°23′47″ N, 85°22′26″ W). Upland switchgrass at KBS was established in June 2008 and was annually fertilized with 56 kg ha^{-1} N beginning in 2009 (Sanford *et al*., 2016). The daily weather information measured at KBS and soil data measured at the site were used as model inputs to validate the model (http://lter.kbs.msu.edu/data/). We used the root-mean-square error (RMSE), calculated by the following equation, to quantify the model adequacy:

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n}(S_i - O_i)^2/n},$$

where i is the ith observation, n is the total number of observations, S_i is the ith simulated value and O_i is the ith observed values. Additionally, we compared the SALUS-simulated switchgrass biomass yield to the reported yield in the literature.

SALUS model inputs used in this study

We used the Soil Survey Geographic Database (SSURGO) and Land Data Assimilation Systems (LDAS) data as spatial soil

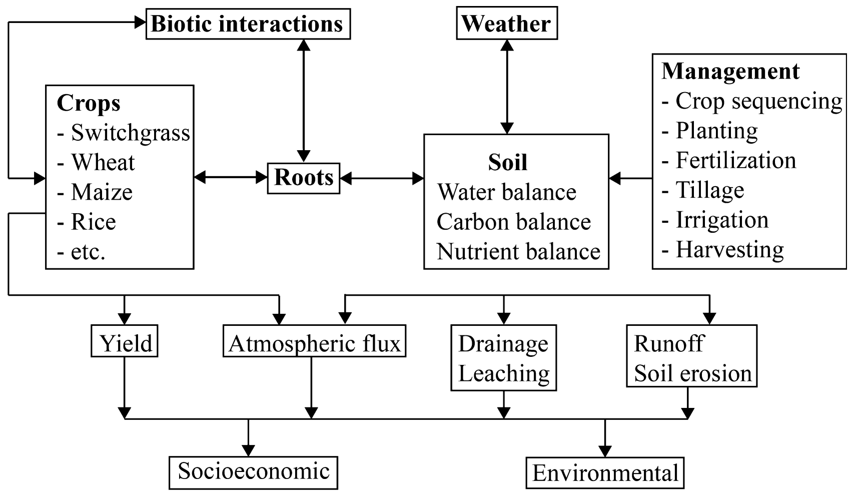

Fig. 2 Overview of the SALUS model (Basso *et al.*, 2006).

Table 1 Values for key switchgrass parameters in the SALUS model

Parameters	Descriptions and unit	Values in the model	Values in the literature	References
RelTT_P1	Relative thermal time near emergence (unitless)	0.15	0.05	
RelLAI_P1	Relative LAI near emergence (unitless)	0.15	0.1	
RelTT_P2	Relative thermal time near flowering (unitless)	0.5	0.5	Kiniry *et al.* (1996)
RelLAI_P2	Relative LAI near flowering (unitless)	0.95	0.9	
LAImax	Maximum leaf area index (m^2 m^{-2})	8	7.6 (±0.7)	Heaton *et al.* (2008)
			8.8	Behrman *et al.* (2014)
RUEmax	Maximum radiation-use efficiency (g MJ^{-1})	3.5	3.7	Kiniry *et al.* (1999)
TbaseDev	Base temperature for development (°C)	10	10	Jain *et al.* (2010)
ToptDev	Optimum temperature for development (°C)	25	25	Kiniry *et al.* (2008)
TTtoGerm	Thermal time from planting to germination (°C day)	20	20	Dzotsi *et al.*, 2013;
TTtoMatr	Thermal time from planting to maturity (°C day)	1100	600–1100	Kiniry *et al.* (2008)

and weather inputs to the model. Soil data including silt, clay and sand content, pH, bulk density and organic matter content were extracted by layer from the SSURGO (USDA/NRCS, 2014). The soil unit in the SSURGO database was the simulation unit used in this study. Dominant soil units in the SSURGO database were used to create the thematic maps. We excluded areas where detailed soil information did not exist in SSURGO or where the land was classified as urban, forest, wetland or vegetable and fruit land in the Crop Data Layer, a product by USDA National Agricultural Statistics Service (Boryan *et al.*, 2011). In total, there were 5264 soil units included in this study (Table 2). Daily minimum and maximum temperatures, precipitation and solar radiation for the baseline climate in 1981–2010 were extracted for each county from the LDAS, a 1/8-degree gridded reanalysis climate data product (Mitchell *et al.*, 2004).

For future climate projections, we chose RCP 2.6 and RCP 6.0 of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014). RCP reflects a greenhouse gas emission mitigation scenario. RCP 2.6 represents a scenario where stringent mitigation plans would be implemented and future global temperature is no more than 2 °C higher than preindustrial temperatures. RCP 8.0 represents the business as usual scenario, leading to higher atmospheric CO_2 and temperatures (Lawrence *et al.*, 2012; IPCC, 2014). We chose the most stringent mitigation scenario (RCP 2.6) and one stabilization pathway (RCP 6.0). To avoid the debate on the reliability of daily precipitation variations from climate model output, we followed the most up-to-date climate change assessment of the United States to construct 30-year RCP 2.6 and RCP 6.0 weather by changing daily weather values in the baseline climate in 1981–2010 (Pryor *et al.*, 2014). For the RCP 2.6 climate scenario, the CO_2 concentration was set at 400 ppm for the 30-year simulation; temperature was increased by 3 °C, and precipitation was increased by 10% in the winter and spring while decreased by 5% in the summer. For the RCP 6.0 climate scenario, the CO_2 concentration was set at 540 ppm; temperature was elevated by 6 °C and precipitation was increased by 20% in the winter and spring while decreased by 10% in the summer. Table 3 shows the level of changes across seasons for CO_2, temperature and precipitation.

SALUS model execution

We simulated switchgrass ANPP under different management regimes. Key sowing and planting parameters in the model were taken from the literature (Table 4), where suggested switchgrass planting dates are from late April to mid-June in the Michigan (Douglas *et al*., 2009). This wide range is due to the range of temperatures across the state (median temperature in May between 1981 and 2010 ranged from 6 to 16 °C). In this study, planting dates range from day of year (DOY) 128 to 155 and harvesting dates ranged from DOY 280 to 300 under the baseline climate conditions. Under climate change scenarios, switchgrass was planted 10 days earlier than under the baseline climate simulation.

Similar to the definitions of yield potential and water-limited yield potential, the ANPP potential was defined as maximum ANPP that a crop can produce without N, water and biotic stresses and is only affected by crop genetics and the climatic variables, CO_2, temperature and solar radiation. Rainfed ANPP potential was defined as ANPP with unlimited N supply, but no irrigation (van Ittersum *et al*., 2013). The minimum attainable ANPP was defined as switchgrass ANPP with no agricultural inputs. Switchgrass ANPP potential, rainfed ANPP potential and minimum attainable ANPP were obtained by running SALUS under the following conditions: (1) well irrigated and well fertilized without water and N stress, (2) rainfed and well fertilized without N stress, and (3) rainfed and unfertilized, respectively. Previous studies have shown that crop simulation models can be used in this way to assess crop potential production and analyze yield gaps (Aggarwal & Kalra, 1994; Boote *et al*., 1996; van Ittersum *et al*., 2013).

We used the cumulative probability function to assess risks associated with switchgrass biomass production by calculating the probability of land producing below 8000 kg ha^{-1} yr^{-1} ANPP (Eqn 1). We chose 8000 kg ha^{-1} yr^{-1} because this level has been reported by numerous field trials in the United States for Cave-in-Rock switchgrass biomass production (Wullschleger *et al*., 2010). We chose 0.25 as the probability threshold to categorize the probability levels. Dillon & Scandizzo (1978) suggested that farmers usually made low-risk choices involving monetary gains. They asked farmers to choose between two risk prospects (one was subsistence assured and the other was subsistence at risk) with a known outcome distribution. Each of the two risk prospects had the same outcome distribution: 0.25 probability of not earning was the worst outcome and 0.75 probability of earning was the best outcome. In our case, land with <0.25 probability (1 in 4 years) of producing <8000 kg ha^{-1} yr^{-1} ANPP is considered a favorable outcome. Less than 0.25 probability of producing <8000 kg ha^{-1} yr^{-1} switchgrass biomass was referred to as low risk for switchgrass biomass production.

$$p = P(X \leq 8000), \quad (1)$$

where p is the probability and X is 30-year simulated switchgrass ANPP.

The differences between ANPP potential, rainfed ANPP potential and minimum attainable ANPP are the ANPP reductions by constraining factors, N and water, as shown in Fig. 3.

Table 2 Summary of properties of soil units included in this study grouped by land capability class (LCC)

LCC/ Attributes	Number of soil units	Land area (km^2)	Mean (SD*) of organic C in top 30-cm layer (%)	Mean (SD*) of soil profile PAWC† (m^3 m^{-3})
I	36	173.7	1.05 (0.45)	0.12 (0.02)
II	1307	16 777.6	1.41 (0.77)	0.11 (0.03)
III	1548	9549	1.18 (0.61)	0.11 (0.03)
IV	897	3010.9	1.07 (0.66)	0.1 (0.02)
V	229	809.1	2.5 (1.12)	0.07 (0.03)
VI	698	1811.7	1.2 (0.94)	0.1 (0.03)
VII	541	507.4	1.04 (0.66)	0.1 (0.3)
VIII	8	16.6	2.2 (0.0)	0.13 (0.07)

*SD denotes standard deviation.
†PAWC denotes plant available water content (the difference between drainage upper limit and lower limit).

Table 3 Climate scenarios in this study

Scenario	Variable	Changes			
		Winter (DJF*)	Spring (MAM†)	Summer (JJA‡)	Fall (SON§)
Baseline (1981–2010)	Not applicable				
RCP 2.6	CO_2	400 ppm			
	Temperature	Add (+) 3 °C			
	Precipitation	Multiple by (*) 1.1	*1.1	*0.95	*1
RCP 6.0	CO_2	500 ppm			
	Temperature	+ 6 °C			
	Precipitation	*1.2	*1.2	*0.9	*1

*DJF denotes December, January and February;
†MAM denotes March, April and May;
‡JJA denotes June, July and August;
§SON denotes September, October and November.

Table 4 Switchgrass sowing and harvesting assumptions in this study

Management	Values used in this study	Values in the literature	Citations
Planting dates	DOY 128–155 in 1981–2010; 10 days earlier in the future climate scenarios	Late April–mid-June, DOY174, DOY171	Douglas *et al.* (2009); Nikièma *et al.* (2011); Sanford *et al.* (2016)
Harvest dates	DOY 280–300	Late fall	Douglas *et al.* (2009)
Population density (plant m^{-2})	20		
Spacing (cm)	18	18.8, 17.8	Nikièma *et al.* (2011); Sanford *et al.* (2016)

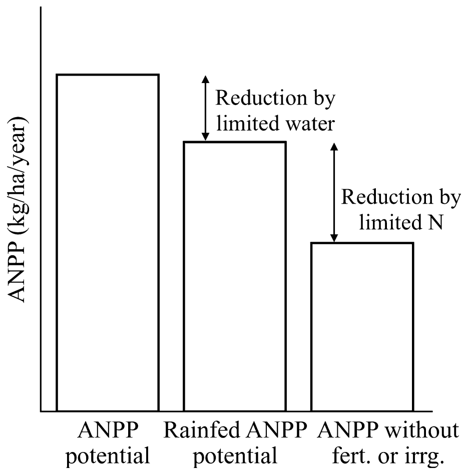

Fig. 3 Illustration of aboveground net primary productivity (ANPP) reduction by N and water (fert. means fertilizer; irrg. means irrigation; adapted from Lobell *et al.*, 2009).

We calculated the ANPP reduction from its potential by N and water based on Eqns (2) and (3) under three climate scenarios (baseline, RCP 2.6 and RCP 6.0). Switchgrass growth is constrained by N and water when the ANPP reduction percentage by N and water is larger than its 30-year state-wide median percentage reduction in the ANPP potential.

$$y = 100 \times \frac{b_{i,j} - c_{i,j}}{a_{i,j}}, \tag{2}$$

where y is percentage ANPP reduction by N, $a_{i,j}$ is ANPP under unlimited N fertilizer and irrigation supply at year i for simulation unit j, $b_{i,j}$ is ANPP under unlimited N fertilizer but limited irrigation supply, and $c_{i,j}$ is ANPP under no N fertilizer or irrigation supply.

$$y = 100 \times \frac{a_{i,j} - b_{i,j}}{a_{i,j}}, \tag{3}$$

where y is percentage ANPP reduction by water, $a_{i,j}$ is ANPP under unlimited N fertilizer and irrigation supply at year i for simulation unit j, and $b_{i,j}$ is ANPP under unlimited N fertilizer but limited irrigation supply.

We also tested the utility of adding N fertilizer to reduce the risk of producing <8000 kg ha^{-1} yr^{-1} switchgrass biomass under each of the climate scenarios. We used the SALUS model to simulate rainfed switchgrass under several different N fertilizer application rates that ranged from 10 to 100 kgN ha^{-1}, increasing 10 kgN ha^{-1} at each interval.

Table 5 Comparisons between the observed and simulated switchgrass yield at KBS

Year	Observed harvest yield (Mg ha^{-1})	Simulated harvest yield (Mg ha^{-1})
2010	4.47	4.19
2011	7.06	6.63
2012	5.07	4.94
2013	9.78	9.97
		RMSE: 0.28 Mg ha^{-1}

Results

SALUS model testing

The SALUS model adequately simulated the upland Cave-in-Rock switchgrass yield at KBS, Michigan. The RMSE between the simulated and observed switchgrass yield in 2010–2013 was 0.28 Mg ha^{-1} (Table 5).

The SALUS-simulated switchgrass ANPP in our study was in agreement with the reported switchgrass productivity in the literature (Fig. 4). Our SALUS-simulated rainfed and unfertilized switchgrass ANPP in 1981–2010 averaged 0.5–16.5 Mg ha^{-1} yr^{-1} across Michigan and was similar to the reported 0–15 Mg ha^{-1} yr^{-1} switchgrass productivity across Michigan in Miguez *et al.* (2012). Field experiment in the upper peninsula of Michigan showed that the average (±standard deviation) rainfed switchgrass ANPP under 112 kgN ha^{-1} fertilization treatment was 11.93 (±0.53) Mg ha^{-1} yr^{-1} (Nikièma *et al.*, 2011). Our simulated rainfed switchgrass ANPP potential for the county where the experiment was conducted was 13.0 (±2.9) Mg ha^{-1} yr^{-1}). We did not find experiments where upland switchgrass was irrigated and fertilized in climate zones similar to those in Michigan. However, the maximum reported upland switchgrass productivity was about 30 Mg ha^{-1} yr^{-1} (Wang *et al.*, 2010), and our simulations similarly showed that switchgrass ANPP could reach up to 28.5 Mg ha^{-1} yr^{-1} under no N and water stress in Michigan.

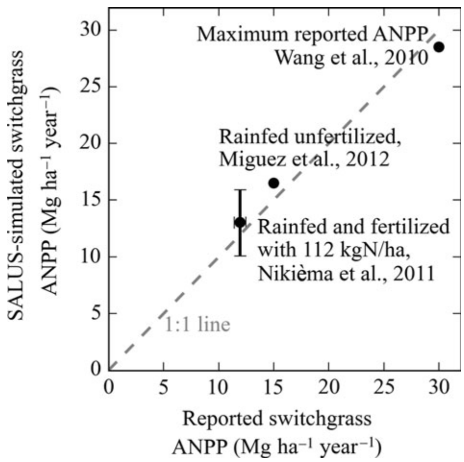

Fig. 4 Comparisons between the SALUS-simulated and reported switchgrass ANPP in the literature (the vertical bar is standard deviation of SALUS-simulated switchgrass productivity at a county level, and the horizontal bar is standard deviation of the observed productivity in the field trial).

Switchgrass ANPP potential and minimum attainable ANPP in Michigan

The ANPP potential ranged from 9612 to 28 468 kg ha^{-1} yr^{-1} (median of 23 448 kg ha^{-1} yr^{-1}) across the simulation units in Michigan under the baseline climate (1981–2010). The median value (±standard deviation) for rainfed switchgrass ANPP potential under the baseline climate was 15 144 (±4064) kg ha^{-1} yr^{-1}. The minimum attainable ANPP under the baseline climate, however, was much smaller and varies widely. The median value (±standard deviation) of the minimum attainable ANPP is 5815 (±2463) kg ha^{-1} yr^{-1} under the baseline climate (Fig. 5a).

The switchgrass ANPP potential, the rainfed ANPP potential and the minimum attainable ANPP decreased under both future projected climate scenarios for the simulated 30-year period. The median switchgrass ANPP potential under RCP 2.6 and RCP 6.0 climate scenarios declined to 20 402 kg ha^{-1} yr^{-1} and 19 373 kg ha^{-1} yr^{-1}, respectively. The median rainfed ANPP potential decreased by 21% and 30% under RCP 2.6 and RCP 6.0, compared to the baseline climate scenario, respectively. The median (±standard deviation) of the minimum ANPP under RCP 2.6 and RCP 6.0 climate

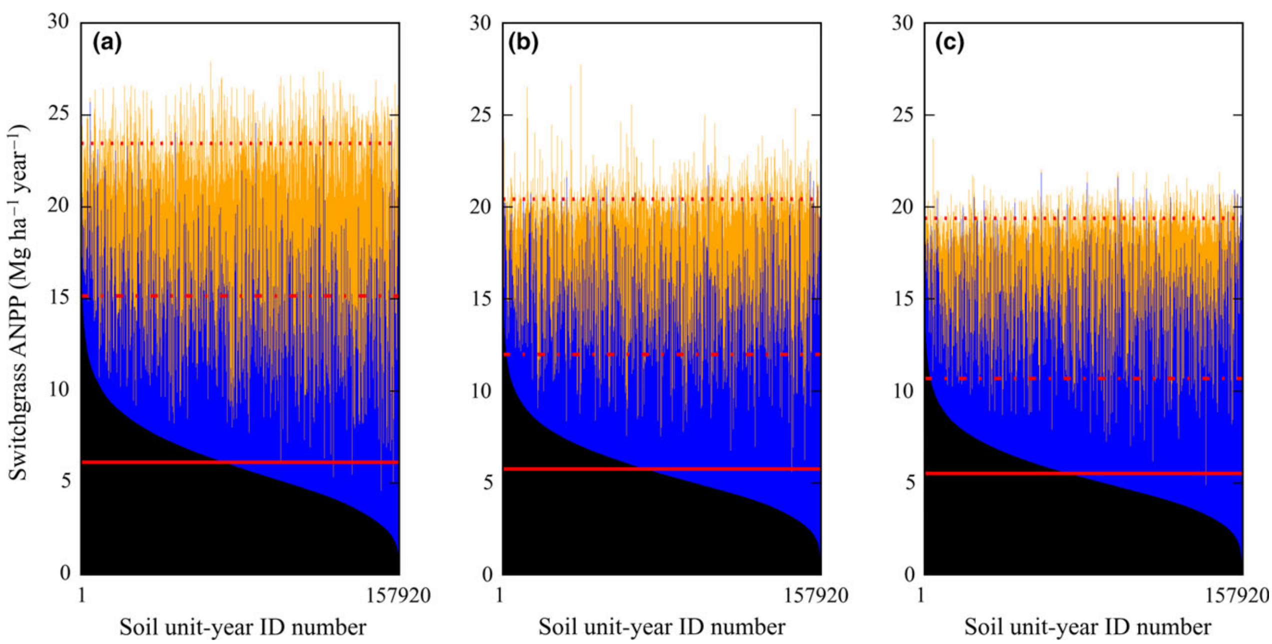

Fig. 5 Simulated 30-year switchgrass aboveground net primary productivity (ANPP) for each simulation unit in Michigan under (a) baseline (1981–2010), (b) RCP 2.6 and (c) RCP 6.0 climates (red solid line —— is the median rainfed and unfertilized ANPP; red dash dotted line -·-·- is the median rainfed ANPP potential; red dotted line ······ is the median ANPP potential; black bars represent rainfed and unfertilized ANPP for each simulated unit at one year; blue bars represent ANPP reduced from its potential by water; yellow bars represent ANPP reduced from its potential by N).

scenarios was 5484 (±2162) kg ha^{-1} yr^{-1} and 5280 (±2054) kg ha^{-1} yr^{-1}, respectively (Fig. 5b and c).

Switchgrass biomass production risks in Michigan

Areas with low risks of producing below 8000 kg ha^{-1} yr^{-1} rainfed and unfertilized switchgrass biomass were limited and were constrained to the southeast regions of Michigan. Under the baseline climate, simulations showed that 15.9% of the land in Michigan could produce large quantities of switchgrass biomass consistently, with probability of failure lower than 25% (Fig. 6a). The results showed that the percentage of land where the risk of producing lower than 8000 kg ha^{-1} yr^{-1} switchgrass biomass was low shrank to 10.0% and 7.4% under RCP 2.6 and RCP 6.0 emission scenarios, respectively (Fig. 6b and c).

Only a small portion of land in Michigan may produce large quantities of switchgrass biomass under rainfed and unfertilized management with a low risk of failure. Of the high-productive and low-risk land, about a quarter was marginal land (27.8%, 28.8% and 26.0% under baseline, RCP 2.6 and RCP 6.0 climate scenarios, respectively; Table 6).

Constraining factors for switchgrass biomass production in Michigan

Limited N contributed to switchgrass ANPP reduction from its potential across usable land in Michigan in 1981–2010 (median (±standard deviation) reduction: 38 (±16)%). The percentage of land with low risk of being constrained by N (i.e., probability <0.25 of having above 38% ANPP potential reduction) for biomass production was 18.3% under the baseline climate. Such land expanded under the two future climate scenarios; 44.9% and 61.1% land were projected to have low risks of being constrained by N for switchgrass growth in the simulated 30 years under RCP 2.6 and RCP 6.0 climates, respectively (Fig. 7).

Limited water caused median (±standard deviation) of 34 (±16)% ANPP decrease from its potential across the simulated land under the baseline climate. The risk of being constrained by water for switchgrass growth

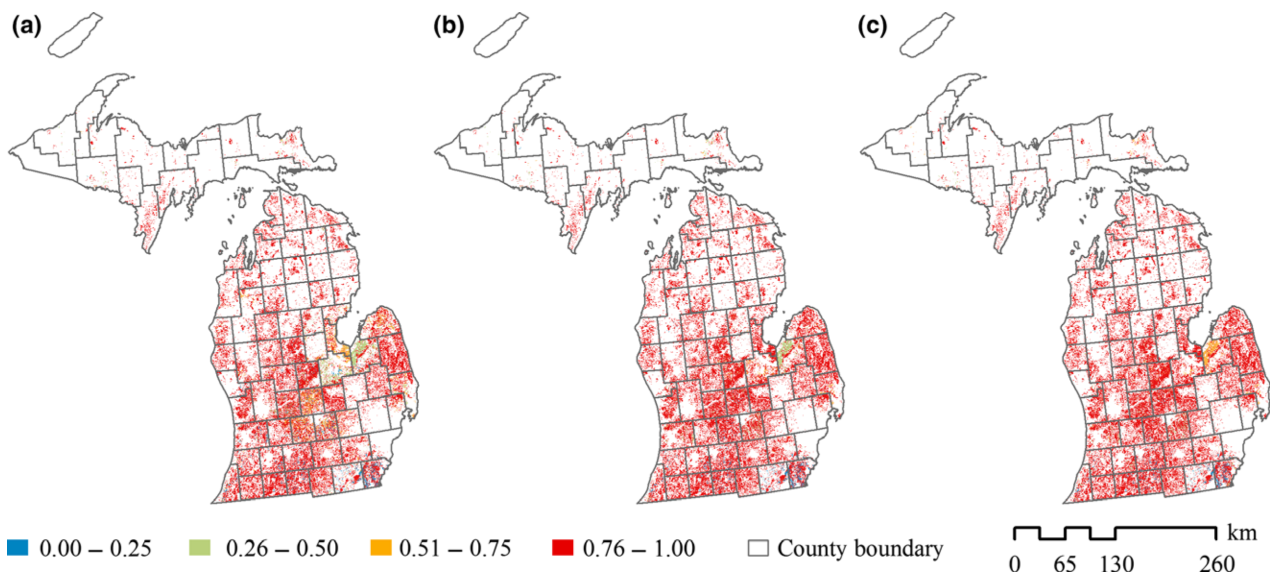

Fig. 6 Probability of switchgrass ANPP below 8000 kg ha^{-1} yr^{-1} in the simulated 30 years under (a) baseline (1981–2010), (b) RCP 2.6 and (c) RCP 6.0 climates in Michigan (0.00–0.25 probability indicates low risks of failing to produce high switchgrass biomass).

Table 6 Area of land that can produce sizable switchgrass ANPP consistently in the simulated 30 years (km^2)

Scenario/LCC	I	II	III	IV	V	VI	VII	VIII
Baseline (1981–2010)	3.4 (1.9)	3752.5 (22.4)	**1072.8 (11.2)**	**302.8 (10.1)**	**13.0 (1.6)**	**54.7 (3.0)**	**6.7 (1.3)**	**0.0 (0.0)**
RCP 2.6	3.4 (1.9)	2319.0 (13.8)	**703.2 (7.4)**	**214.8 (7.1)**	**0.0 (0.0)**	**16.8 (0.9)**	**7.0 (1.4)**	**0.0 (0.0)**
RCP 6.0	3.4 (1.9)	1790.3 (10.7)	**472.4 (4.9)**	**140.6 (4.7)**	**0.0 (0.0)**	**12.5 (0.7)**	**3.9 (0.8)**	**0.0 (0.0)**

Values in the parentheses are the percentage area (%) of land in the land capability class; land capability classes (LCCs) with bold faces are marginal land.

was low for 24.2% of land in Michigan under the baseline climate in 1981–2010. Land that showed low risk of being water constrained under future climate scenarios declined to 8.3% and 4.3% under the RCP 2.6 and RCP 6.0 climate scenarios, respectively (Fig. 8).

A larger area of the marginal land in Michigan was limited more by water than N. A majority (84.8%) of the marginal land had high risk of being constrained by water deficit for switchgrass biomass production in 1981–2010. The shifts in precipitation patterns that are likely to take place under projected future climate conditions worsen the situation. Our simulations showed that the percentage of water-constrained marginal land rose to 96.8% and 99.3% under RCP 2.6 and RCP 6.0 climate scenarios, respectively (Table 7). N-constrained marginal area was slightly less than water-constrained marginal land under the baseline climate. The percentage of marginal land that was subject to high N-constraining risks was 83.0%, compared to 80.5% for fertile land in 1981–2010. The respective percentages of

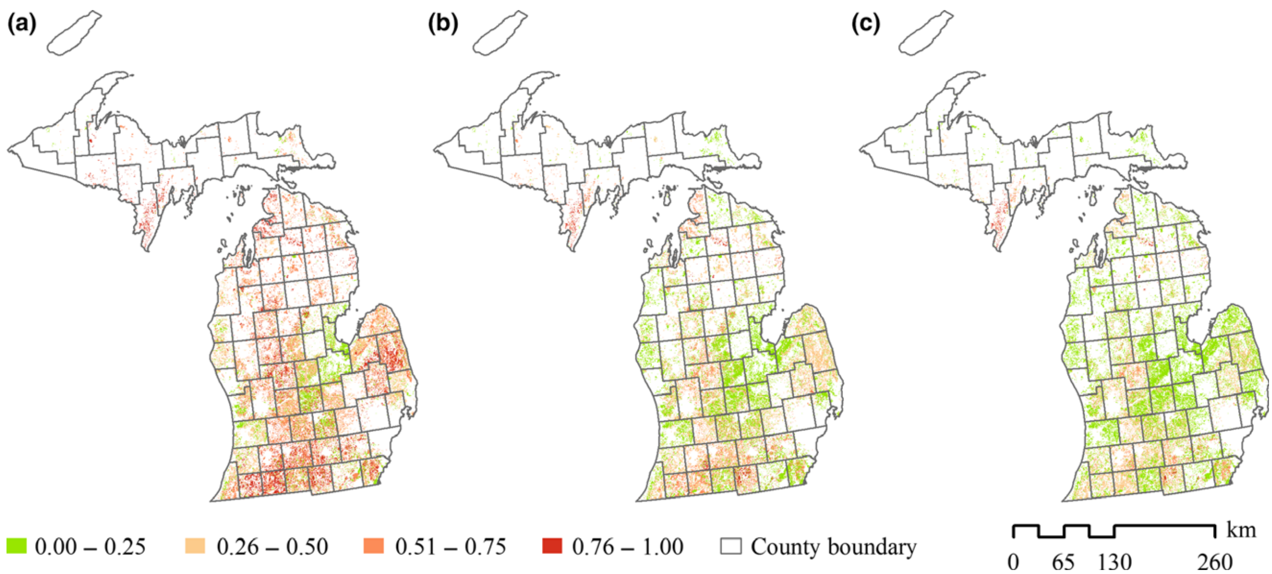

Fig. 7 Probability of switchgrass being constrained by N in the simulated 30 years under (a) baseline (1981–2010), (b) RCP 2.6 and (c) RCP 6.0 climates in Michigan (0.00–0.25 probability indicates low risks of being constrained by N).

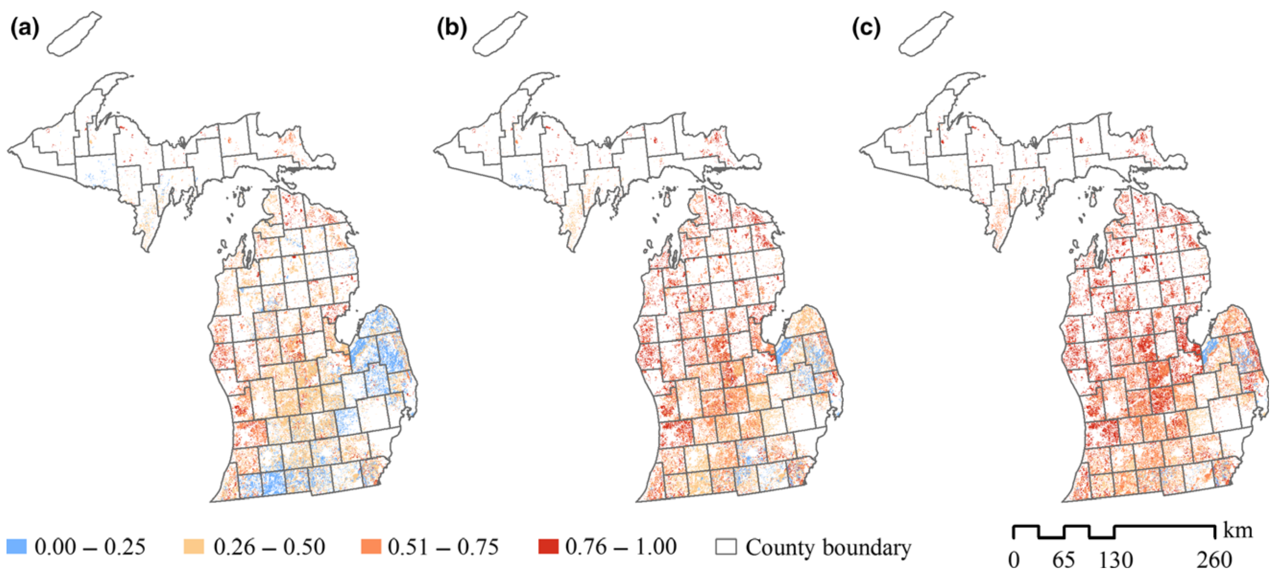

Fig. 8 Probability of switchgrass being constrained by water in the simulated 30 years under (a) baseline (1981–2010), (b) RCP 2.6 and (c) RCP 6.0 climates in Michigan (0.00–0.25 probability indicates low risks of being constrained by water).

Table 7 Area of land where water limitation risks are low in the simulated 30 years (km^2)

Scenario/LCC	I	II	III	IV	V	VI	VII	VIII
Baseline (1981–2010)	73.0 (42.0)	5450.5 (32.5)	**1970.9 (20.6)**	**310.1 (10.3)**	**0.0 (0.0)**	**82.9 (4.6)**	**10.7 (2.1)**	**4.1 (24.9)**
RCP 2.6	12.3 (7.1)	2178.8 (13.0)	**355.9 (3.7)**	**91.8 (3.0)**	**0.0 (0.0)**	**52.0 (2.9)**	**5.3 (1.1)**	**3.5 (21.1)**
RCP 6.0	1.3 (0.7)	1314.1 (7.8)	**66.4 (0.7)**	**20.1 (0.7)**	**0.0 (0.0)**	**13.2 (0.7)**	**5.2 (1.0)**	**0.0 (0.0)**

Values in the parentheses are the percentage area (%) of the land in the land capability class; land capability classes (LCCs) with bold faces are marginal land.

Table 8 Area of land where N limitation risks are low in the simulated 30 years (km^2)

Scenario/LCC	I	II	III	IV	V	VI	VII	VIII
Baseline (1981–2010)	4.9 (2.8)	3295.5 (19.6)	**1095.0 (11.5)**	**475.4 (15.8)**	**746.4 (92.3)**	**204.5 (11.3)**	**137.1 (27.0)**	**7.2 (43.5)**
RCP 2.6	5.9 (3.4)	8137.1 (48.5)	**3031.6 (31.7)**	**1521.0 (50.5)**	**796.8 (98.5)**	**856.5 (47.3)**	**302.6 (59.6)**	**12.9 (78.2)**
RCP 6.0	82.0 (47.2)	10 777.7 (64.2)	**4561.8 (47.8)**	**1985.2 (65.9)**	**807.7 (99.8)**	**1293.8 (71.4)**	**437.1 (86.1)**	**12.9 (78.2)**

Values in the parentheses are the percentage area (%) of the land in the land capability class; land capability classes (LCCs) with bold faces are marginal land.

N-constrained marginal and fertile land fell to 58.5% and 52.0% under RCP 2.6 climate and 42.1% and 35.9% under RCP 6.0 climate (Table 8).

Contributions of N fertilizer application to switchgrass ANPP

Moderate amount of N fertilizer (no more than 60 kgN ha^{-1}) could improve switchgrass ANPP to 8000 kg ha^{-1} yr^{-1} across Michigan. Simulations showed that the area of land that could consistently produce 8000 kg ha^{-1} yr^{-1} switchgrass biomass with reasonable amounts of N fertilizer decreased under climate change scenarios. Of land in Michigan, 95.8% could provide at least 8000 kg ha^{-1} yr^{-1} switchgrass biomass with low risk of failure in the simulated 30 years with no more than 60 kgN ha^{-1} added, but this proportion declined to 91.6% and 81.7% under RCP 2.6 and RCP 6.0 climate scenarios, respectively. Nonetheless, over 95% of marginal land in Michigan could be reliable to produce adequate amounts of switchgrass biomass with below 100 kgN ha^{-1} added fertilizer, but this value also decreases to 87.8% and 76.5% under RCP 2.6 and RCP 6.0 climate scenarios, respectively (Fig. 9).

Some of the potentially usable land is not suitable for switchgrass cultivation because it does not have sufficient nutrient availability or water. Simulations showed that percentage of land area that needed more than 60 kgN ha^{-1} input to achieve 8000 kg ha^{-1} yr^{-1} switchgrass production was 2.7%, 2.5% and 6.2% under baseline, RCP 2.6 and RCP 6.0 climate scenarios, respectively. The fraction of potentially usable land that required both 100+ kg ha^{-1} N fertilizer and irrigation to achieve yields of 8000 kg ha^{-1} yr^{-1} with low risk of failure in the simulated 30 years rocketed from 1.5% under baseline climate conditions to 5.8% and 12.1% for RCP 2.6 and RCP 6.0 climate scenarios, respectively (Fig. 9).

Discussion

Switchgrass ANPP

Spatial and temporal variations in switchgrass ANPP potential, where nutrient application and supplied water are not a factor that affects productivity, reveal the profound impact of climate on switchgrass productivity. For example, simulated switchgrass ANPP potential is lower under future climate scenarios than under the baseline climate, due to the increased temperature and consequently the faster development and shorter growing cycling under the projected future climate. Another example of temperature effect on switchgrass productivity potential is that northern Michigan, where the temperature is lower, has higher switchgrass productivity potential than southern Michigan across the three climate scenarios. Additionally, rainfed switchgrass ANPP is larger for wet regions than for drier regions in Michigan. Research on maize (*Zea mays*), wheat (*Triticum*) and rice (*Oryza sativa*) production systems also found that growing-season weather caused crop productivity uncertainty (Lobell *et al*., 2009; Anderson, 2010; Licker *et al*., 2010). Future research on switchgrass productivity should include the effect of weather on switchgrass productivity.

Climate change impact on switchgrass ANPP and its constraining factors

Our results showed that the interactions between elevated CO_2, precipitation pattern and increased temperature under the projected climate scenarios resulted in on-average lowered ANPP potential (Fig. 5). The levels to which the constraining factors (i.e., N and water) contributed to switchgrass ANPP potential reduction across Michigan were different under the projected climate, when compared to the baseline climate (Figs 7 and 8). These results agree with the literature; the beneficial effects of the CO_2 fertilization were offset by the changes in precipitation pattern and increased temperature (Tubiello *et al.*, 2007). The reason land subject to low risk of N constraining expands under the project climates is primarily due to less biomass accumulation and thus less plant N demand. On the contrary, the land with low risk of water constraining reduces under the future climate. This result indicates that the increased atmosphere demand and changed precipitation pattern would cause more water stress for rainfed and unfertilized switchgrass cultivation under the projected climate scenarios. Similar phenomenon has been reported in the literature as well (Xiao *et al.*, 2005; Tubiello *et al.*, 2007).

Implications of growing switchgrass for bioenergy on Michigan's marginal land

Our results indicated that about 25% of the marginal land in Michigan could support >8000 kg ha^{-1} yr^{-1} switchgrass production with <25% probability of failure

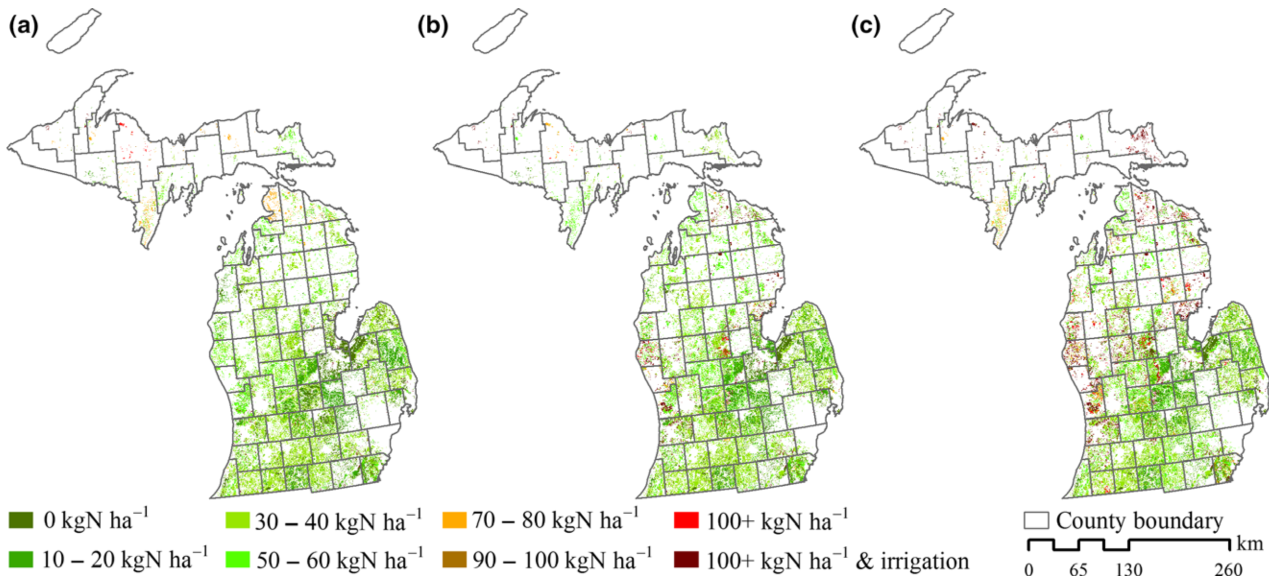

Fig. 9 Management that can improve switchgrass aboveground net primary productivity with <0.25 probability of failing to achieve 8000 kg ha^{-1} yr^{-1} in the simulated 30 years under (a) baseline (1981–2010), (b) RCP 2.6 and (c) RCP 6.0 climates in Michigan.

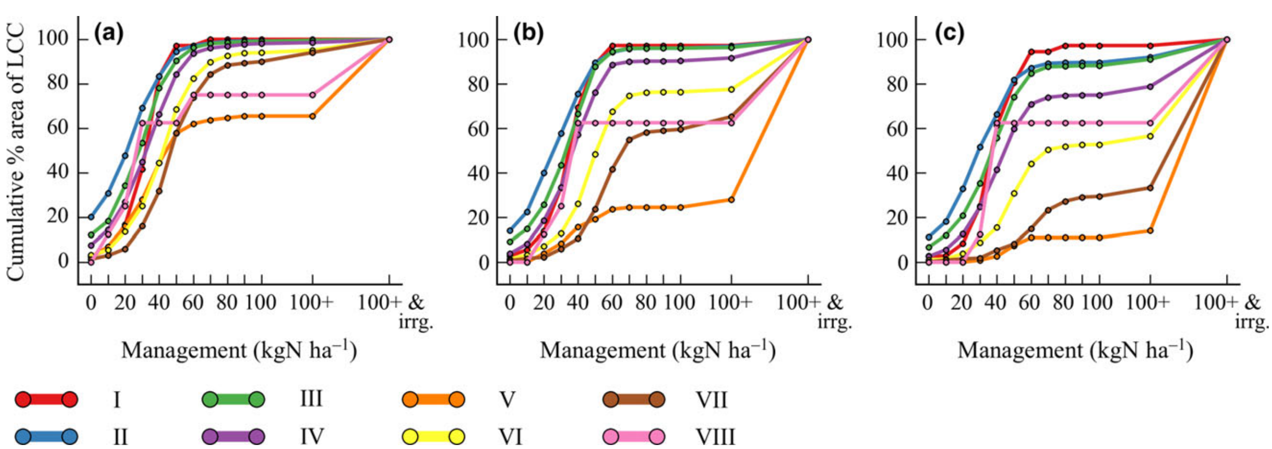

Fig. 10 Percentage area of each land capability class (LCC) that can produce more than 8000 kg ha^{-1} yr^{-1} aboveground net primary productivity under varied management under (a) baseline (1981–2010), (b) RCP 2.6 and (c) RCP 6.0 climates in Michigan (irrg. means irrigation).

in the simulated 30 years. Unlike the large crop yield from land class V in Zhang *et al.* (2010), our simulated switchgrass grown on the class V land was lower than that of land classes I-IV. We modified the soil parameters extracted from SSURGO for soils that had water limitation as its secondary land capability class to represent the water shortage feature (Klingebiel & Montgomery, 1961). The high likelihood of rainfed switchgrass biomass production on marginal land should lead to discussions on strategies to efficiently increase its productivity (Schmer *et al.*, 2008). We showed changes in percentage land area of each LCC where more than 8000 kg ha^{-1} yr^{-1} switchgrass ANPP could be consistently achieved over a period of 30 years under a varied N fertilizer input and identified the minimum management required to achieve such goals (Figs 9 and 10). Additionally, we found regions in Michigan where switchgrass production is not suitable because of limited nutrient availability, N fertilizer and/or irrigation. The other innovation of our study was that we parsed the effect of N and water shortage on constraining switchgrass yield from achieving its potential across each simulated land unit in Michigan. Land capability class was developed to guide choosing profitable land for crop production, but does not correlate with productivity. Marginal land, based on the LCC descriptions, may constrain switchgrass biomass production due to unfavorable climate, low organic matter, shallow soil depth and/or erosion hazard (Klingebiel & Montgomery, 1961), but the specific underlying limiting factors were unknown. We used a crop simulation model – SALUS – and yield gap concept to identify N and/or water constraints for switchgrass in Michigan.

Adaptability of the proposed methodology for bioenergy feedstock productivity on marginal land

Marginal land has been promoted for bioenergy feedstock production, and recent field experiments have started to evaluate bioenergy feedstock yield on marginal land (Tilman *et al.*, 2006; Varvel *et al.*, 2008; Bhardwaj *et al.*, 2011). However, it is unlikely that field experiments will exhaustedly test the feasibility of marginal land to support sizable bioenergy feedstock production or unravel the factors that constrain production. Crop simulation models provide an opportunity to investigate marginal land productivity for bioenergy feedstock cultivation under a range of soil and climate conditions. Our study provided a framework not only to identify high-productive and low-risk land for bioenergy feedstock but also to test management practices that may increase land productivity. This framework can be transferred to other geographic regions and applied to bioenergy feedstock, such as maize and miscanthus (*Miscanthus* × *giganteus*).

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