MODELING SWITCHGRASS ABOVEGROUND NET PRIMARY PRODUCTIVITY AND EVAPOTRANSPIRATION ACROSS MICHIGAN

By

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ABSTRACT

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Switchgrass has been proposed as a biofuel feedstock in the US. Studies in the past decades have shown that switchgrass is able to produce sizable biomass with varied management practices. Recent studies have focused on its cultivation impact on the environment, including water use, nitrate leaching and soil water content. However, little research has evaluated switchgrass aboveground biomass production across lands with varied quality across Michigan nor has research quantified factors limiting switchgrass aboveground biomass. This thesis attempted to fill the research gap. The Systems Approach to Land Use Sustainability model was used to assess switchgrass aboveground net primary productivity (ANPP) and evapotranspiration (ET) across Michigan in 1981-2010 and 2039-2068 and to quantify limited nitrogen and water effect on switchgrass aboveground biomass potential reduction. The results showed that switchgrass ANPP would decrease in 2039-2068 compared to 1981-2010 for a majority region in Michigan. Its ET would increase in 2039-2068 compared to 1981-2010 for most of Michigan but the increase in ET would be attributed to higher soil water evaporation in 2039-2068. The limited nitrogen would affect switchgrass ANPP production less in 2039-2068 than in 1981-2010. However, limited water would affect its production more in the projected future.

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Abstract

Switchgrass has been proposed as a feedstock for bioenergy production since it produces sizable biomass yield and may be produced on marginal land. The ideal switchgrass production system requires few agricultural inputs such as fertilization and irrigation. There is an ongoing debate among scientists on the impact of switchgrass production on groundwater recharge. Comprehensive information on switchgrass evapotranspiration (ET) is missing. The objectives of this review are to assess switchgrass aboveground biomass production under rainfed and unfertilized management; and to quantify switchgrass ET in field trials. Twelve peer-reviewed articles reported switchgrass aboveground biomass production with no additional agricultural inputs across locations of varying soil fertility and water availability. The aboveground biomass production ranged from 1.6 to 33.4 Mg/ha, while ET ranged from 280 to 780 mm using different ET estimation methods.

Traditional biofuel is produced from maize but with the high food demand, there has been a need to produce biofuel from the cellulosic feedstock instead of maize (Gelfand et al., 2013; Robertson et al., 2011). The native switchgrass (*Panicum virgatum*) in the US is one of the species listed by the US Department of Energy for biofuel production although it has also been grown in buffer strips and for forage (McLaughlin and Adams Kszos 2005; Parrish and Fike 2005). As a perennial grass, its growth usually includes an initialization phase (lasting about 2 years after planting) and an established phase (Arundale et al., 2013a; Clifton-Brown et al., 2007). Since switchgrass has long roots and high resource use efficiency it can tolerate various environmental constraining factors, such as nitrogen limitation, and drought conditions (Heaton et al., 2004; Reynolds et al., 2000; Sanderson and Reed, 2000). With high biomass production possibility and ability to adapt to a wide range of environment, switchgrass has been considered as a feedstock for biofuel.

Research has heavily focused on switchgrass biomass production to understand its potential yield and the management practices that can increase the biomass yield (Wright and Turhollow 2010; Wullschleger et al., 2010). With the rising interest in promoting switchgrass cultivation, studies have expanded from emphasizing biomass yield production to evaluating its environmental impacts. In recent decade, studies have been conducted to assess its impact on water balance, particularly ET (Le et al., 2011).

Since intensified agriculture has caused environmental problems and large-scale switchgrass with high fertilizer and irrigation input would not be different from intense agriculture, it is recommended to use low or no agricultural input for switchgrass cultivation. However, a comprehensive review on switchgrass performance under no agricultural input is not available. Therefore, the objective of this chapter is to provide a literature review on biofuel-switchgrass biomass yield in field trials with no agricultural input and field-estimated ET.

Switchgrass aboveground biomass production under no agricultural inputs

Switchgrass has been cultivated in monoculture and in mixtures with other species (eg: Berdahl et al., 2001). Field trials have focused on switchgrass biomass yield, in both monoculture and mixtures, under varied environmental and management conditions. This section only included field experiments where switchgrass was managed for biomass in monoculture and under no agricultural inputs although several authors have reviewed switchgrass biomass production in relation to varied variables such as cultivar and nitrogen addition (Parrish and Fike, 2005; Wang et al., 2010).

Twelve peer-reviewed articles reported switchgrass aboveground biomass production with no agricultural inputs. Several switchgrass cultivars have been tested, including upland (e.g. Sunburst, Blackwell, Dacotah, Forestburg, Shawnee, Pathfinder and Nebraska) and lowland (e.g. Cave-in-Rock, Summer, Kanlow and Alamo) cultivars. The biomass yield for upland switchgrass ranged from 3 Mg/ha to 12.5 Mg/ha whereas it ranged from 1.6 Mg/ha to 33.4 Mg/ha for lowland switchgrass (Table **1** and Table **2**). On average, the reported upland switchgrass biomass (5.96 Mg/ha) was lower than the upland variety (9.73 Mg/ha). Compiling all reported biomass production in the studies, switchgrass aboveground biomass was significantly correlated with stand age (i.e., years after planting) for the upland variety (p = 0.02, r2 = 0.37) but the correlation was not significant for the lowland variety (p = 0.22, r2 = 0.03) (Figure **1**).

Table 1. Reported field experiment upland switchgrass aboveground biomass (Mg/ha)

Reference	Number of observations	Minimum	Maximum	Average
Boe and Lee 2007	4	4.22	10.5	5.8
Boe 2007	1	-[*]	-[*]	10.5
Boe and Casler 2005	10	3	12.5	6.3
Schmer et al., 2012	1	-[*]	-[*]	3.2
Christian 1994	4	1.1	2.42	1.6

[*] Not applicable

Table 2. Reported field experiment lowland switchgrass aboveground biomass (Mg/ha)

Reference	Number of observations	Minimum	Maximum	Average
Boe and Lee 2007	8	1.97	7.26	5.1
Boe 2007	1	-[*]	-[*]	12.6
Boe and Casler 2005	2	6.1	9.7	
Boehmel et al., 2008	1	-[*]	-[*]	8
Christian 1994		1.6	2.2	
Ma et al. 2001	1	-[*]	-[*]	3.7
Muir et al., 2001	7	1.5	6	3.6
Thomason et al., 2005	11	10.9	33.4	19.6
Nikièma et al., 2011	1	-[*]	-[*]	4.83
Boyer et al., 2012	26	3.68	21.3	9.7
Arundale et al., 2013a	1	-[*]	-[*]	10
Arundale et al., 2013b	1	-[*]	-[*]	10.3

[*] Not applicable

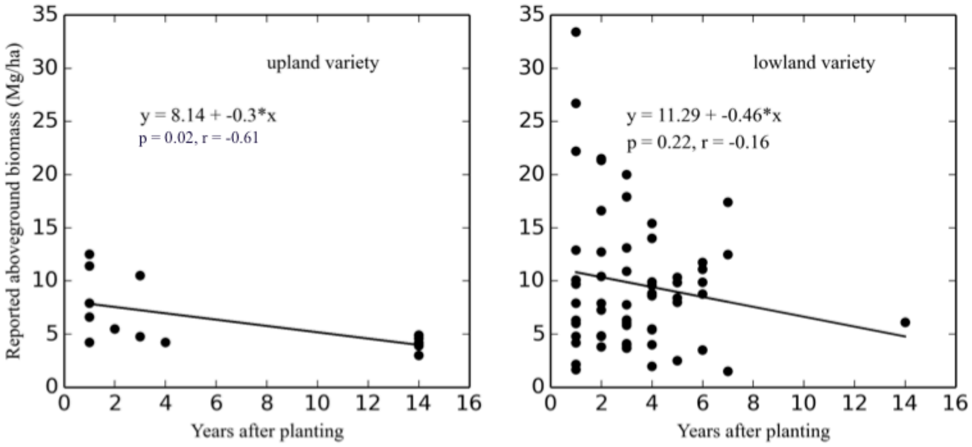

Figure 1. Switchgrass aboveground biomass in relation to stand age under no agricultural inputs

Factors affecting switchgrass biomass yield

As shown above (and many have reported), that switchgrass that switchgrass aboveground biomass yield depends on its cultivar. The lowland varieties (e.g. cultivar ‘Cave-in-Rock’) have higher biomass yield than the upland varieties (e.g. cultivar ‘Blackwell’) (Tulbure et al., 2012).

It is well known that switchgrass biomass yield response to nitrogen addition varies greatly. Several field experiments have focused on switchgrass yield relative to nitrogen addition. While most studies reported a positive relation between switchgrass biomass production and nitrogen addition, the optimal nitrogen rate was not known nor did switchgrass respond to nitrogen addition in the same way across different experiments (eg: Nikièma et al., 2011; Schmer et al., 2012). For instance, a field experiment in Oklahoma where switchgrass was fertilized at annual rates of 0-896 kgN/ha, showed that switchgrass biomass yield was maximized (about 18 Mg/ha with three harvests per year) when it was fertilized at 448 kg N/ha rate (Thomason et al., 2005). In contrast, Aravindhakshan et al. (2011) found that in Oklahoma, the switchgrass biomass reached a maximum yield of about 12.0 Mg/ha at an annual nitrogen fertilization rate of 67 kg N/ha (Aravindhakshan et al., 2011). Switchgrass biomass production reached a plateau when fertilizers were added at the rate of 67 kg N/ha and 134 kg N/ha under the conditions of well-drained floodplain and well-drained sloping eroded upland, respectively. However, under poorly drained floodplain and well-drained level upland landscape, the biomass increased with increasing nitrogen application ranging from 0 to 200 kg N/ha (Boyer et al., 2012). Parrish and Fike (2005) reviewed the literature to show that switchgrass yield increase resulting from nitrogen addition varied from 0 to 6.2 Mg/ha (Parrish and Fike, 2005).

The literature indicated that multiple harvests per year would increase switchgrass aboveground net primary productivity. Across 8 sites in five states in the upper southeastern US, upland switchgrass biomass yield increased by 36% with a second cut per year, and lowland varieties increased by 8% (Fike et al., 2006b). Another study in two sites in Oklahoma reported that yield was consistently highest for three harvests per year (average of 16.3 kg/ha) and lowest for one harvest per year (average of 12.9 kg/ha) (Thomason et al., 2005).

It is believed that switchgrass can sustain its biomass production for over 10 years. Two studies indicated that switchgrass yield did not decline over a long term (≥10 years) with nitrogen application (McLaughlin and Adams Kszos 2005; Fike et al., 2006a). However, unfertilized switchgrass fields across 7 sites in Illinois for 8-10 years showed that switchgrass yield increased for the first 5 years after establishment and then started to decrease after reaching a plateau (Arundale et al., 2013). Declining yield without fertilizer addition was also observed in a field experiment in Texas (Muir et al., 2001).

Besides management and crop genotype influences on switchgrass production, precipitation plays a critical role in biomass accumulation particularly when water is the limiting factor. Fike et al. (2006) reported "Alamo" biomass was statistically related to early season rainfall ($P < 0.05$) for 7 field trials in 5 states in the US (Fike et al., 2006b).

Switchgrass ET

Several publications reported switchgrass ET based on field measurement but ETs was estimated using different methods including water balance, energy balance and the eddy covariance approaches. Field experiments where ETs were reported were conducted in Illinois, Pennsylvania and Oklahoma. The reported switchgrass ET ranged from 280 to 780mm, compiling experiments at varied locations and in different years (Table **3**).

Table 3. Switchgrass ET estimates

Location	Growing days	Estimated ET (mm)	Estimation methods	References
Illinois	166	764.3 ± 33.7	Energy balance	Hickman et al., 2010
Illinois	163	304 (large pot) 337 (small pot)	Water balance	McIsaac et al., 2010
Illinois	182	263 (large pot) 284 (small pot)	Water balance	McIsaac et al., 2010
Illinois	160	319 (large pot) 359 (small pot)	Water balance	McIsaac et al., 2010
Illinois	166	258 (large pot) 278 (small pot)	Water balance	McIsaac et al., 2010

Table 3 (cont'd)

Pennsylvania	152	474	Eddy covariance	Skinner and Adler 2010
Illinois	-[*]	600-750	Eddy covariance	Zeri et al., 2013
Oklahoma	-190	450	Eddy covariance	Wagle and Kakani 2014

[*] not applicable

Although some reported the ET of switchgrass is correlated with biomass accumulation (eg:Skinner and Adler 2010; Zeri et al., 2013), one should not neglect the mechanism behind the ET process. ET consists of water evaporation and plant transpiration. Water evaporated from soil is not only controlled by the potential evaporation but also by soil hydraulic properties (Dickinson 1984). With little or no vegetative cover, ET is dominated by water evaporated from the bare soil. Soil water content, solar radiation, wind, temperature and humidity control the bare soil water evaporation and thus ET (Ritchie 1972). With declining soil surface water, the ET controlling factors shift from the external factors to surface soil hydraulic properties, including water holding capacity, soil hydraulic conductivity and soil infiltration rate (eg: Davidson et al., 1969; Ritchie, 1972). High infiltration rate and high water holding capacity can increase soil water storage and reduce water evaporation (in the storm event) (Dao, 1993; Jones et al., 1994). On the other side, with vegetation development, plant transpiration dominates ET. Both plant stomata and the environment determine plant transpiration (eg: Jones, 1998; Lange et al., 1971; Monteith, 1965).

Conclusions

Numerous studies showed that switchgrass biomass production is determined by cultivar, nitrogen input, cutting frequency, stand age and the amount of precipitation. In general, lowland switchgrass produces higher biomass yield than upland switchgrass. Switchgrass biomass accumulation positively responds to nitrogen addition but the response rate varies widely among the experiments. Nonetheless, under no agricultural inputs, the reported switchgrass biomass yield ranged between 1.6 and 33.4 Mg/ha. Water availability and the precipitation have been shown as constraining factors for switchgrass biomass production. For switchgrass ET estimation, the methods were not consistent and they included water balance, energy balance and the eddy covariance. The estimated switchgrass ET varied greatly, ranging from 280 to 780 mm.

Since switchgrass biomass production and ET are results of crop interactions among soil and weather conditions and management, there needs a systems approach to examine switchgrass biomass production and ET particularly on a large spatial and temporal scale. Crop simulation models can be useful in this realm.

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Chapter 2. Modeling switchgrass growth and evapotranspiration under historical and future climate

Abstract

Switchgrass has been proposed for cultivation on marginal lands with no agricultural inputs. Numerous studies have explored application of crop simulation models to understand spatial variations of switchgrass aboveground biomass productivity and evapotranspiration (ET) with varied management. However, few studies have directly compared switchgrass aboveground net primary productivity (ANPP) across lands with different quality and no research has quantified limiting factors contribution to switchgrass ANPP. The Systems Approach to Land Use Sustainability model was used here to fill this research gap. The objectives of the study were to: 1) simulate switchgrass ANPP and ET on land with seven land-capability classes under historical (1981-2010) and future (2039-2068) climate and 2) quantify the impact of water and nitrogen limitations on switchgrass ANPP in Michigan. The results showed that the simulated switchgrass average ANPP varies greatly under historical and future climate in Michigan. Generally, ANPP decreases with increasing land marginality. With both climate scenarios, agricultural land tends to have larger ET than marginal land. On average, under historical and future climate, limited nitrogen contributes 39% and 22% to average ANPP reduction in Michigan, respectively and limited water contributes 32% and 47%, respectively. Limited water has more effect on switchgrass ANPP on marginal land than agricultural land. Limited nitrogen has less effect on the ANPP on marginal land than agricultural land.

Biofuel production has been expanded to meet increasing energy demands (Kim and Dale, 2005; Murphy et al., 2011). The first-generation biofuel feedstock is largely from maize. With the rising concerns about both food security caused by the bioenergy sector demanding for food grains and negative environmental impacts caused by intensified grain crop cultivation, second-generation bioenergy – cellulosic bioenergy – production has been invoked (Murphy et al., 2011; Robertson et al., 2008). In recent decades, marginal land has been considered to grow cellulosic bioenergy feedstock to avoid competitions between food and biofuel for food and land (Tilman et al., 2006).

Switchgrass is one of the proposed cellulosic biofuel feedstocks. Extensive field trials across the US have tested its biomass yield under varied treatments including nitrogen addition, cutting frequency, stand age and precipitation (Arundale et al., 2013; Wang et al., 2010; Wullschleger et al., 2010). The reported switchgrass yield in the literature ranged from 0 to 40 Mg/ha (Wang et al., 2010). Field experiments also have studied switchgrass cultivation impact on the environment. These research topics included switchgrass and soil water content and evapotranspiration (ET), carbon flux, and nitrate leaching (Hickman et al., 2010; McIsaac et al., 2010; Skinner and Adler, 2010; Wagle and Kakani, 2014).

Ideally, utilizing marginal land for bioenergy feedstock cultivation would produce a sizable biomass while providing beneficial ecosystem services (Robertson et al., 2008; Tilman et al., 2006). Marginal land was first defined from an economics perspective where land marginality was evaluated based on the monetary benefit of agricultural production in relation to both prices in agricultural markets and the cost of production (Peterson and Galbraith, 1932). Several recent studies have developed algorithms that incorporate land biophysical, sociological and economical features for land marginality classification (Gopalakrishnan et al., 2011; Kang et al., 2013). Nonetheless, few studies have related marginal land characteristics to land productivity for switchgrass cultivation.

Although the ideal management practices for switchgrass on marginal land would be without irrigation and fertilization applications, as was suggested by the Department of Energy (DOE), a little research has explicitly and directly studied switchgrass performance under such growing conditions (DOE 2011). Furthermore, switchgrass biomass production has shown a non-linear response to management, weather and soil. For instance, switchgrass biomass may not be linearly correlated with nitrogen addition but when water availability is the limiting factor, its biomass could be significantly related to precipitation (Fike et al., 2006; Thomason et al., 2005; Wang et al., 2010). Therefore, switchgrass cultivation, either on agricultural or marginal land, is best examined with a systems approach that can account for complex interactions among switchgrass cultivars, soil, climate, and management (Robertson et al., 2011). Crop simulation models have shown capability to describe switchgrass aboveground biomass yield and its environmental impact since water balance and nutrient cycles are often embedded in those models (Gelfand et al., 2013; Zhang et al., 2010). Regarding switchgrass aboveground biomass and ET simulations, several crop simulation models such as ALMANAC, EPIC and Terrestrial Ecosystem Model, have been applied to predict switchgrass biomass at field, regional and ecosystem scales (Kiniry et al., 2005; Nair et al., 2012; VanLoocke et al., 2012; Zhuang et al., 2013), and its simulated ET has ranged from 498 to 901 mm (Brown et al., 2000; Kiniry et al., 2008; Le et al., 2011).

It is critical to evaluate switchgrass performance not only under current climate but also projected future climate. With the counter-effect of rising carbon dioxide concentration and temperature, it is not surprising that with projected climate changes, some regions may have an increase in switchgrass biomass yield while other regions would have a decrease in biomass yield (Behrman et al., 2013; Brown et al., 2000; Tulbure et al., 2012). Additionally, the increase of biomass yield under the future climate is spatially dependent. An 8 Mg/ha increase in switchgrass biomass was predicted for Iowa and eastern Nebraska but only a 2-5 Mg/ha increase for Kansas under future climate (Brown et al., 2000). Tulbure et al. (2012) suggested that the maximum switchgrass biomass yield would not change much under future climate but the regions that have high switchgrass potential would change (Tulbure, Wimberly, & Owens, 2012). Under the projected future climate, switchgrass ET was predicted to increase for the Missouri-Iowa-Nebraska-Kansas regions (Brown et al., 2000).

The objectives of this study were 1) to compare switchgrass aboveground biomass production, expressed in aboveground net primary productivity (ANPP), across different land capability classes defined by the US Department of Agriculture (USDA) in Michigan under historical and future climate scenarios and 2) to provide a new approach to quantify factor limiting switchgrass potential ANPP reduction under historical and future climate.

Methods

Model implementation

We used the Systems Approach to Land Use Sustainability (SALUS) model to simulate switchgrass growth at its established phase under rain-fed and non-fertilized conditions with both historical and future climate in Michigan (Figure **2**.a). The SALUS-Switchgrass model was evaluated with field experiments at Kellogg Biological Station in Michigan (42˚23’47” N, 85˚22’26” W, 288 masl). Crop parameters representing mature switchgrass were used in the study.

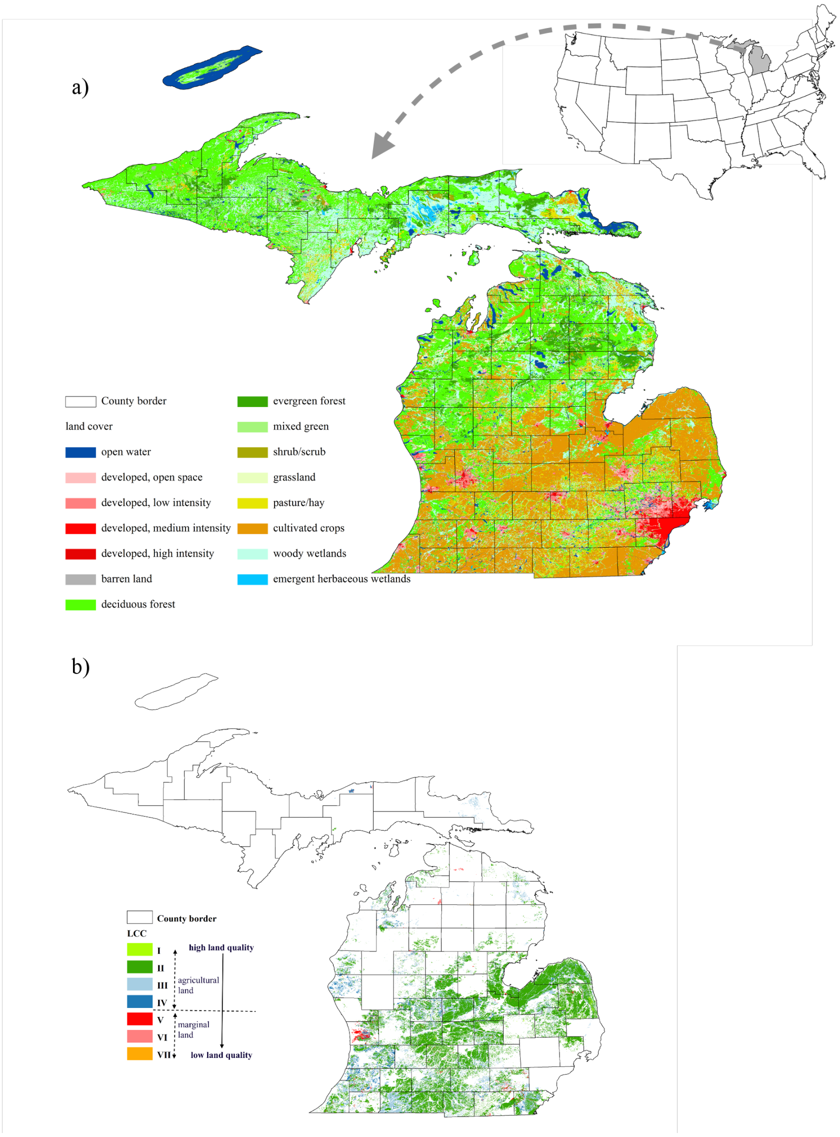


Figure 2. a) Land cover in Michigan and b) land capability class (LCC) for soil units included in this study

SALUS model

The SALUS model is a process-based model that was designed to simulate crop growth, water and nutrient cycles under interactions between weather, soil and management for multiple years (Figure **3**). The SALUS model executes on a daily basis. The crop growth module in the SALUS model was derived from the well-established CERES models, which were designated for simulating monoculture systems for a single year. It simulates crop growth based on the genetic coefficients including thermal time for varied developmental stages, leaf area index and solar radiation use efficiency. The water balance module was adapted from the CERES models with major revisions. The time-to-tipping concept was incorporated to calculate infiltration, evaporation, drainage and runoff, replacing the SCS-runoff-curve-number-based calculations in the CERES models (Basso and Ritchie 2015). The nutrient cycle module was derived from the CENTURY models with modifications (Basso et al., 2011a). More detailed descriptions of the SALUS model can be found in Basso et al. 2006 and Dzotsi et al. 2013 (Basso et al., 2006; Dzotsi et al., 2013).

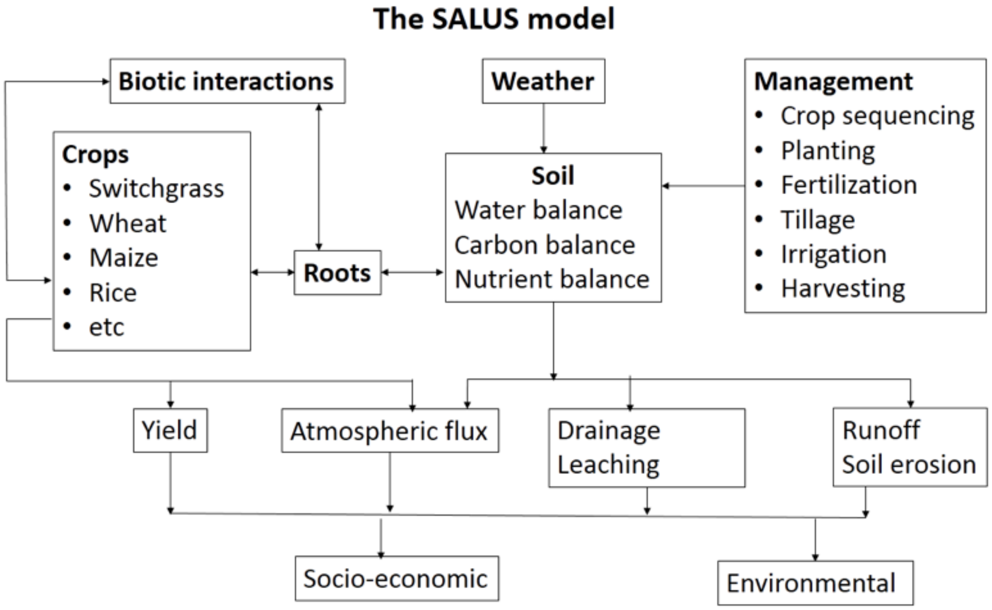


Figure 3. Overview of the SALUS model (Basso et al., 2006)

Besides the capability of simulating crop growth under different combinations of soil, weather and management, the model has switches for disabling/enabling simulations for water, nitrogen and phosphors balance. The SALUS model can be operated in four modes: 1) 'plant growth simulation only' mode where water and nitrogen limitations were not simulated, referred as 'no limitation' mode, 2) 'plant growth and water balance' mode where water balance module is invoked but nutrient cycle modules are not invoked in the simulations, referred as 'limited water' mode, 3) 'plant growth, nitrogen balance and water balance' mode where nitrogen and water cycles are their limitations to crop growth are simulated, referred as 'limited nitrogen & water' mode and 4) 'plant growth, nitrogen, phosphorus and water balances' mode where nutrient cycle and water balance are simulated and their constraining effect on crop growth are considered.

The SALUS model has been evaluated for crop developmental stages and crop yield for multiple years under varied conditions (Basso et al., 2010; Basso et al., 2011b).

It has also been validated for simulating the nutrient cycle, including nitrate leaching, nitrogen uptake, carbon loss under tillage versus non-tillage cropping systems (Basso et al., 2010; Giola et al., 2012; Senthilkumar et al., 2009). Soil water content simulation was also tested under varied nitrogen input treatments (Basso et al., 2010). The SALUS model requires the following input: weather, soil, agronomic management and crop parameters.

Weather data

The centroid of each county was used for extracting daily weather variables under historical (1981-2011) and projected (2039-2068) weather scenarios. Historical daily minimum and maximum temperature, precipitation and solar radiation were extracted from the Land Data Assimilation Systems (LDAS). LDAS is a 1/8-degree gridded reanalysis climate data product (Mitchell et al., 2004). The future climate scenario was extracted from the output of the Canadian Regional Climate Model driven by the Community Climate System Model (CRCS_CCSM), provided by the North American Regional Climate Change Assessment Program (Mearns et al., 2009, updated 2014). The CRCS_CCSM model is based on the A2 future emission scenario in the Special Report on Emissions Scenarios (SRES), in which temperature rises by 3.7°C as a result of relatively high increases in greenhouse gas emissions (Mearns et al., 2009). The CRCS_CCSM model output was chosen because of its spatial and temporal coverage. A study showed that the simulated historical maize yield using weather data from the CRCS_CCSM model as input matched with the observations (Glotter et al., 2014). Several crop simulation studies have demonstrated the need for bias correction for regional climate model output (Baigorria, 2007; Glotter et al., 2014; Olesen et al., 2007).

This study followed the quantile-based mapping strategy in Wood et al. 2002 and Wood et al. 2004 for climate anomaly bias removal. Biases were first identified by comparing cumulative probabilities of the observed weather variables and the CRCS_CCSM climate anomalies on a monthly basis in 1979-1999. Fine resolution weather data from the LDAS was used as observed weather data in the correction process. The quantile mapping process was done for each weather location and for each of the following weather variables: solar radiation, minimum and maximum temperature and precipitation. After the difference identifications in the bias mapping process, additions of the daily-interpolated differences in minimum and maximum temperature were applied to the temperature anomalies; multiplications of the differences in precipitation and solar radiation were applied to the respect weather variables (Wood et al., 2004; 2002). Figure 4 shows summaries of the weather input for the SALUS model (Figure **4**).

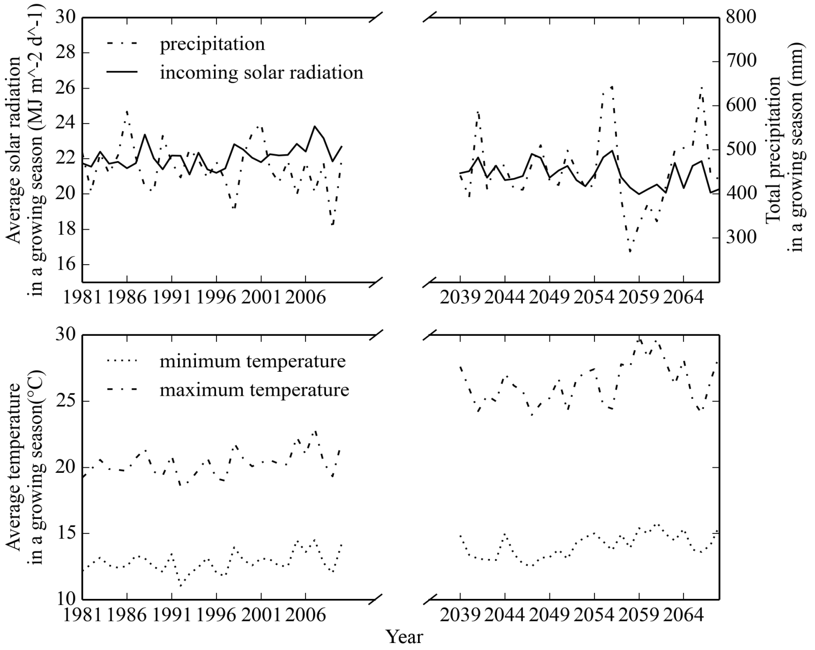


Figure 4. Summary of minimum and maximum temperature, precipitation, incoming solar radiation in growing seasons in 1981-2010 and 2039-2068 averaging among 82 counties in Michigan

Soil data

Soil information including silt, clay and sand content, pH, bulk density and organic matter content by depth were extracted from the Soil Survey Geographic (SSURGO) database (USDA/NRCS 2014). Predominant soils were used for soil units in the SSURGO database. Soil units that did not have the detailed soil information or under land cover of urban, forest, wetland based on the National Land Cover Database were excluded from this study (Jin et al., 2013). In total, there were 2274 soil units included in this study (Table **4** and Figure **2**.b). The land capability class (LCC) in the SSURGO database was used to characterize land for profitable agricultural production. There are eight classes (i.e. LCC I-VIII) of land potentials and constrains for sustained agricultural production. From LCC I to LCC VIII, the potential for crop production decreases and the level to which the land constrains sustainable agricultural production increases (Table **5**). In general, land with LCC I-IV is considered agricultural land and land with LCC V-VIII is considered marginal land (Gelfand et al., 2013; Klingebiel and Montgomery, 1961).

Table 4. Number of soil units for each land capability class (LCC)

LCC	I	II	III	IV	V	VI	VII	Total
Number of soil units included	27	968	807	257	68	118	29	2274

Table 5. Descriptions for each land capability class (LCC) developed by the USDA (Klingebiel and Montgomery, 1961)

LCC	Description
I	Few limitations that restrict their use;
II	Some limitations due to gentle slope, susceptibility to erosion, less than ideal soil depth and slight climatic limitations, etc.; require moderate conservation practices;

Table 5 (cont'd)

III	Severe limitations that reduce the choice of plants; constraining factors include moderately steep slopes, high susceptibility to erosion, frequently overflow, shallow depths, low water holding capacity, low fertility, moderate climatic limitations;
IV	Very severe limitations that restrict the choice of plants; constraining factors include steep slopes, severe susceptibility to erosion, shallow soils, low water holding capacity, frequent overflow, excessive wetness, severe salinity and moderately adverse climate;
V	Little or no erosion hazard but have other limitations impractical to remove that limit their use largely to pasture, range, wildlife; constraining factors include overflow, ponded areas that are not feasible for crops but suitable for grasses;
VI	Severe limitations that are unsuitable to cultivation and limit the use to pasture, range or wildlife; constraining factors include steep slope, erosion hazard, shallow rooting zones, stoniness, low water holding capacity, salinity, severe climate;
VII	Very severe limitations that restrict the use to grazing, woodland or wildlife; constraining factors include very steep slopes, erosion, shallow soil, stones, wetness, sodium, unfavorable climate;
VIII	Limitations that preclude their use for commercial plant production; constraining factors include erosion, severe climate, wet soils, stones, low water holding capacity and salinity;

Switchgrass agronomic management

Switchgrass was simulated under rain-fed and unfertilized management for both historical (1981-2010) and future (2039-2068) climate scenarios. Planting dates ranged from day of year (DOY) 132 to 155 and harvesting dates ranged from DOY 280 to 300 since there is a wide temperature range across Michigan (median temperature in May between 1981 and 2010 ranged from 6 to 16°C).

Limiting factor contribution to ANPP reduction quantification

SALUS was also applied to examine the influence of limiting factors on ANPP, particular nitrogen and water. In addition to running SALUS under 'limited nitrogen &

water' mode to show ANPP under recent and future climate, SALUS was run under the 'no limitation' and 'limited water' modes with the same soil, weather and management practices as in the 'limited nitrogen & water' mode for both climate scenarios. Average ANPP with only nitrogen limitation was calculated by subtracting the difference between ANPP under 'limited water mode' and 'full mode' from ANPP under 'no limitation mode'. Nitrogen and water limitation contributions to ANPP reduction are calculated using equations 1 to 3.

$\text{Percentage ANPP reduction by limited nitrogen} = 100 *(\text{ANPP}_{(\text{limited water mode})} - \text{ANPP}_{(\text{limited nitrogen \& water mode})})/\text{ANPP}_{(\text{no limitation mode})}$ …………………………equation 1

$\text{Percentage ANPP reduction by limited water} = 100 *(\text{ANPP}_{(\text{no limitation mode})} - \text{ANPP}_{(\text{limited water mode})})/\text{ANPP}_{(\text{no limitation mode})}$ ……………………………………equation 2

$\text{Percentage ANPP reduction by limited water and limited nitrogen} = 100 *(\text{ANPP}_{(\text{no limitation mode})} - \text{ANPP}_{(\text{limited nitrogen \& water mode})})/\text{ANPP}_{(\text{no limitation mode})}$ ….equation 3

Results

SALUS model evaluation

The switchgrass ANPP in 2010-2013 simulated by the SALUS model was compared with the observed (cultivar 'Rock-in-Cave') values from the field trials in the Great Lakes Bioenergy Research Center (GLBRC) at the Kellogg Biological Station site in southwestern Michigan. Planting dates in the field experiments ranged from DOY 283 to 315. Nitrogen fertilizer was applied at 56 kg/ha for the first two years after planting, 20 kg/ha for the third year and 57 kg/ha for the fourth year. Field-collected soil and weather information were used for the ANPP comparison (GLBRC, Sanford et. al.). The SALUS model was able to closely simulate switchgrass growth in both initialization and established phases and under varied nitrogen inputs with overall root mean square error of 0.28 Mg/ha/year (Figure **5**).

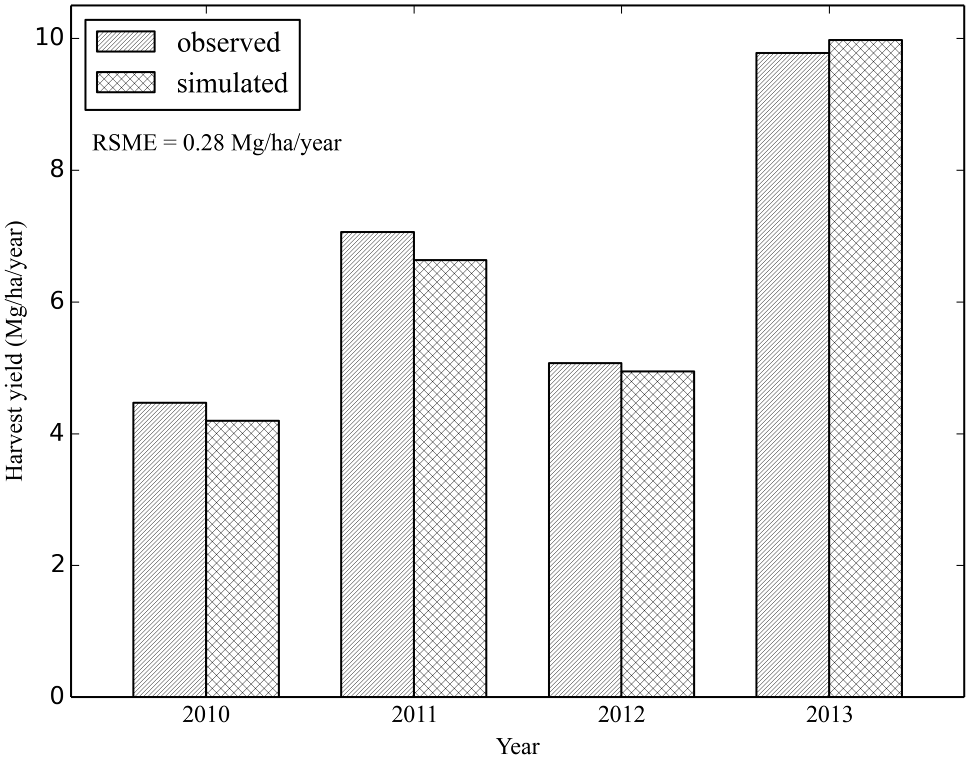


Figure 5. Comparisons between observed and simulated switchgrass ANPP from 2010 to 2013

Switchgrass ANPP in 1981-2010

The simulated switchgrass annual ANPP for each soil unit in 1981-2010 varied greatly, ranging from 15 to 21417 kg/ha/year (Figure **6**). In general, with increases in land marginality, there is a decreasing ANPP trend except for LCC I. The probability that switchgrass ANPP from LCC I exceeds that from LCC II is less than 20% (Figure **6**). Nonetheless, the coefficient of variation (c.v.) for ANPP over the simulated 30 years was smaller for agricultural land (i.e., LCC I-IV, median c.v. is 0.16) than marginal land (i.e., LCCV-VII, median c.v. is 0.21) and LCC V exhibits the highest ANPP variation among all land capability classes (Figure **7**).

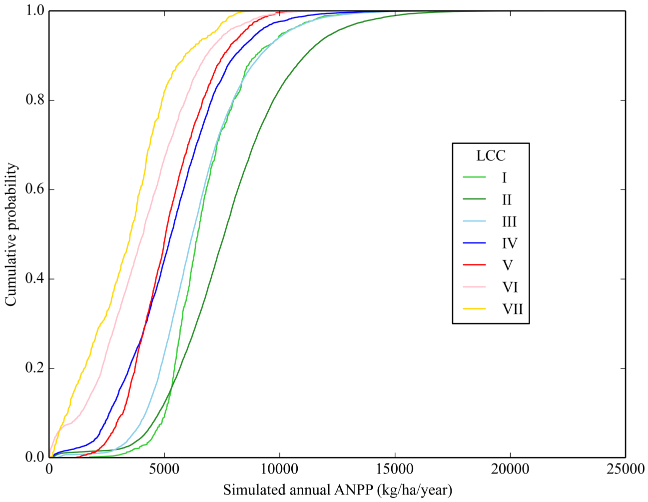


Figure 6. Cumulative probability of switchgrass annual ANPP for the included soil units in Michigan in 1981-2010 by LCC

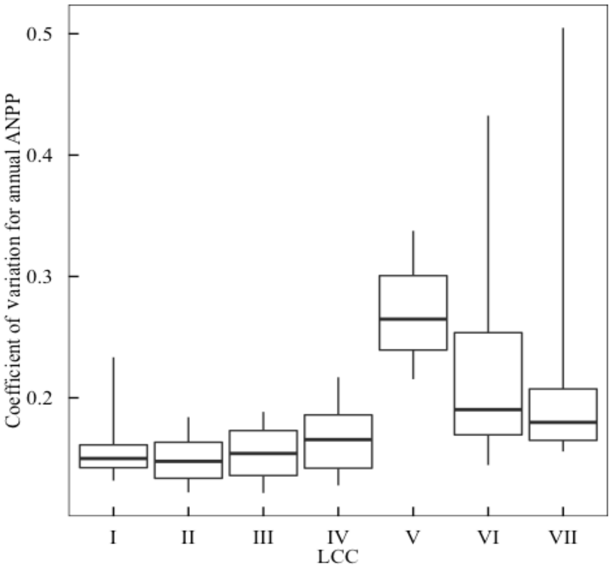


Figure 7. Coefficient of variation for the simulated switchgrass annual ANPP for the included soil units in Michigan grouped by LCC in 1981-2010 (only 10-90 percentile values for each LCC are included)

The simulated switchgrass average ANPP in 1981-2010 for each simulated soil unit in Michigan has a wide range as well. The average ANPP in Michigan in the simulated 30 years is 6703 kg/ha/year and the standard deviation is 2322 kg/ha/year (Figure **8**). Excluding less than 10 percentile and larger than 90 percentile average ANPP values for each LCC, the average ANPP ranges from 928 to 10552 kg/ha/year. Except for LCC I, the median ANPP decreases as land marginality increases. However, the minimum ANPP for LCC I is the largest among all minimum ANPP across all land types (Figure **9**).

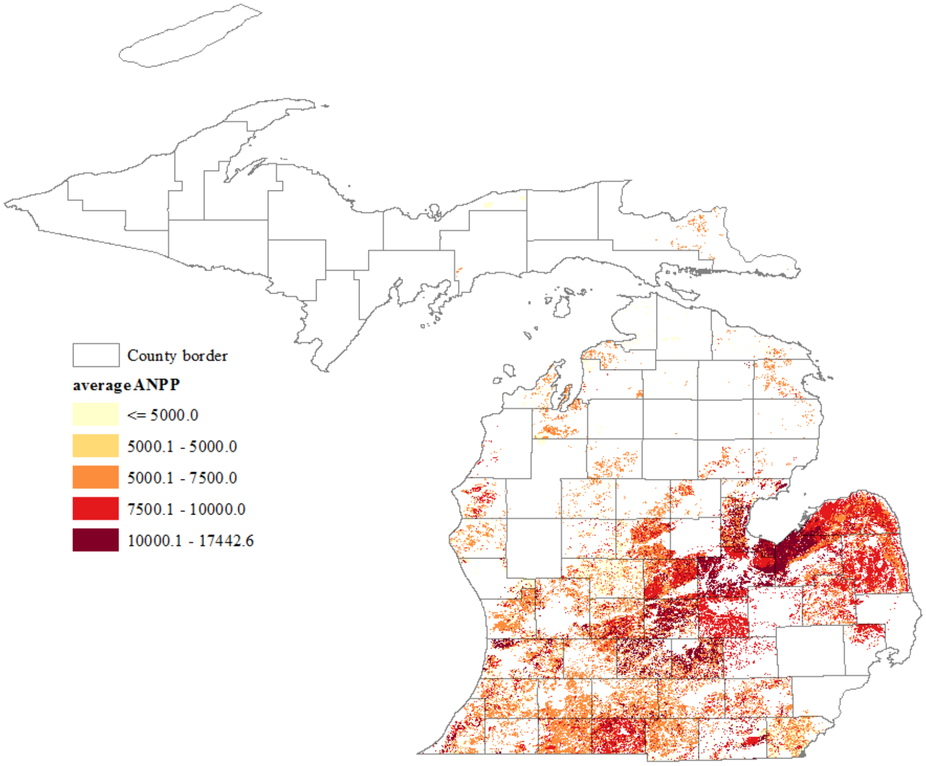


Figure 8. Spatial distribution of average simulated switchgrass ANPP (kg/ha/year) in 1981-2010 in Michigan

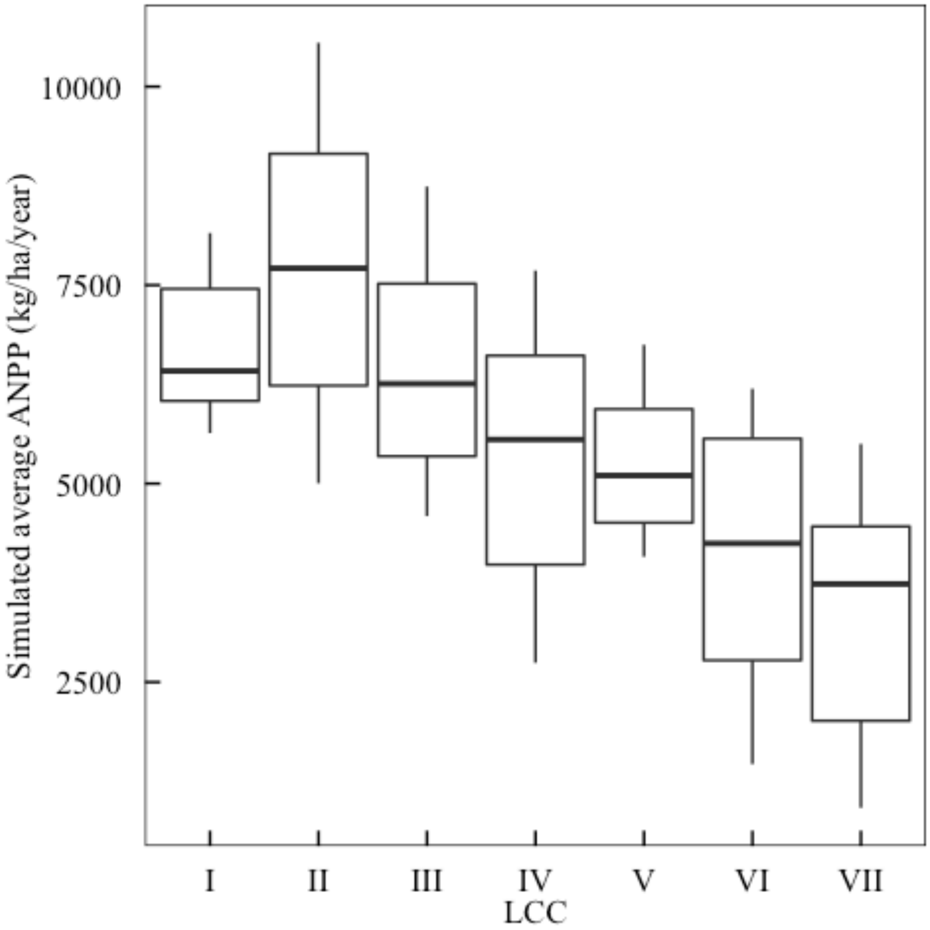


Figure 9. Simulated switchgrass average ANPP for the included soil units in Michigan grouped by LCC in 1981-2010 (only 10-90 percentile values for each LCC are included)

Switchgrass ET in 1981-2010

The average ET in a growing season for the simulated soil units in Michigan in 1981-2010 ranges from 163 to 725 mm (Figure **10**). In general, the growing season ET decreases as the land marginality increases but the average ET is smallest for LCC V soil units in the simulated 30 years. Agricultural land (average ET = 572 mm) tends to have higher ET than marginal land (average ET = 443 mm) (Figure **11**). The average growing season ET in 1981-2010 tends to be large for the southern Michigan than the northern Michigan (Figure **10**).

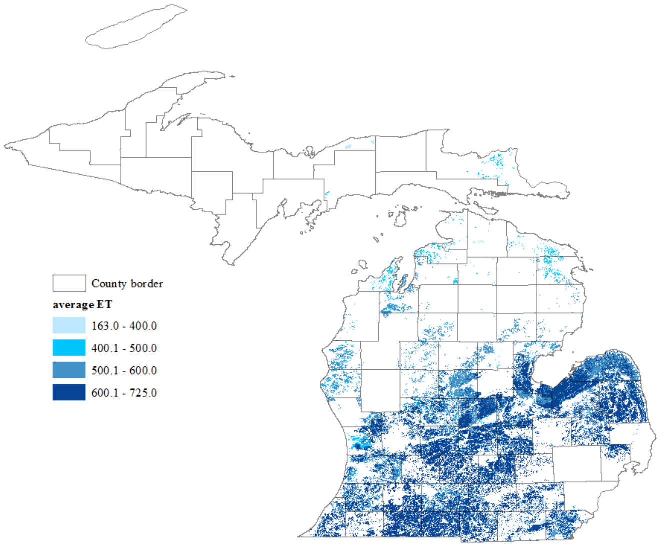


Figure 10. Spatial distribution of average simulated switchgrass growing season ET (mm) in 1981-2010 in Michigan

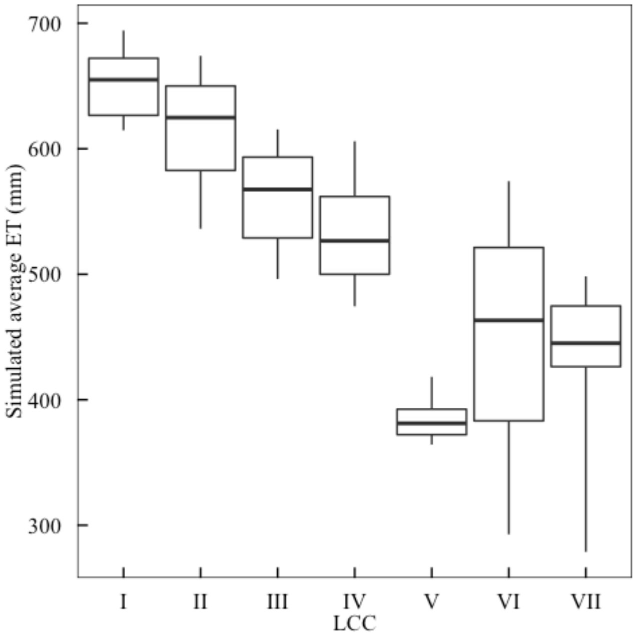


Figure 11. Simulated switchgrass average growing season ET (mm) for the included soil units in Michigan grouped by LCC in 1981-2010 (only 10-90 percentile values for each LCC are included)

Switchgrass ANPP in 2039-2068

Compared to average ANPP in 1981-2010, the average ANPP is predicted to decrease for land with LCC I-VII with high probability in the projected 2039-2068. Over all lands in Michigan, the probability to have increase average ANPP is no more than 22%. Given 50% probability, average ANPP is predicted to decrease by 3-12% for all land classes except for LCC V. Land with LCC V is projected to have 30% decrease in average ANPP given 50% probability (Figure **12**). A majority of Michigan expects a decrease in average ANPP in the projected 30 years (Figure **13**).

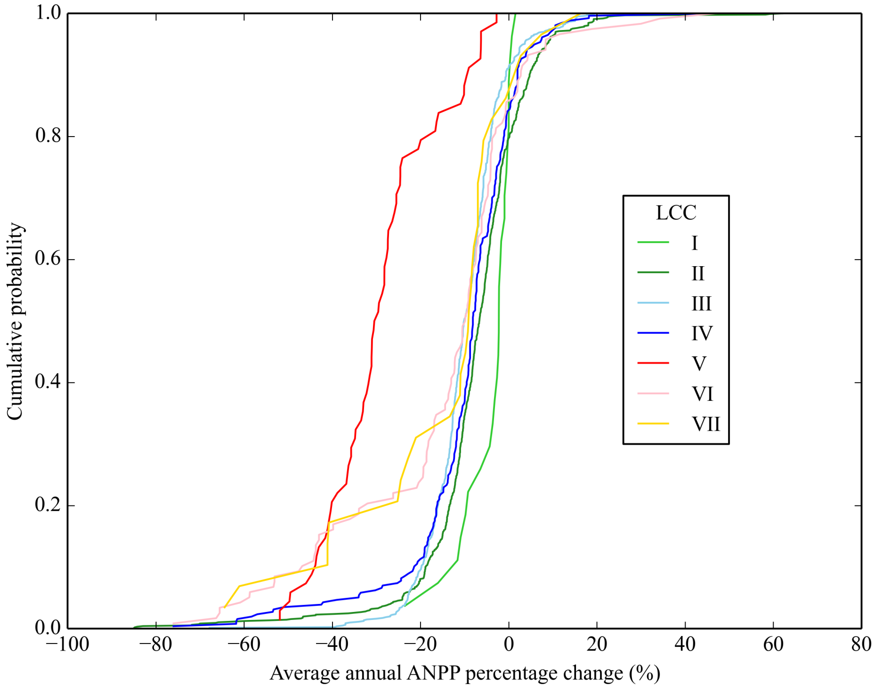


Figure 12. Cumulative probability of switchgrass average ANPP percentage change in 2039-2068 compared to 1981-2010 for the included soil units in Michigan by LCC (negative values denote decrease and positive values denote increase)

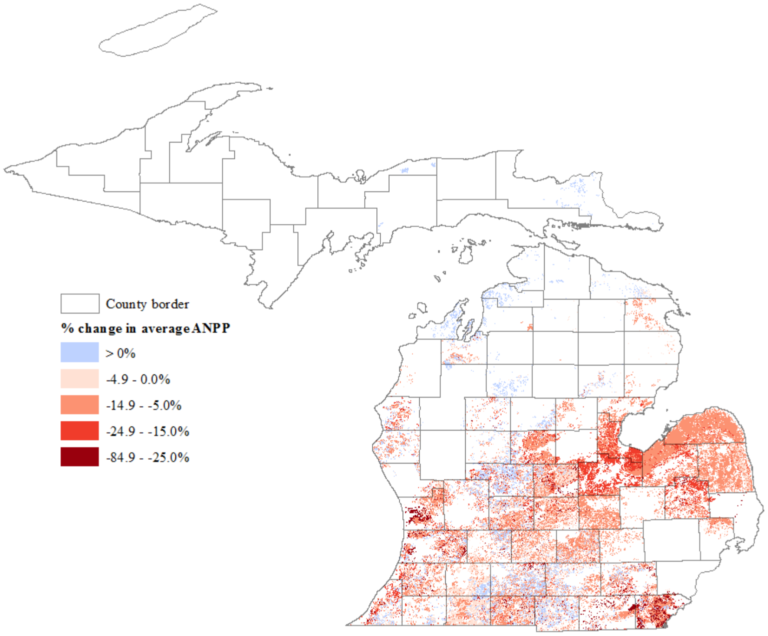


Figure 13. Spatial distribution of percentage changes in simulated average ANPP in 2039-2068 compared to 1981-2010 in Michigan (negative values denote decrease and positive values denote increase)

Similar to the average ANPP with historical climate, the ANPP across Michigan has a wide range with average ANPP of 586-9355 kg/ha/year. The average ANPP decreases with increasing land marginality (Figure **14**). The simulated ANPP has less variation for agricultural land (average c.v. = 0.25) than marginal land (average c.v. = 0.29) (Figure **15**). The maximum average ANPP for Michigan decreases in the projected 2039-2038 but there does not show changes in high productivity regions (Figure **16**).

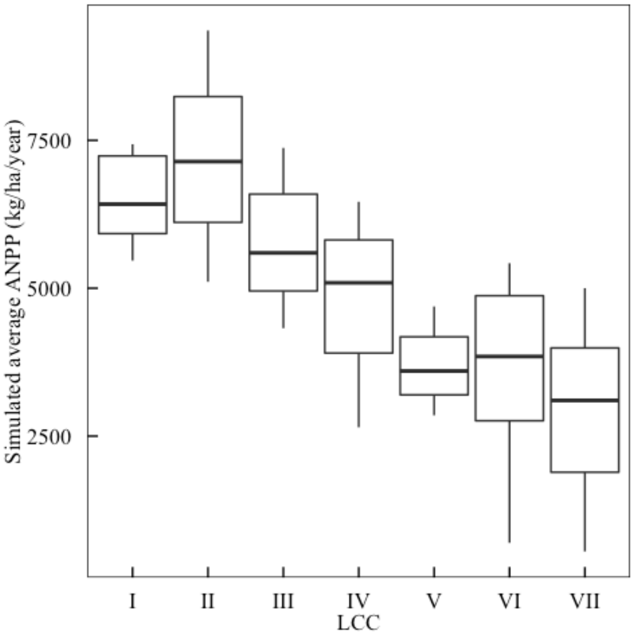


Figure 14. Simulated switchgrass average ANPP for the included soil units in Michigan grouped by LCC in 2039-2068 (only 10-90 percentile values for each LCC are included)

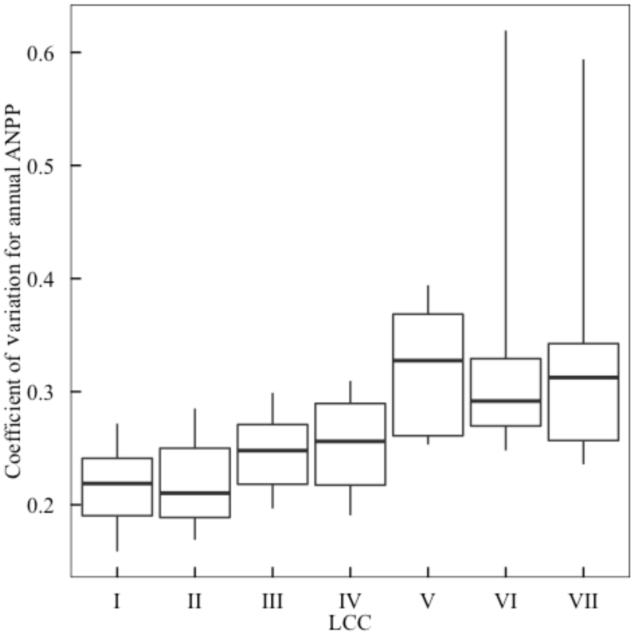


Figure 15. Coefficient of variation for the simulated switchgrass annual ANPP for the included soil units in Michigan grouped by LCC in 2039-2068 (only 10-90 percentile values for each LCC are included)

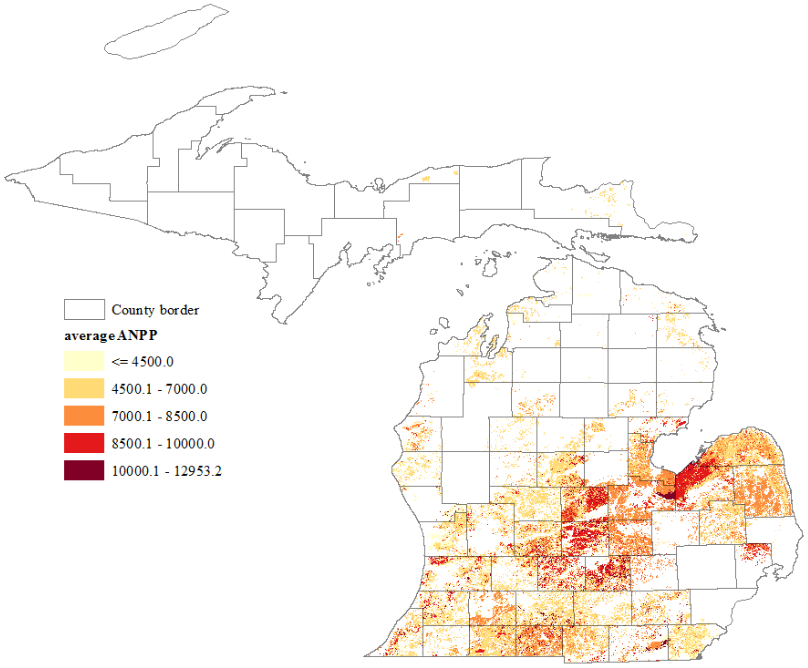


Figure 16. Spatial distribution of average simulated switchgrass annual ANPP (kg/ha/year) in 2039-2068 in Michigan

Switchgrass ET in 2039-2068

With the projected climate in 2039-2068, the simulated growing season ET for each soil units is 180-781 mm. The average growing season ET for soil units included in this study in Michigan is 609 mm in 2039-2068 (Figure **17**). The average ET in 2039-2068 is higher for agricultural land (average growing season ET = 617 mm) than marginal land (average growing season ET = 484 mm) (Figure **18**.a). Generally, we expect higher switchgrass ET in Michigan. Soil units across each land capability class, except for LCC V, are predicted to have increase in average ET by about 6% on average (Figure **18**. b and Figure **20**). Nonetheless, the variations of ETs under future climate would be larger than under historical climate (Figure **19**). However, there appears to be a shift between the evaporation and transpiration components of ET. Under the future climate, average plant transpiration decreases while soil water evaporation increases in most of Michigan (Figure **21** and Figure **22**).

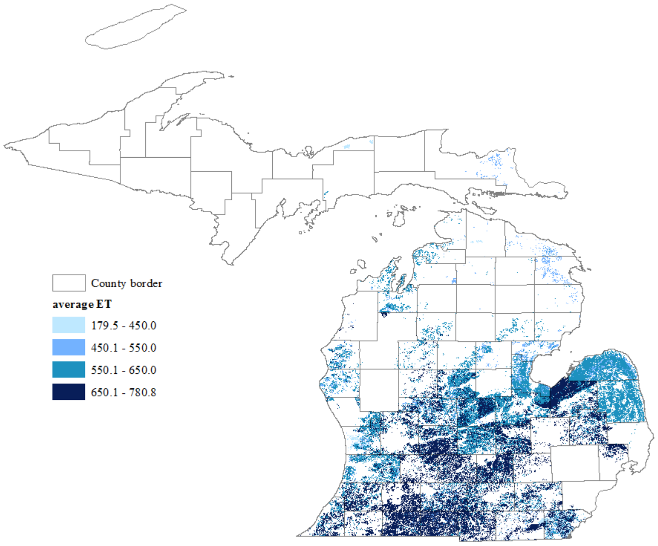


Figure 17. Spatial distribution of average switchgrass ET (mm) in a growing season in 2039-2068 in Michigan

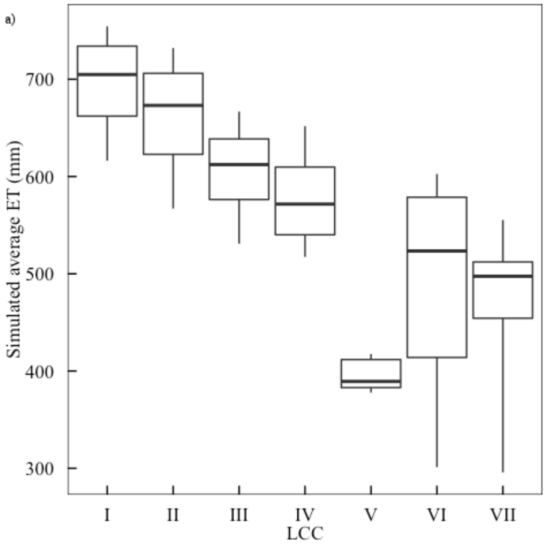
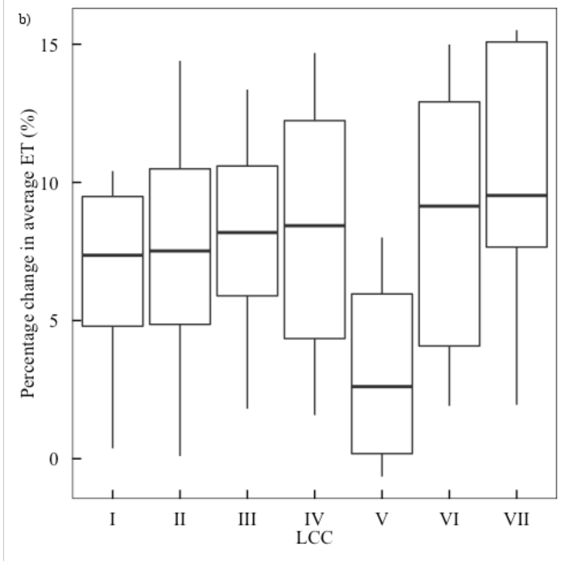


Figure 18. a) Simulated switchgrass average growing season ET (mm) for the included soil units in Michigan grouped by LCC in 2039-2068 (only 10-90 percentile values for each LCC are included), b) Simulated switchgrass average growing season ET percentage change in 2039-2068 compared to 1981-2010 for the included soil units in Michigan grouped by LCC (only 10-90 percentile values for each LCC are included)

Figure 18 (cont'd)



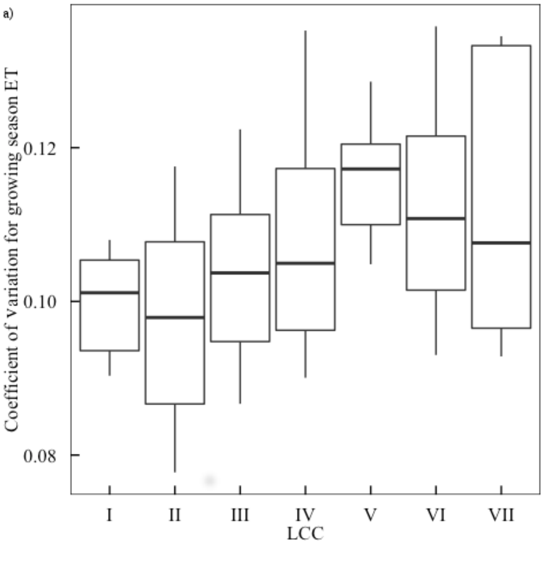
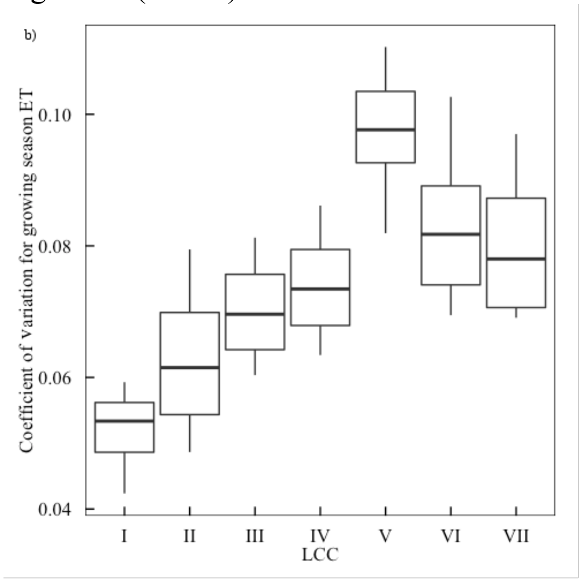


Figure 19. Coefficient of variation for the simulated switchgrass growing season ET for the included soil units in Michigan grouped by LCC in a) 2039-2068 and b) 1981-2010

Figure 19 (cont'd)



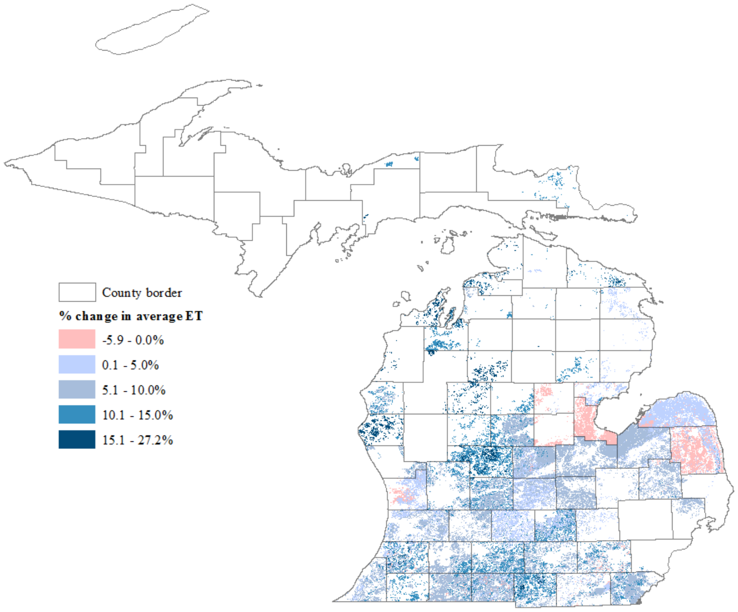


Figure 20. Spatial distribution of percentage changes in average ET in a growing season in 2039-2068 compared to 1981-2010 in Michigan (negative values denote decrease and positive values denote increase)

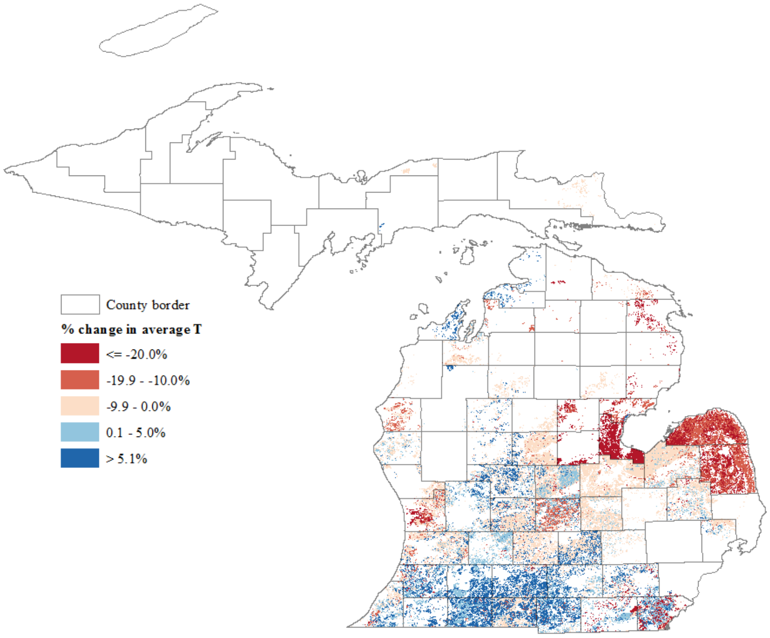


Figure 21. Spatial distribution of percentage changes in average plant transpiration (T) in 2039-2068 compared to 1981-2010 in Michigan (negative values denote decrease and positive values denote increase)

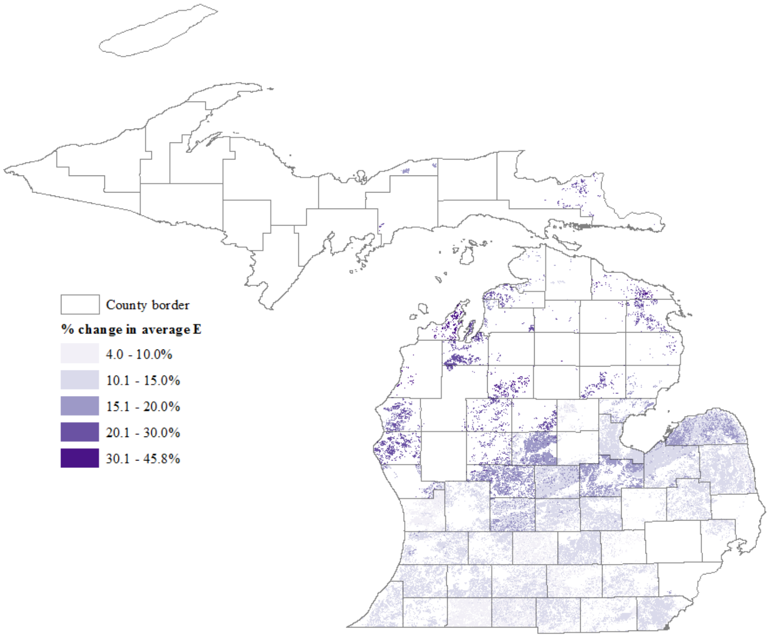


Figure 22. Spatial distribution of percentage changes in average soil water evaporation (E) in 2039-2068 compared to 1981-2010 in Michigan (negative values denote decrease and positive values denote increase)

ANPP reduction attributed to the limited nitrogen and water under historical and future climate

Under historical climate, with unlimited nitrogen and water, the mode of average potential switchgrass ANPP in Michigan is 22810 kg/ha/year; with limited nitrogen but unlimited water, the mode of average switchgrass ANPP is 15263 kg/ha/year; with limited water but unlimited nitrogen, the mode of average switchgrass ANPP is 14558 kg/ha/year (Figure **23-25**).

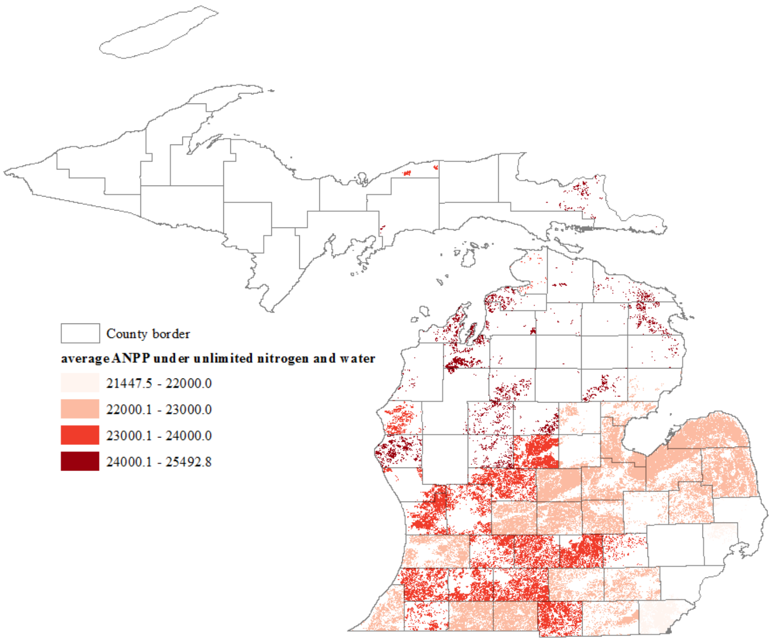


Figure 23. Average ANPP (kg/ha/year) under unlimited nitrogen and water for the included soil units in Michigan in 1981-2010

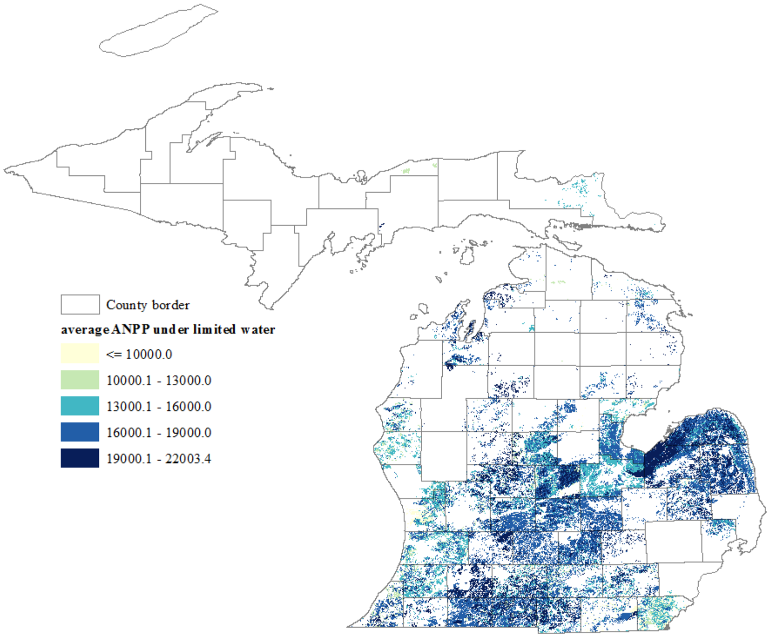


Figure 24. Average ANPP (kg/ha/year) under limited water but unlimited nitrogen for the included soil units in Michigan in 1981-2010

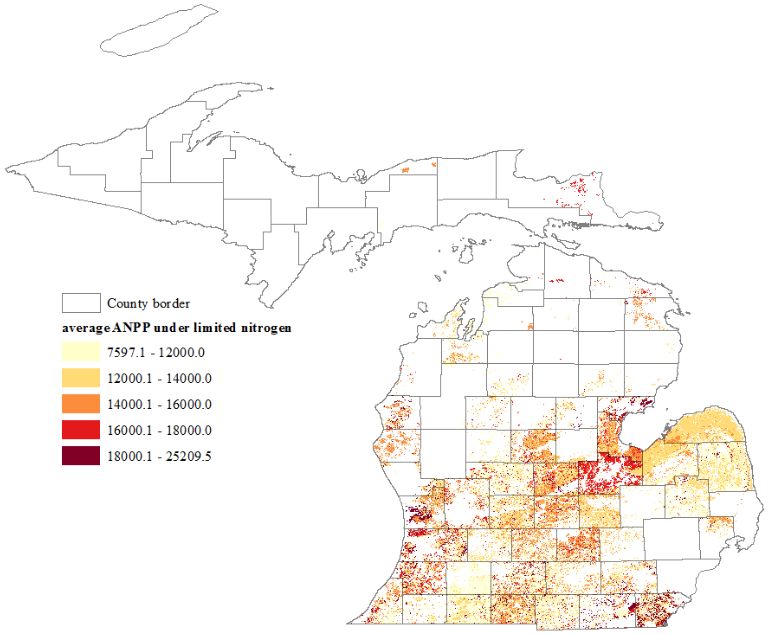


Figure 25. Average ANPP (kg/ha/year) under limited nitrogen but unlimited water for the included soil units in Michigan in 1981-2010

Average ANPP reductions by limited nitrogen, water and a combination of both varies across Michigan but in general, water limitation effects to switchgrass ANPP are less for agricultural land (i.e., LCC I-IV, ANPP reduced by 15-38%) than marginal land (i.e., LCC V- VII, ANPP reduced by 54-72%) but nitrogen limitation effects are more for agricultural land (ANPP reduced by 38-55%) than marginal land (5-28%) (Table **6**). For each soil units included in this analysis, its potential average ANPP reductions by limited nitrogen, water, and both nitrogen and water under historical climate were shown on Figure 26-28.

Table 6. Average simulated ANPP without limiting factor(s) and percentage reduction (%) in ANPP by the limiting factor(s) for the included soil units in Michigan by LCC in 1981-2010

LCC	Limited nitrogen and water		Limited nitrogen		Limited water	
	ANPP	*Reduction (%)*	*ANPP*	*Reduction (%)*	*ANPP*	*Reduction (%)*
I	22503	70	19112	55	10168	15
II	22952	66	17692	43	13036	23
III	23080	72	15374	39	14169	33
IV	23226	77	14317	38	14273	38
V	22956	77	6387	5	21796	72
VI	23460	83	10761	28	16798	54
VII	23768	86	9502	25	17697	60

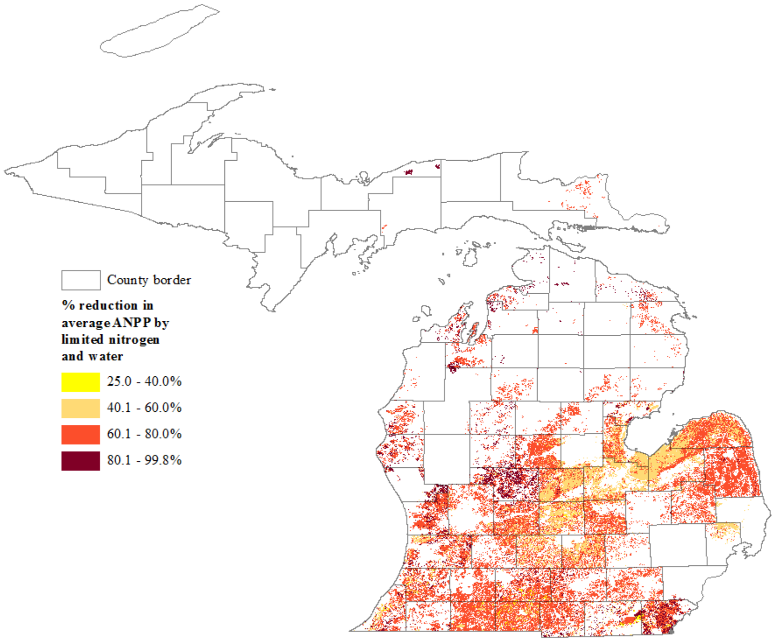


Figure 26. Percentage reduction in average ANPP (%) attributed to limited nitrogen and water for the included soil units in Michigan in 1981-2010

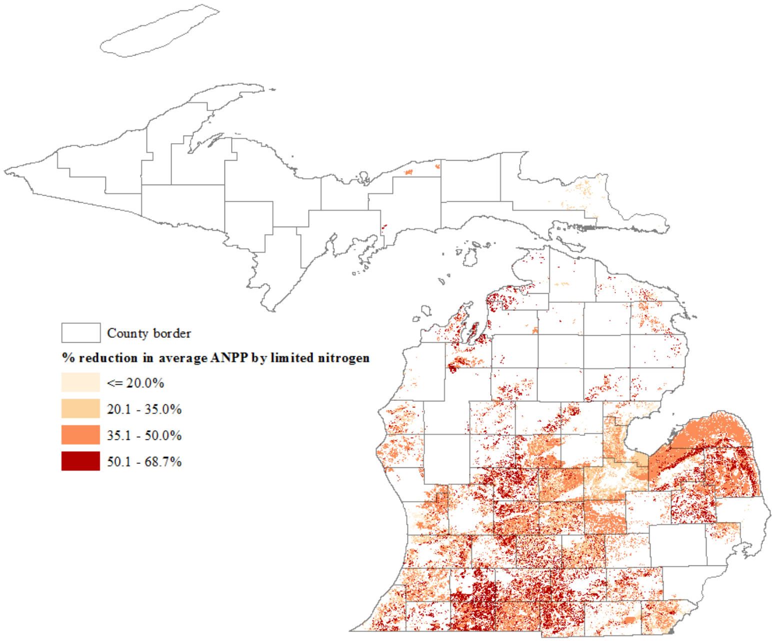


Figure 27. Percentage reduction in average ANPP (%) attributed to limited nitrogen for the included soil units in Michigan in 1981-2010

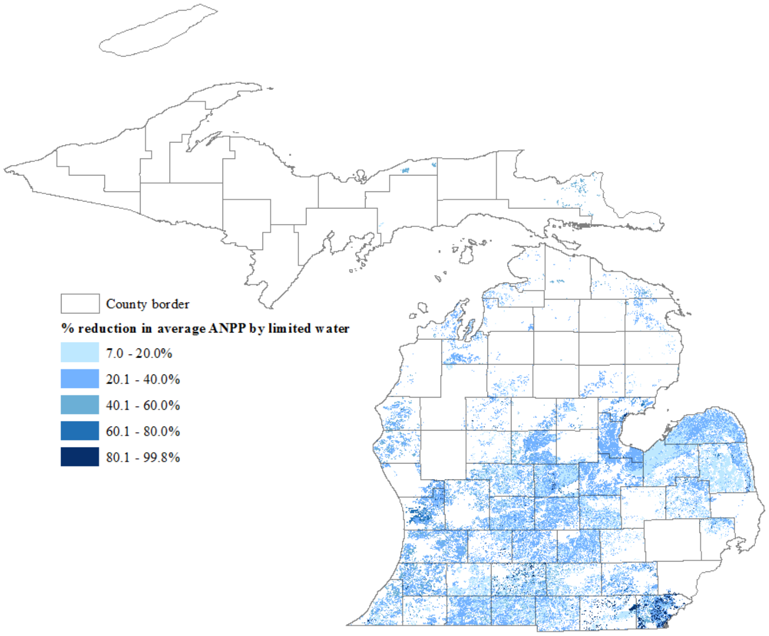


Figure 28. Percentage reduction in average ANPP (%) attributed to limited water for the included soil units in Michigan in 1981-2010

Under the projected future climate, with unlimited water and nitrogen, the mode of average ANPP under unlimited nitrogen and water, limited nitrogen, and limited water are 19650 kg/ha/year, 17312 kg/ha/year, 9260 kg/ha/year, respectively (Figure **29-31**). For each soil unit included in this analysis, its potential average ANPP reductions by limited nitrogen, water, and both nitrogen and water under future climate are shown on Figure 32-34. On average, the effect of limited nitrogen decreases from 39% in 1981-2010 to 22% in 2039-2068, the effect of limited water increases from 32% to 47% and the effect of both limited nitrogen and water decreases from 71% to 69% (Figure **26-28** and Figure **32-34**). Similar to water limitation effect on switchgrass ANPP under the historical climate, average ANPP reduced by limited water are smaller for agricultural land (ANPP reduced by 30-54%) than marginal land (68-79%) in 2039-2068, and limited nitrogen reduces average ANPP more for agricultural land (by 21-36%) than marginal land (3-15%) (Table **7**).

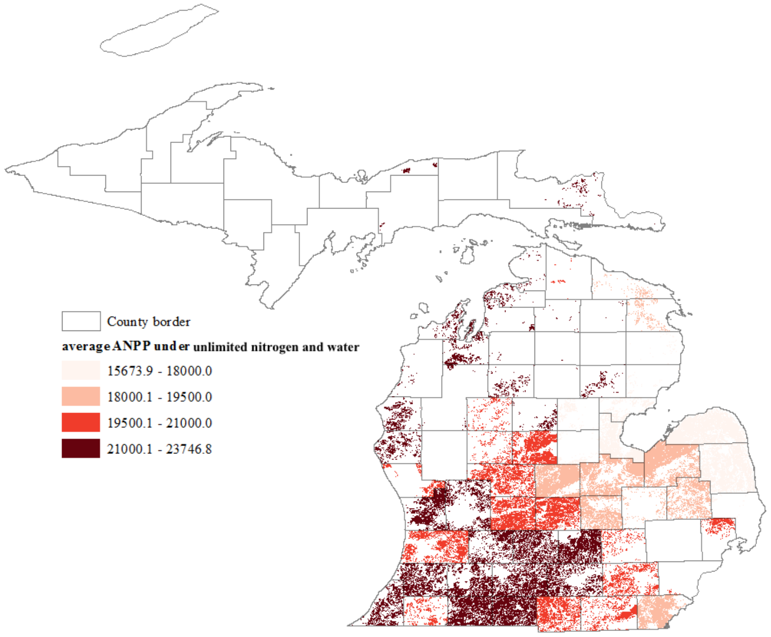


Figure 29.Average ANPP (kg/ha/year) under unlimited nitrogen and water for the included soil units in Michigan in 2039-2068

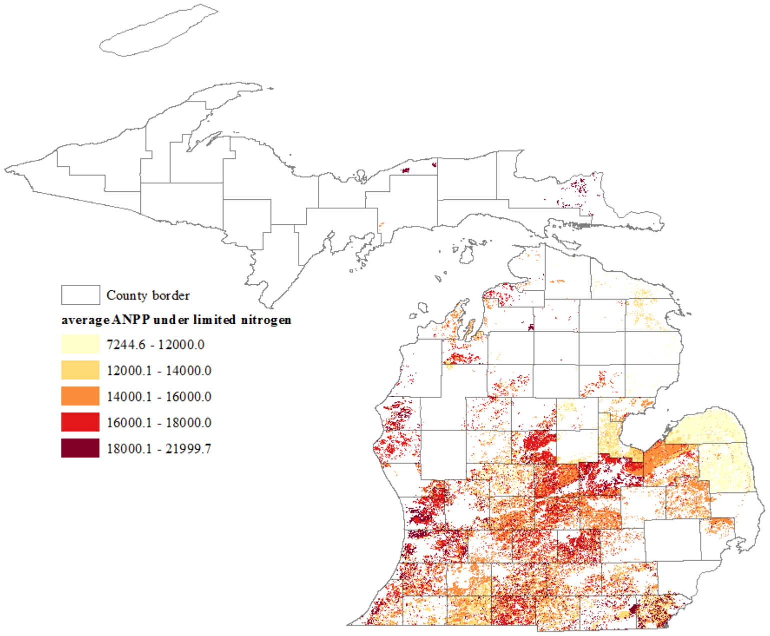


Figure 30.Average ANPP (kg/ha/year) under limited nitrogen but unlimited water for the included soil units in Michigan in 2039-2068

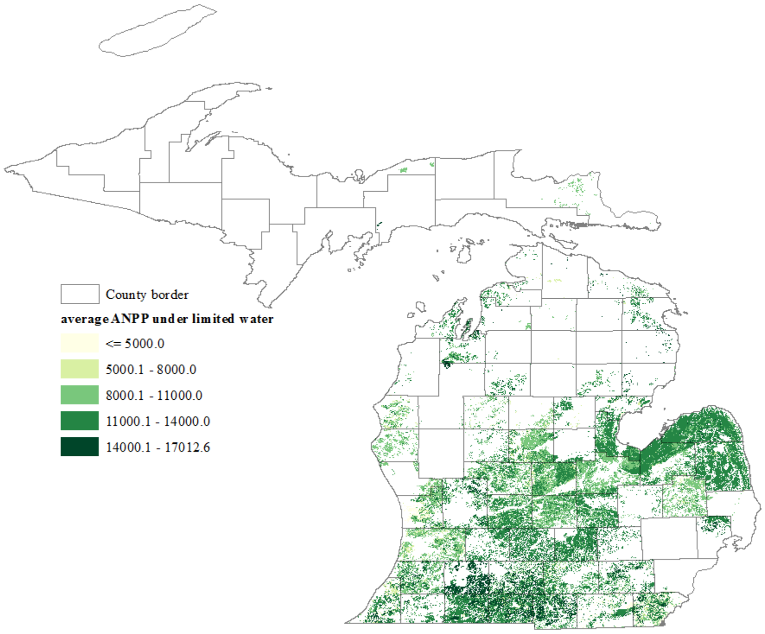


Figure 31.Average ANPP (kg/ha/year) under limited water but unlimited nitrogen for the included soil units in Michigan in 2039-2068

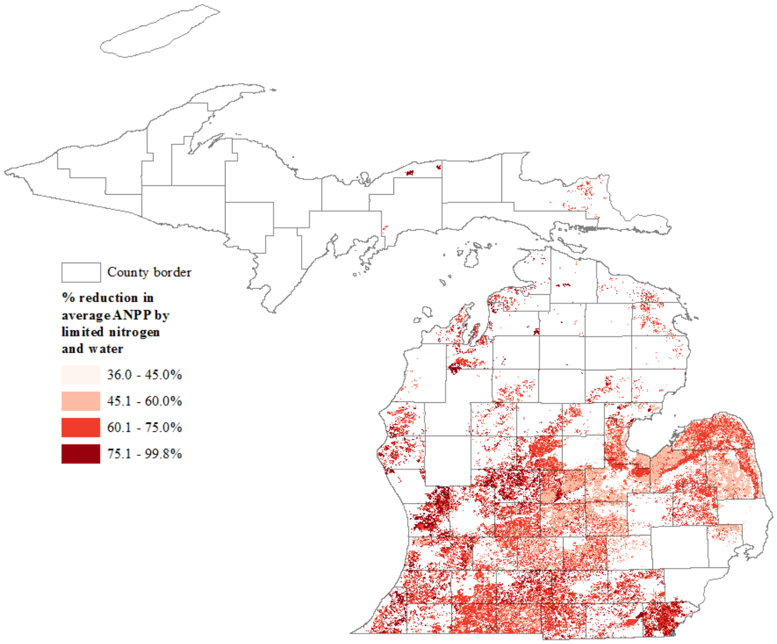


Figure 32. Percentage reduction in average ANPP (%) attributed to limited nitrogen and water for the included soil units in Michigan in 2039-2068

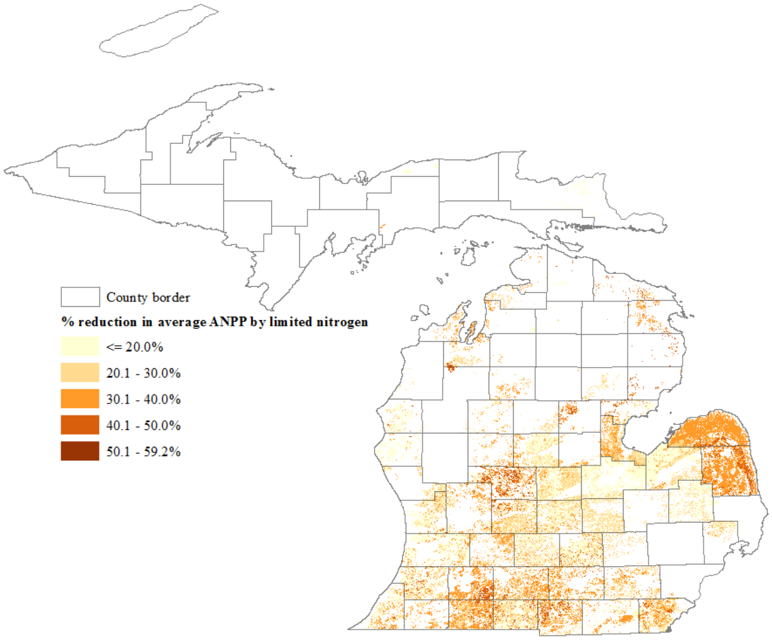


Figure 33. Percentage reduction in average ANPP (%) attributed to limited nitrogen for the included soil units in Michigan in 2039-2068

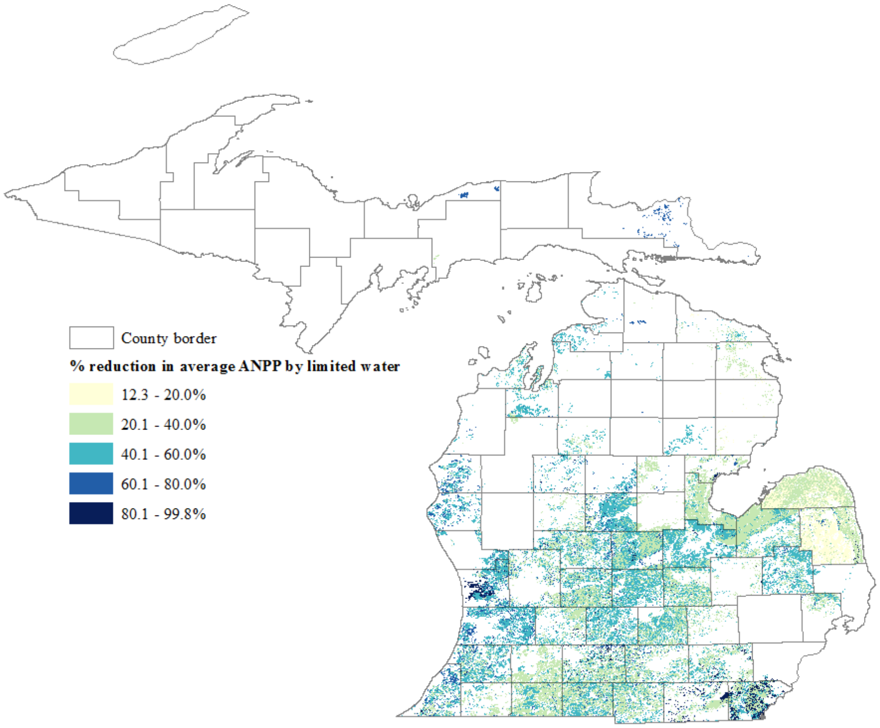


Figure 34. Percentage reduction in average ANPP (%) attributed to limited water for the included soil units in Michigan in 2039-2068

Table 7. Average simulated ANPP without limiting factor(s) and percentage reduction (%) in ANPP by the limiting factor(s) for the included soil units in Michigan by LCC in 2039-2068

LCC	Limited nitrogen and water		Limited nitrogen		Limited water	
	ANPP	*Reduction (%)*	*ANPP*	*Reduction (%)*	*ANPP*	*Reduction (%)*
I	18997	66	13227	36	12260	30
II	19692	64	12036	25	14795	39
III	19861	71	9964	21	15639	50
IV	20020	76	9229	22	15605	54
V	19840	81	4137	3	19383	79
VI	20248	82	6548	15	17256	68
VII	20392	85	5591	13	17796	72

Compared to historical climate, limited water effect on switchgrass ANPP reduction increases but limited nitrogen effect decreases for most of Michigan. The average of differences in water effect on switchgrass ANPP for Michigan between 2039-2068 and 1981-2010 is 15% and the average of differences in nitrogen effect is -16% (Figure **36** and Figure **37**). Depending on the locations of soil units, the overall limited water and nitrogen effect on switchgrass ANPP may increase or decrease but average of the difference in both nitrogen and water effects is -1.5% (Figure **35**).

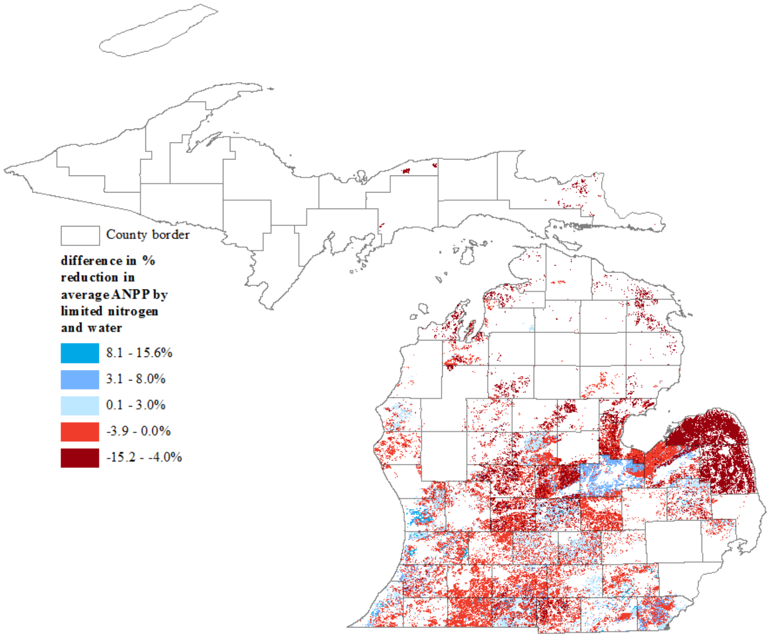


Figure 35.Differences in percentage reduction in average ANPP attributed to limited nitrogen and water between future and historical climate in Michigan (negative values indicate decreases and positive values indicate increases)

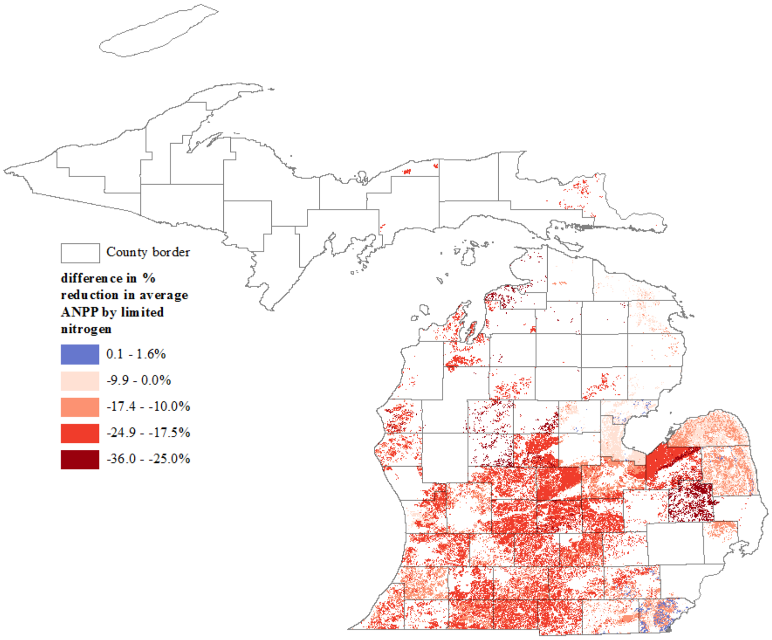


Figure 36. Differences in percentage reduction in average ANPP attributed to limited nitrogen between under future and historical climate in Michigan (negative values indicate decreases and positive values indicate increases)

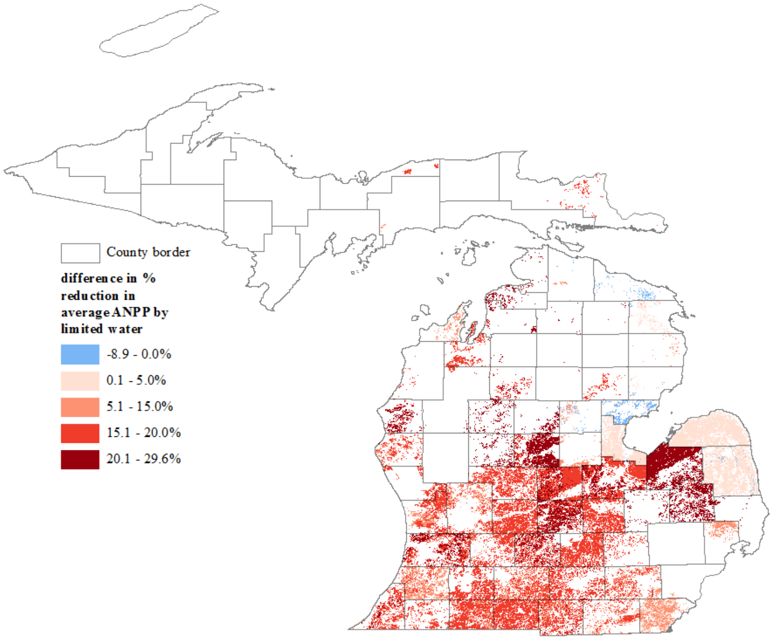


Figure 37. Differences in percentage reduction in average ANPP attributed to limited water between future and historical climate in Michigan (negative values indicate decreases and positive values indicate increases)

Discussions

The LCC developed by the USDA considers the levels of limiting factors to agricultural crop production and profitability. The LCC does not necessarily reflect the productivity of the land (Klingebiel and Montgomery 1961). For instance, Zhang et al. 2010 reported higher maize yield from continuous corn systems on LCC II than LCC I (Zhang et al., 2010). In my study, although there is a general trend of decreasing ANPP with the increasing land marginality, the least marginal land, LCC I, does not produce the highest ANPP but close to ANPP produced by the second least marginal land (LCC II).

The simulated switchgrass ANPP are subject to the cultivar parameters, management and soil information. The simulated ANPP of switchgrass, with crop parameters calibrated with other cultivars, could be higher than presented in this study

(McLaughlin et al., 2006). Nonetheless, the cultivar parameters used here were evaluated against the observed switchgrass ANPP in the field experiment at Kellogg Biological Station in Michigan. The simulated switchgrass ANPP in this study was comparable to the simulated rain-fed switchgrass ANPP in Michigan (0-15 Mg/ha/year) in Miguez et al. 2012 (Miguez et al., 2012). While some studies have reported high switchgrass ANPP of over 15 Mg/ha/year with 120 kg N/ha fertilizer addition, switchgrass was under no agricultural input management in this study (Kiniry et al., 2005). Furthermore, the predominant soil information for each soil-mapping unit at about 30-km resolution was extracted. The results would change provided different soil parameters. Unlike previous study where crop biomass yield had the highest yield on LCC V soils among all LCC category soils, the simulated switchgrass ANPP in this study did not exhibit the most productivity feature (Zhang et al., 2010). That was because the soil drainage limit parameters for the LCC V were adjusted to accommodate its excessive wet and susceptibility to flood feature (Klingebiel and Montgomery 1961). Nonetheless, LCC V land shows the least susceptibility to nitrogen stress since the organic matter on the top layers of the LCC V soils were high (Table **6** and Table **7**). Additionally, one should not interpret the switchgrass ANPP potentials as the absolute caps of switchgrass aboveground biomass production.

The ET estimated from field experiments ranged from 280 mm to 780mm, but the estimation approaches varied. Energy balance, water balance and Eddy covariance approaches were employed (eg: Hickman et al., 2010; McIsaac et al., 2010; Skinner and Adler 2010). In this study, the Ritchie method was used for ET estimation (Ritchie 1972; Basso and Ritchie 2012).

Under future climate, the simulation results suggest that the ANPP would decrease. It may be due to the shortened growing days by higher temperature even though precipitation may increase for some locations in Michigan and carbon dioxide positive effect on carbon assimilation. As a result of less ANPP and smaller leaf area development, plant transpiration reduces under future climate. With higher temperature and less leaf area, soil would be more exposed to the high moisture demand for evaporation, which in turn increase the soil water evapotranspiration. Because of the tradeoff between evaporation and transpiration, there is not a great increase in simulated ET for the future climate scenario. One should note that switchgrass ANPP and ET under future climate could change with different projected future climate scenarios.

As has been suggested by many researchers, crop development and growth are a result of interactions among genotypes, soil, climate and management, it is difficult to separate out which variables are detrimental to crop production (Ritchie et al., 1998; Miguez et al., 2012). However, in this study, the proposed approach where SALUS was run under three different modes provided an opportunity for identifying limited nitrogen and water contribution to switchgrass ANPP.

Conclusions

With both historical and future climate, ANPP for soil units in Michigan varied greatly. The average ANPP for each soil units is 928-10552 kg/ha/year in 1981-2010 and 586-9355 kg/ha/year in 2039-2068 (only 10-90 percentile values for each LCC included). In general, the average ANPP decreases with increasing land marginality. A majority of Michigan expects decreases in switchgrass ANPP in 2039-2068 compared to 1981-2010.

Agricultural land tends to have larger ET than marginal land. The average ET in 1981-201for agricultural land is 572 mm and 443 mm for marginal land in Michigan (only 10-90 percentile values for each LCC included). In 2039-2068, the average ETs are 617 mm and 484 mm for agricultural and marginal land, respectively (only 10-90 percentile values for each LCC included). A majority of Michigan is predicted to have higher evapotranspiration with the projected climate in 2039-2068, but the increase in ET would be mostly due to the increase in soil water evaporation.

Switchgrass ANPP production in Michigan is limited by nitrogen and water availability. On average, limited nitrogen contributes to 39% reduction in ANPP potential and limited water contributes to 32% reduction in ANPP potential for Michigan in 1981-2010. In 2039-2068, the limited nitrogen has less effect on switchgrass ANPP, with average decreasing contribution to 22% but the limited water has more effect, with average increasing contribution to 47%. With both climate scenarios, the limited nitrogen has larger effect on agricultural land than marginal land and the limited water has smaller effect on agricultural land than marginal land.

The SALUS model provides an opportunity for not only simulating switchgrass ANPP and ET under historical and future climate but also understanding limiting factor contributions to switchgrass ANPP reductions.

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Chapter 3. Concluding Remarks

Switchgrass is a promising bioenergy feedstock that can produce sizable aboveground biomass. Decades of research has tested switchgrass cultivar biomass production in relation to a range of variables, including fertilization application, cutting frequency, stand age and precipitation. However, large-scale switchgrass cultivation that requires irrigation and fertilization would not be different from intensified agriculture and its water, carbon and nitrogen footprints have to be evaluated.

Field trials across the US have been testing switchgrass aboveground biomass production under a range of management practices. However, the ideal switchgrass production is under no or low agricultural inputs. Based on the reports in the literature, under no agricultural inputs, the switchgrass aboveground biomass yield ranged between 1.6 and 33.4 Mg/ha. The literature has shown that switchgrass aboveground biomass could be significantly correlated to its stand age, nitrogen addition, cutting frequency and precipitation.

For switchgrass ET estimation, the methods were not consistent and they included water balance, energy balance and Eddy Covariance. The estimated switchgrass ET varied greatly, ranging from 280 to 780 mm.

As has been suggested in the literature, switchgrass aboveground biomass production and ET are results of crop interactions among soil, weather conditions and management practices. Thus analysis of switchgrass aboveground biomass production and ET requires a systems approach.

Particularly, in recent decades, there has been an increasing interest in utilizing the unprofitable marginal land for growing switchgrass as bioenergy feedstock. The marginal land definition was initially from an economics perspective but the prevalent definition is based on the descriptive land capability class developed by the USDA in 1961. In such a situation, it is critical to assess switchgrass capability to produce aboveground biomass and ET on such land and to evaluate limiting factors for its aboveground biomass production, if any.

Crop simulation models simulate crop development and growth and the associated water and nutrient cycles. Therefore, crop simulation models can be applied not only to food crop yield forecasting but also crop growth impact on the environment. The four modes -- 1) ‘plant growth simulation only’ mode, 2) ‘plant growth and water balance’ mode, 3) ‘plant growth, nitrogen balance and water balance’ mode and 4) ‘plant growth, nitrogen, phosphors and water balance’ mode -- provides an unique opportunity to quantifying limiting factor effect on switchgrass aboveground biomass potential reduction. The research in Chapter 2 applied the SALUS model to 1) assess switchgrass aboveground biomass production and ET across land with varied quality and 2) quantify limiting factor effects on switchgrass aboveground biomass in Michigan under historical and future climate.

The land capability classification developed by the USDA was designed for agricultural crop production and may not be suitable for cellulosic feedstock production. Although this thesis did not intend to integrate crop simulation model results for land capability for cellulosic feedstock production identification, the results indicate that crop simulation models would be useful and future research could fill the gap.