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Simulated biomass, environmental impacts and best management practices for long-term switchgrass systems in a semi-arid region

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ABSTRACT

Long-term information on switchgrass (*Panicum virgatum* L.) as a biomass energy crop grown on marginally saline soil and the associated impacts on soil carbon (C) and nitrogen (N) dynamics, greenhouse gas (GHG) emissions, and best management practices (BMPs) are limited. In this study, we employed the DAYCENT model, based on a 4-year switchgrass field experiment, to evaluate the long-term biomass yield potential and environmental impacts, and further to develop BMPs for switchgrass in a semi-arid region.

The model showed that long-term (14-year) annual mean biomass yields were 9.6 and 5.2 Mg ha^{-1} for irrigated and rainfed switchgrass systems, respectively. The simulated biomass yields correlated well with field-measured biomass with r^2 values of 0.99 and 0.89 for irrigated and rainfed systems, respectively. Soil organic carbon (SOC) and soil total nitrogen (STN) accumulated rapidly after switchgrass establishment, with mean accrual rates of 0.99–1.13 Mg C ha^{-1} yr^{-1} and 0.04–0.08 Mg N ha^{-1} yr^{-1}, respectively. Based on the outputs of numerous long-term model simulations with variable irrigation water supplies and N rates, the irrigation regime and N rate with the highest yield to input ratio were chosen as BMPs. The DAYCENT model predicted-BMP was irrigating every 14 days at 70% potential evapotranspiration combined with an N rate of 67 kg ha^{-1} yr^{-1}. Switchgrass established and produced biomass reasonably well in this semi-arid region; however, appropriate irrigation and N fertilization were needed for optimal biomass yield. Switchgrass had a great potential to sequester C into soils with low N_2O emissions while supplying significant quantities of biomass for biofuel synthesis.

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1. Introduction

Switchgrass (*Panicum virgatum* L.) has been identified as a potential bioenergy crop for the North Central Region of the US. It can adapt to a variety of soil conditions, and has the potential for production on marginal lands [1,2]. Schmer et al. [3] observed annual average biomass yields of 5.2–11.1 Mg ha^{-1} for switchgrass on 10 farms of marginal cropland with a mean nitrogen (N) application rate of 74 kg ha^{-1} yr^{-1} in North Dakota, South Dakota, and Nebraska. Marra et al. [4] reported that switchgrass yields averaged 5.76 Mg ha^{-1} on reclaimed surface mines across varieties and years in West Virginia with no N addition, which was about 50% lower than on agricultural lands. Greater yields of 13.4–16.0 Mg ha^{-1} were reported by Kering et al. [5] at an N application rate of 135 kg ha^{-1} on soils with low potassium content in southern Oklahoma. These studies provide important insight into bioenergy crop production on marginal lands. However, previous studies mostly focused on switchgrass production systems with time scales of less than 5 years [1,2]. Information on biomass yields for long-term switchgrass production systems on marginally saline soil is still limited, especially in semi-arid areas.

Switchgrass has a deep and productive root system that can extend over 3.3 m into the soil [6], which contributes to soil carbon (C) sequestration and improve soil quality. Bandaru et al. [7] reported that switchgrass can sequester an average of 0.23 Mg C ha^{-1} yr^{-1} on marginal lands. Another study reported that the rate of soil C sequestration varied from −0.28 to 1.14 Mg C ha^{-1} yr^{-1} over 30 years in the southeastern US [8]. A number of studies have investigated benefits on soil rebuilding and the environment from growing dedicated switchgrass for energy [9]. Many factors can affect soil C sequestration beneath switchgrass systems, such as temperature, precipitation, and above and below ground biomass [8]. In the semi-arid region of Colorado, soil C dynamics beneath long-term switchgrass production systems needs to be further studied.

There is growing evidence that agricultural systems contribute significantly to global warming [10]. The major sources of anthropogenic greenhouse gases (GHGs) associated with switchgrass production are nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) [11,12]. The supply of N fertilizers and irrigation water have a direct effect on GHG emissions, as the result of microbial nitrification and denitrification in the soil, which is controlled principally by soil water, mineral N contents, temperature, and labile organic matter [11]. In addition, GHGs are also emitted indirectly from agricultural soil in some form of nitrogen oxide(s) (NO_x), ammonia (NH_3), and nitrate (NO_3^-) [11,13]. Appropriate management practices can reduce GHG emissions and accelerate soil C sequestration while maintaining profitable yields. Previous studies demonstrate, of all the management practices, soil phosphorus (P) and potassium (K) contents have little effect on switchgrass yield [14,15], while irrigation and N fertilizer management are essential for profitable yields and protecting environmental quality in arid and semi-arid areas [10,16]. However, large amounts of external N and irrigation water inputs with decreasing use efficiencies have contributed to environmental degradation and GHG emissions. Therefore, to meet the increasing demand for bioenergy crop productivity, and promote soil C sequestration while reducing the probability of nitrate leaching and GHG emissions, best management practices (BMPs) for N and irrigation water applications are being promoted.

Previous research on optimal N rates in switchgrass production systems mostly focused on the yield and profit-maximizing N rates and irrigation regimes. For example, Mulkey et al. [17] reported switchgrass did not produce significantly higher yields with N rates above 112 kg ha^{-1} in the central Upper Peninsula of Michigan. Heggenstaller et al. [18] observed maximum yield generally occurred at an N rate of 220 kg N ha^{-1} in Iowa. Recently, Haque et al. [19] reported, based on 3 years of switchgrass yield data from potassium-deficient soils in Oklahoma, that applying 135 and 67 kg ha^{-1} of N and K produced the highest biomass yield, while applying no N or K was the most economical approach; however, if switchgrass feedstock prices were as high as \$110 Mg^{-1} and the price for N and K fertilizers were relatively low, the most economical system shifted from no N or K to favor the 135 N/67 K system.

Best management practices are designed to increase crop yields by improving resource use efficiency while greatly reducing negative environmental impacts, achieving synchrony between N and irrigation water supply and crop demand without excess or deficiency [20]. To the best of our knowledge, there is limited information available for BMPs related to N rates and irrigation water requirements based on trade-offs between yield and environmental impacts, especially when switchgrass is grown on semi-arid land.

However, such long-term experiments necessary to fully develop BMPs are difficult and costly. Computer simulation modeling is one of the best ways for researchers to expand short-term field research to longer and larger scales or situations where field measurements are difficult or costly to conduct. The DAYCENT model is an ecosystem computer model that primarily evaluates plant production and C and N dynamics, and further estimates N_2O, CH_4, and N_2 gas emissions from soil. The model has been successfully applied to various ecosystems (including pasture, agricultural, and native systems) at various locations in the world (including tropical and temperate regions) for assessments of plant production, C:N ratio of plant tissues and soil organic matter, C sequestration, nitrate leaching, and GHG emissions. Recently, the model has been used to predict yields for corn (*Zea mays* L.), switchgrass, and miscanthus (*Miscanthus* × *giganteus* Greef et Deuter) that were managed as biofuel feedstocks [11,21]. By conducting numerous long-term DAYCENT model simulations with variable resource inputs, researchers may select management practices (fertilization and irrigation) with the highest yield to input ratios as the BMPs. Qian et al. [22] and Zhang et al. [23] have successfully used the DAYCENT model as a management support system to generate optimal N fertilization rates as a function of perennial grass stand age with an aim to achieve adequate production under the constraint of minimal nitrate leaching and emissions.

In summary, previous studies on the performance of switchgrass provide important insights into its production potential for bioenergy on marginal lands. However, there is limited information on long-term biomass yields, soil C and N dynamics, and GHG emissions on marginally saline soil in semi-arid regions. Also, BMPs for switchgrass grown on marginal saline soil based on optimizing trade-offs between yield and environmental protection have not been developed. To gain a better understanding of switchgrass growth and environmental enhancement in a semi-arid region, we conducted a 4-year field experiment on a marginally saline soil and used plant and soil data collected to calibrate and validate the DAYCENT model for switchgrass feedstock production. After thorough calibration and validation using multiyear data, we further employed the DAYCENT model (i) to simulate long-term biomass yield, soil C dynamics, and GHG emissions from switchgrass grown on marginally saline soil under rainfed and irrigated conditions; and (ii) to determine irrigation and N fertilization BMPs based on trade-offs between yield and environmental impacts.

2. Materials and methods

2.1. *Field experiment description*

Data used to calibrate and validate the DAYCENT model in this study came from a field experiment that was conducted from 2008 to 2011 on the Colorado State University Horticultural Field Research Center, which is located 10.6 km northeast of Fort Collins, CO (40.56°N, 105.07°W). The initial soil N, P, and K contents were 7, 3.7 and 156 mg kg^{-1}, respectively. The soil pH was 8.1. The study site has a Nunn clay loam (fine, smectitic, mesic Aridic Argiustoll) soil with salinity ranging from 4 to 6 dS m^{-1} (this is marginally saline soil [24–26]). The climate is semi-arid with mean annual precipitation of 380 mm. Prior land use was for a saltgrass (*Distichlis spicata* (L.) Greene) trial. In 2007, the saltgrass was eliminated through repeated use of glyphosate herbicide and cultivation. Six switchgrass plots (10 m length and 5 m width each) were then established for irrigated and rainfed treatments, each with three replicates, plus an additional plot was left bare as a control. The irrigated and rainfed plots were in side-by-side blocks which were separated by a 5 m aisle.

Plots were established in May 2008 using a Brillion seeder (Brillion Farm Equipment, Sure Stand Model SSP-8, Brillion, WI) with the seeding rate of 11.2 kg ha^{-1} pure live seed (PLS) of switchgrass (cultivar 'Pathfinder'). Urea (46-0-0) was applied at a rate of 100 kg N ha^{-1} just prior to seeding with no N applied in the second year. Thereafter, the N rate was 49 kg N ha^{-1} yr^{-1} (Table 1). Immediately after seeding in 2008, irrigation was provided every other day for 3 weeks to ensure germination of switchgrass seeds. Irrigation was then reduced to 1 to 2 times per week for 3 weeks. Thereafter, irrigation was only provided when plants showed drought stress. At each irrigation event, about 1.2–1.7 cm of water was applied. From 2009 to 2011, two irrigation treatments were imposed: 1) no irrigation (completely rainfed conditions), and 2) irrigated with about 1.2–2.7 cm of water when switchgrass exhibited signs of drought stress. Total annual supplemental irrigation water and precipitation during each growing season are summarized in Table 1.

Three weeks after seeding, switchgrass plant density was 60 plants m^{-2}. In 2008, there was considerable weed pressure during establishment. To reduce weed pressure, 2,4-D herbicide was applied for broadleaf weed control 5 weeks after seeding, Drive (quinclorac) was applied 9 weeks after seeding, and atrazine was applied 3 months after seeding. Since then, herbicide was only applied once per year in mid-May (Table 1).

2.2. *Soil and plant sampling and analysis*

Data collected from the field experiment included above- and belowground biomass, C:N ratio of aboveground biomass, soil bulk density, SOC, and soil total N (STN) content.

Aboveground biomass was harvested in early November each year using a New Holland 1469 Haybine swather with a 2.8 m cutting width. Tillers were cut about 12.5 cm above the soil surface. All aboveground biomass from each plot was weighed wet in the field using a hanging load cell scale. Subsamples were collected and weighed wet in the field and then dried at 55 °C for 3 days and reweighed. Bulk samples were converted to biomass yield (dry matter basis) by adjusting for the percent moisture in the subsamples. After biomass yield determination, four sub-samples were collected randomly from each plot to measure biomass C and N content. Dried biomass samples were ground using a Wiley mill to pass through a screen with 425-μm openings. The ground samples were analyzed for total C and N content using a Carlo Erba model NA1500 automatic C–N analyzer (Hake Buckler Instruments, Inc., Saddle Brook, NJ). Following analysis, aboveground biomass C:N ratios were calculated.

Table 1 – Precipitation, irrigation, and chemical inputs during 2008–2011 for irrigated and rainfed switchgrass production systems in Colorado.

Year	Precipitation during growing season (cm)	Irrigation water (cm)		N fertilizer application (kg N ha^{-1})	P fertilizer application (kg P ha^{-1})	Herbicide application (kg a.i. ha^{-1})
		Irrigated treatment	Rainfed treatment			
2008	29	27	27	100	45	3.3
2009	34	7	0	0	0	0.25
2010	26	18	0	49	0	0.25
2011	29	28	0	49	0	0.25

Fertilizer and herbicide applications were the same for irrigated and rainfed treatments.

Soils and roots were sampled in 2011 after aboveground biomass was harvested by excavating four 5.0-cm diameter soil cores from each plot. Soil cores were collected at 0–10, 10–20, 20–40, and 40–60 cm depths. Additional soil cores were obtained from 60 to 90, 90–120, 120–150, 150–180, 180–210, 210–240, and 240–270 cm depths to determine root biomass in the deep soil profile. Soil and root samples were placed in plastic bags and transported to the laboratory, where visible roots were hand-picked from the soil to determine root mass. The remainder of each sample from the 0–10, 10–20, 20–40, and 40–60 cm depths was air dried, then ground to pass a 2 mm screen, and stored in glass bottles. SOC content was calculated as the difference between total C and inorganic C contents. Total soil C and N contents were determined by dry combustion using a Carlo Erba model NA1500 automatic C–N analyzer (Hake Buckler Instruments, Inc., Saddle Brook, NJ). Soil inorganic C (SIC) was determined by a modified pressure transducer method described by Sherrod et al. [27]. In addition, four undisturbed soil cores (5.4 cm diameter by 3 cm in depth) were collected to determine soil bulk density.

2.3. DAYCENT use – parameterization, calibration and validation

In this study, the DAYCENT model was parameterized, calibrated, and validated by using the independent data set from our field experiment conducted on a marginally high salinity soil. Data used to parameterize and calibrate the DAYCENT model included weather data, soil data, and site and plant growth parameters.

Daily weather data (maximum/minimum temperature and precipitation) from 1996 to 2013 for the field site were acquired from the Fort Collins East Weather Station (http://www.northernwater.org/Default.aspx). Long-term daily weather data before 1996 required to drive DAYCENT were acquired from DAYMET (http://www.daymet.org). We reused the daily weather data from 1996 to 2013 as the future weather data; a common approach used in the literature [12,23,28].

Site information (longitude −105.07, latitude 40.56), soil texture (Nunn Clay loam with 37% sand, 35% silt, and 28% clay), and soil bulk density were set according to the data measured before seeding. Model outputs are sensitive to current SOC levels, which in turn are influenced by previous vegetation cover and land management. Thus, initial SOC levels were established by running the DAYCENT model based on 112 years of prior land use history.

DAYCENT has been well parameterized to simulate the growth of switchgrass and other major crops [11,21,29,30]. In this paper, to predict the growth of switchgrass on the site and accurately reflect switchgrass N uptake and biomass yield, we adjusted sensitive site and crop parameters according to measured data from our field experiment. Then, we tested the ability of DAYCENT to simulate the growth of switchgrass on the site. Each year, the start of switchgrass growth, senescence and relocation of N was controlled by the DAYCENT model schedule file combined with soil temperature and moisture. Switchgrass started growth in mid-April under local normal weather conditions. Senescence and relocation of N started in mid-October. Winter dormancy started when soil temperature fell below 2 °C. Drought stress was controlled by the daily water input (precipitation + irrigation) in the weather file and soil water content. Once the parameter values were optimized, they remained unchanged in later simulations.

After the soil baseline conditions, plant growth, senescence, and dormancy parameters were established, a short-time simulation was then run by using the site information, soil texture, weather data, and management practices identical to our field experiment. Simulated above ground biomass, C:N ratio, SOC, and STN were then compared with the measured field data to calibrate and validate the DAYCENT model.

2.4. Long-term prediction of switchgrass under current management scenarios

To examine long-term biomass yield, soil C and N dynamics, GHG emissions, and mineral N leaching under current management scenarios, a 14-year of simulation was run using the calibrated and validated DAYCENT model. Switchgrass stand life is at least 10–15 years. In this study, we set the expected stand life for switchgrass at 14 years.

2.5. Irrigation regime and nitrogen rate for highest- and most economical-yield

To determine the irrigation and N rate for the highest- and most economical-yield on marginal quality soil in semi-arid Colorado, we ran numerous long-term (14-year) simulations with variable irrigation water supplies and N rates using the validated DAYCENT model. Irrigation regimes included two factors - irrigation frequency and water quantity. Simulated irrigation frequencies were every 7, 14, and 21 days during the main switchgrass growth period from May to October. Irrigation water quantity was set at 50, 60, 70 and 100% of potential evapotranspiration (PET) for each irrigation frequency. Simulated N fertilization rates ranged from 0 to 250 kg N ha^{-1}, and N fertilizer was applied once each year in the spring after switchgrass started turning green. Based on the model outputs, the irrigation and N rates for the highest and most economical yields (with the highest yield to input ratio) were determined.

2.6. Trade-offs between yield and environmental impacts for different management practices

Global warming potential (GWP) provides a means for comparing the relative environmental effects of one source against another [31]. To calculate the GWP of switchgrass production systems with variable N rates and irrigation water supplies, we combined the outputs of the DAYCENT model for direct GHG (CO_2, N_2O and CH_4) fluxes with IPCC methodology: Non-CO_2 GHG fluxes were converted to CO_2-equivalents (CO_2-eq) by assuming that N_2O and CH_4 have 296 and 23 times, respectively, GWP of CO_2 on a per molecule basis [31]. For indirect GHG emissions, IPCC methodology assumed that 1% of the N fertilizer volatilized will be converted to N_2O and that 0.75% of the NO_3^--N leached into groundwater will be denitrified to N_2O [31].

GWP of indirect GHG emissions from agricultural chemical inputs (fertilizers and herbicides) were also considered and converted to CO_2-eq to calculate the total GWP of switchgrass production systems [11,13]. Estimates of GWP in relation to production, packaging, and application of fertilizers were 1.3 g CO_2-eq g^{-1} for N, 0.2 g CO_2-eq g^{-1} for P, and 6.3 g CO_2-eq g^{-1} for active ingredients in herbicides [32].

In addition, electrical costs for irrigation systems using water lifted from bore wells was 0.3 kW h m^{-3} [33], The GHG emissions coefficient for electric utilities for Colorado was 879 g CO_2-eq $(kWh)^{-1}$ [34]. GWP for fuel used by agricultural machinery in harvesting and baling the aboveground biomass was estimated at 0.98 g CO_2-eq m^{-2} [11].

The total GWP of switchgrass production systems was calculated as:

$$GWP_{total} = (\Delta CO_2\text{-eq}_{SOC}) + (-CO_2\text{-eq}_{CH4}) + CO_2\text{-eq}_{N2O\ direct} + CO_2\text{-eq}_{N2O\ indirect} + CO_2\text{-eq}_{chemical\ inputs} + CO_2\text{-eq}_{irrigation} + CO_2\text{-eq}_{harvest}$$

where ΔCO_2-eq $_{SOC}$ represents the difference between C returned to the soil via residues and roots from crops vs soil C oxidized to CO_2; CO_2-eq $_{CH4}$ is the CO_2-equivalents of soil CH_4 uptake; CO_2-eq $_{N2O\ direct}$ is CO_2-equivalents of direct N_2O emissions; CO_2-eq $_{N2O\ indirect}$ is the CO_2-equivalents of indirect N_2O emissions from N fertilizer volatilization and N leaching; CO_2-eq $_{chemical\ inputs}$ is the CO_2-equivalents of GHG emissions from production, packaging, and application of fertilizers and herbicides. CO_2-eq $_{irrigation}$ is CO_2-equivalents of electrical costs for irrigation systems; CO_2-eq $_{harvest}$ is CO_2-equivalents for harvesting the aboveground biomass. GWP saved from the fossil fuel (e.g., gasoline, diesel, and coal) displaced by biofuel was not calculated in this study.

As such, the total of GWP for switchgrass systems under different N rates and irrigation water supplies can be determined. Negative values indicate GHGs were sequestrated into soil, while positive values indicate soil GHG emission. Then, by comparing the benefit from switchgrass biomass yield and the total GWP for each management scenario, the optimal fertilization rate and irrigation regime for switchgrass production systems with high biomass yield and low negative environmental impacts were selected.

3. Results and discussion

3.1. *Comparison between measured and simulated results*

Comparison between simulated and measured aboveground biomass yields during the first 4 years is presented in Fig. 1a. After adjusting crop growth parameters within recommended ranges, the DAYCENT model simulated biomass yield of irrigated and rainfed switchgrass production systems very well with r^2 values of 0.99 and 0.89, respectively. Predictions were better for the irrigated than the rainfed system. The DAYCENT model correctly estimated the C:N ratio of switchgrass aboveground biomass with r^2 values of 0.56 and 0.65 for irrigated and rainfed treatments, respectively (Fig. 1b). Because the growth period was too short for full development of switchgrass during the establishment year, the C:N ratio for 2008 was not included in the evaluation.

Checkpoints between simulated and observed SOC before switchgrass establishment (2008) and the fourth year after establishment (2011) demonstrated that SOC was reliably simulated by the DAYCENT model, with deviations of −1.3% and +2.0% for irrigated and rainfed conditions, respectively (Fig. 2). Deviations in simulating STN of irrigated and rainfed switchgrass production systems were −9.2% and −6.2%, respectively. Also, the DAYCENT model did a reasonable job of estimating root biomass with a bias of −10.5% and 3.9%, for irrigated and rainfed treatments, respectively.

Similar to many other studies [11–13], the DAYCENT model can reliably predict growth of switchgrass on marginal quality soil following adjustment of some sensitive parameters. Simulated aboveground biomass, C:N ratio, SOC, and STN contents agreed well with the observed data; also, root biomass was simulated within acceptable levels with a deviation of less than 11%. This study is in agreement with the previous study in which Davis et al. [21] showed that the DAYCENT model accurately simulated aboveground biomass for switchgrass and miscanthus with r^2 value of 0.99. Del Grosso et al. [29] found crop yield was reliably predicted by the DAYCENT model at both field ($r^2 = 0.90$) and regional ($r^2 = 0.66$) levels. Recently, using the DAYCENT model, Cheng et al. [28] reported r^2 values in the range of 0.71–0.85 for measured and simulated crop yield and SOC change.

Results of tests in many soils showed that fluxes of trace gas (N_2O, CH_4) emissions from soils were not always reliably simulated by the DAYCENT model on a daily basis, but total fluxes for trace gases were accurately simulated between different sites and among seasons [12]. In the present study, we focused on the well predicted annual GHG emissions by DAYCENT over an extended period of 14 years, and the parameters used in this study for trace gas emissions associated with switchgrass have been verified previously [21], therefore, we did not calibrate them here.

3.2. *Long-term simulation of switchgrass production under current management scenarios*

3.2.1. *Aboveground biomass*

Aboveground biomass yield for irrigated switchgrass was relatively stable following establishment (Fig. 3). However, rainfed switchgrass showed a general declining trend over years with substantial variability evident among years. The average aboveground biomass yield over years for irrigated switchgrass was 9.6 Mg ha^{-1} during the 14-year simulation period, while rainfed switchgrass was 5.2 Mg ha^{-1}.

The predicted average annual aboveground biomass yield (5.2–9.6 Mg ha^{-1}) in this study was consistent with observed yields of 5.2–11.1 Mg ha^{-1} by Schmer et al. [3] on 10 farms of marginal cropland in North Dakota, South Dakota and Nebraska. In addition, our results indicated that irrigation significantly increased aboveground yields ($P < 0.05$). An adequate water supply would be essential to optimize biomass production in Colorado's semi-arid climate. The

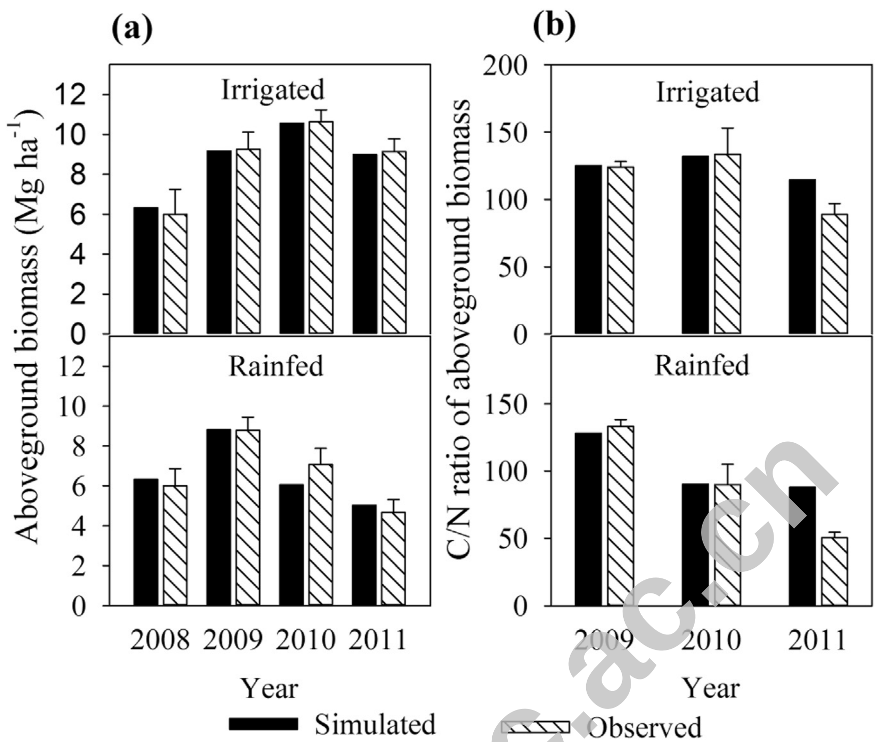

Fig. 1 — Comparison of simulated (DAYCENT model) and observed a) aboveground biomass, and b) C:N ratio of aboveground biomass for irrigated and rainfed switchgrass production systems in Colorado. The observed data were collected from a field experiment conducted from 2008 to 2011 northeast of Fort Collins, CO, US, in which the switchgrass cultivar 'Pathfinder' was grown as a bioenergy crop with two irrigation treatments (irrigated and rainfed). The observed values are the mean of three replicates. Bars indicate the standard error among the three replicates.

mean annual yield of rainfed switchgrass on marginal quality soil in our study was much lower than the observed mean yield for the same switchgrass cultivar grown under rainfed conditions in Missouri, Illinois, and Iowa, with annual precipitation as high as 856–1110 mm [35]. However, average yield in the irrigated treatment in this study was slightly higher than the mean biomass yield of 8.7 Mg ha^{-1} from 25 upland cultivars in the northern US reported by Wullschleger et al. [36]. In addition, it should be noted that the rainfed switchgrass had a declining trend in biomass

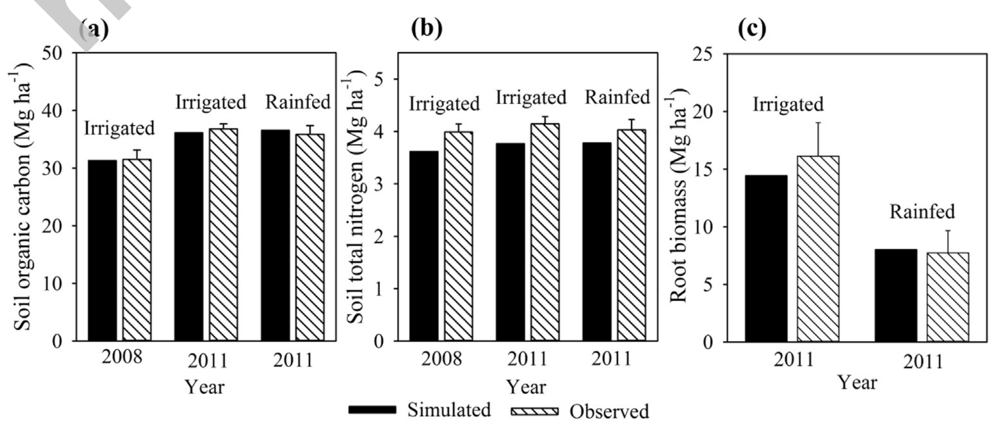

Fig. 2 — Comparison of simulated and observed a) soil organic carbon, b) soil total nitrogen in the top 20 cm of soil before seeding (in 2008) and the fourth year after switchgrass establishment (2011), and c) root biomass in 2011. The observed data were collected from a field experiment conducted from 2008 to 2011 northeast of Fort Collins, CO, US, in which the switchgrass cultivar 'Pathfinder' was grown as a bioenergy crop with two irrigation treatments (irrigated and rainfed). The observed values are the mean of three replicates. Bars indicate the standard error among the three replicates.

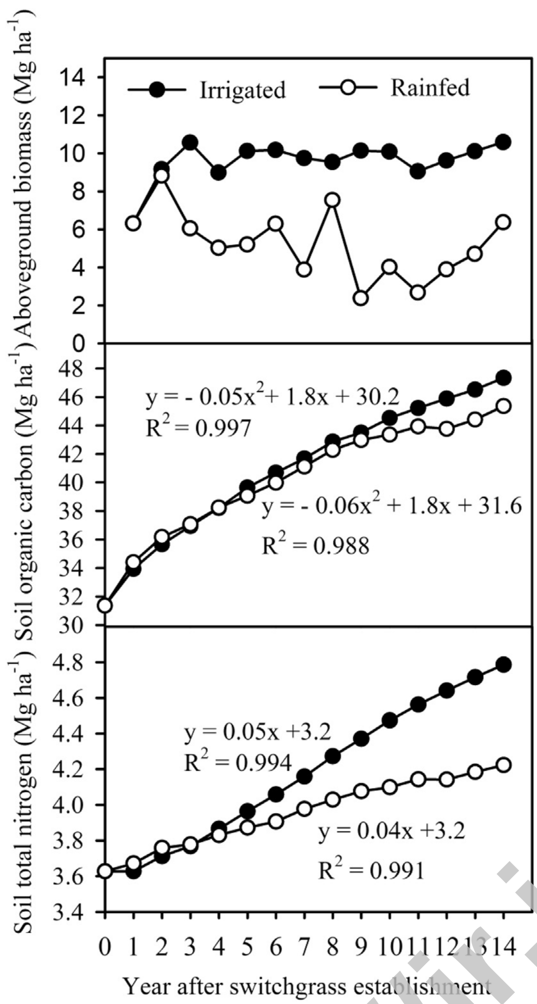

Fig. 3 – DAYCENT model predictions of long-term aboveground biomass, soil organic carbon, and soil total nitrogen in the top 20 cm of soil for switchgrass on marginal quality soil based on management parameters from a field experiment conducted from 2008 to 2011.

yield according to the prediction by the DAYCENT model (Fig. 3), suggesting that long-term field experiments are essential to accurately evaluate growth of switchgrass under rainfed conditions. It appeared that switchgrass grown on marginally saline soil in semi-arid Colorado grew well only when appropriate irrigation and N fertilizer were provided.

3.2.2. *Soil organic carbon and soil total nitrogen*

SOC accumulated rapidly in the top 20 cm of soil after switchgrass establishment according to the DAYCENT model prediction (Fig. 3). The mean rates of SOC accumulation for irrigated and rainfed switchgrass were 1.13 and 0.99 Mg C ha^{-1} yr^{-1}, respectively, during the 14-year period following establishment. Irrigation led to a significant increase in SOC. Total SOC in the 0–20 cm soil profile for irrigated and rainfed plots increased from 31.5 Mg C ha^{-1} at establishment to 47.3 and 45.4 Mg C ha^{-1}, respectively, 14 years after switchgrass establishment. The DAYCENT model estimated SOC accumulation in our study was similar to several other studies. For example, in a 10-year C sequestration study in eastern Nebraska, switchgrass, with an N input of 60 kg ha^{-1}, had an average annual increase in SOC of about 0.9 Mg C ha^{-1} in the 0–30 cm soil depth [37]. Liebig et al. [38] reported SOC increased in the 0–30 cm soil depth at 1.1 Mg C ha^{-1} yr^{-1} for 5 years following switchgrass establishment. Also, our results support the review of Monti et al. [39] that the maximum annual rate of soil C sequestration for perennial vegetation is usually about 1 Mg C ha^{-1} yr^{-1}. Soil water availability, temperature, N fertilization, and initial soil C stocks are all important externalities that can affect soil C dynamics. Therefore, higher SOC sequestration rates of 1.6–4.2 Mg C ha^{-1} yr^{-1} have been reported by Jung and Lal [40] while a lower sequestration rate of 0.23 Mg C ha^{-1} yr^{-1} has been reported by Bandaru et al. [7].

Simulated STN within the 0–20 cm soil depth increased linearly over time for both irrigated and rainfed switchgrass (Fig. 3). The annual average accumulation rates of STN were 0.08 and 0.04 Mg ha^{-1} yr^{-1} for irrigated and rainfed switchgrass, respectively. Proper irrigation promoted the accumulation of N in soil, with much higher STN observed in irrigated switchgrass compared to the rainfed treatment.

Proper irrigation also significantly increased root biomass and crop residue inputs to the soil, which resulted in increases in SOC and STN. Therefore, we observed higher STN and SOC accumulation in the irrigated treatment in the field experiment (Fig. 2), which was also supported by results from the long-term simulation using the DAYCENT model (Fig. 3).

3.2.3. *Nitrogen leaching*

Simulated annual mineral N leaching from the irrigated treatment in the establishment year was as high as 57.0 kg ha^{-1} yr^{-1}, possibly a result of excessive N application in addition to frequent irrigation for better establishment of switchgrass (Fig. 4a); Mineral N leaching in the 4th, 5th, and 6th years after establishment was 1.9, 4.4, and 2.1 kg ha^{-1} yr^{-1}, respectively; thereafter, almost no mineral N leaching occurred. Similar to the irrigated treatment, high mineral N leaching was also found in the establishment year for rainfed switchgrass, because irrigation scheduling was identical for both treatments in an effort to promote better establishment. Thereafter, mineral N leaching mainly occurred in the 4th and 5th years, with rates of 10.1 and 1.6 kg ha^{-1} yr^{-1}, respectively. The N leaching that occurred in the above mentioned years under rainfed conditions was due to heavy rainfall events. Compared to other annual crops, the DAYCENT model predicted very low mineral N leaching for switchgrass production systems except in the establishment year.

3.2.4. *Greenhouse gas flux*

Nitrous oxide is one of the main GHGs associated with switchgrass production systems. Based on current management practices, long-term GHG emissions were predicted using the DAYCENT model (Fig. 4b). The average annual emissions of N_2O for irrigated and rainfed treatments were 0.55 and 0.70 kg N ha^{-1} yr^{-1}, respectively. The emission rate of N_2O for the irrigated switchgrass production system during

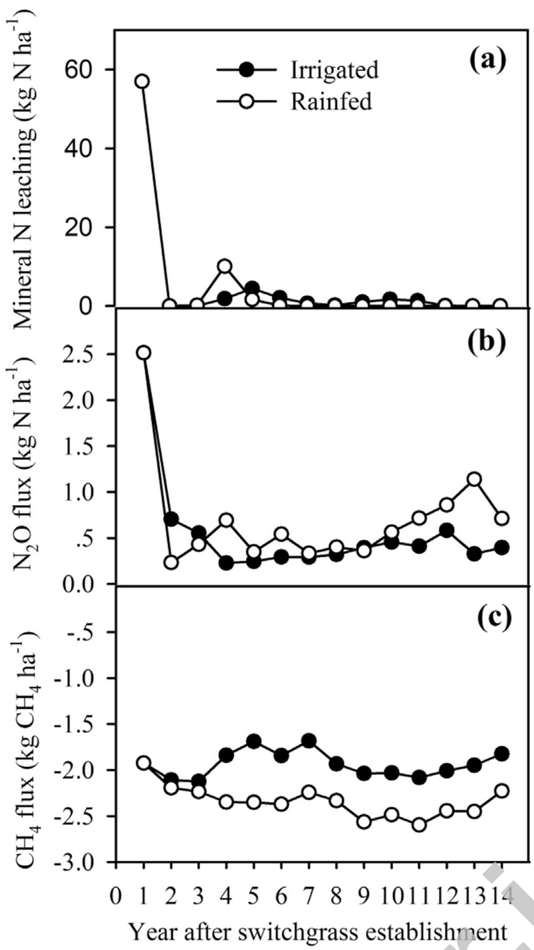

Fig. 4 – DAYCENT model predictions of mineral N leaching, N_2O flux, and CH_4 flux during the 14-year period following establishment based on management parameters from a field experiment conducted from 2008 to 2011.

the 14 years was low and stable except for the first three years, whereas the flux for rainfed system varied over time, averaging about 27% higher than the irrigated system. Compared with major annual crops, switchgrass had a lower N_2O emission rate. A similar result was reported by Davis et al. [21] for biofuel crops grown in arable soils. In central Iowa, N_2O emissions from soil under soybeans ranged from 2.2 to 2.7 kg N ha^{-1} yr^{-1}, while emissions from soil under corn ranged from 7.6 to 10.2 kg N ha^{-1} yr^{-1} [41]. In southwestern Michigan, average N_2O emissions from a corn–soybean–wheat rotation ranged from 1.19 to 1.32 kg N ha^{-1} yr^{-1} over 12 years [42]. Lower N_2O emissions from switchgrass fields were the possible result of lower N requirements [43].

According to the DAYCENT simulation, during the first several years after switchgrass establishment, irrigation promoted the emission of N_2O (Fig. 4b), while from the fourth year and thereafter, the rainfed treatment had a higher N_2O emission rate than the irrigated. This result was possibly related to the higher soil water content under irrigation which created a suitable environment for nitrification and denitrification reactions that drove the higher N_2O flux. However, N_2O flux is controlled not only by soil water content, but also by soil mineral N availability [43]. For the rainfed switchgrass, with a continuous N fertilizer supply identical to the irrigated, N was not fully taken up by plants and accumulated in the soil, resulting in greater N_2O emissions than irrigated switchgrass from the fourth year and thereafter.

Like other dryland crops, switchgrass production systems can oxidize CH_4 in non-saturated soils and act as a sink for atmospheric CH_4 according to the prediction by the DAYCENT model (Fig. 4c). The rainfed system uptook 21% more CH_4 than the irrigated system during the 14-year simulation, likely because the rainfed soil had lower soil water content which is easier for diffusion of CH_4 and O_2.

3.3. *Irrigation regime and nitrogen rate for highest- and most economical-yield*

3.3.1. *Irrigation regime for highest- and most economical-yield*

To evaluate irrigation management for highest-yield, different irrigation regimes including irrigation water quantity and irrigation frequency were simulated by DAYCENT. In these simulations, N and P fertilizer application rates were set at 67 kg N ha^{-1} per year and 45 kg P ha^{-1} every four years, respectively. Simulated average annual aboveground biomass yield increased significantly when the irrigation water quantity increased from 50 to 100% PET, regardless of the irrigation interval (Fig. 5). In dry (annual precipitation below 26 cm) or normal years with relatively lower soil water content (such as the year after a drought year), aboveground biomass yield for switchgrass with irrigation applied to meet full PET was significantly higher compared to when only 50, 60, or 70% of PET irrigation water was applied. But in wet (annual precipitation above 33 cm) and normal years with relatively high soil water content (such as the year after a wet year), aboveground biomass yield with 100% PET irrigation water was similar or even lower than the biomass with 70% PET, especially when the irrigation interval was 7 days.

According to the 14-year average annual aboveground biomass results (Table 2), the irrigation schedule – with irrigation water applied to meet full PET every 7 days – had the highest and most stable yield of 10.7 Mg ha^{-1}, with an annual mean irrigation water requirement of 31.0 cm. But in wet years, yields were higher when irrigation water was applied to meet only 60 or 70% of PET (Fig. 5).

To determine the most economical yield per unit of irrigation water applied, irrigation water use efficiency (IWUE) was employed as the evaluation indicator which was defined as

$$IWUE = (Y_i - Y_d)/I_i$$

where Y_i is the biomass yield for irrigation level i; Y_d is the biomass yield without irrigation; and I_i is the amount of irrigation water [44].

IWUE varied with different annual precipitation amounts and rates of irrigation water application. Schedules with 60%

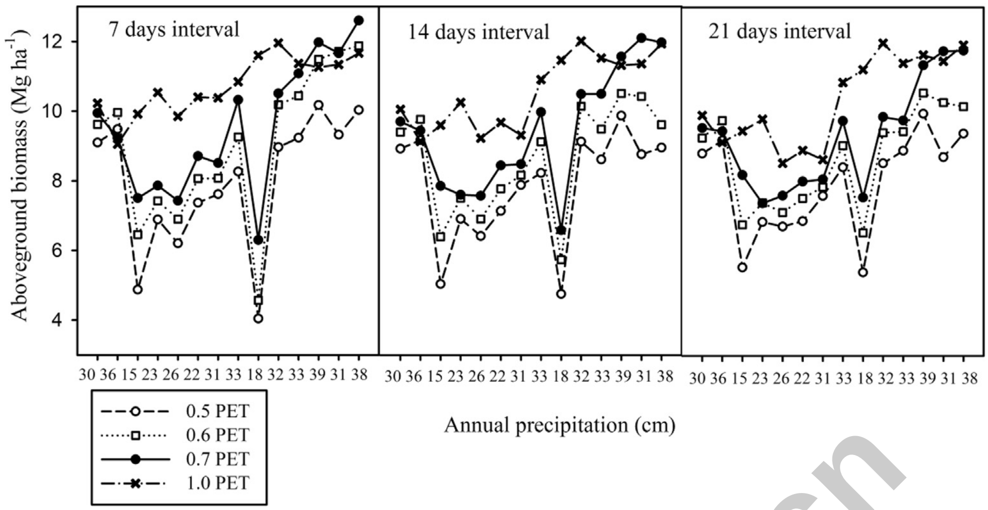

Fig. 5 – Aboveground biomass for different irrigation regimes during the 14 years following switchgrass establishment. Irrigation regimes included two factors - irrigation frequency which was set at every 7, 14, and 21 days during the switchgrass growth period from May to October, and irrigation water quantity which was set at 50, 60, 70, and 100% of potential evapotranspiration (PET) for each irrigation frequency. N rate was 67 kg N ha^{-1} per year; P fertilizer was applied at a rate of 45 kg P ha^{-1} every four years.

and 70% of PET irrigation water usually had the higher IWUE compared to other irrigation rates except in very dry years (Fig. 6). According to long-term average annual IWUE (Table 2), the irrigation schedule with water applied at 70% of PET at an interval of 14 days had the most economical yield (with the highest IWUE). For this schedule, the average annual totals for irrigation water applied, biomass yield, and IWUE were 20.2 cm, 9.4 Mg ha^{-1} and 23.3 kg ha^{-1} mm^{-1}, respectively.

3.3.2. *Nitrogen rate for highest- and most economical-yield*

To estimate the best N rate for switchgrass growing on marginal quality soil with low inputs, we set the irrigation regime at 70% of PET with an interval of 14 days (i.e. most economical irrigation schedule for yield), and the P fertilizer application rate at 45 kg ha^{-1} every four years, we then ran numerous simulations for different N rates ranging from 0 to 250 kg N ha^{-1} per year. According to the simulated results (Table 3), biomass increased as the N application rate increased, with the highest yield of 11.8 Mg ha^{-1} occurring at an N rate of 170 kg ha^{-1} yr^{-1}; thereafter, the biomass did not continue to increase with additional application of N fertilizer.

Agronomic efficiency of fertilizer N (AE_N) was employed as the indicator for determining the most economic N rate, which was calculated as crop yield increase per unit of fertilizer N applied in kg kg^{-1}:

$$AE_N = (Y_N - Y_0)/F_N = \Delta Y/\Delta N$$

where Y_N is crop yield at an N fertilizer rate of F_N, and Y_0 is crop yield measured in a control treatment with no N fertilizer applied [45]. We can see from the simulation results (Table 3) that AE_N increased with increasing levels of applied N for the first 5 increments, and then continually decreased as N rate increased for the remaining increments. The economic N application rates should be in the range of 50–85 kg N ha^{-1} yr^{-1}, which resulted in AE_N ranging from

Table 2 – Average annual biomass, irrigation water, and irrigation water use efficiency (IWUE) for each irrigation schedule simulated by the DAYCENT model.

	Rainfed	Irrigation regime											
		7 day interval				14 day interval				21 day interval			
		50%[a]	60%	70%	100%	50%	60%	70%	100%	50%	60%	70%	100%
Biomass (Mg ha^{-1})	4.8	8.0	9.0	9.5	10.7	7.8	8.6	9.4	10.6	7.9	8.6	9.3	10.3
Irrigation water (cm)	0	15.5	18.6	21.7	31.0	14.4	17.3	20.2	28.9	14.0	16.8	19.6	28.1
IWUE (kg ha^{-1} mm^{-1})	–	20.8	23.0	22.0	18.9	21.4	22.4	23.3	19.7	22.4	23.0	22.9	19.5

Data in this table was the average value calculated by using the 14 years' annual model outputs. The N fertilizer rate was 67 kg N ha^{-1} yr^{-1} and P fertilizer was applied at a rate of 45 kg P ha^{-1} every four years.

[a] Percent of potential evapotranspiration.

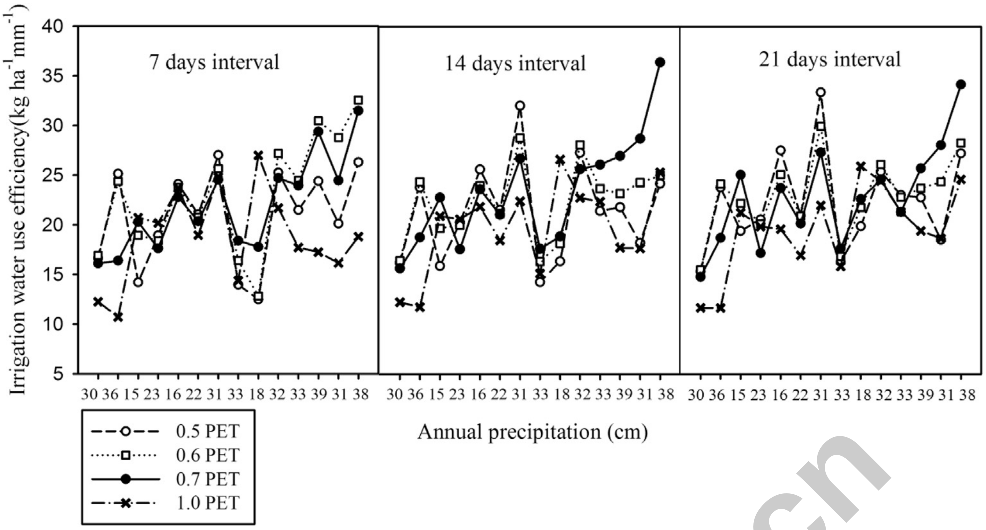

Fig. 6 – Irrigation water use efficiency (IWUE) for different irrigation regimes. Irrigation regimes included two factors - irrigation frequency which was set at every 7, 14, and 21 days during the switchgrass growth period from May to October, and irrigation water quantity which was set at 50, 60, 70, and 100% of potential evapotranspiration (PET) for each irrigation frequency. N rate was 67 kg N ha^{-1} per year; P fertilizer was applied at a rate of 45 kg P ha^{-1} every four years.

78.9 to 80.9 kg kg^{-1}, The most economic N rate (with highest AE_N) was 67 kg N ha^{-1} per year, with a biomass yield of 9.4 Mg ha^{-1}.

The recommended N rates to achieve high biomass yields range from 56 to 448 kg N ha^{-1} [20,30]. Our simulated highest yield was reached at an N rate of 170 kg N ha^{-1} yr^{-1}. Similar results were reported by Muir [46] in Texas, while Palmer et al. [47] reported that about 134–168 kg N ha^{-1} maximized switchgrass biomass production in most years in North Carolina. However, because N rates to achieve high biomass yields vary by temperature, precipitation, N-supplying capability of the soil, and harvest frequency, Vogel et al. [48] reported maximum switchgrass yields were obtained when 120 kg N ha^{-1} was applied in the Midwestern region of the United States. In contrast, optimum economical N rates for switchgrass as a bioenergy crop did not vary as much as the N rates for highest biomass. For example, the optimal economic N rate reported by Garten Jr. [20] in West Tennessee was 67 kg N ha^{-1} based on N balance. Aravindhakshan et al. [49] reported that applying 69 kg N ha^{-1} was most economical if switchgrass was harvested once per year after senescence. Our results showed that the most economic N rate (with highest AE_N) was 67 kg N ha^{-1} per year, which resulted in a mean annual yield of 9.4 Mg ha^{-1} for a one cut system. Our result was consistent with the above reported optimum economical N rates, but was slightly higher than the recommended N rate of 56 kg ha^{-1} reported by Mulkey et al. [17] in South Dakota, maybe as a result of different soil types and weather conditions.

3.4. *Trade-offs between yield and environmental impacts for different management practices*

To develop BMPs that incorporate trade-offs between yield and GWP, long-term simulations (14 years) for switchgrass as a bioenergy crop were run using 4 typical management scenarios based on the above recommended N and irrigation management practices:

1) MP_1, management scenario that combined the highest-biomass irrigation regime with the highest-biomass N rate (i.e., every 7 days, 100% PET irrigation water, and 170 kg N ha^{-1} yr^{-1});

Table 3 – Average annual biomass and agronomic efficiency of fertilizer N (AE_N) for different N rates under the recommended best irrigation regime.

	N rate (kg ha^{-1} yr^{-1})																
	0	50	55	60	65	67	70	75	80	85	90	95	100	150	170	200	250
Biomass (Mg ha^{-1})	4.0	7.9	8.3	8.8	9.2	9.4	9.6	10.0	10.4	10.7	10.9	11.0	11.1	11.7	11.8	11.8	11.8
AE_N (kg kg^{-1})	–	78.9	79.1	79.8	80.8	80.9	80.8	80.6	80.0	79.0	76.9	73.8	70.8	51.2	45.8	39.1	31.3

Data in this table was the average value calculated by using the 14 years' annual model outputs. Irrigation regime was set at 70% of PET with an interval of 14 days (i.e. the most economical irrigation schedule for yield); P fertilizer application rate was 45 kg ha^{-1} every four years.

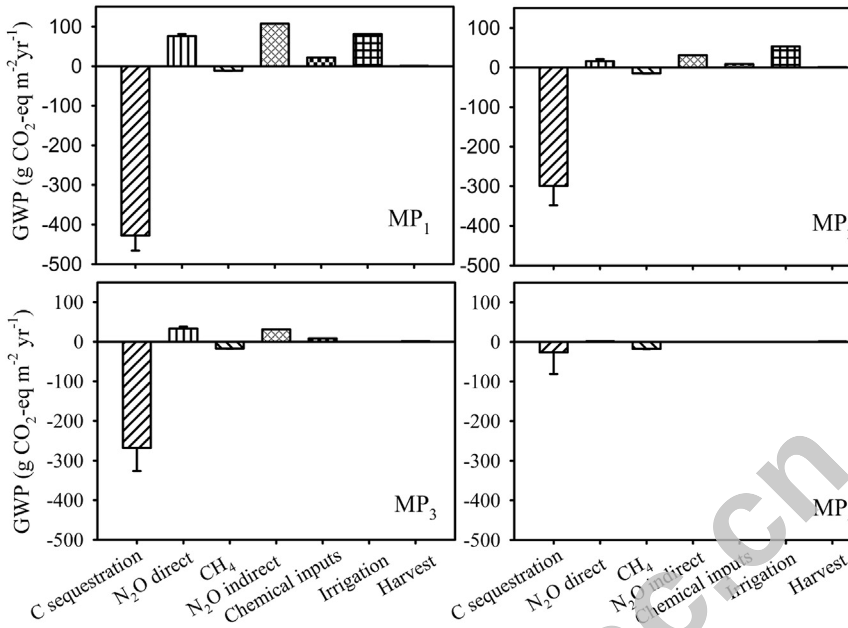

Fig. 7 – Average annual global warming potential (GWP) and its components for different irrigation and N management scenarios. MP_1, the management scenario which combined the highest-biomass irrigation regime with the highest-biomass N rate (i.e., every 7 days, 100% PET irrigation water, and 170 kg N ha^{-1} yr^{-1}); MP_2, the management scenario which combined the highest-IWUE irrigation regime with highest- AE_N N rate (i.e., every 14 days, 70% PET irrigation water, and 67 kg N ha^{-1} yr^{-1}); MP_3, the combination of highest- AE_N N rate with no irrigation supply (i.e., 67 kg N ha^{-1} yr^{-1} and no irrigation); MP_4, as the control (i.e., rainfed conditions and no N application). Error bars represent the standard error between different annual values during the 14 years of simulation period.

2) MP_2, management scenario that combined the highest-IWUE with highest- AE_N N rate (i.e., every 14 days, 70% PET irrigation water, and 67 kg N ha^{-1} yr^{-1});
3) MP_3, combination of highest- AE_N N rate with no irrigation (i.e., 67 kg N ha^{-1} yr^{-1} and no irrigation);
4) MP_4, as the control (i.e., rainfed conditions × no N application).

Average annual GWP and its components are presented in Fig. 7. Switchgrass systems under the four management scenarios all were sinks for GWP. Cumulative N_2O fluxes from the four scenarios were in the range of 1.3–76.5 g m^{-2} yr^{-1} as CO_2-eq. N fertilization and irrigation significantly affected N_2O fluxes ($P < 0.0001$). However, the CH_4 absorption rate was not significantly affected by N fertilization ($P = 0.4661$), but significantly decreased with increasing irrigation water supply ($P = 0.0005$).

Switchgrass under the four scenarios all sequestrated C into soils (Fig. 7). The MP_3 scenario was the biggest GWP sink, with the average annual sequestrating rate as high as 211 g CO_2-eq m^{-2} per year, as a result of high C sequestration rates and low GHG emissions. MP_2 had the second highest sink of GWP among the four management scenarios; it can sequester more C into the soil and emit less N_2O into the atmosphere than MP_3, but needs more irrigation water inputs. The net GWP mitigation of MP_2 was 204 Mg CO_2-eq ha^{-1} yr^{-1}, similar to the MP_3 scenario. The third largest sink of GWP was MP_1. It can absorb large quantities of C into soils, whereas MP_1 also had the highest direct and indirect N_2O emission rates, which were 77 and 115 g CO_2-eq m^{-2} yr^{-1}, respectively. In addition to the GWP from high fertilizer inputs and irrigation energy consumption, the total sink of GWP for the MP_1 scenario was 142 g CO_2-eq m^{-2} yr^{-1}. It was much lower than MP_2 and MP_3. MP_4 had the lowest GWP mitigation of only 41 g CO_2-eq m^{-2} yr^{-1}, as a result of very low C sequestration.

Based on outputs for the four switchgrass production systems, the MP_1 scenario had the highest biomass yield of 14.5 Mg ha^{-1} (Fig. 8), because of the high N rate combined with a sufficient irrigation water supply, which was followed by MP_2 with 9.4 Mg ha^{-1}. Aboveground biomass yields for the MP_3 and MP_4 scenarios were very low at only of 4.8 and 2.2 Mg ha^{-1}, respectively.

If only considering environmental effects, MP_3 was the most environmentally friendly, with the highest GHG sequestration rate, but the biomass yield for this management practice was relatively low. If only considering aboveground biomass yield for switchgrass, MP_1 had the highest, but it was not very environmental friendly due to the high N and irrigation inputs. As mentioned above, switchgrass is often grown on marginal land with low inputs for the purpose of biofuel production and soil rebuilding. The best managed switchgrass production system should not only have high biomass yields, but also have positive environmental impacts. So based on the trade-offs between yield and GWP, the BMP should be the MP_2 scenario, with similar GHG sequestration rate as MP_3, but with much higher biomass yields than MP_3.

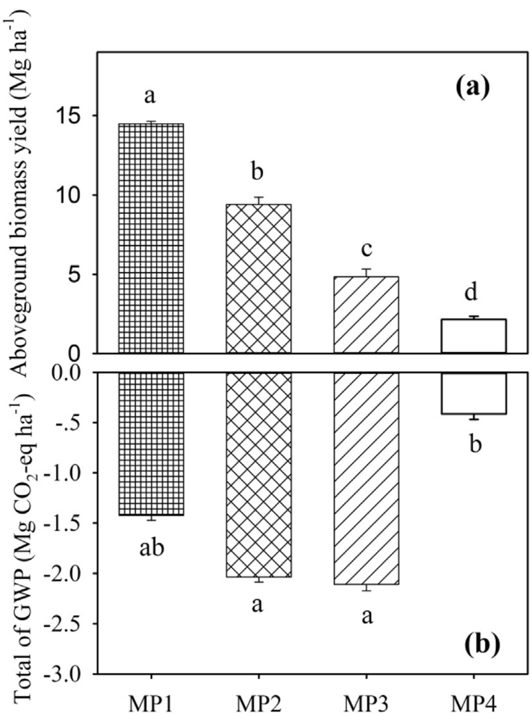

Fig. 8 – Biomass and total of GWP for different irrigation and N management scenarios. MP_1, the management scenario which combined the highest-biomass irrigation regime with the highest-biomass N rate (i.e., every 7 days, 100% PET irrigation water, and 170 kg N ha^{-1} yr^{-1}); MP_2, the management scenario which combined the highest-IWUE irrigation regime with highest- AE_N N rate (i.e., every 14 days, 70% PET irrigation water, and 67 kg N ha^{-1} yr^{-1}); MP_3, the combination of highest- AE_N N rate with no irrigation supply (i.e., 67 kg N ha^{-1} yr^{-1} and no irrigation); MP_4, as the control (i.e., rainfed conditions and no N application). Error bars represent the standard error between different annual values during the 14 years of simulation period.

4. Conclusions

The DAYCENT model can reliably simulate the growth, soil C and N dynamics, and GHG emissions for switchgrass grown on marginal quality soil. Switchgrass established and produced biomass reasonably well on marginally saline soil; however, appropriate irrigation and N fertilizer were needed for optimal biomass yield in this semi-arid region. The yield-maximizing irrigation regime was watering at 100% PET every 7 days in dry and normal years, but adjusting to 70% PET in wet years; however, irrigating at 70% PET every 14 days was the most economic. The yield-maximizing N rate was 170 kg ha^{-1} yr^{-1} while the most economic rate was 67 kg N ha^{-1} yr^{-1}. Based on the optimal trade-offs between yield and GWP, the BMP for switchgrass on marginal quality soil should be irrigating every 14 days at 70% PET and fertilizing with 67 kg N ha^{-1} yr^{-1}. Switchgrass had a great potential to sequester C into soils with low N_2O emissions. Switchgrass production systems can contribute to improved soil quality by C sequestration while supplying significant quantities of biomass for biofuel synthesis.

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