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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