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Potential regional productivity and greenhouse gas emissions of fertilized and irrigated switchgrass in a Mediterranean climate

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ABSTRACT

The potential of switchgrass (*Panicum virgatum* L.) to offset large-scale greenhouse gas (GHG) emissions depends on optimizing external inputs when the crop is primarily managed as a sustainable source for renewable energy production. Due to the heterogeneity of climate and soil conditions and the complexity of agriculture, an evaluation of the effect of adopting switchgrass as a new biofuel crop into agriculture needs to be done at the regional scale. The objective of the study was to predict long-term (100-yr) GHG emissions under different N fertilization (0, 112, and 224 kg N ha^{-1}) and irrigation application (0, 25, 50, 75, and 99 cm H_2O) levels across the Central Valley of California using the DAYCENT model. Six cultivars (Alamo, Kanlow, Cave-in-Rock, Blackwell, Sunburst, and Trailblazer) were selected. The model results suggest that switchgrass productivity is primarily constrained by N inputs when no or low water stress is expected in a Mediterranean climate. In the short-term (the first decade after establishment), soil organic carbon (SOC) stocks (0–20 cm) increased by 0.42–0.92 Mg C ha^{-1} yr^{-1} and N_2O emissions were 1.37–2.48 kg N_2O–N ha^{-1} yr^{-1} across the cultivars with baseline input rates of 224 kg N ha^{-1} yr^{-1} and 99 cm H_2O. All cultivars were net CO_2 sinks in the near term and the potential decreased by 0.09–0.30 Mg C ha^{-1} yr^{-1} (15.5–52.8%) with reduced N input from baseline under varying irrigation rates. There was a reduction in N_2O emissions by 47.2–61.6% by applying less N fertilizer when irrigated at rates $\geq$75 cm H_2O per year over time. In general, higher-yielding cultivars (e.g., Alamo) tended to sequester more CO_2 but also led to higher N_2O emissions. In the near term, the use of N fertilizer and irrigation is needed for switchgrass systems to be a soil GHG sink, but for longer-term GHG mitigation strategies reducing both N fertilization and irrigation inputs is required.

1. Introduction

Cultivation of biofuel crops and biomass conversion to biofuels (e.g., ethanol and biodiesel) can reduce CO_2 emissions by displacing fossil fuels and sequestering C into soil (Bransby et al., 1998; Adler et al., 2007). Biofuel crops, particularly perennials compared to annuals, can also reduce soil N losses that have the potential to affect direct and indirect N_2O emissions (Bransby et al., 1998). This has led to renewed interest in biofuel crops as a renewable fuel and an important element in a portfolio of GHG mitigation technologies for the next decades (Pacala and Socolow, 2004; Sims et al., 2006). However, the feasibility of large-scale biofuel production for energy and as a GHG mitigation option is still debated. First of all, it requires large-scale land-use change for sufficient land, possibly increasing a risk for initial soil C loss and poor soil fertility (Lemus and Lal, 2005; Searchinger et al., 2008). It also assumes no biophysical constraints from the availability of external inputs, such as N and water, and minimal environmental impacts (Giampietro et al., 1997). The ecological benefits and risks of candidate biofuel crops have been previously found to vary with plant characteristics, nutrient demand, soil C inputs, N retention, and biomass quality (Anderson-Teixeira et al., 2009). Therefore, large-scale assessment of biofuel crops and management effects is a prerequisite to determine environmental and socio-economic effects of converting biomass to energy when adopting a new biofuel crop into agriculture.

In the USA, switchgrass (*Panicum virgatum* L.) has been extensively evaluated as one of promising biofuel crops (McLaughlin and Walsh, 1998; Wullschleger et al., 2010). Switchgrass is a perennial C_4 grass that is successfully grown across environmental conditions and a diverse range of geographical regions of North America. Switchgrass presents several agronomic advantages. For example, switchgrass is high-yielding, characterized by high nutrient and water-use efficiency as well as broad tolerance to

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disturbance compared to other perennial herbaceous grasses (Lewandowski et al., 2003; Wright, 2007), which can be cultivar-specific (Wullschleger et al., 2010). To reduce C and other soil emissions, Lal (2005) recommended biofuel crops that produce a minimum of 10–15 Mg ha^{-1} yr^{-1} of biomass when 30–40% of crop residues is assumed to be removed annually. The characteristics of switchgrass generally meet many important selection criteria for producing energy. However, switchgrass is nonnative to the Pacific Coast in the USA, including California, and has never been grown commercially in this region. California, and specifically the Central Valley, is one of the most productive agricultural regions in the world and leads national production and sales of many crop commodities, such as almonds, cotton, grapes, hay, rice, and tomatoes. Presumably, these high-value commodities are less likely to be replaced with switchgrass. Barney and DiTomaso (2008) reported that switchgrass has a highly invasive potential in the region and therefore further evaluation of invasive characters is necessary under various environmental conditions. Clearly, it is relevant to determine if switchgrass adoption in California induces direct land use changes and is environmentally sound over time.

Switchgrass is considered an option to restore some of the soil C previously lost by conventional agricultural production (Mensah et al., 2003; Skinner and Adler, 2010). Compared to annual crops, the larger root system of switchgrass significantly increases potential belowground C input, although increased C loss would be expected by soil respiration (Al-Kaisi and Grote, 2007). The potential to mitigate CO_2 emissions depends on how it is managed. Established switchgrass is generally suitable for the recovery of N from fertilizer or other sources via its existing root system, and direct N_2O emissions under switchgrass tend to vary under different N fertilizer rates (Nikièma et al., 2011). Sufficient N inputs are still required to sustain switchgrass productivity and soil N balance (Boehmel et al., 2008; Monti et al., 2012). Therefore, N fertilization management is an important factor for growing switchgrass. In addition, application of inorganic fertilizer or manure is an important consideration if switchgrass is grown for C sequestration (Lee et al., 2007; Liebig et al., 2008). However, optimizing N rates is difficult because there are large uncertainties in the extent of trade-offs due to variation in environmental conditions.

California switchgrass cultivar trials were established at four sites (El Centro, Five Points, Davis, and Tulelake) in 2007 and total 11 different cultivars have been evaluated under different management practices until 2010 (Pedroso et al., 2011, 2013). The field trials data provide empirical data on switchgrass growth across distinct environmental and management conditions of California (Fig. 1). However, the field data accounted for limited combinations of climate, land use, and management systems. The potential for regional and longer-term switchgrass productivity and effects on the environment remain largely unknown under California conditions. So far, Pedroso et al. (2014b) is the only field study, which was conducted in a Mediterranean climate and reported the response of switchgrass to N fertilization and irrigation interactions. No measurements of soil C changes or emission of N_2O and CH_4 have been made for switchgrass systems in California. External N fertilization is required especially for establishing switchgrass due to poor soil fertility. In the Mediterranean regions of California, irrigation demand is also expected to be high for switchgrass management and likely affect soil C and N dynamics. It is therefore important to assess the interactive effects of N fertilization and irrigation on potential soil emissions.

From a practical point of view, it is difficult to consider wide variation in management practices, soils, and microclimates to measure switchgrass productivity and soil GHG emissions. Most frequently, biogeochemical models can be used to predict regional long-term changes in plant productivity and soil quality. Previously, the DAYCENT model was calibrated and validated for GHG emissions from agricultural soils in California by considering typical crop rotations (De Gryze et al., 2010, 2011; Lee et al., 2011). Lee et al. (2012) further calibrated and validated the DAYCENT model for six selected switchgrass cultivars: Alamo (southern lowland); Kanlow (northern lowland); Blackwell and Cave-in-Rock (southern upland); Sunburst and Trailblazer (northern upland). Genetic differences in biomass yield among cultivars were simulated reasonably well across the four sites representing diverse ecoregions of California. A recent analysis suggests that switchgrass production is economically feasible and can replace other crops in some part of the Central Valley (Yi et al., 2013). The objective of this study was to predict the long-term (100-yr) effects of different inorganic N fertilizers applications and irrigation intensities on biomass yield, SOC changes, and N_2O emissions of switchgrass in the Central Valley of California using the DAYCENT model.

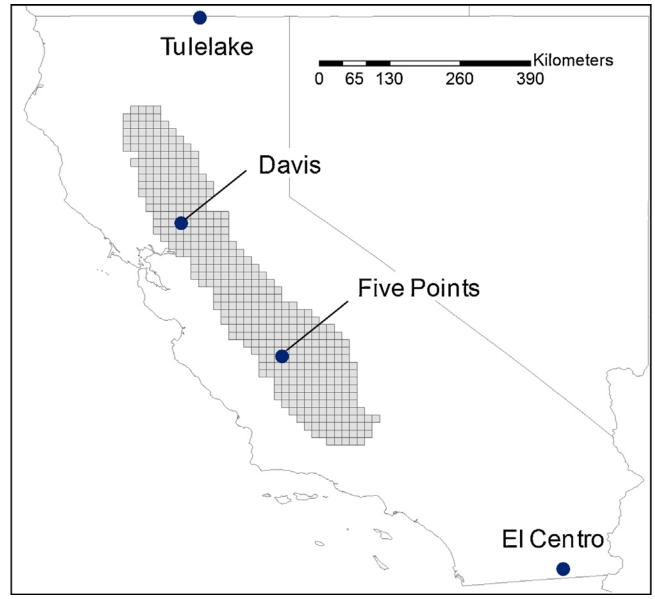

Fig. 1. Location of 537 grid cells (12 km × 12 km) established within the Central Valley of California. Points show the location of California switchgrass cultivar trials.

2. Materials and methods

2.1. Model description

We used the DAYCENT model (version 4.5), a fully resolved biogeochemical model that simulates the major processes associated with the dynamics of C, N, soil temperature, and water (Del Grosso et al., 2001). Key model outputs include plant growth, soil organic matter (above 20 cm depth), daily flux of N gases (N_2O, NO_X, and N_2), and CH_4 oxidation. Phenology, net primary productivity, shoot:root ratio, and the C:N ratio of biomass in plant components are species-specific and determined by soil and air temperature and soil-water stress. Soil-water availability is a function of current soil water, precipitation, irrigation water, and potential evapotranspiration. The effects of N from soil organic matter pools or fertilizer on plant growth are determined by specific grass/crop requirements. The type and timing of each management event can be specified, including tillage, fertilization, organic matter (e.g., manure) addition, harvest (with variable residue removal), drainage, irrigation, burning, and grazing intensity. If the growing degree days following submodel is