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Modification of the CERES grain sorghum model to simulate optimum sweet sorghum rooting depth for rainfed production on coarse textured soils in a sub-tropical environment

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ABSTRACT

There is potential to reduce irrigation water requirements in bioenergy feedstock cropping systems by breeding for deep rooted sweet sorghum cultivars that intercept more rainfall water. Such cultivars would require little or no irrigation in some environments. Consequently, the objective of this study was to quantify the potential benefit of deeper rooted sweet sorghum cultivars by simulating a range of root depth and planting date scenarios in the subtropical climate of the southeastern USA by modifying the CERES grain sorghum cropping system model for sweet sorghum. A two year field study was conducted to collect data for model development. The new sweet sorghum model was validated against independent studies from six different locations around the world. The root mean squared error of prediction of the model was 4.7% for days to maturity (6 days), 21% for total biomass weight, and 22.6% for stem dry weight. We then simulated sweet sorghum growth and yield for nineteen hypothetical rooting depths between 30 and 210 cm. Based on model simulations, including uncertainty analysis associated with model parameters, the optimal root depth for our environment in the southeastern USA under rainfed conditions, was between 110 and 140 cm to maximize final biomass yield. The simulated hypothetical 120 cm root depth sweet sorghum had final biomass yields up to 48.2% higher than the simulated widely grown cultivar 'M81 E' in rainfed systems and would require up to 32% less irrigation to meet actual evapotranspiration demand. These results highlight the importance of breeding for deeper rooted sweet sorghum cultivars along with optimized sowing dates for higher biomass yields. However, model simulations also indicated that, even with optimal rooting depth and density, irrigation would be needed to maximize final biomass yields.

1. Introduction

Sweet sorghum has been identified as a promising biofuel crop for the southeastern United States (Erickson et al., 2012, 2011). Although sweet sorghum as a C_4 crop uses water relatively efficiently to produce biomass (Stanhill, 1986) and is relatively drought tolerant (Ali et al., 2009), concerns over the impacts of bioenergy crop production on water resources remain. For example, it has been reported that bioenergy crop production in the southeastern U.S.A. could lead to an increase of 25% or more in additional irrigation (Evans and Cohen, 2009). Reducing irrigation could potentially be achieved by breeding sweet sorghum genotypes with deeper root systems and access to deeper soil water. Crops with deeper root systems can access water stored in deep soil layers, and thus could have higher yields in dry years (Acuña et al., 2010).

The effect of root depth on yield must be considered in the context of the climatic and edaphic conditions of a given region, as well as the specific features of the cropping system. High root length density in deeper soil layers has been associated with higher yields under drought by increasing the amount of water available to the crop (Kashiwagi et al., 2006). However, in regions where the crop relies mainly on stored soil water, vigorous root growth during the vegetative phase can deplete soil water reserves before anthesis, thus reducing water available during grain filling and reducing grain yield (Vadez, 2014). In situations where deeper root systems are advantageous, selecting for deep-rooted genotypes remains a

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Nomenclature

CSM	Cropping system model
DAP	Days after planting
DD	Growing degree day or thermal time (°C d)
DSSAT	Decision Support System for Agrotechnology Transfer (software)
ET	Evapotranspiration (mm)
GS1	Growth stage one: emergence – end juvenile
GS2	Growth stage two: end juvenile – floral or panicle initiation
KCAN	Canopy extinction coefficient
KGROSTM	Stem growth rate (g plant^{-1} DD^{-1})
LA	Leaf area (cm^{-2})
LAI	Leaf area index
LDW	leaf dry weight (g)
MSE	Mean squared error
MSEP	Mean squared error of prediction
ORD	Optimal root depth (cm)
R^2	Coefficient of determination
RLD	Root length density (cm cm^{-3})
RMSE	Root mean sqaured error
RRMSE	Relative root mean squared error
RUE	Radiation use efficiency (g MJ^{-1})
RWUMX	Maximum water uptake per unit root length (cm^3 water cm^{-1} root)
SDW	Stem dry weight (kg ha^{-1})
SGRF	Root growth factor
SLW	Specific leaf weight (g cm^{-2})
Ta	Simulated mean seasonal transpiration (mm)
TDW	Total aboveground dry weight (kg ha^{-1})
TT1	Cumulative DD between emergence and the end of leaf expansion
TT2	Cumulative growing degree days (DD) from the onset of stem growth to the beginning of grain filling
μ^*	Mean of the elementary effects

difficult task. Different strategies have been proposed to achieve this goal in the field, such as burying herbicides at a certain depth in the soil that will injure the plant if roots are present at that depth (Al-Shugeairy et al., 2014; Robertson et al., 1985) or visually rating the plant for crown root angle, which has been shown to be correlated with rooting depth (Trachsel et al., 2011).

In theory, deep-rooted sweet sorghum cultivars could be developed by plant breeders to produce bioenergy mainly on rainfall water in some environments. Cropping system models, which consider soil and environmental conditions, can be used to simulate the performance of such cultivars and evaluate their potential. Having a crop model calibrated across different seasons and environments, the effect of variation of specific traits on model outputs can be evaluated (Brown et al., 2011; Brunel-Muguet et al., 2011; Koehler and Challinor, 2011; Sarlikioti et al., 2011) to study new crop ideotypes (Boote et al., 2001; Donald, 1968), i.e., particular value of a trait or suite of traits that optimize yield for a particular environment. For example, Manschadi et al. (2006) simulated the effect of root traits on wheat yield in various environments, Sinclair and Muchow (2001) simulated the effect of two contrasting root depths on maize yield, and Wong and Asseng (2007) evaluated the impact of incremental changes in potential root depth on wheat yield. However, the impact that a change in rooting depth will have on sweet sorghum crop performance across a broad spectrum of possible root depths and sowing dates in a subtropical production environment has not been studied yet.

There are different approaches to simulate root growth (Dupuy et al., 2010). The Cropping System Model (CSM) CERES model within the decision support system for agrotechnology transfer modeling platform (DSSAT; Hoogenboom et al., 2012; Jones et al., 2003) is a mechanistic model that can relate crop rooting depth with water uptake and biomass production using local weather, soil, and crop data as inputs. The model simulates root depth and root length density throughout the growing season and can be parameterized with field data using soil cores (Robertson et al., 1993).

However, the current implementation of CSM CERES for sorghum (White et al., 2015) does not simulate the rapid stem growth and carbohydrate partitioning of sweet sorghum (Li et al., 1991). This is not surprising as most of the previous studies on sorghum using this model were with grain sorghum (MacCarthy et al., 2010; Singh et al., 2014; Staggenborg and Vanderlip, 2005; White et al., 2015). Additionally, the optimal root ideotype for water uptake will be highly dependent on interactions with rainfall and soils. In the subtropical southeastern U.S.A., coarse textured soils are common and annual rainfall is relatively abundant. However, there is a distinct dry season (approx. December through May), and often intermittent water stress during the wet season. Thus, planting date may also play a role on optimal rooting depth as crops sown early in the growing season (e.g., April) will grow in a drier environment, and thus may benefit more from deeper rooting than crops sown later (e.g., June). Therefore, the objectives of this study were to 1) modify the current version of CSM CERES to simulate sweet sorghum growth and partitioning; and 2) to evaluate a range of root depth by planting date scenarios for sweet sorghum grown on a sandy soil in a subtropical climate using the CSM CERES crop model, and estimate potential gains in yield of deeper rooted cultivars without irrigation.

2. Materials and methods

2.1. Growth study field trials for model development

Sweet sorghum cultivar ‘M 81E’ was planted at the University of Florida Plant Science Research and Education Unit (PSREU) located in Citra, Florida (29°24′38″ N, 82°8′30″ W). Plants were sown in rows 0.76 m apart and the spacing within rows was 0.1 m. The soil was a deep, well drained Hague sand (Loamy, siliceous, semiactive, hyperthermic, Arenic Hapludalfs; NCRS, 2014). The study was conducted for two years and was planted on May 10th in 2012 and on May 15th in 2013. Liquid fertilizer (11-37-0) was applied at planting at a rate of 19 kg N ha^{-1}. The remainder of the fertilizer N was applied three and five weeks after planting at rates of 76 and 40 kg N ha^{-1} respectively. A total of 135 kg K_2O was side dressed along with the second and third N applications. This level of fertility has been shown to not limit yield in this environment (Adams et al., 2015).

Destructive growth samples were collected at approximately 14 day intervals. At each sampling date, 1.5 m long rows were harvested from three (2012) or four (2013) different locations in the field. Plants were divided into stem, panicle, and leaves and oven dried at 60 °C until the samples reached a constant weight. Leaf number, phenology, and leaf area index (LAI) were also measured each time. Leaf area was measured using a Li-3100 area meter (Li-Cor, Inc. Lincoln, Nebraska, U.S.A.). In 2013, root samples were collected using 3.8 cm diameter cores at 8 depths (15, 30, 60, 90, 120, 150, 180 and 210 cm) at each harvest time. Samples were collected from within the row and between rows at each sampling location, giving a total of 8 samples per depth per harvest (4 sampling sites × 2 locations within sampling site). The roots were separated from the soil using water and a 2 mm screen, and