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Research paper

Maize, sweet sorghum, and high biomass sorghum ethanol yield comparison on marginal soils in Midwest USA

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ABSTRACT

Emerging biofuel feedstock systems are well suited for use on less productive marginal soils in the Midwestern USA. The systems could replace commodity crop agriculture that may not be economically feasible on these soils with current input and output prices, and meet a growing renewable energy demand. Three annual bioenergy crops, maize (*Zea mays* L.), sweet sorghum (*Sorghum bicolor* (L.) Moench), and high biomass sorghum (HBS) were grown in rotation with soybean (*Glycine* max L.) for five years on marginal soils at two locations. Maize aboveground dry matter (DM) yield and grain yield, sweet sorghum aboveground DM yield, and juice yield and Brix, and HBS DM yield were evaluated and used to calculate theoretical ethanol yields. Intermittent drought occurred at both sites during three of the five years notably reducing yield; a terminal drought in 2011 reduced sorghum yields and inhibited maize grain development at both sites. Theoretical ethanol yields averaged across years from sweet sorghum and HBS were greater than from maize at both locations, and indicate that sweet sorghum has the greatest yield potential, but HBS yield was the most stable. The central Missouri site maintained greater dry matter yield, and theoretical ethanol yield than the southwestern Missouri site. Due to the occurrence of drought during the study, the findings have relevance for evaluating marginal land management for annual bioenergy crops in differing rainfall patterns with climate change.

1. Introduction

Marginal lands that are used for commodity cropping systems and belong to Natural Resource Conservation Service (NRCS) Land Capability Class IIs and IIw, and Class IIIs, may be better utilized in low-input annual biofuel cropping systems. These marginal lands have limited production potential for major Midwestern USA crops because of drought, flooding, soil conditions, and landscape position. Additionally, loss of soil carbon, enhanced erosion, and reduced water-use efficiency are likely to occur on marginal lands, mostly as a result of tillage and land-use changes [1,2]. These concerns will then need careful attention when changing marginal land use to biofuel cropping systems [3–5]. Transferring marginal areas to biofuel cropping systems, albeit forage or row crops, could reduce negative environmental impacts from row crop production on these lands through reduced fertilizer requirements by the intended biofuel crop and increasing land productivity by relegating commodity crops to more productive lands [6].

Sweet sorghum and high biomass sorghum are annual C4 crops proposed for biofuel feedstock production on marginal lands where environmental factors may limit maize and soybean yields. Sweet sorghum and HBS are known for large dry matter yields, sugary stems, and drought hardiness [7–13]. Sorghum stem juice can be directly converted to ethanol while the DM has potential for lignocellulosic ethanol conversion. In contrast to sweet sorghum, development of HBS has focused primarily on maximizing DM production for the potential lignocellulosic ethanol conversion with little attention given to stem juice production. Current HBS varieties are photoperiod sensitive and do not flower until day length is less than 12 h, allowing for maximum biomass accumulation [14].

Few direct two-way comparisons exist between maize and sweet sorghum, while to date, no studies have focused on comparing maize, sweet sorghum, and HBS. Previous research reveals that sweet sorghum often yields more total fermentable carbohydrates than maize, and HBS has the potential to yield much greater DM than both maize and sweet sorghum [10–13]. Yields of all three crops are influenced differently by environmental factors and site conditions such as drought, soil, and latitudinal gradient, yet few studies have investigated this topic. Under drought conditions, Putnam et al. [12] reported 33% greater sweet sorghum ethanol yields than maize and Geng et al. [15] found that sweet sorghum required only 36% of the nitrogen required by maize. Similar sweet sorghum biomass yields across a USA latitudinal gradient

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from Michigan to Mississippi were reported by Smith et al. [16] and reveal the broad latitudinal adaptability of sorghum. This was also demonstrated for HBS by Gill et al. [17]. In their six-state, five-year study, HBS DM of variety ES 5200 ranged from 2.8 to 41.1 Mg ha^{-1} with an average of 17.9 Mg ha^{-1}.

This research was undertaken to evaluate the relative productivity of two sorghum bioenergy cropping systems compared to a traditional maize cropping system on two marginal land sites. To do this, above-ground herbaceous dry matter production, potential lignocellulosic ethanol production, maize grain ethanol production, and sweet sorghum juice ethanol production were determined, and the total ethanol production potential of these three cropping systems were compared.

2. Materials and methods

2.1. Site description and crop management

Two sites differing in latitude and frost zones (mid-Missouri and southwest Missouri, USA) were selected for this study. Fields were located on marginal lands at the University of Missouri (MU) Horticulture and Agroforestry Research Center in New Franklin, MO (39° 02′ N, 92° 76′ W) and the MU Southwest Research Center near Mount Vernon, MO (37° 08′ N, 93° 86′ W). Each site was considered marginal for row crop production because of landscape position, soil physical characteristics, and environmental limitations [5,18], with each site posing different production limitations. The New Franklin site is a ridge top to back slope site with well-drained Sibley silt loam (fine-silty, mixed superactive, mesic Typic Argiudolls) weathered from loess parent material with a mean pH of 6.7. This site is labeled as marginal and is considered a NRCS Class IIIe because of 2–9% slope and the potential for erosion. Adjacent private land of similar Class IIIe is currently row-cropped with maize and soybean. At Mount Vernon, the soil is a Dapue silt loam (fine-silty, mixed, active, mesic Fluvertic Hapludolls) with alluvium parent material. The soil has a mean pH of 6.6 and 0–2% slope and is a NRCS class IIw and IIs and is classified as marginal because of occasional flooding and highly variable soil texture including gravel, stone, and heavy clay. Irrespective of these limitations neighboring producers grow maize and soybean in adjacent fields. Previously, the New Franklin site was an aging apple orchard and the Mount Vernon site was in cultivation of alfalfa (*Medicago sativa* L.) over part of the study area during the previous crop year. Prior to initial tillage for this study in 2010, both sites were predominantly managed as mixed perennial grasses, predominantly tall fescue (*Lolium arundinaceum* Schreb.).

Weather data including mean monthly precipitation and monthly maximum and minimum temperatures were recorded for the growing season of 1 May to 31 October for each site-year. Mount Vernon and New Franklin weather data were recorded daily and downloaded from nearby NOAA weather stations, located within 3 km and 1 km, respectively, from each research site.

Experimental plots were established in the spring of 2010, with each site having four replications in a randomized complete block design. Sweet sorghum-soybean, maize-soybean, and HBS-soybean crop rotations were established at the two sites beginning in late May 2010. Plots measured 18 m × 18 m and were split into 9 m by 18 m half-plots with one half of the plot planted to a commercial maize hybrid (Pioneer 33M16, years 1–3; Pioneer 32D79, years 4–5), sweet sorghum (cv. M-81E, MSU Cares), or HBS (ES5200) and the other half planted to a single commercial soybean variety within year, but changing varieties over the course of the study. Soybeans were established to mimic the standard rotation with maize in the region, and were included in the sorghum systems to mimic the rotation as well. Each spring, soybean was rotated with each half-plot of sorghum or maize, such that sweet sorghum, HBS, and maize were established on the half-plots planted to soybean the previous year and soybean planted on the half-plots where maize or sorghum were grown. One exception to the rotation in HBS occurred in the first two study years, where another HBS variety was in the rotation in place of soybean, but soybean was substituted into the rotation in year three to match the maize and sweet sorghum crop rotations.

Prior to planting, plots were disked (~0.15 m deep) at each location. Immediately following soil preparation, all crops were planted 0.02 m deep on 0.76-m row spacing. For each cropping system, one half of the plot contained 8 rows of either maize, sweet sorghum, or HBS and the other half consisted of 8 rows of soybean. The sweet sorghum target population was 208,000 plants ha^{-1}, the maize target population was 79,000 plants ha^{-1}, and the HBS was 125,000 plants ha^{-1}. Soybean was planted for a target population of 325,000 plants ha^{-1}.

Pelletized urea was broadcast at planting, with maize receiving 200 kg N ha^{-1} and sweet sorghum and HBS each receiving 100 kg N ha^{-1}. Soybean was not fertilized with N fertilizer. Pre-and post-emergent herbicide applications of glyphosate were used for the maize and soybean plots as needed. Pre-emergent herbicide applications of Dual II Magnum (S-metolachlor) were conducted in the sweet sorghum and HBS plots at the most restrictive label rate depending on the particular site, followed by post-emergent herbicide applications of 2,4-D with additional in-season manual weed control. Following sampling at the end of the growing season, plots were cleared of above-ground biomass to simulate biomass removal associated with proposed production systems for lignocelluslosic ethanol production.

2.2. Biomass, juice, and grain yield measurements and ethanol yield calculations

Maize grain yield was determined at maturity based on ears harvested from 10 m of row per plot. Ears were husked, shelled, weighed, and grain yield adjusted to a moisture of 155 g kg^{-1}. Theoretical grain-derived ethanol yield (MEY) was calculated following Wang et al. [19], using a conversion factor of 417 L Mg^{-1} grain. To determine maize dry matter yield, plants from 5 m of row were cut at 0.01 m above the ground, dried at 60 °C to constant weight, and DM yield calculated. Theoretical lignocellulosic ethanol yield (LEY) of maize was estimated according to McAloon et al. [20], using the conversion factor of 311 L Mg^{-1} DM. Total ethanol yield (TEY) from maize was determined as the sum of MEY and LEY.

Sweet sorghum biomass yield was determined after the first killing-frost from randomly selected 0.5 m sections of plants in two adjacent rows in each plot. Plants were cut 0.01 m from the soil surface and sample fresh weights recorded. Plants were then crushed with a three-roller sugarcane press to extract stem juice. The stem juice was filtered through cheesecloth to remove stem parts, and weight and volume of the extracted stem juice were recorded. Juice Brix was determined with an r^2 mini handheld refractometer (Reichert Technologies, Inc., Buffalo, NY) immediately after extraction. Subsamples of bagasse (crushed leaves and stems after juice extraction) were weighed and dried at 60 °C to constant weight and used to calculate DM yield. The conversion factor of 415 L Mg^{-1} DM [21], was used to estimate LEY of sweet sorghum. Then sweet sorghum stem juice yield (SJY) was multiplied by Brix readings to calculate fermentable sugar yield (FSY), assuming sugars account for 75% of Brix [12,22]. Estimates of theoretical juice-derived ethanol yield (JEY) were derived from FSY by calculating using the conversion of 1.76 kg sugars L^{-1} stem juice with an assumed 80% ethanol conversion efficiency [12,16]. Final TEY was calculated by summing LEY and JEY.

Similar field harvest procedures as described for sweet sorghum were used for HBS, and fresh weights of whole samples were recorded. From each whole sample a representative subsample of three plants was then chosen, fresh weight recorded, and then dried similar to sweet sorghum to calculate DM yield. Estimates of LEY of HBS were determined using the same conversion factor as used for sweet sorghum bagasse.