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An evaluation of cassava, sweet potato and field corn as potential carbohydrate sources for bioethanol production in Alabama and Maryland

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ABSTRACT

The recent emphasis on corn production to meet the increasing demand for bioethanol has resulted in trepidation regarding the sustainability of the global food supply. To assess the potential of alternative crops as sources of bioethanol production, we grew sweet potato (*Ipomoea batatas*) and cassava (*Manihot esculentum*) at locations near Auburn, Alabama and Beltsville, Maryland in order to measure root carbohydrate (starch, sucrose, glucose) and root biomass. Averaged for both locations, sweet potato yielded the highest concentration of root carbohydrate (ca 80%), primarily in the form of starch (ca 50%) and sucrose (ca 30%); whereas cassava had root carbohydrate concentrations of (ca 55%), almost entirely as starch. For sweet potato, overall carbohydrate production was 9.4 and 12.7 $\mathrm{Mg\,ha^{-1}}$ for the Alabama and Maryland sites, respectively. For cassava, carbohydrate production in Maryland was poor, yielding only 2.9 $\mathrm{Mg\,ha^{-1}}$. However, in Alabama, carbohydrate production from cassava averaged $\sim$10 $\mathrm{Mg\,ha^{-1}}$. Relative to carbohydrate production from corn in each location, sweet potato and cassava yielded approximately 1.5× and 1.6× as much carbohydrate as corn in Alabama; 2.3× and 0.5× for the Maryland site. If economical harvesting and processing techniques could be developed, these data suggest that sweet potato in Maryland, and sweet potato and cassava in Alabama, have greater potential as ethanol sources than existing corn systems, and as such, could be used to replace or offset corn as a source of biofuels.

1. Introduction

Energy security, declining oil reserves and climate change have served as drivers for new governmental initiatives to increase alternative fuel sources, principally ethanol from biological feedstocks. Although future methodologies are anticipated with respect to cellulosic fermentation and ethanol production, at present, most of the ethanol needs of the United States are being met by the conversion of carbohydrate in corn (i.e., starch) to ethanol [1]. In 2006, approximately 20% of US corn production was diverted to ethanol, with a projected increase to 27% for 2007 [2]. At the present

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rate of growth, ethanol production is projected to increase to approximately $45 \times 10^6\ l\ yr^{-1}$ before the end of the decade [2].

Since corn is one of the three principle cereals (i.e., corn, wheat and rice) that supply 50% of the world's calories, there is increasing apprehension that greater diversion of corn feedstocks to meet ethanol demand may contribute to rising food prices and global hunger [3]. Increasing reliance on corn as the principle source of biofuel has also led to additional social and environmental concerns [4].

Research into second and third generation biofuels (e.g. cellulosic ethanol, algal oil), which may avoid many of the problems of starch-based biofuels, is ongoing. However, the present reliance regarding corn-based ethanol suggests the need for additional evaluation of other plant-based bioethanol sources. Two potential biofuel crops that are not principle cereals, and are grown with minimum inputs (e.g. fertilizer, pesticides) are cassava (*Manihot esculentum*) and sweet potato (*Ipomoea batatas*). However, neither crop has been evaluated as a biofuel in the United States. At present, sweet potato is grown principally for culinary purposes on only 40,000 ha, (in contrast field corn is grown on $\sim 35 \times 10^6$ ha) and data on cassava production in the U.S. are not available [5]. We are unaware at the present time of published evaluations comparing the biofuel potential of cassava and sweet potato to field corn in the U.S. To that end, we quantified carbohydrate type and production from these crops at two geographic locations differing in climate (Alabama and Maryland) to determine potential ethanol production.

2. Materials and methods

2.1. Experimental sites

Experimental plots were located at the USDA experimental farm in Beltsville Maryland (39° 2′ 5″ N, 76° 54′ 28″ W) and at the soil bin facilities at the USDA-ARS National Soil Dynamics Laboratory, Auburn, Alabama (32° 36′ 35″ N, 85° 28′ 50″ W). The bin used for the Alabama study is 2 m deep, 6 m wide and 76 m long. Field soil at Beltsville was classified as a Cordurus silt-loam (Cordurus harboro), while soil at Auburn was classified as Hiwassee sandy loam (Typic rhodudults). Soil testing by the Auburn University Soil Testing Laboratory indicated high availability of potash, phosphate and calcium, and recommended an input of $96.8\ kg\ N\ ha^{-1}$ for both sites (Table 1).

Stakes of cassava (*M. esculentum*, cv. "South Dade", a sweet variety) approximately 25 cm long and 2 cm in diameter were obtained from a Miami nursery and sent to both locations. The stakes were planted in 25 cm pots filled with a jiffy mix/vermiculite mixture (3:1) and placed in greenhouses on 19 and 20 April 2007 for both locations. The cooperating Alabama ARS unit provided slips of sweet potato (*I. batatas*, cv. "Beauregard"). These slips were planted in 10 cm plots filled with jiffy mix and placed in the greenhouse on 27 April 2007 at Maryland.

All rooted cuttings of cassava and sweet potatoes were transplanted in the Maryland and Alabama field plots on 17 May 2007. Four plots per species and location, each approximately $10\ m^2$, were used for cassava and sweet potato. Individual plants were spaced at 60 cm intervals. Fertilizer ($90\ kg\ ha^{-1}$ ammonia nitrate) was applied to the study areas on 25 May, 2007. Due to drought conditions which prevailed throughout the duration of the study, plants at the Alabama study site were irrigated (approximately 25 mm per application) three times per week. Irrigation occurred at the Maryland location if precipitation was less than 25 mm per week. All plots were weeded weekly until 100% canopy cover.

Table 1 – Soil characteristics of Maryland and Alabama locations.

	Maryland	Alabama	Range
Soil group[a]	2, 3	2	
pH	5.8	6.3	5.4–6.4
P[b]	99.5	63.3	60.5–99.7
K[b]	270.9	156.7	148.8–363
Mg[b]	243.6	280.7	222.6–260.2
Ca[b]	2368	1225.1	1187–4677.9

The Maryland soils were less than or equal to the pH of the Alabama soil. P and Ca levels were greater in the Maryland soils but both soils had high levels of Ca. K in the Maryland soils were greater than or equal to the Alabama soil. Maryland and Alabama had equal levels of Mg. Nitrogen fertilization recommendations were 96.8 kg/ha for both soils. The soil analysis was done by the Auburn University Soil Testing Laboratory.

[a] 2: Loams and light clays ($CEC = 4.6–9.0\ cmol_c\ kg^{-1}$), 3: Clays and soils high in organic matter ($CEC > 9.0\ cmol_c\ kg^{-1}$).

[b] Extractable nutrients in kilograms per hectare.

For the Maryland location, four corn plots ($10\ m^2$, randomized complete block design) adjacent to the sweet potato/cassava experiments were harvested for comparison. These plots were part of a larger field trial experiment by Dr. James A. Bunce (USDA-ARS). At this location, corn was planted on May 17, 2007 (cv. "Yellow Dent"), and harvested September 12th. At the Auburn experimental site, an adjacent long-term rotational experiment on corn (randomized complete block design) was also utilized to determine regional yield (planted May 3, 2007, harvested September 5th, Dr. Charlie Mitchell, Auburn University). Corn plants at this location were also irrigated in a similar manner to the cassava and sweet potato plants.

Sweet potato and cassava were harvested at 138/175, and 146/190 days after transplanting in Maryland and Alabama, respectively. Since sweet potato tubers were not being utilized for fresh market, they were allowed to stay longer in the soil and individual tubers were as large as 3.5 kg at harvest. The sweet potato and cassava plants from the central 3×3 grid of each plot were harvested. Vegetative plant parts were separated and tubers and roots were extracted by hand to a depth of approximately 30 cm. Fresh weights were recorded for sweet potato vines and tubers and for cassava roots and above ground vegetative growth. Following drying at 68 °C to a constant weight, dry weights of tubers and roots were recorded. However, prior to drying, sample cores were taken from tubers and roots for carbohydrate analysis.

2.2. Carbohydrate analysis

Freshly harvested fleshy roots of cassava and sweet potato from the Beltsville location were removed from the ground and 1 cm root cores were removed with a sharpened cork borer. The periderm was excised with a razor blade and the remaining core tissue was frozen in liquid N_2. Root cores were lyophilized for 3 days and then ground to a fine powder under liquid N_2. Fleshy roots from the Auburn location were cut into small sections immediately after harvest and these were quickly placed in liquid N_2. The root samples were freeze dried with the periderm intact and then ground to a fine powder in a Wiley mill. All dried tissue was stored at −20 °C. Prior to analysis the freeze-dried tissue was transferred to a desiccator and allowed to come to room temperature in dry air. Approximately 50 mg of the dried tissue was extracted at 4 °C with 2 ml of 80% aqueous ethanol using a ground glass tissue homogenizer. The homogenates were collected in 15 ml centrifuge tubes and spun at 5800 g for 15 min in an Avanti J20-XP centrifuge (Beckman Coulter, Fullerton, CA, USA). The pellets were rinsed with 1 ml 80% ethanol and centrifuged as described above. The supernatant fractions were combined and evaporated to dryness under a stream of N_2 at 37 °C. The dried extracts were dissolved in 1 ml deionized H_2O. Pellets obtained in the centrifugation step were suspended in 2 ml H_2O and gelatinized in a boiling H_2O bath for 30 min. Starch was converted to glucose at 50 °C in 1 ml reactions containing 1 mg α-amylase and 0.05 mg amyloglucosidase (A-2771 and A-7255, respectively, Sigma Chemicals, St. Louis, MO, USA) and 0.1 M sodium acetate buffer, pH 5.0. Both commercial enzyme preparations were purified by column chromatography prior to use. Sucrose, glucose and the glucose liberated from starch were quantified using coupled enzyme assays as described previously [6]. Starch and carbohydrate for corn were determined from published values [7].

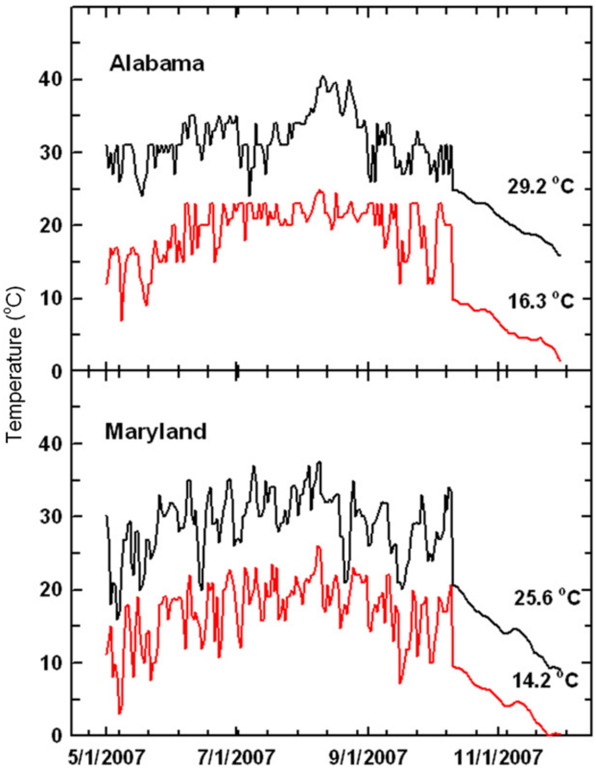

Fig. 1 – Daily maximum and minimum temperatures for Prince George's and Lee counties in Maryland and Alabama, respectively for the 2007 growing season. Values at the end of each graph indicate the average daily maximum and minimum temperatures for each location.

2.3. *Data analysis*

The study was arranged in a completely randomized block at each location for both sweet potato and cassava plots. A two-way analysis of variance (location, crop) was used to analyze carbohydrate concentration and total production. A Fisher's least significant difference (lsd) was used to separate treatment effects.

3. Results

Cultivars, cultural and edaphic conditions were consistent between locations. Phosphorous and potassium levels were above optimal concentrations, and nitrogen fertilization recommendations were similar for both soils. Length of growing season (number of days above 0 °C), was 14 days longer at the Alabama location, as were average maximum and minimum temperatures (29.2 and 16.3 vs. 25.6 and 14.2 °C, respectively, Fig. 1).

For cassava, carbohydrate production was primarily in the form of starch, and was significantly greater for the Alabama relative to the Maryland location (64 vs. 49%). Less than 2% of carbohydrate for cassava was in the form of glucose or sucrose (Table 2). Similarly, carbohydrate production for corn was also principally starch. In contrast, carbohydrate production for sweet potato was from both sucrose and starch for both locations. No difference was observed between populations in sucrose production; however, the Maryland population of sweet potato had a significantly higher percentage of starch (62 vs. 42% Table 2).

Total carbohydrate production was determined as the product of the percent carbohydrate and below ground dry root or tuber biomass. Shoot biomass of cassava did not differ between locations (16.2 and 18.9 Mg ha^{-1} for Alabama and Maryland, respectively), but root biomass was significantly higher for the Alabama relative to the Maryland populations, with a greater overall increase in total carbohydrate production (9.9 vs. 2.9 Mg ha^{-1}, Table 2). Corn production was roughly equivalent at both sites. For sweet potato, no difference in sucrose production was observed between locations, while starch production was greater in Maryland compared to Alabama. Sweet potato and cassava had 1.5 and 1.6× the total carbohydrate production for corn in Alabama; 2.3 and 0.5× the total carbohydrate production for corn in Maryland.

Estimates of potential ethanol production were made using recent conversion estimates from Ref. [8], in order to compare field trials at each location to U.S. average yields (Table 3). While it is not always possible to make comparisons (e.g. cassava yield data for the U.S. are not available); it is clear that the potential ethanol production of cassava and sweet potato are competitive with most other biofuel crops in the United States.

Table 2 – Production of selected carbohydrates for cassava and sweet potato grown in Alabama and Maryland in comparison to field corn production in those two locations.

Alabama	Yield	Starch	Sucrose	Glucose	Total carbs
Corn (field)	9.15 b	5.85 b	0.37 b	NA	6.22 b
Sweet potato[a]	13.02 a	5.43 b	3.75 a	0.21a	9.38 a
Cassava[a]	14.81 a	9.48 a	0.24 b	0.16a	9.88 a
Maryland	Yield	Starch	Sucrose	Glucose	Total carbs
Corn (field)	8.29 b	5.39 b	0.13 b	NA	5.52 b
Sweet potato[a]	14.00 a	8.64 a	3.81 a	0.26 a	12.71 a
Cassava[a]	5.79 b	2.87 c	0.08 b	0.01 b	2.87 c

Field corn data was obtained from adjacent plots located at each experimental site (e.g. Beltsville field station and Auburn experimental farm). Fresh weights of sweet potato and cassava were 70.0/65.1 and 15.3/37.3 Mg ha^{-1} for Maryland and Alabama experimental plots, respectively. Data are given in Mg ha^{-1}. Different letters for a column indicate significant differences using Fisher's protected lsd.

a Dry weight of roots/tubers.

4. Discussion

Cultivation and yield of cassava is highly variable depending on cultural conditions. In the tropics, cassava root yields are between 5 and 20 Mg ha^{-1}; in part because cassava is considered as a subsistence crop, and resource inputs (e.g. water, fertilizer) are low [9]. However, yields as high as 75–90 Mg ha^{-1} (fresh weight) and 25–30 Mg ha^{-1} (dry weight) are possible under experimental conditions [10]. At present the USDA does not keep statistics on cassava production in the United States [5]; consequently, direct comparisons are not possible. However, consistent with the tropical origins of cassava, production in Alabama with warmer maximum and minimum temperatures and a frost-free period of over 220 days was sufficient to produce significant root biomass. In contrast, the growing season in Maryland was long enough to produce shoots, but not long enough for root development to adequately occur.

Sweet potato is a minor crop in the United States growing on less than 40,000 ha [11]. It is primarily grown either for culinary, fresh market or animal consumption. Typically roots are harvested when production of number 1 grade (5–9 cm in diameter) is at its peak. However, because of its high starch content (approximately 80% of the dry matter in sweet potatoes is carbohydrate), efforts are underway to produce an industrial sweet potato (ISP), with a higher starch content with larger tubers [12]. Similarly, in the current study, the sweet potato harvest was delayed in order to increase both tuber size and starch content.

Table 3 – Estimated ethanol production from potential bioethanol crops.

Crop	Ethanol (l ha^{-1})
Cassava[a]	6717
Cassava[b]	2746
Corn[a]	3797
Corn[b]	3399
Corn[c]	3880
Potato[c]	4884
Sugarbeet[c]	5891
Sugarcane[c]	6195
Sweet potato[a]	8141
Sweet potato[b]	8839
Sweet potato[c]	2608

Average yields were obtained from www.nass.usda.gov/QuickStats/indexbysubject.jsp for 2007. Data are liters per hectare. Conversion factors are from Table 2, Johnston et al. 2009.

a This study (Alabama).

b This study (Maryland).

c Based on average U.S. yield per hectare.

How does the carbohydrate yield of these crops compare to other bioethanol crops now in production? At present, the most widely used bioethanol crop globally is sugarcane, which contains 10–15% sucrose, and can produce 8–12 Mg of carbohydrate ha^{-1} [13]. For the United States, corn is the overwhelming bioethanol source, containing 60–65% starch and producing between 7 and 10 Mg carbohydrate ha^{-1} [14,15]; values consistent with the Maryland and Alabama locations. What is intriguing in the current assessment are the high carbohydrate values and potential ethanol production of cassava at the Alabama site, and sweet potato at both locations. Conversion values to determine liters of ethanol per metric ton of harvested crop were taken from Ref. [8]. The values reported here suggest that both cassava and sweet potato may be highly competitive as potential sources of plant biofuel, particularly in the southeast.

Why are the yield values for cassava and sweet potato so high for the current study? This may be due to the fact that both are considered as security crops in subsistence and rural economies and are typically grown with few external resources. With low inputs, average yields can be low. Global yields of cassava and sweet potato are only 12.2 and 13.9 Mg ha^{-1}, respectively [16] even thought potential yields are 4–5× these averages [e.g. Ref. [9]]. Recent values for ISP in field trials at North Carolina State University indicate fresh weights at harvest exceeding 65 Mg ha^{-1} [17].

Where can cassava and sweet potato be grown in the United States? Outside of a few Hispanic neighborhoods in South Florida where it is grown for culinary purposes, cassava is not extensively cultivated in the U.S. for either feed or fuel [18]. It requires at least 8 months of temperatures above 5 °C, a minimum of 50 cm of water and grows best at temperatures between 20 and 35 °C [19]. Based on these climate requirements, cassava could be grown in most of the southeast below latitude 35° N and east of longitude 95° W. Sweet potato requires a shorter growing season, about 4–5 months of frost free days, average temperatures of about 25 °C and a minimum of 50 cm of water during the growing season [11]. Both cassava and sweet potato grow best in slightly acidic (pH 5.6–6.5) sandy loam or light clay soils that are well drained, consistent with the soil characteristics for the Alabama and Maryland locations (Table 1) [19,20]. Both sweet potatoes and cassava grow best on sandy well-drained soils, and heavy clays are avoided due to root malformation [11]. Sweet potato in the United States is primarily in the Southeast, although production can occur as far north as New Jersey. New sweet potato cultivars such as "Jet" and "Centennial " can mature in 90 days, which means that some varieties could be grown all the way to the Canadian border [21]. At present, both Japan and China have made some use of ISPs for ethanol production [11].

There may be additional advantages to sweet potato and cassava, particularly in the Southeast. At present, while corn is the principle source of biofuel, the Southeastern U.S. only produces 2.5% of the U.S. corn crop [5]. In addition, sweet potatoes and cassava are associated with low-input agricultural systems [19,22], whereas corn production *per se* is known to require large fertilizer input, (recommended inputs of 1 kg of N for 40 kg of corn) and can be pesticide intensive (e.g. corn herbicides account for about 40% of the total pounds of herbicides, insecticides, and fungicides that are applied annually by U.S. farmers; Table 3.2, [23]). Sugarcane cultivation requires a tropical or subtropical climate, with a minimum of 600 mm of annual moisture, a climate not currently suitable for much of the United States. Alternatively, cassava can grow over a wide range of rainfall and can tolerate prolonged drought periods. Sweet potato is considered to be moderately drought tolerant [24], although supplemental water is needed to establish cuttings (slips). Weed problems are usually minimal for sweet potato because of the rapid growth of the vines; however, early weed control is necessary for cassava cultivation.

There are uncertainties and concerns that are also associated with cassava and sweet potato. Disadvantages for sweet potato and cassava are primarily related to start-up costs, particularly hand-labor associated with planting either stems (cassava) or slips (sweet potato) or hand cultivation to either dig up the roots or to sort them mechanically during harvest. At present, this makes the cost of culinary sweet potatoes as bioethanol prohibitively expensive. For sweet potato however, efforts are underway to develop ISPs with increased yields that can be grown successfully by mechanically planting seed pieces; overall, improved mechanization of planting and harvest of ISPs could make them economically competitive with corn [25]. Culturally, there is a lot known about how to grow sweet potato on a state by state basis, i.e., irrigation, nutrient and pest applications, crop rotation e.g. Ref. [21]; in contrast, little is know in regard to cassava production in the U.S., even as to whether agronomic practices utilized elsewhere would be effective.

Overall, the combination of high bioethanol production, combined with lower input costs makes these root crops potential alternatives to corn-based ethanol. However, additional work is needed to reduce economic and cultural uncertainties; including direct comparisons of cassava and sweet potato cultivation with corn production systems with respect to inputs of fertilizer, water, pesticides and subsequent estimates of energy ratio of the bioethanol produced from each crop. In addition, post-harvest and transport concerns will have to be evaluated for sweet potato and cassava with respect to ease of conveyance, possible changes in starch/sugar ratios, etc. Overall, however, the current data suggest that alternative sources of biofuel are available, justifying the establishment of pilot programs to examine the feasibility and sustainability of root crops like sweet potato and cassava for ethanol production, particularly on marginal land. Additional research regarding the feasibility of cassava and sweet potato could, therefore, help to develop alternative ethanol sources without harming the supply of corn within the United States.

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