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Agronomic productivity, bioethanol potential and postharvest storability of an industrial sweetpotato cultivar

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ABSTRACT

An industrial sweetpotato cultivar, CX-1, offers several advantages as an alternative crop for bioethanol production, including high agronomic productivity and high starch content as well as viable coproducts for additional bioenergy recovery. A two-year agronomic field trial resulted in a root yield of 12.3 dry t ha^{-1} after optimization of planting strategy and improved site drainage. Starch content (73.5% dry matter (DM) for Year 1 and 72.1% DM for Year 2) exceeded that of any other industrial variety grown in the Southeastern USA. In contrast to other industrial cultivars, starch concentrations were maintained over a six-month storage period, making this a favorable year-round feedstock. The bioethanol potential of the CX-1 (4.2 t ha^{-1} or 5300 L ha^{-1}) was determined based on the conversion of CX-1 dry biomass into ethanol by simultaneous saccharification and fermentation combined with the agronomic root yield from the Year 2 field trial. The cull rate was 36% of the overall root yield, as determined based on United States Department of Agriculture culinary grades. However, assessment of the culls from an industrial processing perspective would significantly reduce the cull rate. Approximately 45% of the culls were classified as cull material (i.e. secondary rootlets) that could feasibly be converted into ethanol. The remaining 55% of the culls could be used for biogas recovery to offset the energy required to produce ethanol from sweetpotatoes.

1. Introduction

Industrial sweetpotatoes (*Ipomoea batatas* L.) are a high-yielding crop that can be grown on marginal lands and used in the production of bioethanol. Sweetpotatoes thrive in tropical to sub-tropical climates and are known for their resistance to extreme weather conditions such as droughts and flooding. Minimal fertilization, irrigation and weed control favor this crop as a sustainable agricultural system; however, cultivation and harvesting practices need further mechanization and improvement. Industrial sweetpotato cultivars can be differentiated from standard table varieties by their high dry matter (DM) and starch content (Mussoline and Wilkie, 2015). A life cycle assessment (LCA) that evaluated all agronomic and biotechnological aspects of converting an industrial sweetpotato into ethanol resulted in a positive net energy ratio of 1.48 and a net energy gain of 6.55 MJ L^{-1} (Wang et al., 2013). Thus, from agronomic and energetic perspectives, industrial sweetpotatoes are a viable alternative crop for bioethanol production.

Corn (maize, *Zea mays* L.) is currently the primary feedstock for bioethanol production, despite its limited agronomic productivity in warm climates. Approximately 60% of the world's ethanol is produced in the USA (Renewable Fuels Association, 2015) and 90% of US biorefineries use corn as a feedstock (Ethanol Producer Magazine, 2015). Corn, however, has limitations as an ethanol feedstock, particularly with regard to agronomics and land-use controversies. In warmer climates such as the Southeastern USA, sweetpotatoes had twice the bioethanol yields than corn primarily due to superior agronomic yields (Ziska et al., 2009). From a societal perspective, corn is a staple food that has a dominant nutritional role in most of the world's diet and its use as an energy crop is controversial. In China, for example, recent regulations have directed the ethanol industry toward non-grain-based feedstocks (Qui et al., 2010). This decision was largely motivated by food security issues, but reduced greenhouse gas emissions (263,000 t CO_2 predicted

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for 2015) was found to be an important environmental benefit of using sweetpotatoes rather than grain-based feedstocks (Li et al., 2010). Of the non-grain-based feedstocks considered (namely sweet sorghum (*Sorghum bicolor* (L.) Moench), cassava (*Manihot esculenta*), molasses, agricultural straw and sweetpotato), sweetpotato was also the most economical (3840 Yuan t^{-1}) for bioethanol production (Li et al., 2010). Thus, in addition to the agronomics, the industrial sweetpotato has a socioeconomic advantage as an alternative crop for bioethanol production.

The process of converting starch into bioethanol is a well-established technology that involves the following steps: 1) gelatinization or solubilization of the starch molecules; 2) liquefaction or the conversion of long-chain glucose polymers into dextrins; 3) saccharification or the hydrolysis of dextrins to fermentable sugars; 4) fermentation or the conversion of sugars into alcohol and carbon dioxide using yeast; and 5) distillation or the concentration of the alcohol through evaporation and condensation. The initial gelatinization of starch requires a certain temperature that is best determined by the ratio of linear starch polymers (amylose) to branched starch polymers (amylopectin) (Power, 2003). Common corn and sweetpotatoes have relatively the same proportion of amylose (20 to 25%) to amylopectin (75 to 80%) and thus the optimal gelatinization temperature will be essentially the same (Power, 2003; Walter et al., 2000). Once the starch is gelatinized into a highly viscous liquid, hydrolysis is carried out by two specific enzymes, namely *α-amylase* (liquefaction) and *amyloglucosidase* (saccharification) (Power, 2003). The enzymatic hydrolysis is the only additional step required for starch feedstocks compared with sugar feedstocks, but these procedures are common in the biorefinery industry. Lignocellulosic feedstocks, such as corn stover and sugarcane bagasse, can also be converted into fuel ethanol; however, the pretreatment required for these feedstocks is often energy intensive and cost prohibitive (Wilkie et al., 2000).

Another benefit of the industrial sweetpotato crop is the associated coproducts, including aerial vines, culls and stillage, that can be used to produce substantial quantities of biogas via anaerobic digestion (Mussoline and Wilkie, 2015). As determined by LCA, the most significant improvement for converting sweetpotatoes to ethanol was displacing the fossil fuels used to generate steam with a cleaner-burning fuel such as natural gas (Wang et al., 2013). Biogas from the coproducts can be used directly to heat boilers and generate the steam for the distillation process. Successful bioenergy recovery and utilization from sweetpotato distillery waste in the Shochu industry has been demonstrated (Kanai et al., 2010; Kobayashi et al., 2014). The energy recovery from the coproducts not only reduces fossil fuel demand and associated greenhouse gas emissions, but also promotes the industrial sweetpotato as a new potential feedstock for advanced biofuels that could be considered under the US EPA's Renewable Fuel Standard Program (USEPA, 2015).

The objectives of this research were to determine the agronomic yield, starch content, bioethanol yield, and postharvest storability of a newly developed industrial sweetpotato. The CX-1 has a light yellow flesh color and was specifically selected for fuel ethanol production because of its high DM and starch content. Roots with high DM content promote more efficient handling processes including harvest, transport, curing and storing, and contain a higher starch content (Hall and Smittle, 1983; Hamilton et al., 1986; Martin and Jones, 1986). Site conditions and planting strategies were established during a preliminary trial in Year 1 and optimized agronomic yields are reported for Year 2. As part of the agronomic study, cull rates were determined to quantify the biomass that would be available for bioenergy recovery processes. Definitions of culls based on culinary practices were used; however, further delineation of the culls for industrial processing is discussed. Carbohydrate concentrations were determined for the roots and feedstock-specific ethanol yields were combined with agronomic yields to determine the bioethanol yield in tonnes per hectare (t ha^{-1}). Finally, the postharvest storability of the CX-1 industrial sweetpotato was investigated in order to assess its potential for utilization as a year-round ethanol feedstock.

Table 1
Classification used for grading sweetpotato roots.

Grade	Diameter (cm)	Length (cm)	Fresh Weight (kg)
No. 1	4.5 to 9.0	7.6 to 23.0	<0.6
No. 1 petite	3.8 to 5.7	7.6 to 18.0	ND
No. 2	>4.0	ND	0.6 to 1.0
Jumbo	ND	ND	1.0 to 3.0

Source: Johnson et al., 1992; USDA, 2005.
ND – Not defined.

2. Materials and methods

2.1. Agronomic field trials

An exploratory field trial was conducted in Gainesville, Florida (29° 37′ 38.32″ N, 82° 21′ 40.37″ W) from June to December 2014 (referred to herein as Year 1), to optimize the planting strategy and site conditions for the industrial CX-1 sweetpotato crop. Plant material was propagated in South Carolina and provided by CAREnergy, LLC, North Charleston, South Carolina, USA. Rooted plants were established in trays for 30 days prior to planting while non-rooted cuttings were stripped from recently harvested vines and planted directly in the ground. A total of 96 rooted plants and 96 non-rooted cuttings were initially planted in two plots on 6 June 2014. Each plot consisted of three replications of raised beds with an inter-row plant spacing of 30 cm. Raised beds were 50 cm wide by 30 cm high and formed on 1-m centers. The beds were oriented in a North-South direction. The soil type was a loamy Blichton sand, gently sloping and somewhat poorly drained (USDA, 2013). A compound fertilizer (N:P:K 6:6:6) was applied at a rate of 88.5 kg N ha^{-1}. Total rainfall was measured onsite during the growing season and no additional irrigation was applied.

A second field trial was conducted in the same location in the following year (2015), which is referred to herein as Year 2. During the Year 2 field trial, the initial planting material consisted of rooted plants only and the rows were oriented in an East-West direction rather than the previous North-South direction to promote better soil drainage. All other experimental conditions remained the same. There was some variation in climatic conditions such as rainfall and temperature.

The roots from both the Year 1 and Year 2 field trials were harvested by hand, 182 days after planting (DAP). The roots were graded by hand and weighed fresh in the field immediately following harvest. The roots were graded into four categories, namely No. 1, No. 1 petite, No. 2, and Jumbo, as defined in Table 1 (Johnson et al., 1992; USDA, 2005). Although not defined by the United States Department of Agriculture (USDA) for marketable sweetpotatoes, the Jumbo category is necessary to classify industrial sweetpotatoes since they can be larger than edible varieties. Root yields were determined on both a fresh matter and DM basis.

Culls from both Year 1 and Year 2 were separated by hand during the harvest. According to the USDA, a cull is defined as a root with evidence of soft rot, black rot, internal discoloration, bruises, cuts, growth cracks, damage from insects such as sweetpotato weevil or wireworm, or other diseases (USDA, 1997). Cull material includes fragments, root crowns, and secondary rootlets (USDA, 1997). Culls and cull material were separated from the graded roots and weighed to determine the cull rate for both years.

2.2. Sample collection and preparation of roots

Representative samples of fresh roots from each plot were collected upon harvest and prepared for analyses for both Year 1 and Year 2. The representative root samples consisted of ten roots from each plot with at least two roots from each grade. The excess soil was removed from the roots with a brush and then all ten unpeeled roots were chopped into 2.5-cm cubes with a knife. The chopped material was further reduced in a Sunbeam Food Processor using a serrated blade. The processed material was placed in a drying oven at 60 °C for 72 h and milled to pass through a 425-μm sieve using a Wiley mill (Arthur H. Thomas Co., Philadelphia, Pennsylvania, USA). After milling, the CX-1 sweetpotato flour (SPF) was stored in sealed polyethylene bags and placed in a desiccator at room temperature for further analyses.

Roots remaining from the Year 1 harvest of the non-rooted plot were stored whole in a climate-controlled room at 25 °C for six months after harvest to determine if losses occurred over time. After six months of storage, a total of ten stored roots were chopped, processed, dried and milled following the same procedures described previously.

2.3. Laboratory analytical methods

Upon harvest during Years 1 and 2, a subsample of the ten fresh roots were chopped and analyzed immediately for DM and organic matter (OM) according to standard methods (APHA, 2012). After drying and grinding the root material, SPF was sent to Dairy One Forage Testing Laboratory in Ithaca, New York, for analysis of DM, total nitrogen (N), total phosphorus (P), total starch, water-soluble carbohydrates (WSC), and ethanol-soluble carbohydrates (ESC). Resistant starch was also measured for the SPF and analyses were performed at the University of Florida Bioenergy and Sustainable Technology Laboratory in Gainesville, Florida. For N analyses, pre-ground samples were analyzed by combustion using a CN628 carbon/nitrogen determinator. For P analyses, samples were digested using a microwave accelerated reaction system (MARS6, CEM Corporation, Matthews, North Carolina, USA) and then analyzed using a Thermo iCAP 6300 inductively coupled plasma (ICP) radial spectrometer. For starch analyses, samples were pre-extracted for sugar by incubation in a 40 °C water bath and filtration on Whatman 41 filter paper. Residues were thermally solubilized using an autoclave, then incubated with glucoamylase enzyme to hydrolyze starch to produce dextrose (glucose). Prepared samples were injected into the sample chamber of a YSI analyzer, where dextrose diffused into a membrane containing glucose oxidase. The dextrose was immediately oxidized to hydrogen peroxide and D-glucono-4-lactone. The hydrogen peroxide was detected amperometrically at the platinum electrode surface. The current flow at the electrode is directly proportional to the hydrogen peroxide concentration, and hence to the dextrose concentration. Starch was determined by multiplying dextrose by 0.9. Resistant starch was measured using a resistant starch assay kit (K-RSTAR, Megazyme, Ireland), which is based on a method developed by McCleary and Monaghan (2002) and approved by the Association of Official Analytical Chemists (AOAC) and the American Association of Cereal Chemists (AACC). The WSC and ESC were partitioned according to Hall et al. (1999) and results were measured using a Thermo Scientific Genesys 10S Vis spectrophotometer. All laboratory analyses were performed in triplicate and the results are expressed as mean ± standard deviation. The starch data were subjected to analyses of variance using single factor ANOVA in Microsoft Excel and the means were separated using Tukey-Kramer's test at the 0.05 probability level (i.e. $P < 0.05$).

A representative sample of CX-1 roots was evaluated for bioethanol potential at the National Corn to Ethanol Research Center (NCERC) at Southern Illinois University, located in Edwardsville, Illinois, USA. Fresh material and SPF were both converted into ethanol by simultaneous saccharification and fermentation (SSF) in 250-ml and 1000-ml batch assays, respectively. The experiment with fresh material was replicated six times and the experiment with SPF was replicated three times.

During the Year 1 field trial, soil grab samples were collected from each row of both the rooted and non-rooted plots in the middle of the growing season (100 DAP) and analyzed for soil moisture. The DM content of the soil was measured according to standard methods (APHA, 2012) and used to calculate the moisture content.

Table 2
Agronomic root yields for CX-1 sweetpotato cultivar from two-year field trial.

	Fresh matter yield ($t\,ha^{-1}$)	Dry matter yield ($t\,ha^{-1}$)
Year 1 (Non-rooted)	21.1	4.5
Year 1 (Rooted)	27.3	7.6
Year 2 (Rooted)	46.9	12.3

3. Results and discussion

3.1. Agronomic yields

The quantity of roots produced from sweetpotato crops varies widely depending on the planting strategy (i.e. rooted versus non-rooted cuttings), climatic conditions, cultivar, geographic region, soil type, fertilization rate, irrigation patterns, drainage conditions and length of growing season. The agronomic yields from both the Year 1 and Year 2 field trials conducted for the CX-1 sweetpotato cultivar in Gainesville, Florida (USA) are shown in Table 2. During Year 1, all variables were kept constant with the exception of the planting strategy. Agronomic yields and DM content from rooted plants were compared with that of the non-rooted cuttings to determine the influence of planting strategy. Agronomic yields (on a fresh matter basis) increased by almost 30% using the rooted plants versus the non-rooted cuttings, as shown in Table 2. At the end of the 182-day growing season, the rooted plants also had a higher DM content (28%) than the non-rooted plants (21%). Thus the DM yield improved by nearly 70% using the rooted plants. The DM content is an important characteristic for an industrial crop because it promotes better handling efficiency since there is less water to transport. The DM content of the roots from the rooted CX-1 plots (Year 1 = 28%, Year 2 = 26%) is consistent with the average of 11 different industrial sweetpotato cultivars previously grown in Georgia (26%) (Hall and Smittle, 1983).

In addition to higher agronomic yields, root size and development were influenced by the planting strategy. In Year 1, both plots were planted and harvested on the same schedule, but the roots enlarged and developed more quickly in the rooted plot than in the non-rooted plot. For example, the proportion of Jumbo roots was more than double in the rooted plot compared with the non-rooted plot. Additionally, as stated above, the DM content of the roots from the rooted plot was higher than those in the non-rooted plot. These observations suggest that size and DM content of the root are not only a function of its genotype, but they are also influenced by planting strategy and soil moisture. The soil type was the same for both plots, but visual observation after heavy rains indicated that the soil moisture was different. The furrows between the beds remained saturated longer after heavy rains in the non-rooted plot compared with the rooted plot. Soil moisture was determined for both plots near the middle of the growing season (100 DAP) and results indicated that soil moisture was higher in the non-rooted plot (20.2 ± 0.3%) compared with the rooted plot (11.6 ± 3.7%).

Thus, in addition to the planting strategy, the primary variable that was modified during the Year 2 field trial (compared with Year 1) was the drainage pattern. The raised beds and furrows were oriented in an East-West direction to align with the natural topography of the land, which significantly improved the drainage conditions in the Year 2 field trial. Although soil moisture was not analyzed during Year 2, visual observation after heavy rainfall events confirmed that no standing water was present in the furrows. Climatic conditions also varied from Year 1 to Year 2. Rainfall was the only source of irrigation during both years, but recorded rainfall was lower in Year 1 (76 cm) compared with Year 2 (95 cm). Rainfall distribution was also more heavily weighted in the first 30 DAP during Year 2, and more rainfall during the establishment period is favorable for the sweetpotato crop. In other studies, excessive moisture conditions (greater than 100% field capacity) during the establishment phase (10 to 28 DAP) contributed to a higher number and length of roots (Pardales et al., 2000), while flooding during mid-season (60 DAP) stunted the growth of the roots (Roberts and Russo, 1991).

The agronomic root yields from the Year 2 field trial were significantly improved by optimizing the site drainage conditions and planting strategy. Rainfall distribution, which was more heavily weighted toward the establishment phase of the crop, also likely contributed to the improved agronomic root yields during the Year 2 field trial. Although industrial sweetpotato crops are widely grown in China and Brazil for ethanol production, the agronomic yields of industrial sweetpotatoes grown in the Southeastern USA are more suitable for comparison due to similar regional and climatic conditions. The agronomic yields (DM basis) measured for the CX-1 during Year 2 (12.3 t ha^{-1}) are within the range for industrial sweetpotatoes previously grown in Maryland (14.0 dry t ha^{-1}) and Alabama (13.0 dry t ha^{-1}) (Ziska et al., 2009), and they are higher than yields from five different cultivars grown in South Carolina over multiple cropping seasons (Jones et al., 1983). They are lower than the average of 11 different industrial cultivars previously grown in Georgia (16.5 dry t ha^{-1}); however, the length of the growing season was different (Hall and Smittle, 1983). The Georgia-grown cultivars were harvested 195 DAP compared with 182 DAP for the CX-1. Roots continue to grow in size and accumulate mass the longer they remain in the ground and yields increase linearly until 200 DAP (Chen and Yang, 1980; Locascio and Dangler, 1986; Wu and Bagby, 1987). Ten Chinese industrial varieties, for example, were grown for 100, 130 and 160 days, and average fresh root yields increased from 20.9 to 26.6 to 30.1 t ha^{-1}, respectively (Jin et al., 2012).

In summary, significantly higher agronomic root yields (DM basis) were obtained from the rooted plants compared with the non-rooted cuttings during the Year 1 exploratory field trial. Optimization of the planting strategy, improved drainage patterns and highly favorable climatic conditions resulted in optimal agronomic yields for the CX-1 cultivar during the Year 2 field trial. Further optimization of the CX-1 sweetpotato crop with particular emphasis on length of growing season and variety of soil type across the Southeastern USA is recommended to obtain even higher agronomic root yields from this particular cultivar.

3.2. Grading classifications and cull rates

The size distribution of CX-1 roots as well as the cull rate from the field trials was determined. In Year 2, besides the culls/cull material (36% of the crop yield), the most common grading classifications were No. 1 (26% of the crop) followed by No. 2 (22% of the crop). The remaining fractions of the CX-1 crop were made up of No. 1 petites (13%) and Jumbos (3%). The grading distributions of industrial sweetpotatoes are not reported in the literature and therefore no comparisons with different industrial cultivars are available. Jewel, a common table variety, resulted in a crop that consisted mainly of No. 1 (35% of the crop) and Canners, comparable to No. 1 petites, (30% of the crop) over a five-year cropping period with no nematode treatment, while the proportion of Jumbos was the same as for the CX-1 (Johnson et al., 1992).

Published data is limited regarding the percentage of culls that are generated from the sweetpotato crop, particularly for industrial cultivars. The culls can be a result of excessive soil moisture, disease, or damage from pests. The CX-1 crop had a similar cull rate (36% of the crop yield) as that reported from a table sweetpotato crop planted continuously during two consecutive years (32% of the cumulative root yield) (Guertal et al., 1997). Less culls were observed when sweetpotatoes were planted in rotation with other crops compared with continuous cropping (Guertal et al., 1997). In another study that incorporated five years of intercropping sweet corn-Jewel sweetpotato-vetch, the average cull rate decreased from 32% to 26% with nematode treatments (Johnson et al., 1992). Another management strategy is to use multi-pest resistant sweetpotato cultivars (Ryan-Bohac et al., 2006).

The most common insect causing damage to the sweetpotato crop is the *Cylus formicarius* complex, commonly known as the sweetpotato weevil (Sorensen, 2009). Sweetpotato weevils are particularly problematic in Florida because moderate temperatures allow them to persist year-round (Ryan-Bohac et al., 2006). Sweetpotato weevil pheromone (Z-3-dodecen-1-yl-*E*-2-butenoate) was obtained from Great Lakes IPM Inc. in Vestaburg, Michigan, and traps baited with the pheromone were staged in the sweetpotato plots. Although the weevil population increased significantly from Year 1 (5 weevils trapped) to Year 2 (150 weevils trapped), there was no major change in the CX-1 cull rate from Year 1 (33% for the rooted crop) to Year 2 (36%). In contrast, an edible sweeetpotato cultivar (Beauregard) grown in the same vicinity as the CX-1 was likely impacted by the increased weevil presence since the Beauregard cull rate increased from 39% in Year 1 to 52% in Year 2. Certain sweetpotato varieties including Beauregard have a relatively high sensitivity to sweetpotato weevils, while others tend to be more resistant (Ryan-Bohac et al., 2006).

The most common observations in culls of the CX-1 crop were either a section of the root consisting of soft discolored flesh or small undeveloped rootlets. Since the entire flesh was often not impacted, further delineation of the culls was considered in order to optimize ethanol productivity from this industrial crop. Sweetpotato culls are broadly defined by the USDA as roots that do not meet the definition of any culinary grade or have some type of damage or serious disease (USDA, 1997). Some culls are caused by soft or black rot and are characterized by a moist, paste-like texture that is black or brown. Other culls may be characterized by insect damage such as a series of small holes in a section of the root caused by weevils. There are varying degrees of culls as some may have only 10% to 25% of the flesh impacted while others may be completely impacted. Some culls may simply be badly misshapen or have growth cracks and thus the interior flesh is not impacted at all.

Roots that are classified as culls in the edible market regulated by the USDA would not necessarily be classified as culls in the energy market. Cull material, for example, is defined as pieces of sweetpotato, root crowns, sprouts, or secondary rootlets (USDA, 1997). Cull material from the CX-1 sweetpotato has the same white flesh as the larger roots and though it would not be suitable for the edible market, it would be suitable for ethanol production despite its smaller size and carrot-like shape. Therefore, in addition to the overall cull rate determined for the crop, the CX-1 culls were further differentiated as culls and cull material. Approximately 45% of the culls consisted of cull material, primarily secondary rootlets, that would still be suitable as a feedstock for ethanol production.

Table 3
Composition of CX-1 sweetpotato roots.

	Nitrogen (% DM)	Crude Protein (% DM)	Phosphorus (% DM)	Total Starch[a] (% DM)	Resistant Starch (% DM)	WSC (% DM)	ESC (% DM)
Year 1 (Non-rooted)	0.78 ± 0.01a	4.84 ± 0.04a	0.27 ± 0.01a	66.8 ± 0.5a	ND	10.7 ± 0.5a	7.0 ± 0.3a
Year 1 (Rooted)	1.04 ± 0.01b	6.48 ± 0.06b	0.23 ± 0.00b	73.5 ± 0.3b	31.4 ± 0.9a	6.4 ± 0.2b	2.4 ± 0.1b
Year 2 (Rooted)	0.72 ± 0.01c	4.49 ± 0.06c	0.24 ± 0.00c	72.1 ± 0.5c	29.1 ± 1.4a	6.6 ± 0.1b	2.5 ± 0.1b

WSC – Water-soluble carbohydrates, ESC – Ethanol-soluble carbohydrates, DM – Dry matter, ND – Not determined.
Data are means ± standard deviation (n = 3). Values within the same column with different lower-case letters are significantly different ($P < 0.05$).
[a] Total starch equals resistant starch plus soluble starch.

Thus, it is important to establish new definitions and parameters to clearly identify culls for an industrial crop versus a food crop.

The remaining 55% of the culls that are partially degraded or have insect damage would not be useful for conversion to ethanol. They could, however, be utilized as a feedstock to generate biogas via anaerobic digestion that could be used to offset the energy required for the ethanol production process or for other biorefinery operations. Anaerobic digestion is the conversion of organic matter into biogas, which is mostly methane, by a mixed consortium of microorganisms (Wilkie, 2008; Wilkie et al., 2004). Full-scale facilities producing ethanol from sweetpotatoes have utilized methane generated from distillery wastewater to make steam for the distillation process (Kanai et al., 2010; Kobayashi et al., 2014). Further analysis is necessary to determine the optimal conditions and ultimate methane potential of the CX-1 sweetpotato culls to assess the feasibility of using them as a feedstock for anaerobic digestion.

3.3. Starch and bioethanol yields

3.3.1. Fermentable components and starch yields from the CX-1 sweetpotato

Total fermentable components in sweetpotatoes consist of the summation of starch and sugar (Hall and Smittle, 1983; Wu and Bagby, 1987). Industrial varieties generally have a higher DM and starch content than table sweetpotatoes. The fermentable components of the CX-1 sweetpotato are predominantly starch, as shown in Table 3. The starch content of sweetpotatoes varies widely among different genotypes of sweetpotato; however, there is a strong positive correlation between DM content and starch (Hall and Smittle, 1983; Zhang et al., 2002). Six common table varieties grown in Raleigh, North Carolina, including Covington, Beauregard, O'Henry, Hernandez, Norton and Porto Rico, had an average DM of 22.6% and starch content of 14.5% DM (Brinley et al., 2008). Particular industrial genotypes have been evaluated and selected to maximize starch yields. A total of 106 genotypes obtained from the world germplasm collection held at the International Potato Center (CIP) in Peru were evaluated for starch content and related properties such as amylose content and pasting properties that affect extraction procedures (Brabet et al., 1998). Seven genotypes were selected specifically for starch production, and they had an average DM of 39.4% and starch content of 64.3% DM (Brabet et al., 1998).

Starch concentrations (DM basis) for the CX-1 crops from both Years 1 and 2 are shown in Table 3. The total starch concentrations for the CX-1 cultivar (rooted crop) are generally higher than that of the starch-abundant cultivars evaluated from the CIP, which ranged from 62.9 to 68.4% DM (Brabet et al., 1998). They are also higher than that observed in all the other industrial varieties grown in the Southeastern USA (see Table 4). Statistical differences ($P < 0.05$) were evident among the total starch concentrations between Year 1 rooted and non-rooted crops, and also between Year 1 and Year 2 rooted crops (Table 3). Since the roots were established prior to planting, the rooted crops had more time for starch biosynthesis compared with the non-rooted crop during Year 1, as evidenced by lower sugar concentrations and higher starch concentrations in the rooted crop. The slightly higher starch concentration in the Year 1 rooted crop compared with the Year 2 rooted crop is likely related to the higher DM content of the roots from Year 1 (28%) compared with Year 2 (26%), which affirms the positive correlation between DM content and starch (Hall and Smittle, 1983; Zhang et al., 2002). There was no significant difference ($P < 0.05$) between the resistant starch concentrations for the Year 1 and Year 2 CX-1 rooted crops (Table 3). The resistant starch concentrations of the CX-1 roots were 40–43% of the total starch, which is much higher than that measured for table cultivars, namely Hernandez (29% of total starch) and Beauregard (26% of total starch).

Table 4
Starch content and agronomic starch yield of industrial sweetpotatoes grown in the Southeastern USA.

Cultivar	Starch content (% DM)	Starch yield (t ha^{-1})	Reference
CX–1[a]	72.1 ± 0.5	8.87	This study
Unknown (Alabama)	41.8	5.43	Ziska et al. (2009)
Unknown (Maryland)	61.7	8.64	Ziska et al. (2009)
TG–2	55.9	5.25[b]	Jones et al. (1983)
W–190	68.6	6.86[b]	Jones et al. (1983)
W–201	61.6	6.65	Jones et al. (1983)
73–42 × 61–2	56.1	6.07	Hall and Smittle (1983)
61–15–35	62.0	9.44	Hall and Smittle (1983)
73–61–2–W	57.9	8.13	Hall and Smittle (1983)
73–61–2–S	58.8	10.02	Hall and Smittle (1983)
Rojo Blanco	55.6	5.88	Hall and Smittle (1983)
75–96–1A	55.2	9.77	Hall and Smittle (1983)
75–E × 29–1	54.2	9.32	Hall and Smittle (1983)
73–42–1	64.0	9.78	Hall and Smittle (1983)
75–Cent–2	64.1	12.68	Hall and Smittle (1983)
White Star	60.8	12.39	Hall and Smittle (1983)
75–96–1B	62.1	14.42	Hall and Smittle (1983)

[a] Year 2 rooted crop.
[b] Average of three cropping seasons.

The sugar concentrations in the CX-1 rooted crops contributed less than 10% of the total carbohydrates. Nutrient concentrations in the CX-1 crops were consistent with or higher than those measured in table sweetpotatoes. Crude protein measured in 16 table cultivars averaged 4.41 ± 1.38% DM and phosphorus concentrations averaged 0.18 ± 0.03% DM; however, these cultivars were not fertilized (Ravindran et al., 1995). The nitrogen concentrations in the CX-1 crops were nearly twice that of four table cultivars grown in Florida with similar fertilization rates (Locascio and Dangler, 1986).

Based on the DM agronomic yield reported in Table 2, the overall starch yield was 8.9 t ha^{-1} for the Year 2 CX-1 field trial. Starch yields for other industrial sweetpotato cultivars grown in the Southeastern USA are included in Table 4 for comparison. Starch yields from the CX-1 cultivar are higher than those determined by Ziska et al. (2009) and Jones et al. (1983) for other industrial sweetpotato cultivars. However, some of the starch yields reported by Hall and Smittle (1983) are higher due to a longer growing season that contributed to higher agronomic root yields, as discussed previously in Section 3.1.

Table 5
Measured and estimated bioethanol yields of industrial sweetpotatoes.

Cultivar	Ethanol yield[a] ($t\,ha^{-1}$)	Reference
CX–1[b]	4.2	This study
NS 88	3.4	Jin et al. (2012)
XS 18	3.0	Jin et al. (2012)
YZ 263	4.0	Jin et al. (2012)
NS 009	3.6	Jin et al. (2012)
NS 007	4.8	Jin et al. (2012)
200730	2.4	Jin et al. (2012)
SS19	5.0	Jin et al. (2012)
WS 34	4.5	Jin et al. (2012)
2–I2–8	4.2	Jin et al. (2012)
XS 22	4.3	Jin et al. (2012)
Unknown (Alabama)	6.5[c]	Ziska et al. (2009)
Unknown (Maryland)	7.0[c]	Ziska et al. (2009)
73–42 × 61–2	3.8[d]	Hall and Smittle (1983)
61–15–35	5.8[d]	Hall and Smittle (1983)
73–61–2–W	5.0[d]	Hall and Smittle (1983)
73–61–2–S	6.4[d]	Hall and Smittle (1983)
Rojo Blanco	3.9[d]	Hall and Smittle (1983)
75–96–1A	5.6[d]	Hall and Smittle (1983)
75–E × 29–1	5.5[d]	Hall and Smittle (1983)
73–42–1	5.5[d]	Hall and Smittle (1983)
75–Cent–2	7.1[d]	Hall and Smittle (1983)
White Star	6.9[d]	Hall and Smittle (1983)
75–96–1B	8.0[d]	Hall and Smittle (1983)

[a] Reported in metric tonnes per hectare ($t\,ha^{-1}$) assuming that 1 metric tonne = 1262 L of ethanol.
[b] Year 2 rooted crop.
[c] Estimated from ethanol conversion: 125 L ethanol t^{-1} fresh sweetpotatoes (Johnston et al., 2009).
[d] Estimated from ethanol conversion: 1 gal ethanol per 13.6 lbs fermentable carbohydrates (Sachs, 1980).

3.3.2. Bioethanol potential of the CX-1 sweetpotato

Agronomic ethanol yields for the rooted CX-1 from the Year 2 field trial and for other industrial sweetpotato cultivars are reported in Table 5. Experiments conducted at NCERC resulted in an ethanol yield of 0.34 ± 0.01 g ethanol g^{-1} DM from the CX-1 fresh material and SPF. The measured ethanol yield was combined with the measured agronomic yield to determine the agronomic ethanol yield ($4.2\,t\,ha^{-1}$). Despite the previous discussion regarding the cull rate of the CX-1 crop (see Section 3.2), the entire crop yield was used to calculate the ethanol agronomic yield for comparison purposes since reported values in the literature incorporate the entire crop yield and do not distinguish between viable and non-viable roots for bioethanol production. Although agronomic yields were measured for the sweetpotato cultivars grown in Maryland, Alabama, and Georgia, estimations were used to predict agronomic ethanol yields for these particular cultivars (Hall and Smittle, 1983; Ziska et al., 2009). Ziska et al. (2009) combined measured agronomic yields with biomass-to-ethanol conversion factors reported specifically for sweetpotatoes (125 L ethanol t^{-1} of fresh sweetpotatoes) (Johnston et al., 2009; Ziska et al., 2009). Hall and Smittle (1983) used measured agronomic yields and assumed that one gallon of ethanol was produced from 13.6 lbs of fermentable carbohydrates, which included sugar and starch (Hall and Smittle, 1983; Sachs, 1980).

Estimations, however, are not precise since the characteristics that influence fermentation efficiency such as DM, bulk density, fiber, pectin, soluble sugar, starch, and amylose/amylopectin ratios vary among different cultivars. Therefore, more reliable data that incorporates fermentation efficiencies for specific cultivars were also used for comparison. Ten cultivars of industrial sweetpotatoes from China were evaluated specifically for ethanol production efficiency (i.e. minimal feedstock and land use for maximum ethanol production) (Jin et al., 2012). Agronomic ethanol yields from roots harvested at 160 DAP ranged from 2.4 to $5.0\,t\,ha^{-1}$, as shown in Table 5 (Jin et al., 2012). The agronomic ethanol yield was lowest for the 200730 cultivar ($2.4\,t\,ha^{-1}$), mainly due to a low fermentation efficiency (88.8%) when compared with the other Chinese cultivars (Jin et al., 2012). By contrast, the CX-1 cultivar had relatively high fermentation efficiencies for both the fresh root (92%) and SPF (100%), indicating that the agronomic ethanol yield could be vastly improved with continued optimization of the agronomic root yields from this crop.

3.4. Postharvest storage of the CX-1 sweetpotato

Since starch is generally easier to store than sugar, the postharvest storability of the CX-1 cultivar is of particular interest. The potential for postharvest storage is one advantageous characteristic that supports the use of industrial sweetpotatoes for ethanol production. Although the crop is normally harvested in November or December, the roots can potentially be stored up to six months and used as a continual feedstock supply for ethanol production. Previous studies, however, have documented changes in the carbohydrate fractions and decreases in starch content over time for certain cultivars. Six sweetpotato cultivars stored at 20 °C and 75% relative humidity were evaluated for starch content at harvest, and then at 60, 120 and 180 days following harvest (Zhang et al., 2002). All the cultivars exhibited some loss in starch over the 180-day storage period, but the most dramatic decrease was observed in the Hi-dry cultivar which decreased from 73.6% DM to 51.1% DM (Zhang et al., 2002). The Hi-dry had the highest DM content and initial starch content among the six cultivars, but the stability of these properties was not proven over time (Zhang et al., 2002). In another study, the average starch content in four different table varieties diminished by 44% after seven months of storage (Reddy and Sistrunk, 1980). Similarly, two table varieties (Porto Rico and Goldrush) showed losses in starch of approximately 50% after six months of storage at 60 °C (Sistrunk, 1971).

In contrast to these studies, the starch content in the CX-1 roots was stable over a six-month storage period. There was no significant difference between the starch content of the CX-1 root that was evaluated immediately following harvest and the starch content of the CX-1 root that was processed and analyzed after six months of storage ($P < 0.05$). This starch stability may be related to both the high DM content of the CX-1 root as well as the elevated presence of resistant starch. Resistant starch is physiologically defined as starch that is not broken down by human enzymes in the small intestine and thus it behaves more like dietary fiber in the digestion scheme. Certain structural differences in the starch, particularly higher amylose content, have been correlated with higher resistant starch concentrations (Berry, 1986). Resistant starch can reduce ethanol productivity, particularly with low-temperature liquefaction (Sharma et al., 2010). However, the resistant starch in the CX-1 root did not significantly affect its ethanol yields as determined by the relatively high fermentation efficiencies for both the fresh root (92%) and SPF (100%). Since more than 40% of the CX-1 starch fraction was resistant starch as opposed to soluble starch, it is reasonable to assume that the starch conservation within the intact root was influenced by the presence of resistant starch. Further research is necessary to confirm whether or not there is a correlation between resistant starch concentrations and starch conservation during storage. The starch stability in the CX-1 root, when compared with other industrial and table varieties, is a valuable characteristic and combined with the root's superior starch content contributes to the suitability of CX-1 as a year-round feedstock for ethanol production.

The soluble starch component of the CX-1 root could be extracted immediately following harvest to further improve storability of the starch. After milling or blending the root material, cold water extraction (i.e. steeping at 4 °C) or water suspension

at room temperature is recommended to effectively recover the soluble starch without initiating gelatinization or swelling of the starch granules. After adequate time for settling, the starch granules can be isolated and dried for extended storage. Sweetpotato starch can be converted to glucose and used in the manufacturing of several value-added products including noodles, jelly, syrups, citric acid (as a flavor enhancer in soft drinks), organic acids and various amino acids (Woolfe, 1992). A monosaccharide-rich syrup that consisted primarily of glucose was made from starch extracted from Mississippi Red sweetpotatoes, and the mineral contents were significantly higher than typical pancake syrup or ginger syrup, making it a more nutritious option (Dominque et al., 2013). In Asia, the sweetpotato starch industry is well-established and uses in confectionery products, textile industries, paper manufacturing and brewing industries have been reported (Radley, 1976).

4. Conclusions

Industrial sweetpotatoes offer several advantages as a bioethanol feedstock including high productivity in warm climates, well-established starch conversion processes, less land-use controversies from a socio-economic perspective, and viable coproducts for additional bioenergy recovery opportunities. A two-year agronomic field trial resulted in root yields of 47 t ha^{-1} (12.3 dry t ha^{-1}) after modifications in the planting strategy (rooted plants versus non-rooted cuttings) and improved drainage conditions. The planting strategy and drier soil conditions within the rooted versus non-rooted CX-1 plots in Year 1 improved the agronomic yield by nearly 70% (on a DM basis). The cull rate from the CX-1 industrial sweetpotato crop was 36%, which is consistent with table sweetpotato crops. The definition of culls for industrial crops, however, should be differentiated from the current USDA definitions established for culinary practices. Cull material (i.e. secondary rootlets), for example, has the same texture as the graded roots and could feasibly be used for ethanol production. Thus, from an industrial processing perspective, 45% of the culls could be used for conversion to ethanol while the remaining 55% could be used to generate biogas that could help offset the energy required for biorefinery operations.

The starch content of the CX-1 roots (73.5% DM for Year 1 and 72.1% DM for Year 2) exceeded the starch content from any other industrial variety grown in the Southeastern USA as well as those specifically selected for starch production from the world germplasm collection at the International Potato Center in Peru. In contrast to the results from other studies, the CX-1 root maintained its superior starch content even after six months of storage and thus could be used as a year-round feedstock for ethanol production. The bioethanol potential of the CX-1, determined from the fermentation process combined with the agronomic root yield from the Year 2 field trial, was 4.2 t ha^{-1} (5300 L ha^{-1}). Based on the elevated starch concentrations and high fermentation efficiency from the CX-1 roots, continued optimization of agronomic root yield specifically targeting the length of the growing season and the most appropriate soil and climate conditions is recommended. Further research is also recommended to determine the ultimate methane potential of the CX-1 culls for biogas recovery.

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