Farm-Scale Cost of Producing Perennial Energy Cane as a Biofuel Feedstock

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Abstract Energy cane varieties are high-fiber sugarcane clones which represent a promising feedstock in the production of alternative biofuels and biobased products. This study explored the crop establishment and whole farm production costs of growing energy cane as a biofuel feedstock in the southeastern USA. More specifically, total production costs on a feedstock dry matter biomass basis were estimated for five perennial energy cane varieties over alternative crop cycle lengths. Variable production costs for energy cane production were estimated to be in the \$63 to \$76 Mg⁻¹ range of biomass dry matter for crop cycles through harvest of fourth through sixth stubble crops. Total production costs, including charges for fixed equipment costs, general farm overhead, and land rent, were estimated to range between \$105 and \$127 Mg⁻¹ of feedstock biomass dry matter material.

Keywords Energy cane · Biomass · Bioenergy · Biofuel · Economics

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Abbreviations

ha Hectare
kg Kilogram
l Liter
Mg Megagram

Introduction

Cellulosic biofuel production is expected to utilize a much more diverse set of feedstock materials compared to the production of first-generation biofuels such as corn ethanol. One option for states in the subtropical Gulf Coast region of the USA is to grow energy cane for the production of cellulosic biofuel and biobased products. Energy cane is a high-fiber clone of sugarcane. Approximately 98 % of the sugarcane produced in the USA is grown in the southeastern states of Florida, Louisiana, and Texas. In 2012, these three states produced 26.873 million metric tons of sugarcane from 338,560 ha of sugarcane grown for sugar (excluding seed cane production) [34]. Production and harvesting practices for energy cane would be very similar to those currently employed in sugarcane production. Although energy cane may not replace sugarcane production to a large extent, the existence of equipment and expertise in producing a heavy-tonnage perennial crop so similar to sugarcane would be expected to give the prospects of energy cane production a comparative advantage with other potential nontraditional feedstock crops. Varieties of energy cane are high-fiber sugarcane varieties that can be harvested with existing sugarcane harvest equipment. Perhaps the most promising feature of energy cane as a biofuel feedstock is the fact that it has a greater yield potential, in tons of biomass per hectare, than that of traditional sugarcane varieties [21]. Average yields for sugarcane production in the southeastern

states were in the 74.0 to 84.7 Mg ha⁻¹ range for the 2012 crop [34]. The extended stubbling ability of energy cane would provide the potential for yields which could exceed those of currently commercially produced sugarcane.

Although the production practices for energy cane are similar to those of sugarcane production, it is not likely that the production of energy cane would replace significant production areas of sugarcane. Given the degree of vertical integration through the marketing chain between raw sugar factories and cane sugar refineries, as well as the significant level of recent capital investment in new sugar refining capacity, it is generally expected that much of the area in sugarcane production would remain devoted to that crop, particularly in Florida and Louisiana. Energy cane would be expected to compete for farm production area on the fringes of current sugarcane production area as well as other regions in states across the southeastern USA.

The general objective of this study was to estimate the expected costs of producing energy cane as a feedstock to supply a cellulosic biofuel industry in the southeastern USA. More specifically, the study's objective was to estimate the total cost of producing energy cane as a biofuel feedstock on a dry fiber weight basis. With potentially greater cold tolerance than commercial sugarcane varieties currently produced, energy cane has the potential to be grown in areas outside, and further north, than the current sugarcane production regions of the USA. The agronomic practices and mechanical field operations associated with energy cane production would be very similar to existing practices for sugarcane. However, because energy cane has not been traditionally produced, projected production costs and potential yields will need to be estimated in order to determine its potential as a biomass feedstock. The minimum market price offered by a biofuel feedstock processor would need to cover total production costs and provide net returns comparable with existing crop production alternatives in order to be an economically viable crop for feedstock producers.

One of the greatest factors directly impacting the economic feasibility of biomass production for biofuel or other biobased products is the relative adaptability of various potential feedstock crops to local or regional production areas. Certain potential biofuel feedstock crops are better suited agronomically for production in particular areas over other possible areas of production. Potential feedstock crops such as energy cane, being a subtropical perennial crop, would be expected to have a more limited production area than other feedstock crops such as sweet sorghum, switchgrass, or *Miscanthus* which have a greater cold tolerance. In addition, the feasibility of harvesting feedstock crops, both from a mechanical and economical perspective, is another critical issue. Cultivation and harvest technologies are more developed for crops such as energy cane or sweet sorghum. Additional research into feasible harvest technologies would

need to be conducted for other less traditional crops, such as switchgrass or *Miscanthus*.

Review of Relevant Previous Research

The selection of feedstock for the production of biofuel remains a popular area for research because of its major role in determining the cost competitiveness of the biofuel. According to Balat and Balat [3], feedstock purchase price represents approximately 60–75 % of total biofuel production cost, making it an important consideration for financial assessments of feedstock options. Calculating the breakeven prices of potential feedstocks has become a popular method used by economists to analyze potential biomass sources. To compare the alternative costs and yields of various perennial, annual, and intercrops for biomass production, Hallam, Anderson, and Buxton [12] computed the breakeven price for each alternative by dividing cost per hectare by the expected yield per hectare. In estimating the opportunity cost of land for conversion to perennial grass in Illinois, Khanna, Dhungana, and Clifton-Brown [14] estimated profits per hectare from a corn–soybean rotation. Profits were calculated as the difference between revenues from a corn–soybean crop valued at the loan rates for each county and the cost of production. To obtain site-specific breakeven prices of *Miscanthus*, the authors incorporated spatial yield maps and crop budgets for bioenergy crops and row crops with transportation costs.

Focusing on a nontraditionally produced crop, Mark, Darby, and Salassi [20] conducted their energy cane analysis using relevant data on sugarcane production. In their study, the authors estimated the breakeven price that producers must receive in order to cover energy cane's cost of production, as well as the tons per hectare of energy cane to be grown in order to equate it with corn–ethanol production costs. Grower breakeven costs included variable, fixed, overhead, land rental, and transporting costs. Results for the grower breakeven analysis found that the combination of an average field wet yield of 78 Mg ha⁻¹ and reaching harvest of a sixth stubble crop would provide the grower with a price comparable to that of the average price of sugarcane per hectare in Louisiana from 2000 to 2007, but only when transportation costs are excluded. A study by Alvarez and Helsel [1] tested the economic feasibility of growing energy cane on mineral soils in Florida for cellulosic ethanol production. The authors calculated the breakeven price of ethanol for biomass yields ranging from 56 to 89 Mg ha⁻¹ net tons per hectare when cellulosic processing costs were \$0.28 and \$0.44 l⁻¹ and found that energy cane had potential to become a useful bioenergy crop on unmanaged mineral soils in south central Florida.

Several studies have evaluated the relative feasibility of producing bioenergy feedstock crops. Much of the initial

economic research has focused on the use of switchgrass as a biofuel feedstock [7, 9, 12, 17, 24, 32, 33]. An early study by Epplin [9] estimated the cost to produce and deliver switchgrass biomass to an ethanol-conversion facility. Cost estimates were in the range of \$35 to \$40 Mg⁻¹, including crop establishment, land, harvest, and transportation costs. A study by Aravindhaksham et al. [2] estimated switchgrass production costs to be in the \$44 to \$52 Mg⁻¹ range. A study in Italy by Monti et al. [22] determined the dependence on higher yields and market prices required for production of switchgrass to be economically viable.

Miscanthus is another potential biomass feedstock crop which has garnered some attention [4–6, 13, 16]. Khanna et al. [14] estimated the breakeven farm gate price of *Miscanthus* produced in Illinois to range between \$42 and \$58 Mg⁻¹. Their results suggested that there is a need for policies to provide production incentives based upon their environmental benefits in addition to their energy content. Linton et al. [18] evaluated the economic feasibility of producing sweet sorghum as a biofuel feedstock in the southeastern USA. Conclusions from this study indicated that while sweet sorghum may be a viable source of biofuel with ethanol yields comparable to corn, current production incentives lie with other nonfeedstock crops for a profit-maximizing producer.

As a perennial crop similar to sugarcane, energy cane is generally grown in a monocrop culture. Therefore, economic viability of energy cane production is much more directly a function of optimal crop production cycle length, rather than rotations with other crops. In Louisiana, a central question is the challenge of developing an economically viable and sustainable biorefinery which would process biofuel feedstocks at existing facilities [15]. For existing raw sugar factories to process biomass to produce biofuel, those processing operations would have to occur in months when the factory is not being used to process sugarcane. This may be a limitation on the utilization of existing sugar factories for biofuel production, in favor of construction of processing facilities devoted exclusively to biofuel production. Models have recently been developed which can determine the economically optimal crop cycle lengths for sugarcane cultivars in production [28, 30]. Such a model could be easily revised to accommodate energy cane production with higher yields and longer years of harvest between plantings. Optimal processing facility location is an important issue related to the production of new feedstock crops. Dunnett et al. [8] developed a mathematical modeling framework which incorporated feedstock production and processing costs as well as processing facility location in a bioethanol supply chain. Mark [19] developed a mathematical programming modeling framework on a county level basis which optimizes facility location based upon specified feedstock production locations and quantities.

Methods

Conceptual Model

Estimating the biomass production costs of energy cane as a feedstock crop is not a straightforward process due to the fact that energy cane is a perennial crop and not a commonly produced crop, and only limited data on expected yields are available. However, because of the many similarities between sugarcane production and energy cane production, production costs for the various crop phases of perennial energy cane production were assumed to be similar, on a per hectare basis, to the costs of producing sugarcane in a given region [29]. Whole farm adjustments were made for energy cane production based on changes in required seed cane expansion area, which is directly related to per hectare biomass yields, as well as the estimation of crop establishment and production costs on a unit of biomass basis.

Before discussing the detailed process that was used to estimate energy cane production costs, it is important to first explain the mechanics of crop establishment including the phases of vegetative seed cane expansion. In addition, energy cane, like sugarcane, is a perennial crop which means that multiple annual harvests can occur before fallowing and replanting operations in a field are necessary. While sugarcane crops are commonly left in production for a total of three or four annual harvests before they are replanted, energy cane crops have the potential ability to reach a sixth or even a seventh annual harvest before the land is fallowed and new seed cane are replanted.

In this analysis, it was assumed that the initial crop establishment of energy cane production would be similar to existing practices utilized in commercial sugarcane operations. Cultured seed cane of an energy cane variety would be purchased from a seed cane source and expanded by means of a two-phase process in order to generate sufficient seed cane to plant for eventual biomass production. This seed cane expansion process is depicted in Table 1 for an initial 1 ha of purchased energy cane seed cane in the initial year of crop establishment. In year 1, 1 ha of seed cane is planted, purchased from a seed cane source. In the following year, that hectare is harvested (plant cane crop) and immediately replanted based on an expected planting ratio. The planting ratio used in this analysis was 5:1, meaning that 1 ha of harvested seed cane will provide a sufficient quantity to plant 5 ha of energy cane. This initial phase of harvesting and replanting seed cane is termed the “first seed cane expansion.” In year 3, the 5 ha planted in year 2 is harvested (termed the first stubble crop) and replanted, again assuming a 5:1 planting ratio. This second phase of harvesting and replanting seed cane is termed the “second seed cane expansion.” This final planting will be harvested over a multiyear period for biomass. Also indicated in Table 1 is

Table 1 Energy cane for biomass seed cane expansion and planted area

Field operation	Year 1	Year 2	Year 3	Year 4
	<i>ha</i>			
a. Plant initial seed cane	1			
b. Harvest initial seed cane		1	1	
c. Plant 1 st seed cane expansion		5	5	
d. Harvest 1 st seed cane expansion			5	5
e. Plant 2 nd seed cane expansion			25	25
f. Total acres fallow/seedbed preparation	1	5	30	25
g. Total acres hand planted	1	—	—	—
h. Total acres mechanically planted	—	5	30	25
i. Total acres planted	1	5	30	25
j. Total acres harvested for seed cane	—	1	6	5
k. Total acres for seed cane or planted	1	6	36	30

the fact that this two-phase seed cane expansion process is repeated again, utilizing the first stubble harvest (year 3) of the initial hectare planted in year 1. Utilizing this seed cane expansion process, the area of biomass production can be quickly increased up to full production on a given farming operation.

Table 2 provides values for the area of energy cane to be harvested for biomass resulting from the initial planting of 1 ha of seed cane for biomass crop cycle lengths ranging from the harvest of a fourth, fifth, and sixth stubble crop. The initial hectare of seed cane, planted in year 1, would be harvested for seed cane as plant cane and first stubble in years 2 and 3. In the following years, that area would be harvested for biomass, beginning in year 4. The planting of the 5 ha of the first seed cane expansion, harvested as plant cane for further seed cane

expansion, would be harvested for biomass, beginning in year 4 for the area planted in year 2 and beginning in year 5 for the area planted in year 3. All of the area related to the second seed cane expansion plantings (25 ha in this example) would be harvested for biomass beginning with the plant cane crop (year 4 for first planting and year 5 for the second planting).

Once the production of energy cane has reached full crop rotational equilibrium status, energy cane production would remain in relatively constant production phases from year to year, similar to current operations on commercial sugarcane farms. The various production phases for energy cane production would be similar to that of sugarcane. A portion of total farm area is devoted to a two-phase vegetative seed cane expansion process. A portion of total farm area is devoted to fallow and planting activities. Portions are also

Table 2 Energy cane area harvested for biomass

Land tracts harvested for biomass	Acres harvested for biomass per year	Harvest years per crop cycle length		
		4th stubble	5th stubble	6th stubble
	ha	Year		
Harvest initial seed cane for biomass	1	4–6	4–7	4–8
Harvest 1 st seed cane expansion for biomass				
Planted in year 2	5	4–7	4–8	4–9
Planted in year 3	5	5–8	5–9	5–10
Harvest 2 nd seed cane expansion for biomass				
Planted in year 3	25	4–8	4–9	4–10
Planted in year 4	25	5–9	5–10	5–11

devoted to a plant cane crop (first harvest year) and stubble crops (succeeding years of harvest). Producers organize their crop area to have the same proportion of farm area in each crop phase each year. This provides for approximately the same amount of area required to be planted and harvested each year. This whole farm rotational concept will be utilized here as a structure within which to estimate total energy cane production costs per unit of dry matter biomass.

Generally, 25 % of total farm area is fallow for a crop cycle length through a second stubble crop and 20 % of total farm area for a crop cycle length through harvest of a third stubble crop. The reasoning behind these numbers is as follows: for production through a second stubble crop, total farm area must be divided equally among (1) fallow/plant hectares, (2) plant cane hectares (first year of harvest), (3) first stubble hectares (second year of harvest), and (4) second stubble hectares (third year of harvest). As crop cycle lengths are increased to produce additional annual harvests, total farm area must then be reallocated proportionately. Since energy cane has greater stubbling ability than sugarcane, additional changes in farm areas dedicated to fallow and planting operations must be calculated for each additional year that the crop remains in production. For a crop cycle length through a fourth stubble energy cane crop, total farm hectares dedicated to fallow and field operations were determined using the following equations:

$$FLW = TFA \times 0.167 \quad (1)$$

$$CSCPLT = FLW / ((1 + (2 \times PR1) + (2 \times PR1 \times PR2))) \quad (2)$$

$$TAHPLT = CSCPLT(1 + 2PR1) \quad (3)$$

$$TAMPLT = 2 \times CSCPLT \times PR1 \times PR2 \quad (4)$$

$$TAPLT = TAHPLT + TAMP \quad (5)$$

where FLW is total farm hectares in fallow, TFA is total farm area, and one sixth of total farm area is dedicated to fallowing the land for a fourth stubble energy cane crop. The variable CSCPLT is total hectares of cultured seed cane planted, where the planting ratio (hectares planted per hectare of harvested seed cane) for the first seed cane expansion is given as the variable PR1, and PR2 is the planting ratio for the second seed cane expansion. The planting ratio simply refers to the number of hectares that can be replanted from one harvested hectare of seed cane, with two seed cane expansions generally performed, and typically varies by cane variety and whether the seed cane is hand planted or mechanically planted. The variables TAHPLT and TAMPLT are total hectares hand planted and total hectares machine planted, respectively, and

TAPLT is total hectares planted. Farm hectares harvested through a fourth stubble crop cycle are defined as follows:

$$PCHVSD = CSCPLT(1 + 2 \times PR1) \quad (6)$$

$$PCHVBM = 2 \times CSCPLT \times PR1 \times PR2 \quad (7)$$

$$PCHV = PCHVSD + PCHVBM \quad (8)$$

$$ST1HVSD = CSCPLT \quad (9)$$

$$ST1HVBM = 2((CSCPLT \times PR1) + (CSCPLT \times PR1 \times PR2)) \quad (10)$$

$$ST1HV = ST1HVSD + ST1HVBM \quad (11)$$

$$ST2HVBM = ST1HVSD + ST1HVBM \quad (12)$$

$$ST3HVBM = ST2HVBM \quad (13)$$

$$ST4HVBM = ST3HVBM \quad (14)$$

$$TFA = TAPLT + PCHV + ST1HV + ST2HVBM + ST3HVBM + ST4HVBM \quad (15)$$

where PCHVSD is the plant cane hectares harvested for seed cane, PCHVBM is plant cane hectares harvested for biomass, PCHV is total plant cane hectares harvested, ST1HVSD is the first stubble hectares harvested for seed cane, ST1HVBM is the first stubble hectares harvested for biomass, ST1HV is total first stubble hectares harvested, ST2HVBM is second stubble hectares harvested for biomass, ST3HVBM is third stubble hectares harvested for biomass, and ST4HVBM is fourth stubble hectares harvested for biomass. Extending the crop cycle length to harvest through a fifth stubble crop requires the following changes to the total farm area model:

$$FLW = TFA \times 0.143 \quad (1a)$$

$$ST5HVBM = ST4HVBM \quad (14a)$$

$$TFA = TAPLT + PCHV + ST1HV + ST2HVBM + ST3HVBM + ST4HVBM + ST5HVBM \quad (15a)$$

where ST5HVBM is fifth stubble hectares harvested for biomass. Equation (1a) reflects the change to required farm area devoted to seed cane expansion, which is one seventh, or 14.3 %, of total farm area for a fifth stubble harvest. The model equations can be further adjusted to determine the total farm area devoted to fallow and planting operations for a crop

cycle length through a sixth stubble harvest with the following changes:

$$\text{FLW} = \text{TFA} \times 0.125 \quad (1b)$$

$$\text{ST6HVBM} = \text{ST5HVBM} \quad (14b)$$

$$\begin{aligned} \text{TFA} = & \text{TAPLT} + \text{PCHV} + \text{ST1HV} + \text{ST2HVBM} \\ & + \text{ST3HVBM} + \text{ST4HVBM} + \text{ST5HVBM} + \text{ST6HVBM} \end{aligned} \quad (15c)$$

where ST6HVBM is sixth stubble hectares harvested for biomass. Equation (1b) reflects the change to required farm area devoted to seed cane expansion, which is one eighth, or 12.5 %, of total farm area for a sixth stubble harvest. Table 3 shows crop production phase land area allocations, as a percent of total farm area, for energy cane production operations for alternative crop cycle lengths of harvest through fourth stubble (6 years), fifth stubble (7 years), and sixth stubble (8 years).

Sensitivity analysis of energy cane feedstock production costs and yields estimated as part of this research project were conducted by performing Monte Carlo simulation analysis of projected cost values. Monte Carlo analysis is a stochastic simulation technique which can randomly generate sequences of random values for specified parameters and estimate economic values using those randomly generated values as input [25]. Projected multivariate empirical distributions of feedstock yields and production input costs were generated following a procedure developed by Richardson et al. [26].

More specifically, the *Simetar* software package [27] was utilized to generate multivariate input cost distributions. These distributions were then used to project energy cane feedstock costs under stochastic price and yield conditions. Due to the limited yield data available for energy cane varieties, yield mean and standard deviation values were utilized to simulate energy cane yield variability.

Crop Establishment and Production Costs

The variable costs of energy cane production were estimated as the sum of crop establishment costs and biomass cultivation and harvest costs. In this analysis, the cost of transporting the energy cane from the field to a processing facility is assumed to be paid by the processor, as is currently done in sugarcane production. Annualized values for these cost categories are shown in Table 4 for three crop cycle lengths evaluated in this study on a weighted average, rotational hectare basis. Using the seed cane expansion process presented in Table 1, the total variable cost of crop establishment was estimated as the sum of area devoted to specific seed cane planting or harvesting operations multiplied by their respective variable cost per hectare. Published production cost estimates for sugarcane for 2013 were utilized in this estimation [29]. The net present value of these total variable costs was estimated using an 8 % discount rate and then was annualized using the annuity formula $A = PV [0.08 / (1 - (1.08)^{-n})]$. This annualized value was then divided by the average area per year devoted to crop establishment to result in an annualized crop establishment cost per hectare. As evidenced in Table 4, this annualized crop

Table 3 Total farm area distribution for biomass harvest through alternative crop cycle lengths

Farm area	Farm area distribution		
	Harvest through 4th stubble crop ^a	Harvest through 5th stubble crop ^a	Harvest through 6th stubble crop ^a
	Percent of farm area		
Cultured seed cane	0.27 %	0.23 %	0.20 %
1st seed cane expansion planted	2.73 %	2.34 %	2.05 %
2nd seed cane expansion planted	13.67 %	11.71 %	10.25 %
Plant cane harvested for seed	3.01 %	2.58 %	2.25 %
Plant cane harvested for biomass	13.67 %	11.71 %	10.25 %
1st stubble harvested for seed	0.27 %	0.23 %	0.20 %
1st stubble harvested for biomass	16.40 %	14.05 %	12.30 %
2nd stubble harvested for biomass	16.67 %	14.29 %	12.50 %
3rd stubble harvested for biomass	16.67 %	14.29 %	12.50 %
4th stubble harvested for biomass	16.67 %	14.29 %	12.50 %
5th stubble harvested for biomass	—	14.29 %	12.50 %
6th stubble harvested for biomass	—	—	12.50 %
Total area harvested for biomass	80.08 %	82.92 %	85.05 %
Total farm area	100.00 %	100.00 %	100.00 %

^a Crop cycles through harvest of fourth, fifth, and sixth stubble crops represent crop cycles of 6, 7, and 8 years, respectively, excluding seed cane expansion

Table 4 Annualized variable crop establishment and production costs per area for alternative crop cycles

Annualized variable cost/ yield item ^a	Harvest through 4th stubble crop (\$ ha ⁻¹)	Harvest through 5th stubble crop (\$ ha ⁻¹)	Harvest through 6th stubble crop (\$ ha ⁻¹)
Crop establishment costs	221	196	177
Biomass cultivation/ harvest costs	888	921	945
Total variable crop production costs	1,109	1,117	1,122

^a Crop establishment and cultivation/harvest costs are annualized over 9 years for harvest through fourth stubble, 10 years for harvest through fifth stubble, and 11 years for harvest through sixth stubble

establishment cost per hectare declines as the crop production cycle is extended to more years of harvest due to the smaller percentage of farm area devoted to seed cane expansion required as the years of harvest are extended. Variable crop establishment cost estimates in this analysis range vary from \$221 ha⁻¹ for a five-harvest cycle (through fourth stubble) down to an estimate of \$177 ha⁻¹ for a seven-harvest cycle (through sixth stubble). Annualized variable costs per hectare for biomass cultivation and harvest were estimated to increase from \$888 to \$945 ha⁻¹ per rotational hectare as the crop cycle length is extended.

The major components of total biomass crop production costs include charges for variable costs, fixed costs, and general farm overhead as well as charges for land rent. The fixed costs published in commodity budget reports typically include depreciation and interest on equipment and are commonly allocated per hectare on an hourly basis, and therefore, they do not take into account a specific farm size. In order to calculate total energy cane production costs, this study assumed that fixed costs and overhead costs were \$346 and \$74 ha⁻¹, respectively, similar to corresponding cost values on commercial sugarcane farms [29]. The farm overhead cost includes expenses such as tax services, insurance, and property taxes. Land rent is another cost that must be considered when total farm costs are calculated. For this study, it was assumed that land rent would be charged at a rate of 20 % of the total biomass production value. Since biofuel feedstock prices are not readily available, due in part to the lack of an established market, the value of land rent as a production cost was determined by estimating the breakeven price required to cover total production costs.

$$\text{PRICE} = (\text{TVCOST} + \text{TFCOST} + \text{TOCOST}) / (\text{TPROD} \times 0.80) \quad (16)$$

$$\text{RENT} = \text{TPROD} \times \text{PRICE} \times 0.20 \quad (17)$$

The variable PRICE is the estimated breakeven price of biomass and represents a “farm gate” price for biomass;

TPROD is the total whole farm production of biomass in tons; TVCOST, TFCOST, and TOCOST represent total farm variable, fixed, and overhead costs; and RENT is the total rent charge for the whole farm. In traditional sugarcane production, the mill’s share (charge) for processing the sugarcane into raw sugar is taken out of the yield. The mill, grower, and landlord each receive the same raw sugar market price for their respective shares of production. In this analysis for energy cane production, the processor’s charge (share) for converting the biomass into biofuel is taken out of the biomass price paid. The rental charge for land is assumed to be a simple share lease with the landlord receiving a share of the biomass production valued at the price paid by the processor.

In order to estimate the expected variability of energy cane production costs, random input prices for selected production inputs were generated in order to incorporate the stochastic nature of input prices used in energy cane production. Diesel fuel, nitrogen, phosphate, and potassium fertilizers were the four inputs for which random prices were simulated using a multivariate empirical distribution. All other variable and fixed production costs were held constant at their 2013 estimated values. Trend residual values from historical annual input price data ranging from 2002 to 2011 were utilized to generate random input prices for fuel and fertilizer. Input price values for 2013 for diesel fuel, nitrogen, phosphate, and potassium were utilized as distribution means at values of \$0.92 l⁻¹, \$1.23 kg⁻¹, \$1.43 kg⁻¹, and \$1.04 kg⁻¹, respectively. Using the process outlined in Richardson et al. [26], parameters for the multivariate empirical distributions were then estimated. These parameters, which included the 2013 projected mean input prices listed above, as well as historical deviations from trend forecasts and the correlation matrix for the deviations from the trend, were then used to generate 1,000 random prices for each of the four inputs.

Energy Cane Yield Data

Potential energy cane stubble yields were estimated using plant cane, first stubble, second stubble, and third stubble data for yield and fiber content collected from the energy cane field trials that are currently being conducted at the Sugar Research Station in St. Gabriel, Louisiana [10, 11]. The field trial includes five varieties of energy cane, Ho 02-144, Ho 02-147, Ho 06-9001, Ho 06-9002, and HoCP 72-114, which were first planted in September 2008. Mean cane yield, fiber content, and dry matter weight for each crop age by variety are shown in Table 5. The cane yield refers to the yield measured in wet tons, and the dry weight is simply the product of cane yield and fiber content. In order to reflect the estimated yields for fourth through sixth stubble in units of dry tons per hectare, the average fiber content of plant cane through third stubble was calculated for each variety.

Table 5 Mean energy cane yields from field trials conducted at St. Gabriel, Louisiana, 2009–2012

Crop age/ variety	Cane yield (Mg ha ⁻¹)	Fiber content (%)	Dry weight (Mg ha ⁻¹)
Plant cane			
Ho 02-144	68.4	20.6	14.1
Ho 02-147	99.0	17.8	17.6
Ho 06-9001	64.8	26.4	17.1
Ho 06-9002	57.2	25.3	14.5
HoCP 72-114	96.0	20.7	19.8
First stubble			
Ho 02-144	56.1	25.9	14.5
Ho 02-147	105.4	19.5	20.5
Ho 06-9001	58.4	29.7	17.3
Ho 06-9002	54.7	29.6	16.2
HoCP 72-114	80.2	24.0	19.2
Second stubble			
Ho 02-144	123.9	23.6	29.2
Ho 02-147	162.3	18.4	29.9
Ho 06-9001	128.2	28.7	36.8
Ho 06-9002	113.7	28.3	32.2
HoCP 72-114	128.0	22.6	29.0
Third stubble			
Ho 02-144	77.5	23.2	17.9
Ho 02-147	111.4	19.6	21.9
Ho 06-9001	61.2	24.8	15.2
Ho 06-9002	62.8	25.7	16.2
HoCP 72-114	88.3	21.5	19.0

Due to the great degree of similarities between energy cane and sugarcane, it was assumed that energy cane yields would decline in a pattern similar to that of existing commercial sugarcane varieties, once the maximum annual yield was reached. On average, sugarcane varieties have their maximum yield in the first year of harvest (plant cane crop) and decline in succeeding crops. Given the energy cane yield data available at the time of this study, it was assumed that second stubble yields for energy cane would be the maximum yield level reached and would decline in succeeding crops at a rate similar to sugarcane, as has been observed in field trials of commercial sugarcane varieties [31]. More specifically, it was assumed that on average, older stubble yields for energy cane would be estimated as a percentage decline from the plant cane through third stubble average yield. It was further assumed that on average, energy cane yields for a fourth-, fifth-, and sixth-stubble crop would be projected at levels of 85, 82, and 79 % of the plant cane through third stubble average yield for each variety. Projected estimates of energy cane yield for the harvest of fourth through sixth stubble crops, using the specified yield decline relationships, are shown on Table 6.

Table 6 Projected mean energy cane yields for older stubble biomass crops

Energy cane variety	4th stubble crop (Mg ha ⁻¹)	5th stubble crop (Mg ha ⁻¹)	6th stubble crop (Mg ha ⁻¹)
Ho 02-144	69.3	66.8	64.4
Ho 02-147	101.6	98.0	94.4
Ho 06-9001	66.4	64.1	61.7
Ho 06-9002	61.2	59.0	56.9
HoCP 72-114	83.4	80.4	77.5

Mean yields for fourth, fifth, and sixth stubble crops were estimated as 85, 82, and 79 %, respectively, of the plant cane through third stubble yields for each variety

To incorporate yield variability into the analysis, mean and standard deviation estimates of the sample energy cane yield data were used to generate 1,000 random values of plant cane and older stubble energy cane harvest yields, using the assumption that energy cane yields for a given crop age follow a normal distribution. For simulation of fourth, fifth, and sixth stubble energy cane yields, the estimated standard deviation of third stubble yields was applied to the estimated mean yield for older stubble in order to simulate yields of energy cane older than third stubble.

Results

Estimates of total energy cane biomass feedstock production costs are presented in Table 7. These costs represent the situation in which the farm has reached full equilibrium production. Under this production situation, the area of land planted for both seed cane expansion and biomass production as well as the area of land harvested for biomass remains relatively constant each year. Production cost estimates presented here are on a per-hectare, total farm area basis. Variable costs were estimated to be in the \$1,203 to \$1,224 ha⁻¹ range and include annual charges for crop establishment and biomass cultivation and harvest. Fixed and overhead costs were charged at a flat rate per hectare basis of \$346 and \$74 ha⁻¹, respectively [29]. Estimated land rent charges per farm area were determined by first calculating a breakeven price by dividing total variable, fixed, and overhead costs by the grower's share of total biomass production, and then valuing the landlord's share of the biomass crop at this breakeven price. This land rent determination resulted in rent charges in the range of \$406 to \$411 ha⁻¹. Total farm production costs for a grower producing energy cane as a biomass feedstock were then estimated to be approximately \$2,029 to \$2,055 ha⁻¹.

Production costs per hectare were divided by biomass production yields to determine total production costs per dry

Table 7 Energy cane total production cost estimates per area and per unit

Production cost item	Energy cane crop cycle length		
	Harvest through 4th stubble crop	Harvest through 5th stubble crop	Harvest through 6th stubble crop
	\$ ha ⁻¹	\$ ha ⁻¹	\$ ha ⁻¹
Costs per total farm area			
Total variable costs	1,203	1,215	1,224
Total fixed costs	346	346	346
Total overhead costs	74	74	74
Total rent costs ^a	406	409	411
Total costs	2,029	2,044	2,055
	Mg ha ⁻¹	Mg ha ⁻¹	Mg ha ⁻¹
Yield per harvested area—dry tons ^b	20.3	19.8	19.3
Yield per total farm area—dry tons ^b	16.3	16.4	16.4
	\$ Mg ⁻¹	\$ Mg ⁻¹	\$ Mg ⁻¹
Costs per dry ton			
Variable cost	73.98	74.18	74.86
Fixed cost	21.27	21.12	21.11
Overhead cost	4.56	4.53	4.52
Rent	24.95	24.95	25.07
Total cost	124.75	124.77	125.37

^a Rent estimated as 20 % of the product of total production (wet tons) and breakeven price, divided by total farm area

^b Average energy cane yield over all five energy cane varieties; yield calculated as total production divided by area harvested for biomass and total farm area, respectively

matter ton of biomass produced. Projected energy cane yields of biomass on a dry-ton basis were estimated to be 20.3, 19.8, and 19.3 tons per harvested hectare for crop cycles through fourth, fifth, and sixth stubble. Converting these harvested yields to values per total farm area resulted in estimated average farm area yields of 16.3, 16.4, and 16.4 tons of dry biomass per total farm hectare. Based upon the production cost estimates per hectare and the projected yields averaged over all varieties, total production costs per dry ton of biomass were estimated to be approximately \$125 Mg⁻¹. Variable costs were the largest component of total farm cost, representing approximately 59 % (\$74 Mg⁻¹) of total production costs. Land rent accounted for 20 % of total costs, fixed equipment costs represented approximately 17 %, and general farm overhead costs accounted for about 4 % of total costs.

The estimated mean and variability of variable production costs per dry matter output unit for each of the five energy cane varieties evaluated in this study are presented in Table 8.

Cost per unit parameters varied in this estimation included the input unit prices for fuel, nitrogen, phosphorus, and potassium fertilizer in addition to the yield per harvested hectare. Variability differences in variable cost estimates across varieties were directly related to the differences in yield variability. In general, energy cane varieties which had higher average yields with lower variability were estimated to result in lower variable production costs per unit of biomass production with lower variability in costs per yield unit. For a crop cycle through harvest of a fourth stubble crop, variable production costs were estimated to range from \$63 Mg⁻¹ of dry biomass for the variety Ho 02-147 to \$75 Mg⁻¹ for the variety Ho 02-144. Mean estimates of variable production cost per dry matter unit of biomass were approximately the same for extended crop cycles through fifth and sixth stubble crops for each of the five varieties. This similarity in costs per unit for longer crop cycles is probably due to the fact that the projected yield for older stubble crops was approximately

Table 8 Estimated mean and variability of energy cane variable production costs per dry matter unit

Energy cane variety	Through 4th stubble (\$ Mg ⁻¹)	Through 5th stubble (\$ Mg ⁻¹)	Through 6th stubble (\$ Mg ⁻¹)
Ho 02-144	75.10 (8.03)	75.12 (7.42)	75.51 (6.60)
Ho 02-147	62.64 (4.30)	62.75 (4.18)	63.12 (3.87)
Ho 06-9001	65.88 (5.80)	66.01 (5.53)	66.39 (5.39)
Ho 06-9002	71.49 (5.60)	71.65 (5.38)	72.08 (5.31)
HoCP72-114	64.94 (4.17)	65.00 (3.87)	65.35 (3.70)

Costs estimated for stochastic yield levels and stochastic input prices at 2013 mean values. Numbers in parentheses are standard deviations

Table 9 Estimated mean and variability of energy cane total production costs per dry matter unit

	Energy cane variety	Through 4th stubble (\$ Mg ⁻¹)	Through 5th stubble (\$ Mg ⁻¹)	Through 6th stubble (\$ Mg ⁻¹)
Costs estimated for stochastic yield levels and stochastic input prices at 2013 mean values. Numbers in parentheses are standard deviations	Ho 02-144	126.43 (12.92)	126.18 (11.32)	126.61 (10.33)
	Ho 02-147	105.47 (6.52)	105.40 (5.97)	105.85 (5.67)
	Ho 06-9001	110.93 (9.19)	110.87 (8.70)	111.32 (8.41)
	Ho 06-9002	120.37 (8.73)	120.35 (8.34)	120.87 (8.16)
	HoCP72-114	109.33 (6.22)	109.18 (5.64)	109.57 (5.28)

close to what would be the breakeven yield for determining the optimal length of crop cycles. This result would imply that actual older stubble yields which would be below projected values would result in a shorter optimal crop cycle length, possibly only through fourth stubble. Conversely, actual older stubble yields which would be above projected values would result in optimal crop cycles in production out through a fifth or sixth stubble crop.

Total production costs per dry matter yield unit represent a breakeven price for production of energy cane as a biofuel feedstock (Table 9). Once again, differences in the estimated mean levels of yields as well as yield variability across varieties had a direct impact on the mean level and variability of total production costs per unit. For the five energy varieties evaluated in this study, total estimated production costs ranged from \$105 to \$126 Mg⁻¹ on a dry matter basis for a 5-year harvest cycle through fourth stubble. Varieties Ho 02-147 and HoCP 72-114 had the lowest estimated total costs, at \$105 and \$109 Mg⁻¹, as well as the lowest variability of costs with estimated coefficients of variation of 6.2 and 5.7 %, respectively. The variety Ho 02-144 had the highest estimated total cost at a mean level of \$126 Mg⁻¹.

Conclusions

Results from this study provide initial estimates of the costs of producing energy cane as a biofuel feedstock based upon initial yield data from energy cane field trials. Crop establishment costs were estimated for a two-phase vegetative seed cane expansion process which covered the timeframe from initial seed cane planting to final planting for biomass harvest for a one-crop cycle. Production costs were estimated for a commercial farm-scale operation in full equilibrium production which incorporated all of the many seed cane expansion, planting, and harvesting operations which would be involved in the commercial production of the energy cane feedstock. The impact of extending energy cane crop cycle lengths out to harvest of a fourth, fifth, and sixth stubble crop on the distribution of farm area associated with planting, cultivation, and harvest of energy cane was specified. Whole farm production costs were estimated using relevant, and closely related, sugarcane production costs as a base.

Using actual energy cane yield data from field trials conducted for plant cane through second stubble crops of five varieties of energy cane, projected values of energy cane yields for older stubble crops were estimated for each of the varieties. Variable and total production costs were estimated on both a wet ton and dry matter ton basis. Variable energy cane production costs on a dry matter basis were estimated to range between \$63 and \$76 Mg⁻¹ of feedstock dry matter biomass, depending upon the specific yield levels of the variety as well as the length of crop cycle. Total energy cane production costs, including charges for fixed equipment costs, general farm overhead, and land rent, were estimated to range between \$105 and \$127 Mg⁻¹ of dry matter biomass. Estimates of total production costs of energy cane utilized as a cellulosic feedstock, as estimated in this study, were similar in magnitude to total costs which have been estimated for other potential cellulosic feedstock. A 2011 study by the National Research Council [23] estimated values of willingness-to-accept prices of biofuel suppliers for a range of potential cellulosic feedstock. Although including transportation charges as well as total production costs, this study estimated total feedstock costs of \$101 Mg⁻¹ for corn stover, \$108 Mg⁻¹ for switchgrass in the south central region, \$127 Mg⁻¹ for *Miscanthus*, and \$98 Mg⁻¹ for short-rotation woody crops.

These total cost estimates provide useful information regarding the necessary level of biomass market prices paid by processors to purchase energy cane biomass for the production of biofuel and other biobased products. In order to maintain a constant and reliable supply of feedstock being grown in a specific region, the market price for biomass paid by a processor must cover a grower's total production cost as well as provide some measure of return above costs over the long run. As estimates of biofuel feedstock production costs become more accurate and reliable, market price discovery mechanisms will also need to be developed in order to provide agricultural producers the needed information in making farm production plans. The development of a biomass feedstock market with a means of price discovery for producers is required if biofuel feedstock crops such as energy cane are going to compete for cropland, marginal land, or otherwise, with existing crops being produced.

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