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Research article

Biomass supply chain management in North Carolina (part 1): predictive model for cropland conversion to biomass feedstocks

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Abstract: Increased interest in biomass cultivation requires detailed analysis of spatial production potential of possible biorefinery locations, with emphasis on feedstock production cost minimization. Integrated assessment of publicly available spatial data on current crop production, soil type, and yield potential, coupled with techno-economic production cost estimates, can support a functional method for rapid analysis of potential biorefinery sites. A novel predictive model was developed to determine cropland conversion using a probabilistic profit based equation for multiple biomass crops: giant reed, miscanthus, switchgrass, and sorghum (with either canola or barley as a winter crop). The three primary regions of North Carolina (Mountains, Piedmont, and Coastal Plain) were used as a case study and with a single parameter uncertainty analysis was completed. According to the model, the county chosen to represent the Coastal Plain (Duplin County) had the largest potential acreage that would be converted (15,071 ha, 7.1% total land, 9.3% of cropland) primarily to sorghum with canola as a winter crop. Large portions were also predicted to convert to giant reed and switchgrass, depending on the price and yield parameters used. The Piedmont (Granville County, 7697 ha, 5.5% total land, 6.9% cropland) and Mountain (Henderson County, 2117 ha, 2.2% total land, 2.3% cropland) regions were predicted to convert primarily to switchgrass acreage for biomass production, with much less available biomass overall compared to the Coastal Plain. This model provided meaningful insight into regional cropping systems and feedstock availability, allowing for improved business planning in designated regions. Determination of cropland conversion is imperative to develop realistic biomass logistical operations, which in conjunction can assist with rapid determination of profitable biomass availability. After this rapid analysis method is conducted in-depth on-ground biorefinery feasibility analysis can occur, ensuring resource are used only in

locations with a high potential for available low cost biomass feedstocks.

Keywords: Biomass; techno-economic; feedstock modeling; bioenergy; spatial analysis; yield determination; giant reed; switchgrass; sorghum; miscanthus

1. Introduction

Inclusion of bioenergy into the United States energy portfolio can have positive environmental, political, economic, and societal implications. The need for increased production of domestic energy sources in the U.S. was emphasized with the Energy Infrastructure and Security Act (EISA) of 2007, which called for an increase in renewable energy including those produced from terrestrial biomass sources [1]. In the U.S., biofuels (ethanol and biodiesel) have increased dramatically throughout the 21st century, in 2011 accounting for 22.1% of renewable energy production, with renewable sources accounting for 11.8% of total U.S. energy production [2]. Multiple conversion technologies, split into biochemical and thermochemical methods, exist for biomass sources, all of which have benefits and drawbacks [3].

Biomass feedstocks can be divided into several different categories (Figure 1), with primary sources related to forestry and agricultural practices. Each of these categories may be associated with different production and conversion technologies. The Billion Ton Study [4] and subsequent update [5] highlighted the importance of dedicated herbaceous biomass feedstocks for the emerging bio-based economy. The favorable climatic conditions of the Southeastern U.S., which includes North Carolina, show it to be a potentially large contributor of dedicated herbaceous feedstocks [5].

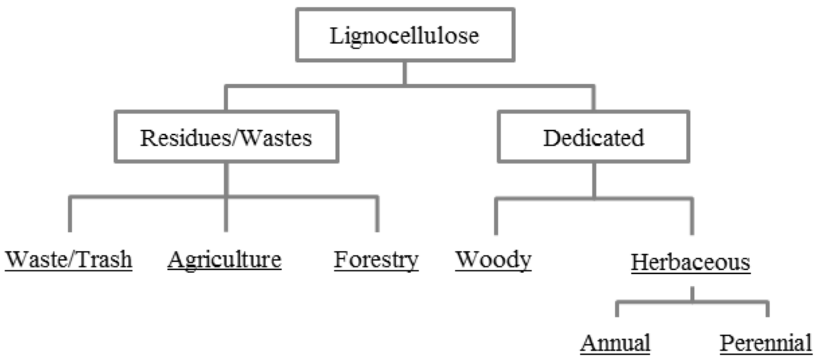


Figure 1. Lignocellulosic Biomass Feedstock Categories.

Dedicated herbaceous biomass feedstocks are commonly separated into either perennial grasses or annual crops. A list of associated benefits and drawbacks of perennial and annual herbaceous biomass feedstocks is presented in Table 1. Both of these feedstock types are harvested annually, with the major difference being planting schedule. Annual crops require yearly planting and perennials are set on some multi-year replanting schedule. To ensure compositional uniformity it is important to set a defined replanting schedule for perennial grasses, since grasslands can commonly become infested with nuisance plants like crabgrass (*Digitaria sanguinalis* (L.) Scop.) [6]. Annual crops allow for inclusion of biomass feedstocks into multiple year rotation strategies (such as tobacco or sweetpotato), reduce grower risk to single years, allow annual incorporation of updated seed stock, and can incorporate winter annual crops improving year-round economic conditions for the farmer. The rapid development of annual biomass feedstocks to full maturity and need for replanting every year allows for crop improvements through breeding and genetic modification to be made more quickly than in perennial crops, which once planted may take at least 3 years to fully assess desired characteristics.

Table 1. Comparison of Perennial and Annual Dedicated Herbaceous Biomass Feedstocks.

	Perennial	Annual
Establishment	Single establishment for multiple years	Annual establishment required
	Establishment failure may take a year to determine, very costly	Rapid determination of failure, replanted same year
	High initial investment	Annual investment
Yield	Annual ramp up in yield to full maturity	Annual full yields
Crop Improvements	Wait until next replanting	Best seed planted annually
Winter Cover	No winter cover	Can be incorporated
Annual Field Rotation	Field dedicated for multiple years	Can fit into traditional field rotations
Soil Carbon	Large soil carbon accumulation from roots	Reduced soil carbon accumulation
Time Requirement	Reduced annual field operations	Similar operations to traditional agricultural products
Nutrient Requirement	Some nutrients recycled annually	Similar nutrient removal to forages

*For purposes of this manuscript "Agricultural Product" was used to describe whatever product produced on the cropland. Whether this is a commodity crop (corn, soybean), produce (sweetpotato), animal feed (hay), fallow land, biomass crop (annual or perennial), or any other agricultural product. "Traditional Agricultural Product" is used for the current product produced on the defined cropland parcel.

Three warm season perennial grasses of interest in the Southeast U.S. are: Switchgrass (*Panicum virgatum* L.), Miscanthus (*Miscanthus x giganteous*), and Giant Reed (*Arundo donax* L.). Switchgrass is a native grass referred to by Wright & Turhollow [7] as the model bioenergy feedstock, leading to its use by the U.S. Department of Energy for comparison of other biomass feedstocks. Miscanthus (*Miscanthus x giganteous*) is a hybrid between *Miscanthus sacchariflorus* (Maxim.) Franch. and *Miscanthus sinesis* Anderss., and the genus originated in tropical/subtropical regions [8]. Giant reed is thought to have originated in Asia propagating through rhizomes and canes [9], and has shown some characteristics of invasiveness [10]. Interest in giant reed is related to reported high yields [11], with similar management cultivation requirements to other perennial biomass feedstocks. Perennial biomass feedstocks have benefits of a single high yielding crop that can last for multiple years, requiring only maintenance and harvest annually, which greatly reduces inputs reducing cost after initial stand establishment.

Sorghum is an annual biomass feedstock of interest for the southeast U.S., which has been demonstrated in a regional set of yield trials to have beneficial yields [12]. Common types of sorghum are forage, grain, sweet and more recently, biomass, and are designated by product end use [13]. There are multiple benefits of sorghum including short maturity window, high yield, drought tolerance, nutrient use efficiency, favorable production on marginal soils, and functional use of existing agricultural equipment for production [14]. Two potential winter annual crops that could be incorporated with sorghum cultivars are barley (*Hordeum vulgare* L.) and rape/canola (*Brassica napus* L.), though most winter annual crops can fit within this rotation. Barley is a common grain crop with existing markets and the potential for use in bioenergy production, from both grain [15] and straw [16]. Rapeseed is an oilseed with existing edible food and lubricant markets, and is a major biodiesel feedstock in Europe [17].

With the high capital investment required for bioenergy production facilities, determination of available feedstock is incredibly important. U.S. DOE [18] found that a 10,000 MT/day Iowa biorefinery utilizing corn stover would require a collection radius of 56 km (35 mi), 72 km (45 mi), and 169 km (105 mi) for 100%, 50%, and 10% cropland inclusion, respectively. The collection radius has a major impact on hauling charges from $6.71 to $15.51 per metric ton ($6.09 to $14.07 per short ton) for 0 to 24 (0 to 15) and 80 to 161 (50 to 100) kilometers (miles), respectively [18]. This change in distance would lead to a theoretical maximum for economies of scale at a cropland inclusion rate of 10% for a facility above 8,000 MT/day as a result of increases in logistical operations, offsetting the cost savings from facility operations [18]. To avoid the issues of indirect land use change [19] (e.g. conversion of natural habitat in developing countries to supplement conversion of arable land), marginal cropland [20] and unconventional land areas [21] have been proposed for production of biomass feedstocks, but these areas commonly have lower yields than productive cropland. Babcock & Iqbal [22] have shown that outside of developing countries, increases in crop production are accomplished by intensive not extensive practice. This is especially prevalent in industrialized countries, such as the U.S. and EU members, where total cropland is diminishing [23]. Current production of dedicated bioenergy feedstocks in the Southeast U.S. is limited, mostly because the significant investments in viable biorefinery facilities have not been established. The ability to establish prediction methods for potential cropland conversion from traditional agricultural products to biomass feedstocks would be beneficial to biorefinery and economic development in different regions globally.

The objectives of this study were to construct a predictive model to determine cropland conversion from traditional agricultural products to biomass feedstocks, using a probabilistic equation based on agricultural margins, and demonstrate the usefulness of this method with case studies of an individual county within each of the three major regions of North Carolina (Coastal Plain, Piedmont, Mountains). Uncertainty analysis within each case study was included to determine variability within the model from different yield, price and composition parameters.

2. Methodology

2.1. Yield determination

Traditional agricultural product yields were determined by soil type and county (in North Carolina) using the NCSU Soil Science Department's Realistic Yield Expectations [24]. With ArcGIS (ESRI Redlands, CA), 2003 soil survey [25] and 2013 cropland cover [26] data were used to determine the acreage of selected North Carolina crops (Table 2) and soil types for specific counties representative of regions of interest, Duplin (Coastal Plain), Granville (Piedmont) and Henderson (Mountains). Since data were not available for sweetpotato yields by soil type in North Carolina, proportional tobacco yields on Leon Sand (Duplin County) that are comparable to the state average [27], were used to create a yield ratio for the different soil types. A ten percent coefficient of variation on average crop yields for traditional agricultural products and winter biomass rotational crops was used in the analysis.

Table 2. Crop/product proportions of county land area for select agricultural products (2013).

Code[1]	Crop	Duplin (Coastal Plain)	Granville (Piedmont)	Henderson (Mountains)
	Total Area[2]	213,050 ha	139,000 ha	97,150 ha
1	Corn	9.42%	1.03%	3.52%
2	Cotton	2.05%	0.10%	0.00%
4	Soybean	0.43%	0.03%	0.00%
5	Sorghum	4.91%	0.92%	0.68%
10	Peanut	0.72%	0.00%	0.00%
11	Tobacco	0.55%	0.10%	0.01%
21	Barley	0.04%	0.00%	0.00%
24	Wheat	0.48%	1.31%	0.00%
26	Dbl Crop WinWht/Soybean	7.91%	0.69%	0.01%
36	Alfalfa	0.00%	0.00%	0.01%
37	Other Hay/Non Alfalfa	5.16%	4.01%	4.80%
46	Sweet Potato	0.15%	0.00%	0.00%
60	Switchgrass	0.00%	0.00%	0.00%
61	Fallow/Idle Cropland	5.13%	7.55%	0.51%
176	Grassland/Pasture	0.81%	10.51%	3.95%
225	Dbl Crop WinWht/Corn	0.00%	0.02%	0.00%
235	Dbl Crop Barley/Sorghum	0.00%	0.00%	0.00%
236	Dbl Crop WinWht/Sorghum	0.17%	0.05%	0.00%
237	Dbl Crop Barley/Corn	0.00%	0.03%	0.00%
238	Dbl Crop WinWht/Cotton	0.00%	0.00%	0.00%
239	Dbl Crop Soybean/Cotton	0.00%	0.00%	0.00%
241	Dbl Crop Corn/Soybean	0.00%	0.00%	0.00%
254	Dbl Crop Barley/Soybean	0.00%	0.00%	0.00%
	Total Agricultural Area[2]	162,000 ha	110,900 ha	90,300 ha

*Dbl Crop means Double Crop, or two specific crops cultivated and harvested on a single land area in the same year.

[1]Code represents the grid code given in the USDA [26].

[2]Total area of counties may not be exact due to raster format of data within ArcGIS, transformation of data, and geodetics.

The most accessible publically available biomass crop yields and coefficients of variation for North Carolina were used for perennial grasses [11] and canola [28]. For sorghum yields an unpublished variety trial conducted at the NCSU Biofuel's Field Lab (Duplin County, NC 34.7622°N, 78.0995°W) on favorable sorghum cultivars was used. The highest observed dry matter yield from this trial was used as an average yield for sorghum (Sugar T), with standard deviation calculated using the top four yielding cultivars (Table 3), considering higher yielding cultivars would be selected for large scale production. Using the specific soil types these trials were conducted on, ratios were established between similar crops where extensive data already existed in databases. For perennial grasses, fescue was used in the Mountains, bermudagrass in the Coastal Plain, and an average between the two for the Piedmont. Sorghum yields were considered proportional to sorghum in the Mountains, sorghum sudan in the Coastal Plain, and an average of the two in the Piedmont. Wheat was used to proportionally determine the yield of canola in all regions. For example the average canola yield (averaged across varieties and years) used for Duplin County (Goldsboro Loamy Sand, representative slope) was 2.47 tonne/ha (36.8 bu/ac), while wheat in the same county and soil type had a realistic yield expectation of 4.37 tonne/ha (65 bu/ac) [24]. To predict the yield of canola in Duplin County on Pantego Loam (representative slope) where wheat has a realistic yield expectation of 4.04 tonne/ha (60 bu/ac), a ratio of 4.04:4.37 would be used, giving a predicted yield of canola at 2.28 tonne/ha (33.97 bu/ac).

Table 3. Sorghum 2013 cultivar trial (Wallace, NC (Goldsboro Loamy Sand, Duplin County)).

Cultivar	MC (wet basis)	Yield (dry tonne/ha)
ES 5140	63%	15.18
EJ 7282	63%	17.03
ES 5155	64%	16.89
Sugar T	67%	20.09

2.2. Agricultural product margins

Traditional agricultural product enterprise budgets were used from the NCSU Department of Agricultural and Resource Economics [29-47], using the most updated budgets provided. When multiple management systems for the crops were provided (e.g. till and no-till) the values were averaged. These budgets were used to determine average fixed and variable production costs for the various crops shown in Table 2. Peanuts were assumed to be Virginia peanuts because of profitable margins, and tobacco was averaged between coastal plain and piedmont production practices, with piedmont operations assumed to be half hand harvested and half machine harvested.

Biomass enterprise budgets were constructed with best publically available data, and knowledge from variety trials at NCSU. All perennial crops were assumed to be on a ten year replanting schedule, using big square bales stored for a maximum of six months on a gravel pad in tarped piles. This harvest and storage method was selected to reduce transportation costs by cubing out loads [48] and allows for low dry matter losses using the lowest cost storage method [49]. Annual yields used accounted for losses during storage and a three year yield maturity required for perennial grasses (50%, 75%, and 100% of anticipated biomass yield with each year). Giant Reed was assumed to be forage chopped with a specialized willow harvester outlined in Buchholz & Volk [50] as a best management practice tied to minimizing invasiveness potential. An even split of traditional and minimum tillage operations were assumed throughout the production area, since depending on soil type and production methods management strategies vary. Rapeseed costs were determined using the ratio of canola to wheat costs shown in Atkinson et al. [51] with the most up to date wheat enterprise budget [40,41].

Agricultural product prices were determined from USDA [27] for average prices in North Carolina. Sorghum was priced at 95% the value of corn on a weight basis, as has been done in contracts by Murphy Brown [52]. The value of pastures was based on two thirds of the dry matter yields of hay, with this assumption accounting for management strategy variations between hay and pasture operations, such as stubble height requirements. Canola was valued from 2013 Canadian prices [53], after converting to U.S. dollars. Biomass was valued on a dry ton basis, after taking into account cellulose content. Primary price of cellulose was determined using a 37% cellulose content of switchgrass [54] rather than a set value for biomass on a dry tonnage basis. The coefficient of variation of switchgrass cellulose content was used for all biomass feedstocks in this analysis. A coefficient of variation for agricultural product yields of ten percent was also used for this analysis.

2.3. Cropland conversion probability

After agricultural product and biomass feedstock margins were determined, a probabilistic function was constructed to determine cropland conversion. Three categories of land managers were assumed to exist: 1) those that would convert as long as the profit margin was positive, 2) those that would change once the profit was greater than current profits—represented by a linear increase in probability from proportional margins with existing profits to double margins, and 3) those that would not convert regardless of increases in margins above twice the existing current profits—represented by the maximum probability of conversion of 25% (Figure 2). There are positive benefits of converting to a biomass feedstock including guaranteed annual contracts reducing land manager risk, increases in soil carbon from perennial crop [55], diversification of crop production, and some land managers may wish to contribute to advancing an emerging bio-economy. As profits begin to grow beyond that of existing agricultural products land managers will continue to convert cropland. With the high capital costs of specialized agricultural operations (combines, cotton pickers, etc.) there would be some maximum probability of converting cropland, regardless of increases in profit. Additionally some land managers would leave cropland in traditional agricultural products for similar reasons which may include: variability in agricultural products can produce high profits at a risk, annual crop rotations of high value products may limit annual use, and traditional products provide a certain level of reassurance to many producers. For this analysis, a minimum and maximum probability of converting land use practices of one and twenty five percent, respectively, was chosen, with a linear increase from proportional to double profits from current agricultural product (Figure 2).

Accounting for profitability (Equation 1) a probability function was developed (Equation 2) derived from Figure 2 for total converted acreage of each soil type [25] and cropland cover [26] within the specified counties. This probability of conversion was used as a proportion of land converted (Equation 3), since as the size of the dataset increases probability can be used as an estimate of proportion.

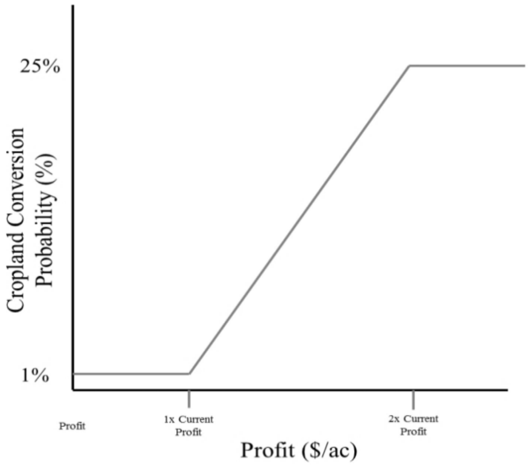


Figure 2. Cropland conversion probability function.

2.4. North Carolina case study with uncertainty analysis

A case study using the predictive model was constructed for the three major regions of North Carolina, and the representative county: Coastal Plain (Duplin County), Piedmont (Granville County), and Mountains (Henderson County). Each of these counties contained a research station with biomass feedstock data, allowing for greater comparison between soil types. Spatial data for these counties was used to evaluate the acreage that would convert to biomass feedstocks production.

An uncertainty analysis was conducted for each case study using a single parameter sensitivity analysis method. Coefficients of variation of ten percent were used for traditional agricultural crops and available data for biomass feedstock yields and switchgrass cellulose content, which was used for all biomass crops. An average biomass feedstock value of $71.65/dry tonne ($65/dry ton) was used, with a higher price of $82.67/dry tonne ($75/dry ton) and lower of $60.63/dry tonne ($55/dry ton).

A wide range of biomass costs have been used in other publications, with selected values slightly higher than those reported, since many of these did not account for grower profits. U.S. DOE [18] used a feedstock price of $33.07 per dry tonne ($30/dry ton), with further updated research efforts showing increase to $64.82/dry tonne ($58.80/dry ton) [56]. Glassner et al. [57] evaluated corn stover costs in Iowa determined a cost of $39.30/dry tonne ($35.70/dry ton) for a low yield scenario, common for sloped terrain, and $34.76/dry tonne ($31.60/dry ton) for higher yields, which was commonly selected by most farmers. U.S. DOE [18] using life cycle analysis from Oak Ridge National Laboratory found a corn stover cost of $62/dry tonne ($56/dry ton) after accounting for fertilizer inputs, transportation, baling/staging, and a farmer premium of 18% ($11.16/dry tonne, $10.08/dry ton). The higher feedstock values used (price per dry tonne) were assumed because the analysis used dedicated biomass feedstocks and not agricultural residues as included in the referenced studies. A baseline for the uncertainty analysis was produced using average values, then best and worst case scenarios two standard deviations above and below the mean for each parameter were determined. This resulted in either an increase or decrease in the predicted acreage converted from the estimated average acreage. Each individual parameter was subsequently increased and decreased by two standard deviations to determine the sensitivity of each.

The uncertainty analysis was conducted from the average converted cropland calculations, using two standard deviations from the mean, followed by the "Extreme" scenario which took all parameters of influence into account. The parameters of interest for this analysis were: Winter Cover Yield (related to sorghum production), Winter Cover Price (related to sorghum production), Biomass Yield (perennial and annual crops), Biomass Price (perennial and annual crops), Biomass Composition (cellulose content), Current Crop Price (current crop production), and Current Crop Yield (current crop production). The response variables used were converted acreage, from current crop production to biomass feedstock, and cellulose yield.

3. Results and Discussion

3.1. Yield determinations

Yield ratios for biomass crop were usually lower than one (biomass crop yield from chosen trials: traditional crop used as an indicator on other soil types), showing that yield trials were conducted on productive soils in the regions. County specific yield average and coefficients of variation for each biomass feedstock are shown in Table 4. Zero values associated with some soil types that were not suitable for production are not included.

Table 4. Average Biomass Feedstock Yields across County Soil Types (dry tonne per hectare).

	Coastal Plain Duplin County		Piedmont Granville County		Mountains Henderson County	
	Mean	CoV	Mean	CoV	Mean	CoV
Switchgrass	14.1	0.23	12.1	0.25	13.2	0.21
Miscanthus	14.6	0.23	10.6	0.25	12.7	0.21
Giant Reed	19.7	0.23	13.6	0.25	16.67	0.21
Sorghum	14.9	0.25	15.9	0.34	15.0	0.23
Barley (straw)	4.5	0.20	4.1	0.31	4.3	0.19
Barley (grain)	1.9	0.20	1.7	0.31	1.8	0.19
Canola (grain)	1.9	0.20	1.2	0.31	1.1	0.19

3.2. Agricultural product margins

Biomass feedstock enterprise budgets were constructed for each of the biomass feedstocks and are summarized in Table 5. Establishment costs for perennial grasses were low because they were annualized over the ten year life span, with annual maintenance costs accounting for yearly operations. Sorghum and giant reed harvest costs were high as the assumed best management practice harvest operation used large self-propelled forage choppers, with giant reed using a specialized header. Storage costs were slightly higher in the barley as a result of a higher proportion of the annual yield of biomass delivered since barley straw does not have a multi-year ramp up period. Differences in transportation costs were related to bulk density, biomass format, and moisture content of the different crops.

Table 5. Annual biomass enterprise budget values.

	Establishment ($/ha)	Maintenance ($/ha)	Harvest ($/ha)	Storage ($/dry tonne)	Transport ($/dry tonne)	Delivered Biomass Yield	Grain Transport ($/tonne)
Sorghum	$459.76		$130.50		$4.56	100%	
Barley	$633.48		$195.06	$1.69	$2.94	97%	$5.51
Switchgrass	$44.18	$289.41	$81.12	$1.60	$2.94	90%	
Miscanthus	$122.42	$289.41	$81.12	$1.60	$2.94	90%	
Giant Reed	$122.42	$289.41	$179.99		$1.93	90%	

*Canola is not included in Table 5 since production cost was calculated from Atkinson et al. [51], after being updated for current commodity prices

Values shown in Table 5 were calculated using existing equipment cost information from Lazarus [58] and Lazarus [59] using field capacity and equipment information from major commodity crop production in Minnesota, with the intent of modeling costs for the n^{th} field. Though establishment equipment costs are probably relatively similar, depending on seeding rates, a major difference may be related to harvest operations. With higher crop yields compared to hay and additional wear on equipment from larger diameter, more rigid stems of perennial biomass crops, actual field operations may be considerably more expensive, impacting equipment lifetime and maintenance costs. The higher yields of the perennial biomass crops compared to hay may also reduce field efficiency, especially for round balers that must stop to bind and discharge each bale. The values in Table 5 did not account for land value since the commodity enterprise budgets used for calculations did not account for this value, However, if land valuation were included it would have raised per hectare costs by $207.57 annually for non-irrigated cropland in North Carolina ($84 per acre) [60].

3.3. Cropland conversion probability

Estimated yield and enterprise budget parameters were applied to the produced set of equations (Equation 1—profitability of agricultural crop; Equation 2—probability of cropland conversion; Equation 3—total area of cropland converted), and related variables (Table 6) to estimate cropland conversion probability, and subsequently converted area. These equations can be used for a range of feedstocks, land areas, parameters, and bioenergy production technologies. Though specifically designed for biomass, this equation can be used for any cropland conversion analysis to determine land availability. It is also possible to update the probability function depending on specific information from land managers on requirements for conversion.

Equation 1: Profitability of agricultural products.

$$P_{C,B} = (Y_{C,B} * Pr_{C,B}) - [F_{C,B} + (Y_{C,B} * V_{C,B})]$$

$$Pr_B = \left[Pr_{dry} * \frac{1}{Cell_{SW}}\right] * Cell_B$$

Equation 2: Probability of cropland conversion.

$$if\ 0 < P_B < P_C, Prob = 1\%$$

$$if\ P_C \leq P_B \leq 2P_c, Prob = \left[\frac{0.24}{P_C} P_B\right]\%$$

$$if\ 0 < P_C\ \&\ 2P_C < P_B, Prob = 25\%$$

$$if\ P_C < 0\ \&\ \frac{1}{2} P_C < P_B, Prob = 25\%$$

Equation 3: Total Area of cropland converted to biomass feedstock production.

$$CA = \sum Prob * A(Soil, Crop)$$

Table 6. Probabilistic cropland conversion equation variables (Equation 1; Equation 2; Equation 3).

C:	Current Crop	F:	Fixed Cost ($/hectare)	CA:	Converted Area (hectare)
B:	Biomass Feedstock	V:	Variable Cost ($/tonne)	A:	Area (hectare)
P:	Profit ($/hectare)	Cell:	Cellulose Content (SW-model switchgrass) (%)	Pr:	Price ($/tonne)
Y:	Delivered Yield (tonne/hectare)			Prob:	Conversion Efficiency (%)

For example data from Duplin County for corn and switchgrass (Table 7) on Blanton Sand, 1 to 6 percent slope (BnB) and pantego loam, 0 to 1 percent slope (PnA) soil types showed a total area converted to biomass crop production of 15.39 hectares (38.04 acre) (Figure 3).

Table 7. Example data for profit based cropland conversion Coastal Plain (Duplin County).

	Corn [C] (15.5% MC)	Switchgrass [B] (dry)
Fixed Cost [F] ($/ha)	$979.90	$414.72
Variable Cost [V] ($/tonne)	$12.20	$4.54
Cellulose Content [Cell] (%)	NA	40.34%
Price [Pr] ($/tonne)	$192.90	$82.67
Delivered Yield [Y]		90% annual yield
BnB [Soil] (tonne/ha)	4.46	12.21
PnA [Soil] (tonne/ha)	10.17	13.87
Area (A)		
BnB [Soil] (ha)	56.0	NA
PnA [Soil] (ha)	139.3	NA

Biomass Feedstock Cost

$$\left[\$82.67\ (Pr_{DT}) * \frac{1}{0.37\ (Cell_{SW})}\right] * 0.4034\ (Cell_B) = \$90.13\ (Pr_B)$$

Blanton Sand, 1 to 6 % slope (BnB)

$$\left(4.46(Y_C) * \$192.90(Pr_C)\right) - [\$979.90(F_C) + (4.46(Y_C) * \$12.20(V_C)] = -\$173.98\ (P_C)$$

$$\left(12.21(Y_B) * \$90.13(Pr_B)\right) - [\$414.72(F_B) + (12.21(Y_B) * \$4.54(V_B)] = \$630.33\ (P_B)$$

$$-\$86.99\ \left(\frac{1}{2}P_C\right) < \$630.33(P_B), Prob_{BnB} = 25\%$$

Pantego Loam, 0 to 1 % slope (PnA)

$$\left(10.17(Y_C) * \$192.90(Pr_C)\right) - [\$979.90(F_C) + (10.17(Y_C) * \$12.20(V_C)] = \$820.70\ (P_C)$$

$$\left(13.87(Y_B) * \$90.13(Pr_B)\right) - [\$414.72(F_B) + (13.87(Y_B) * \$4.54(V_B)] = \$772.41\ (P_B)$$

$$0 < \$772.41\ (P_B) < \$820.70\ (P_C), Prob_{PnA} = 1\%$$

Converted Land Area

$$[0.25(Prob_{BnB}) * 56(A_{BnB})] + [0.01(Prob_{PnA}) * 139.3(A_{PnA})] = 15.39(CA)$$

Figure 3. Profit Based Cropland Conversion Equation Example for Values Given from Table 7.

3.4. North Carolina case study with uncertainty analysis

Using average parameter values, the model predicted that a considerably higher amount of land would be converted from current crop production in Duplin County (15,072 ha, 7.1% total land, 9.3% cropland) than either Granville (7697 ha, 5.5% total land, 6.9% cropland) or Henderson (2117 ha, 2.2% total land, 2.3% cropland) (Figure 4). These values make some sense since Duplin County has more than 1.5 and 2.5 times the area in production of agricultural crops (Table 2) compared to Granville and Henderson counties, respectively. For all selected counties the combination of parameters in the extreme negative case (e.g. lower yields, low cellulose composition, low prices) showed drastic decreases in converted cropland, but considerably smaller gains when all parameters were similarly increased (Figure 4). This suggests that the average parameter values already have set the probability function near its maximum value, so increasing these parameters would not entice many additional land managers to convert their cropland. For single parameters, modifications in the current crop price and yield had the greatest effect on cropland conversion probabilities and ties back to profitability margins (Figure 4).

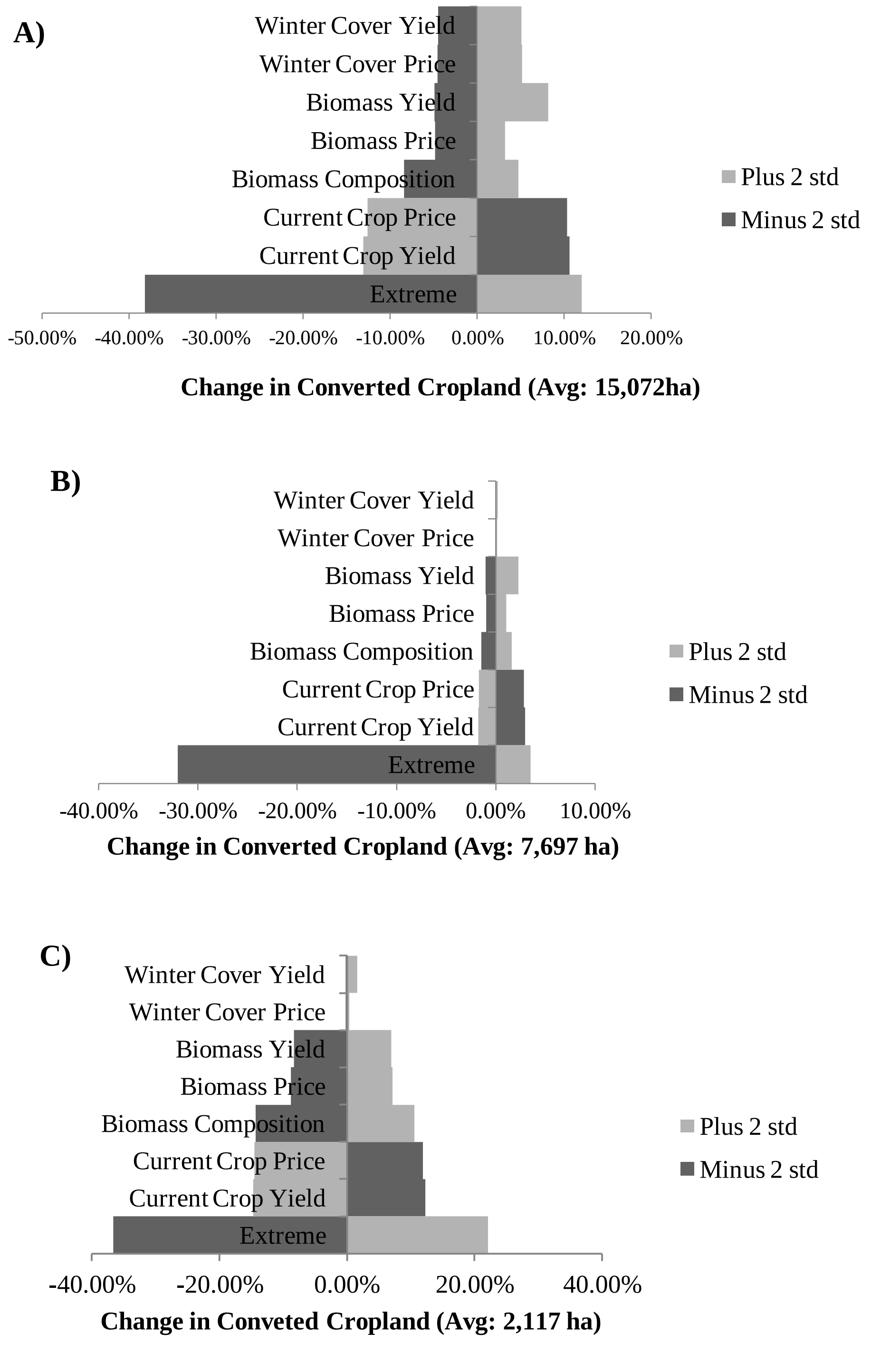


Figure 4. Influence of model parameter values on the change in converted cropland from the average estimates for A) Coastal Plain (Duplin County, NC), B) Piedmont (Granville County, NC), C) Mountains (Henderson County, NC). The uncertainty analysis was completed for low (−2σ) and high (+2σ) values for each individual parameter, with the "Extreme" scenario representing a change in all parameters either positively or negatively as they effected the response variable of cropland conversion.

Variations in the selected parameters also had an effect on the mix of biomass feedstocks predicted to be adopted and cellulose yield from each specific county (Figure 5). The model indicated that for Granville County of the area converted the biomass feedstock that would be grown was almost entirely switchgrass (Figure 5B), while Duplin County (Figure 5A) and Henderson County (Figure 5C) generally had a mix of sorghum (with a winter cover) and switchgrass as the feedstocks adopted. Some giant reed was included in Duplin County (Figure 5A) and miscanthus only was selected as part of the extreme low case and when biomass yields were reduced in Duplin and Granville Counties (Figure 5A; Figure 5B). Inclusion of giant reed was most likely related to its high yield capacity in the Coastal Plain Region and miscanthus was commonly not selected by the model because of its high establishment cost compared to switchgrass (Table 5). Inclusion of miscanthus in poor biomass yield situations (Figure 5) was likely tied to its low yield standard deviation [11]. The higher cellulose content of perennial grasses compared to sorghum had a greater effect on availability per county compared to production acreage (Figure 5). The added soluble carbohydrate concentration of sorghums and an integrated soluble sugar animal feed system was not included in this model, which could alter the economics and overall feedstock value. To put cellulose yield into context, a 75 million liter nameplate facility using a feedstock that is 37% cellulose (Lee et al. 2007) with a dry tonnage conversion of 322 liters per dry tonne [61] would require approximately 86,000 tonnes of cellulose annually (assuming no storage or handling losses). This would mean that using average parameter values, Duplin County could produce enough feedstock to supply an entire 75 million liter facility with converted cropland using average input values, and under the best case parameters it could produce feedstock for more than two and a half facilities of similar capacity (Figure 5A).

For all scenarios in the Coastal Plain, canola was found to be the winter crop of choice with sorghum, while in the Piedmont barley was mostly predicted. Though barley does assist with the economics for production it does not contribute a large amount of cellulosic material as part of the excess straw collected (Figure 5C). Henderson County was split between the two with the majority of sorghum production land area adopted in combination with a barley winter cover, though some soil types showed beneficial yields to justify canola (Table 8).

The number of crop types shown in Table 2 was reduced to those that were at least ten percent of the converted area in at least one of the counties/regions (Figure 6), using average parameter values within the model. In Granville (Piedmont) and Henderson (Mountains) Counties cropland associated with grassland and hay production was the primary type converted to biomass feedstocks, while in Duplin County profitability was observed over a greater number of traditional agricultural products, with the greatest proportions being tied to corn, hay and grassland (Figure 6). When the proportion of total land area converted from current use for each of the selected agricultural products in a county were taken into account there was a high percentage of hay, grassland, and fallow land converted (Table 9). This was a result of all of these land areas being related to the average price of hay, which is commonly undervalued. NCSU [62] provided a range of prices for hay production after accounting for all operations and storage losses between $180 to $245 per dry tonne, which was considerably higher than the $143 per dry tonne ($121/tonne, at 15% MC) average sales price for hay in North Carolina [27]. In combination with the model results, this suggests the market value and price of a commodity will significantly impact land management decisions.

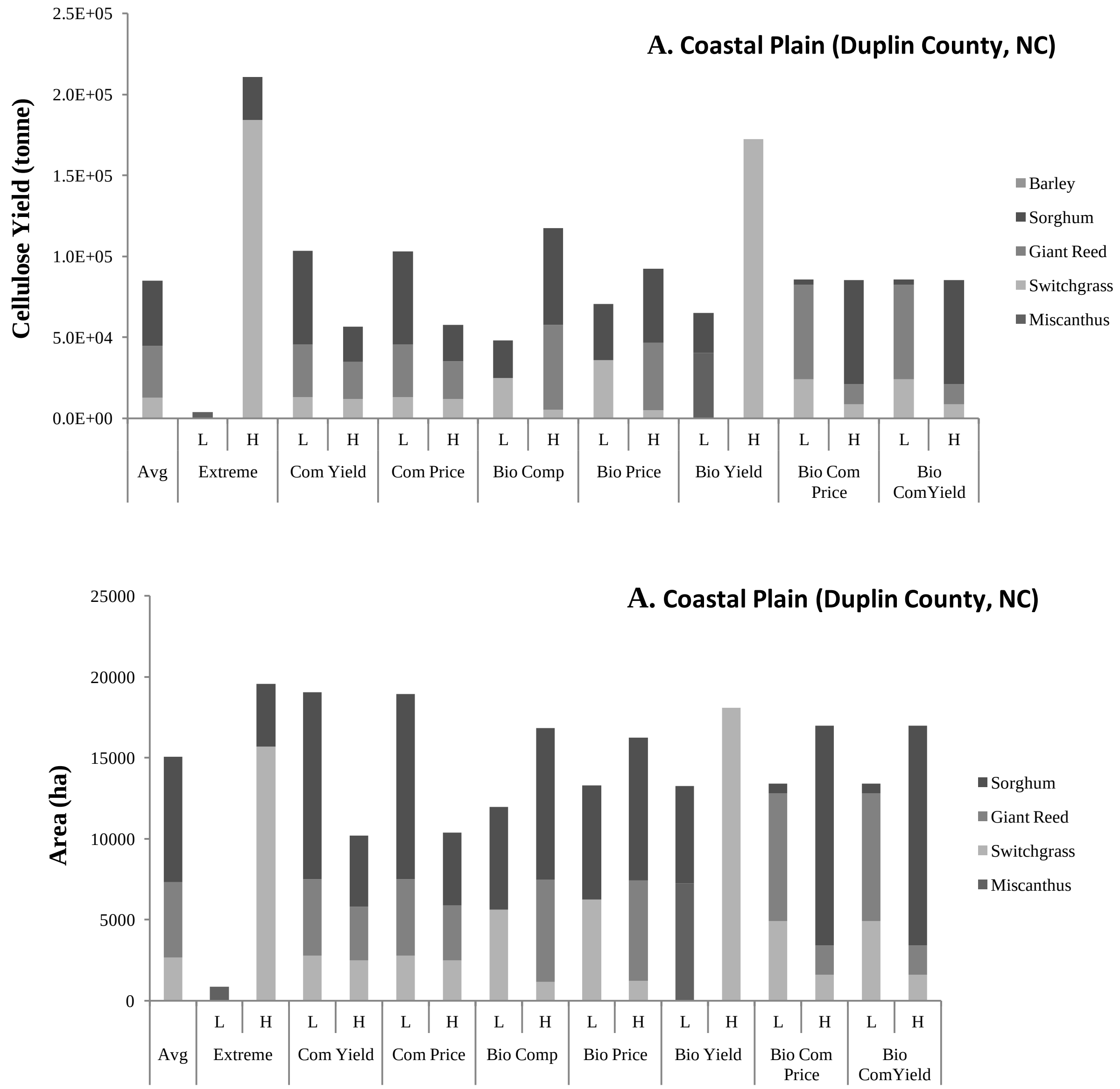
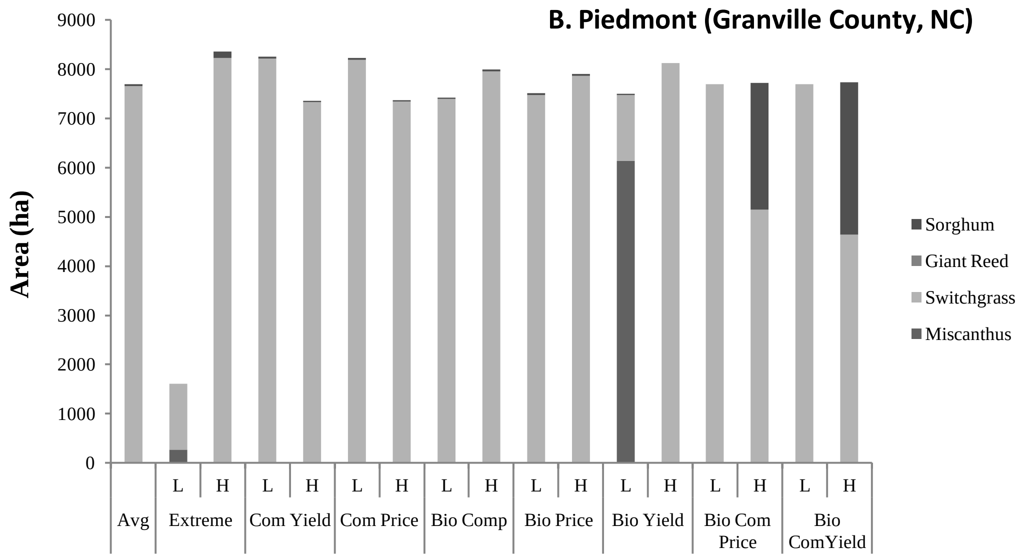


Figure 5A. Converted cropland and cellulose yield from single parameter variation [L: −2σ, H: +2σ] from average model parameters A) Coastal Plain (Duplin County, NC). The "Extreme" scenario accounts for positive and negative effects to all parameters of influence as they effect the response variable of converted cropland (Commodity Yield, Commodity Price, Biomass Composition, Biomass Price, Biomass Yield, Biomass Commodity Price, Biomass Commodity Yield). The legend reflects the biomass crop and the order of appearance in the figure, if converted, is maintained as indicated in the legend.



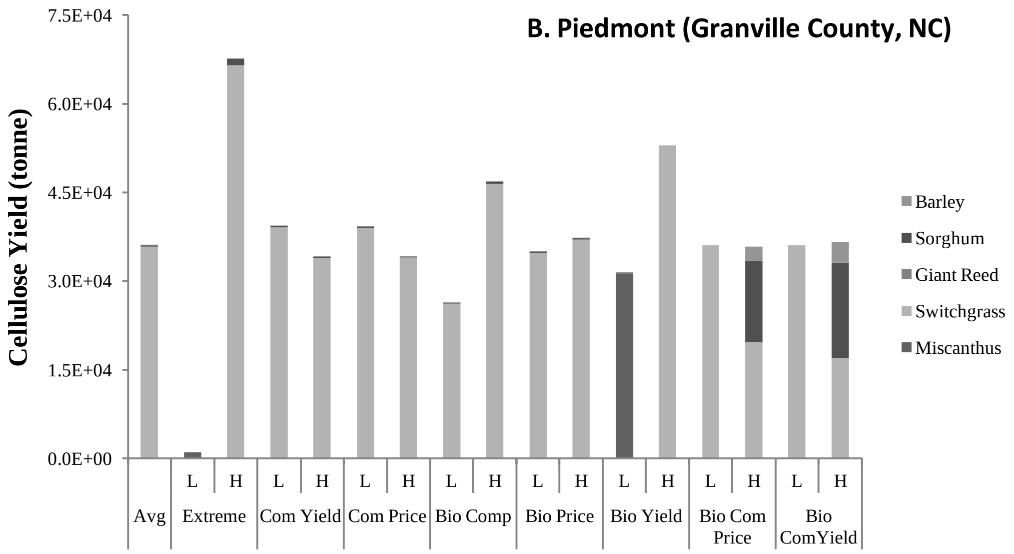
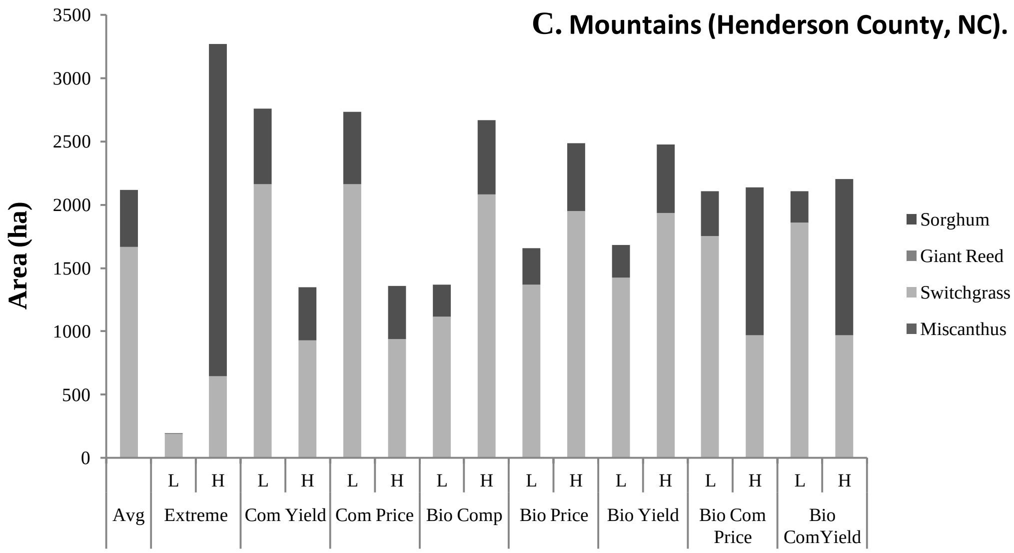


Figure 5B. Converted cropland and cellulose yield from single parameter variation (L: −2σ, H: +2σ) from average model parameters B) Piedmont (Granville County, NC). The "Extreme" scenario accounts for positive and negative effects to all parameters of influence as they affect the response variable of converted cropland (Commodity Yield, Commodity Price, Biomass Composition, Biomass Price, Biomass Yield, Biomass Commodity Price, Biomass Commodity Yield). The legend reflects the biomass crop and the order of appearance in the figure, if converted, is maintained as indicated in the legend.



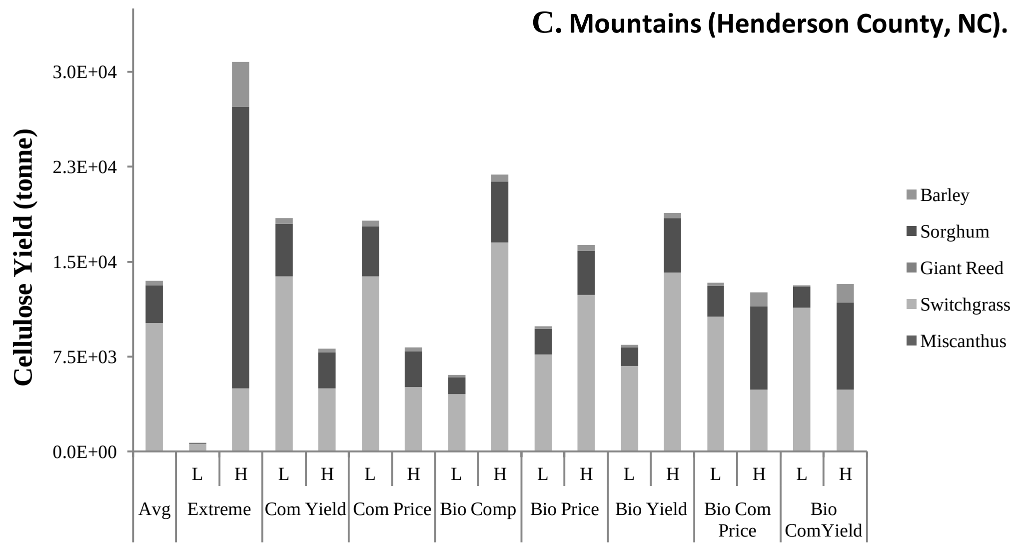


Figure 5C. Converted cropland and cellulose yield from single parameter variation (L: −2σ, H: +2σ) from average model parameters C) Mountains (Henderson County, NC). The "Extreme" scenario accounts for positive and negative effects to all parameters of influence as they affect the response variable of converted cropland (Commodity Yield, Commodity Price, Biomass Composition, Biomass Price, Biomass Yield, Biomass Commodity Price, Biomass Commodity Yield). The legend reflects the biomass crop and the order of appearance in the figure, if converted, is maintained as indicated in the legend.

Table 8. Proportion of Winter Cover with Sorghum in Mountains (Henderson County) for Average and Extreme Parameter Values and Low (−2σ) and High (+2σ) Values of Individual Parameters.

	Low		High	
	Canola	Barley	Canola	Barley
Average	11%	89%	11%	89%
Extreme	81%	19%	8%	92%
Commodity Yield	9%	91%	11%	89%
Commodity Price	9%	91%	11%	89%
Cellulose Content	19%	81%	9%	91%
Biomass Price	17%	83%	10%	90%
Biomass Yield	19%	81%	10%	90%
Biomass Commodity Price	14%	86%	4%	96%
Biomass Commodity Yield	20%	80%	4%	96%

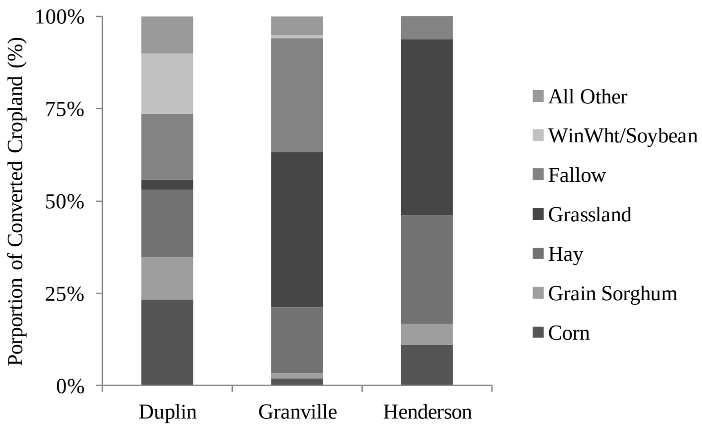


Figure 6. Proportion of total converted land by selected current agricultural product.

Table 9. Proportion of total current cropland converted to biomass feedstocks.

	Duplin	Granville	Henderson
Corn	17%	10%	6%
Grain Sorghum	18%	4%	21%
Hay	23%	24%	15%
Grassland	24%	23%	25%
Fallow	24%	23%	25%
WinWht/Soybean	14%	2%	21%

Cropland conversion estimates from this North Carolina case study have demonstrated the utility of the developed prediction model to potential biorefinery facility planners seeking new sources of biomass feedstocks from landowners. The enterprise budgets used functioned as expected, with cash crops like tobacco, cotton, and sweetpotato showing low cropland conversions. Use of soil type to determine realistic yield provided flexibility for the model to be used over many different land areas and provided meaningful estimates for a range of feedstocks to be produced in the different regions (Figure 6). Uncertainty analysis showed that the different land areas displayed varied parameter sensitivity, with average values being near the higher end of the probability function and the combination of factors in the worst case showing drastically reduced conversion of cropland (Figure 6).

A major limitation to this modeling approach is data availability. Increased information from land owners on what is required for cropland conversion and use of more detailed crop production by land parcel information can produce more accurate results. This type of data can be acquired through intensive surveys of local areas. It may also be useful to set a minimum field size that is required for conversion, such as one hectare, to allow for optimal logistical operations if harvest equipment is to be moved between locations. Use of multiple years of data would allow for determination of which fields would be best suited for conversion to a perennial biomass crop, and those suited for a multi-year rotational schedule with annual biomass crop production for improved land management and product diversification.

In 2012 the data derived from the billion ton update [5] found that at a biomass price of $66 per dry tonne ($59.87 per dry ton) Duplin County had 28 to 56 thousand dry tonnes of agricultural biomass available (30.86 to 61.73 thousand dry tons), while Granville and Henderson Counties would produce between 0 and 4 thousand dry tonnes (0 and 4.4 thousand dry tonnes), including residues [63]. By 2022 this was estimated to increase to between 60 and 150 thousand dry tonnes for Duplin County (66.1 and 165.3 thousand dry tons), and agricultural biomass in Granville and Henderson Counties was estimated to increase to between 0 and 25 thousand dry tonnes (0 and 27.6 thousand dry tons) [63]. Using standard cellulose content for model switchgrass at 37% [54] the developed predictive model presented here estimates total biomass produced in Duplin, Granville, and Henderson at 30, 12, and 4 thousand dry tonnes annually, respectively (33.1, 13.2, 4.4 thousand dry tons), using average parameters. The discrepancy between the reported values and those calculated by U.S. DOE [63] may be related to this model only focusing on dedicated biomass feedstocks and not accounting for crop residues that may increase total availability. Consideration for inclusion of residues and specific system parameters used need to be addressed when data from this presented modeling exercise are evaluated outside of the specific parameters in the analysis.

4. Conclusion

Implementation of the described probabilistic profit based approach to biomass feedstock production systems provided useful information for feedstock availability and selection of appropriate crops for spatial locations. After use of this spatial modeling approach more detailed logistical analysis can be conducted to establish optimal cropping systems, storage depots configuration, and biorefinery location. The case study for North Carolina showed that switchgrass was the perennial crop of choice with the addition of some sorghum, which varied in winter cover depending on the region (Figure 5). Use of this modeling approach is not limited to biomass feedstocks, but can be used for determination of cropland conversion potential or determination of profitability for land managers for other agricultural crops.

Acknowledgments

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Conflict of interest

All authors declare no conflicts of interest in this paper.

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