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Availability of Crop Residues as Sustainable Feedstock for Bioethanol Production in North Carolina

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Abstract

The amount of corn stover and wheat straw that can be sustainably collected in North Carolina was estimated to be 0.64 and 0.16 million dry t/yr, respectively. More than 80% of these crop residues are located in the coastal area. The bioethanol potential from corn stover and wheat straw was estimated to be about 238 million L (63 million gal/yr) in North Carolina. The future location of ethanol plant in North Carolina was estimated based on feedstock demand and collection radius. It is possible to have four ethanol plants with feedstock demand of 400, 450, 500, and 640 dry t/d. The collection radii for these four ethanol plants are 46, 60, 42, and 67 km (28, 37, 26, and 42 miles), respectively. The best location for a bioethanol plant includes four counties (Beaufort, Hyde, Tyrrell, and Washington) with feedstock demand of 500 t/d and collection radius about 26 mile.

Index Entries: Crop residues; ethanol; corn stover; wheat straw.

Introduction

The conversion technology for ethanol production from crop residues has been extensively studied *(1–4)*. The conversion of biomass to ethanol includes the following processes, sometimes in combination:

1. Pretreatment that breaks the long-chain hemicellulose down into five- and six-carbon sugars and makes the cellulosic components of the biomass more accessible to enzymatic attack;
2. Hydrolysis by acids, or by enzymes that break down the long-chain cellulose into six-carbon sugars;
3. Fermentation by microbes, converting the five- and six-carbon sugars to ethanol and other oxygenated chemicals;
4. Distillation and dehydration of the fermentation broth to produce fuel ethanol.

The hydrolysis and fermentation steps can be combined in a process called simultaneous saccharification and fermentation. The solid residue

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after fermentation mainly consists of lignin, which can be used as a fuel. Among these processes, a critical step in production of ethanol from crop residue is the conversion of cellulose and hemicellulose to simple sugars usable by fermentation yeast.

Agricultural residue is a low-cost feedstock for near-term bioethanol production. Corn stover and wheat straw are the most plentiful sources of the agricultural residues for bioethanol production. Corn stover contains approx 37.3% cellulose, 20.6% hemicellulose, and 17.5% lignin and wheat straw contains approx 32.6% cellulose, 20.5% hemicellulose, and 16.9% lignin *(5)*. The availability of corn stover as a sustainable feedstock for bioethanol production in the US has been studied by Kadam and McMillan *(6)* on a state by state basis. The amount of corn stover that can be sustainably collected is estimated to be 80–100 million dry t/yr in United States. Perlack and Turhollow *(7)* indicated that corn stover can be collected, stored, and transported for about $43 to $60/dry t using conventional baling equipments for ethanol facilities consuming from 500 to 4000 dry t/d. Transportation, collection, baling, and farmer payments account for over 90% of the total delivered costs *(7)*.

In this article, we have investigated the availability of major crop residues (corn stover and wheat straw) in North Carolina for bioethanol production at the county level. The sustainable amount of residue in each county was calculated based on the residue yield and collection factor. Finally, the counties were clustered for the purposes of identifying potential feedstock supply area for future bioethanol plants.

Methodology

Sustainable Crop Residue

Corn and wheat production data for North Carolina were obtained from the North Carolina Department of Agriculture and Consumer Services *(8)*. Average values of corn and wheat production in North Carolina for 2002–2004 were extracted from agricultural statistics *(8)* and were used in this study. The total production of major crops in millions of bushels in North Carolina for the years of 2002–2004 was as follows: corn (71.70), soybean (41.32), wheat (18.61), barley (0.92), and sorghum (0.64). As these data show, corn, wheat, and soybean are the three major crops in North Carolina. Because soybeans generate a relatively small amount of residue *(9)*, and it rapidly degrades in the field *(10)*, its utility as a feedstock for ethanol production is limited. Therefore, soybean residue was not considered as a potential feedstock for ethanol production.

The amount of crop residue that can be removed sustainably depends on the quantity of residue generated, the portion of the residue that can be removed without damaging soil quality, and site accessibility. The portion of residue that can be removed without damaging soil quality depends on a variety of factors such as: weather (wind and rainfall), crop rotation practices, soil fertility, slope of the land, and tillage practices. We have conducted a survey in the Piedmont and Coastal areas of North Carolina about yields and competitive uses of residue in 2003. Our survey indicates that the average residue yields for corn stover and wheat straw were 0.81 and 0.65 t/ha (2 and 1.6 t/acre), respectively. These survey results are in accord with findings reported by Kadam and McMillan *(6)* and Perlack and Turhollow *(7)*. Based on these data, grain to stover ratios of 1:1 for corn and 1:0.8 for wheat were used in this study. About 35% of the crop residue can be sustainably collected considering factors such as the condition of the land, accessibility, and competitive uses.

An index of biomass availability was defined as the amount of sustainable crop residue per square kilometer (mile). It is the sustainable amount of crop residue that can be collected per square kilometer (mile). The land area of each county was obtained from the state agricultural report sources *(11)*. Biomass availability is an important index to evaluate the collection cost of biomass for ethanol production.

Bioethanol Production Potential

There is considerable variation in the literature regarding the yield of ethanol from a given substrate. It is affected by the composition of the crop residues and ethanol production technology. The theoretical ethanol yield is about 471 L/dry t (124.4 gal/dry t) using an average corn stover composition and assuming that both hexose and pentose sugars are fermented *(12)*. Estimated ethanol yield of 300 L/dry t (79.3 gal/dry t) were used for corn stover feedstock sources, which is about 64% of theoretical ethanol yield. Ethanol yield of 292 L/dry t (77.1 gal/dry t) has been used by Kadam et al. *(6)* to estimate the national ethanol potential in the United States from wheat straw. Ethanol yield of 292 L/dry t (77.1 gal/dry t) was used in this study to predict the ethanol potential of wheat straw. The hydrolysis technologies assumed are either dilute acid hydrolysis or enzymatic hydrolysis. The fermentation process should be able to convert hexose and some of the pentose.

Results and Discussion

Biomass Availability

The total sustainable amount of corn stover and wheat straw in North Carolina was estimated to be 638,782 and 159,848 dry t/yr, respectively (Tables 1 and 2). The sustainable amounts of corn stover produced in mountain, piedmont, and coastal area were estimated to be 20,372, 67,783, and 550,626 dry t/yr, respectively (Table 1). About 86.2% of the sustainable corn stover was determined to be available from the coastal area (Fig. 1). The sustainable amount of wheat straw produced each year in mountain, piedmont, and coastal area were estimated to be 2649, 42,362, and 114,838 dry t/yr, respectively (Table 2). About 71.8 and 26.5% of the wheat straw was

Table 1
Sustainable Amount of Corn Stover and Ethanol Potential in North Carolina by Region

Region	Plant area ha (acres)	Grain production t/yr (bushel/yr)	Residue production dry t/yr	Sustainable residue amount dry t/yr	Ethanol potential l/yr (gal/yr)
Mountain	8195 (20,233)	58,206 (2,286,667)	58,206	20,372	6,111,636 (1,614,524)
Piedmont	34,061 (84,100)	193,667 (7,608,333)	193,667	67,783	20,335,000 (5,371,940)
Coastal	241,245 (595,667)	1,573,218 (61,805,000)	1,573,218	550,626	165,187,909 (43,638,037)
State total	283,500 (700,000)	1,825,091 (71,700,000)	1,825,091	638,782	191,634,545 (50,624,500)

Table 2
Sustainable Amount of Wheat Straw and Ethanol Potential in North Carolina by Region

Region	Plant area ha (acres)	Grain production t/yr (bushel/yr)	Residue production (dry t/yr)	Sustainable residue amount (dry t/yr)	Ethanol potential l/yr (gal/yr)
Mountain	3510 (8667)	8409 (308,333)	7568	2649	773,468 (204,329)
Piedmont	51,570 (127,333)	134,482 (4,931,000)	121,034	42,362	12,369,638 (3,267,713)
Coastal	139,320 (344,000)	364,564 (13,367,333)	328,107	114,838	33,532,563 (8,858,368)
State Total	194,400 (480,000)	507,455 (18,606,667)	456,709	159,848	46,675,669 (12,330,410)

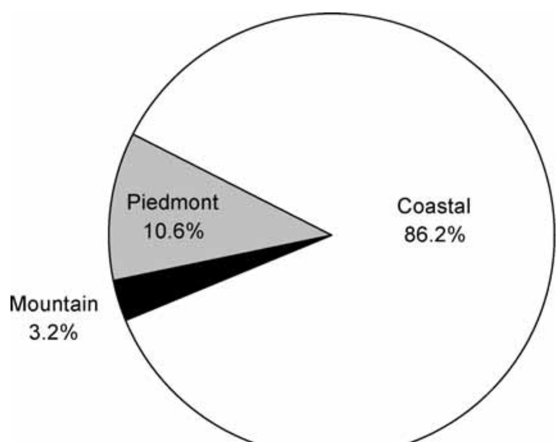

Fig. 1. Distribution of sustainable amount of corn stover in North Carolina.

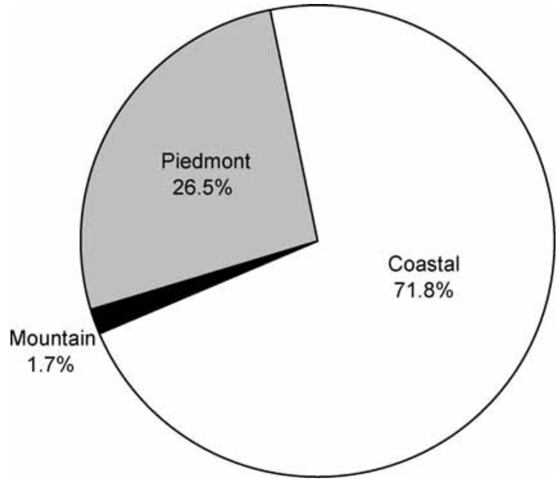

Fig. 2. Distribution of sustainable amount of wheat straw in North Carolina.

Fig. 3. Sustainable amount of crop residues (dry t/d) in the Mountain area of North Carolina (values in the parenthesis show the land area in km^2).

located in the coastal and piedmont areas (Fig. 2). The sustainable crop residue produced in the Mountain area was negligible.

The amounts of sustainable crop residues (corn stover and wheat straw) for each county of North Carolina are shown in Figs. 3–5. The data presented

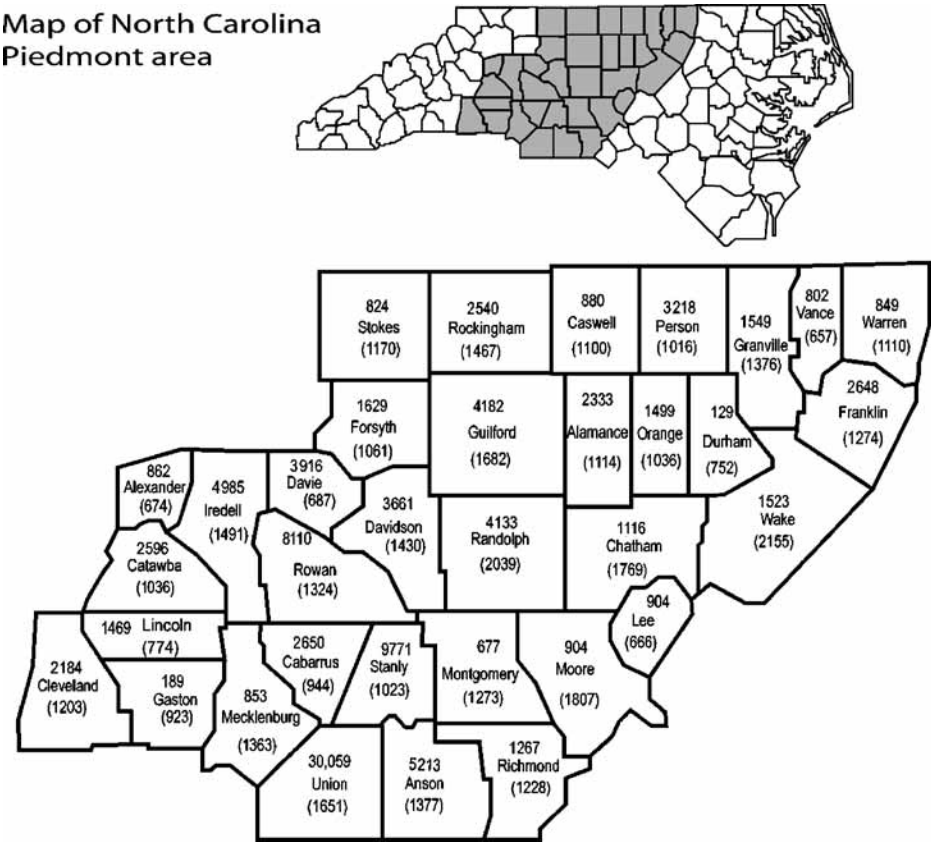

Fig. 4. Sustainable amount of crop residues (dry t/d) in the Piedmont area of North Carolina (values in the parenthesis show the land area in km^2).

in the parentheses is the land area of the county in square kilometer. The biomass availability of each county was distinguished with different color based on the sustainable amount of crop residue per square kilometer in Fig. 6. Pasquotank has the highest biomass availability 52.7 dry t/km^2 (136.4 dry t/square mile). The biomass availability of four counties (Tyrrell, Perquimans, Washington, and Camden) falls between 30 and 40 dry t/km^2 (80–100 dry t/square mile). The biomass availability of five counties (Lenoir, Wayne, Currituck, Duplin, and Beaufort) falls between 20 and 30 dry t/km^2 (50–80 dry t/square mile). The biomass availability of nine counties (Bladen, Columbus, Sampson, Pamlico, Carteret, Greene, Union, Robeson, and Hyde) falls between 10 and 20 dry t/km^2 (25–50 dry t/square mile).

Bioethanol Production Potential

The bioethanol potential in North Carolina was estimated to be about 238 million L (63 million gal)/yr. The bioethanol potential in the coastal area was estimated to be about 200 million L (53 million gal)/yr, which would account for about 83% of the total ethanol potential in North

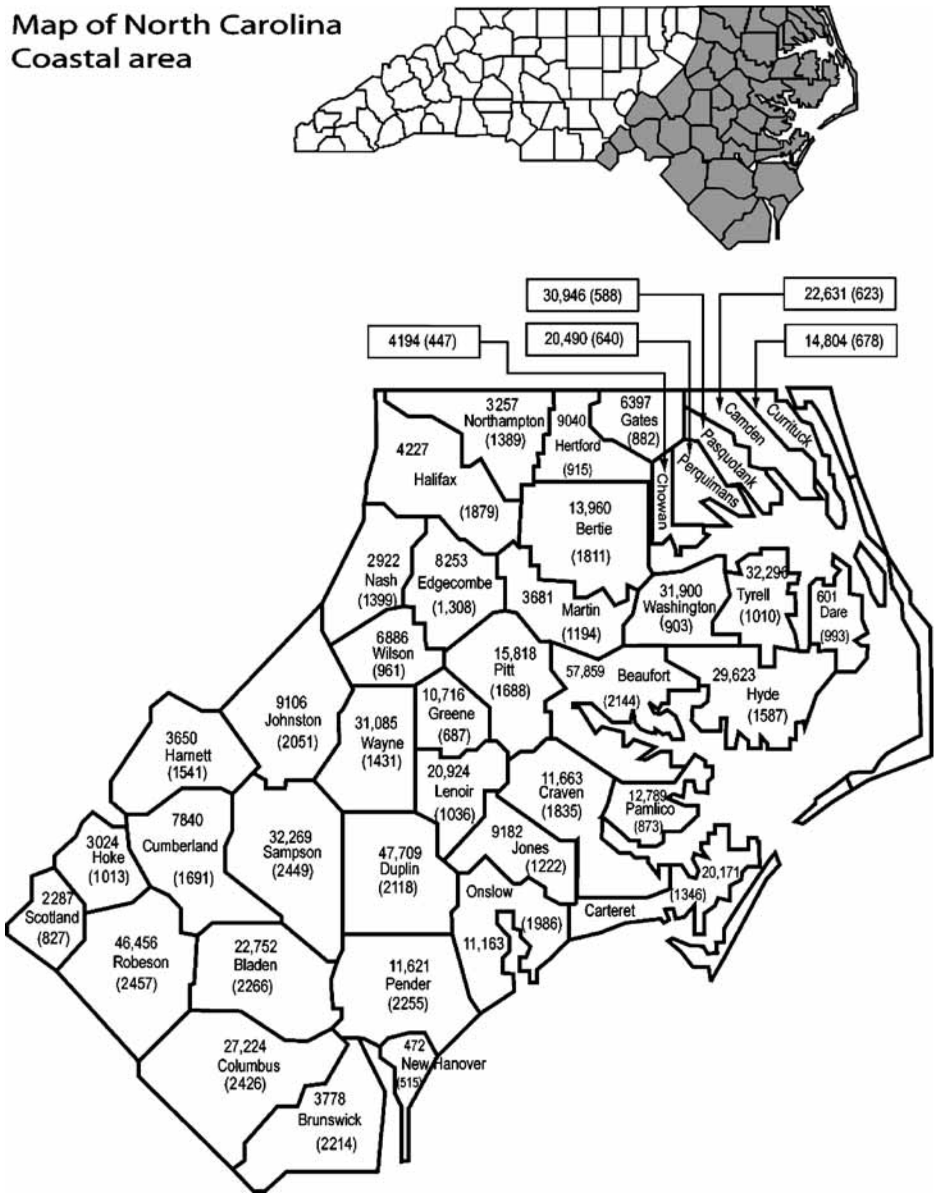

Fig. 5. Sustainable amount (dry t/d) of crop residues in the Coastal area of North Carolina (values in the parenthesis show the land area, km^2).

Carolina. The amounts of ethanol potential for each county in North Carolina are shown in Figs. 7–9. The data presented in the parentheses is the land area of the county in square kilometer.

The delivered cost of biomass is the most important factor for the bioethanol producer. Nearly one-third of the biomass ethanol cost can be attributed to the cost of feedstock *(7)*. The total feedstock cost includes collection, storage, transportation, and fertilizer replacement

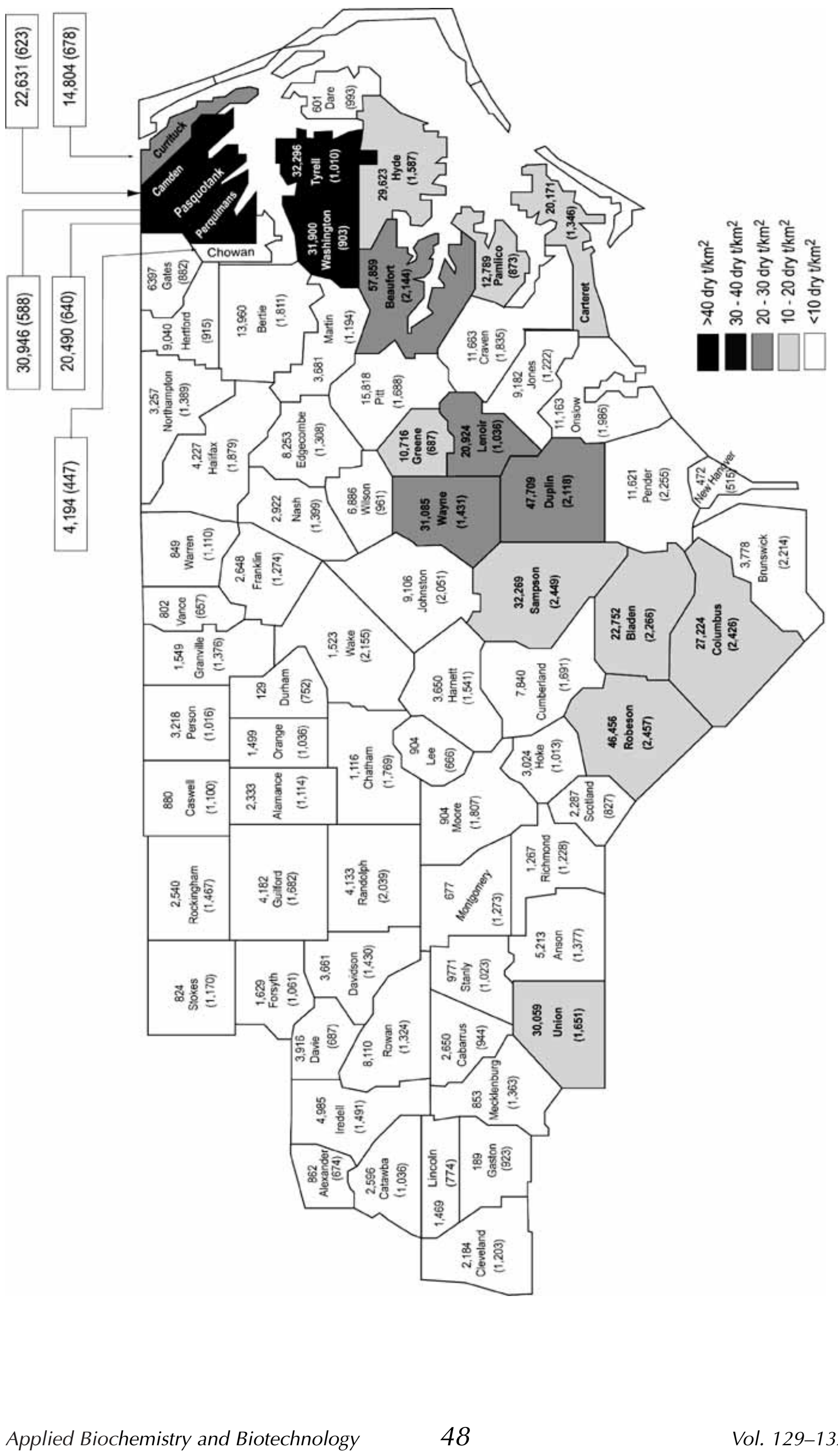

Fig. 6. Biomass availability in the Piedmont and Coastal area of North Carolina.

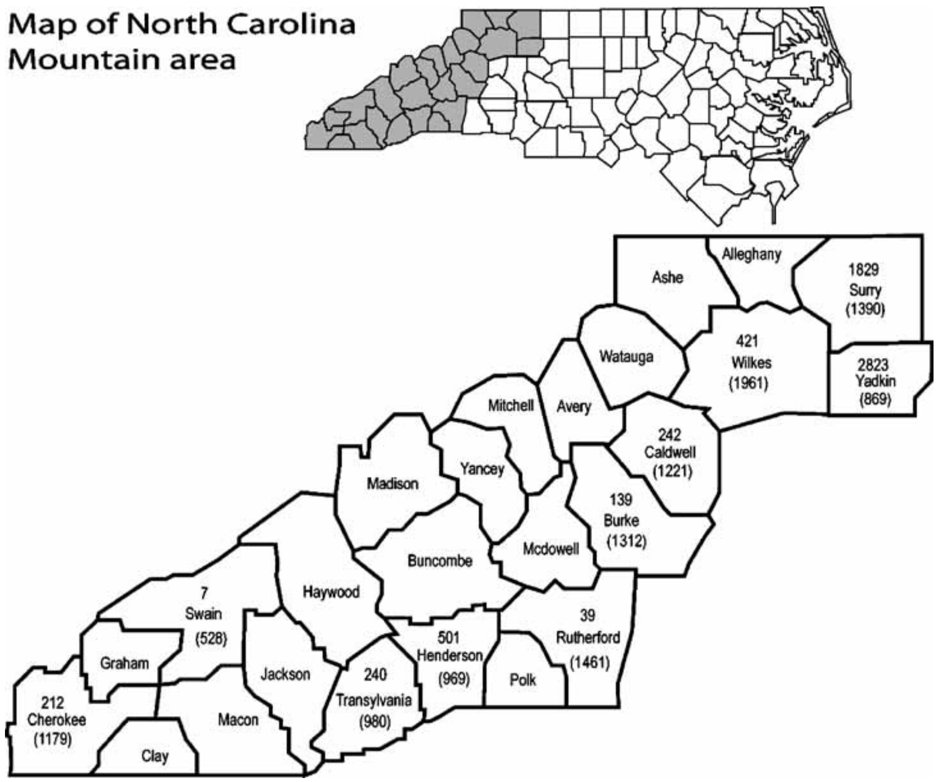

Fig. 7. Ethanol potential (kL) from corn stover and wheat straw in the Mountain area of North Carolina (values in the parenthesis show the land area in km^2).

costs, as well as any payment to the landowner. The cost of delivery of feedstock from the farm to an ethanol plant is mainly a function of the transportation distance. Economies of scale are relatively significant for bioethanol conversion facilities. Generally, capital costs for ethanol plants increase by 60–70% for each doubling of output capacity *(7)*. As plants increase in capacity, the cost saving from economies of scale can be offset somewhat by increased transportation costs associated with hauling feedstock to greater distances. Consequently, the ideal location of an ethanol plant involves striking a balance between larger handling capacities and higher feedstock costs.

Selection of Potential Ethanol Plant Sites

Based on considerations of economies of scale and biomass availability, we studied the optimal locations of potential ethanol plants in North Carolina. Feedstock transportation cost was assumed to have a fixed component of \$5.50/dry t and a variable component of \$0.88/mile (\$0.54/km) *(13)*.

Based on the amounts of crop residue and land area of each county, counties with high biomass availability could be clustered to provide four

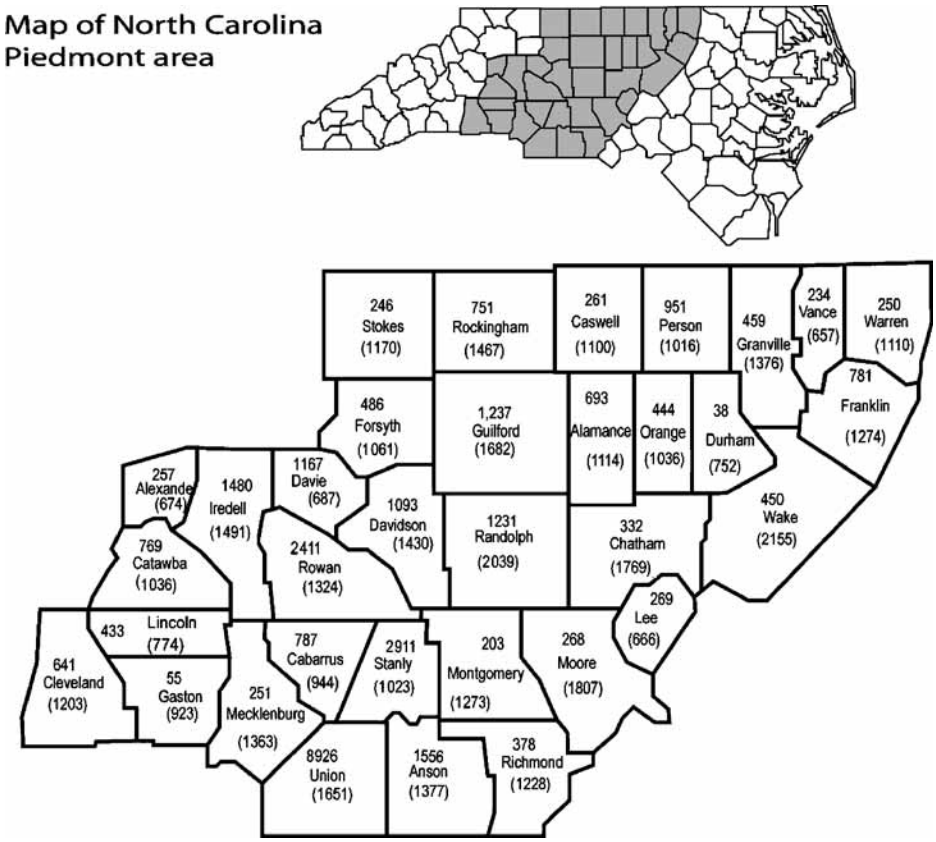

Fig. 8. Ethanol potential (kL) from corn stover and wheat straw in the Piedmont area of North Carolina (values in the parenthesis show the land area in km^2).

ethanol plants with feedstock demands of 400, 450, 500, and 640 dry t/d, respectively (Fig. 10).

Cluster 1 consists of eight counties including: Bertie, Chowan, Gates, Hertford, Currituck, Camden, Pasquotank, and Perquimans (Fig. 10). These eight counties can sustainably produce about 400 dry t of residues/d, which can supply an ethanol plant of about 36.6 million L (9.7 million gal) ethanol/yr. The equivalent collection radius for this ethanol plant was estimated to be about 46 km (28 mile). The equivalent collection radius was calculated based on the total area of the counties in the cluster.

Cluster 2 consists of four counties including: Tyrell, Washington, Beaufort, and Hyde (Fig. 10). These four counties can sustainably produce about 500 dry t of residues/d, which can supply an ethanol plant of about 45.3 million L (12.0 million gal) ethanol/yr. The equivalent collection radius for this cluster was estimated to be about 42 km (26 miles).

Cluster 3 consists of 10 counties including: Craven, Pitt, Onslow, Jones, Greene, Lenoir, Pamlico, Carteret, Wayne, and Duplin (Fig. 10). These 10 counties can sustainably produce about 640 dry t of residues/d, which

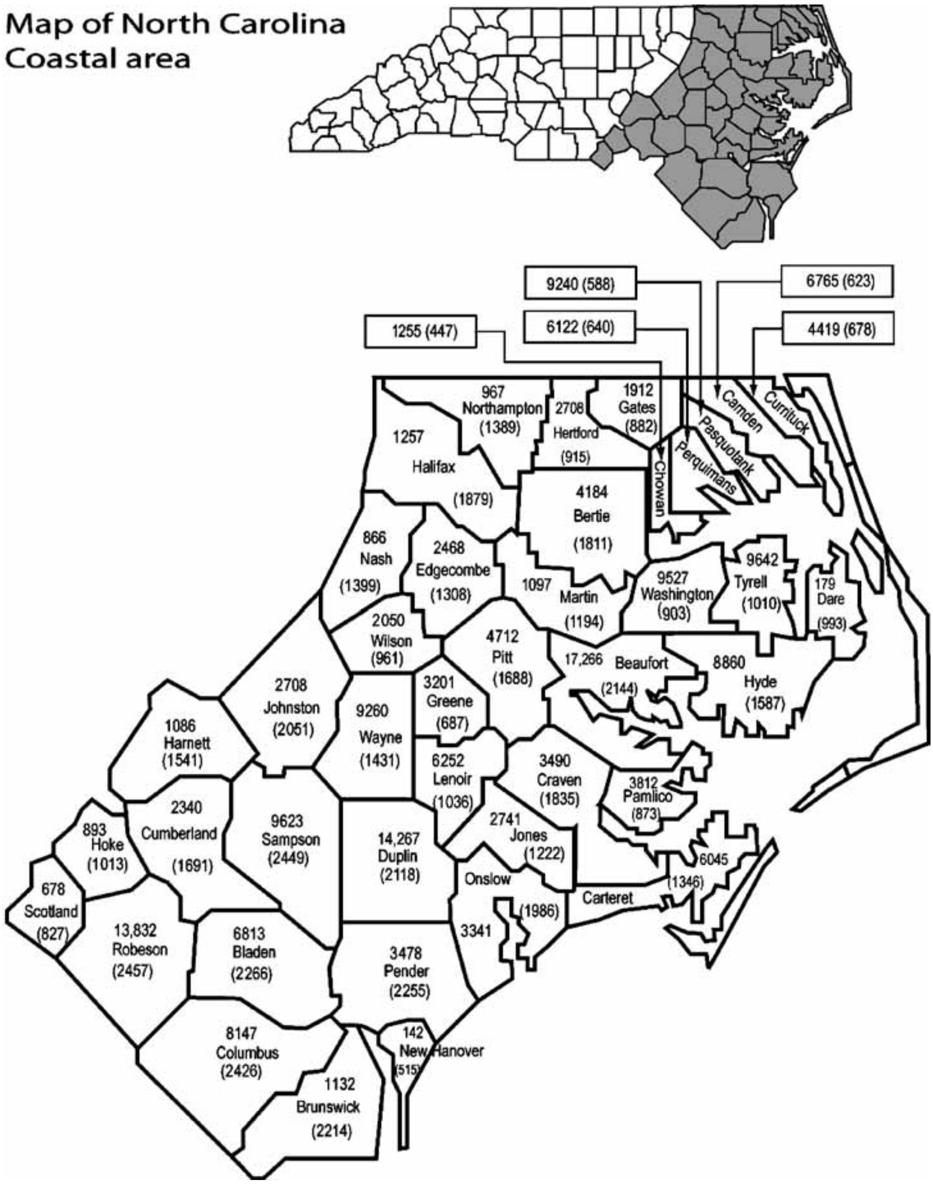

Fig. 9. Ethanol potential (kL) from corn stover and wheat straw in the Coastal area of North Carolina (values in the parenthesis show the land area in km^2).

can supply an ethanol plant of about 57.1 million L (15.1 million gal) ethanol/yr. The equivalent collection radius for this cluster was estimated to be about 67 km (42 mile).

Cluster 4 consists of five counties including: Bladen, Columbus, Cumberland, Robeson, and Sampson (Fig. 10). These five counties can sustainably produce about 450 dry t of residues/d, which can supply an ethanol plant of about 40.8 million L (10.8 million gal) ethanol/yr. The

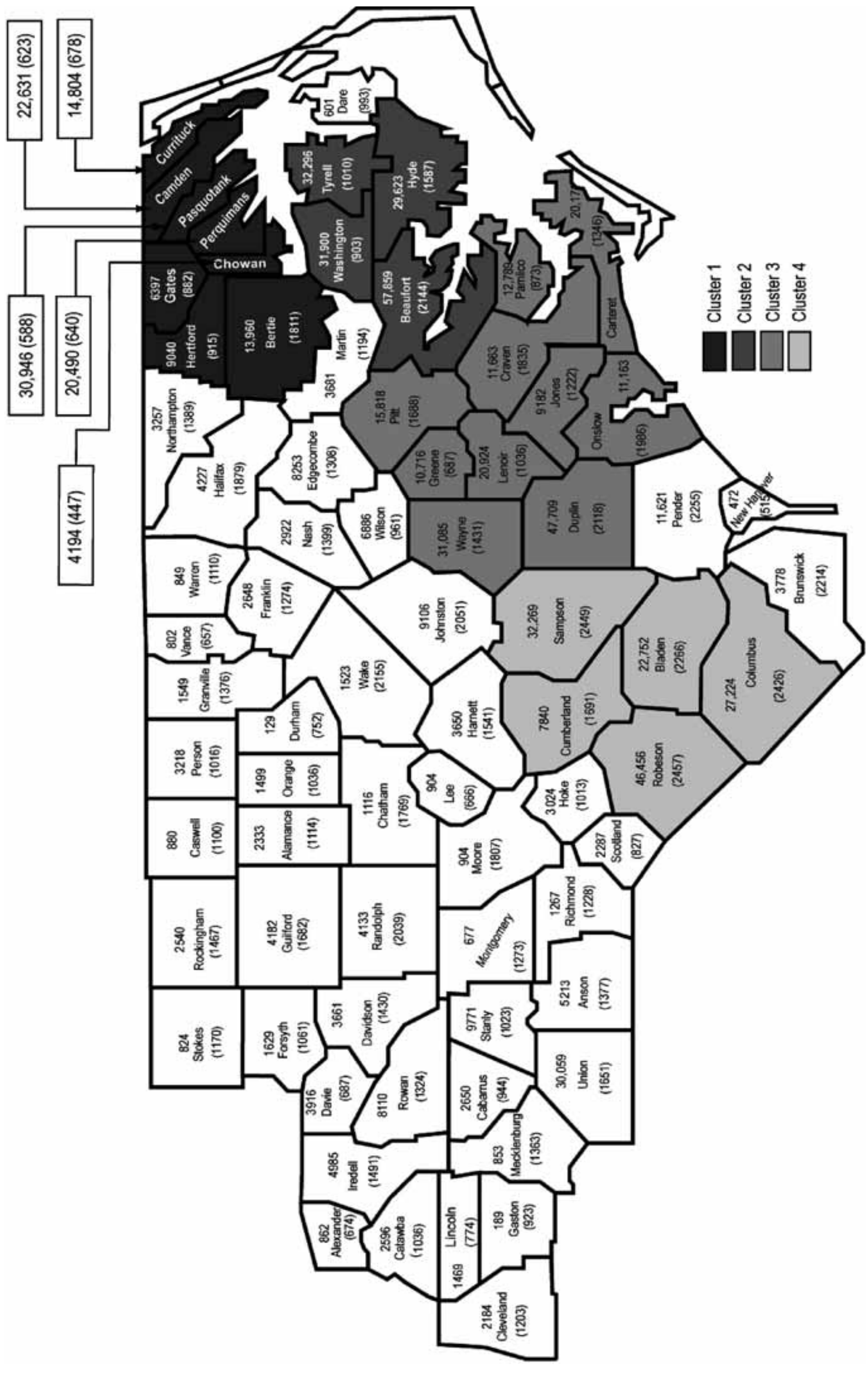

Fig. 10. Clusters of counties for ethanol production in the Coastal area for North Carolina.

Table 3
Estimated Collection Radius, Sustainable Feedstock Amount, and Ethanol Potential for the Proposed Clusters of Counties

		Cluster 1	Cluster 2	Cluster 3	Cluster 4
Equivalent radius	km	45.8	42.4	67.3	59.9
	mile	28.4	26.3	41.8	37.2
Crop residue amount	dry t/d	408.2	505.6	637.4	455.1
Ethanol potential	million L/yr	36.6	45.3	57.1	40.8
	million gal/yr	9.7	12.0	15.1	10.8

equivalent collection radius for this cluster was estimated to be about 60 km (37 miles).

The summary of the estimated collection radius, feedstock amount, and ethanol potential of these proposed clusters of counties are shown in Table 3. The best cluster for ethanol production is cluster 2, which has a minimum collection radius of 26 miles and sustainable feedstock demand about 500 dry t/d.

These clusters of counties are just selected examples of how to combine the counties to provide feedstock for an ethanol plant within a minimum collection radius. The location of any future ethanol plant would be determined using the biomass availability of each county.

Conclusion

1. More than 80% of the crop residues in North Carolina are located in the coastal area. Crop residues of corn stover and wheat straw were considered in this study.
2. Corn stover and wheat straw in the coastal areas of North Carolina can be utilized to produce about 200 million L (53 million gal) of ethanol/yr.
3. The best location for bioethanol production in North Carolina is in the coastal area. A cluster of four counties can provide 500 dry t/d of crop residues for a bioethanol plant of about 45.3 million L (12.0 million gal)/yr. The equivalent collection radius of this cluster was estimated to be 42 km (26 mile).
4. It is possible to have four ethanol plants in North Carolina with feedstock demands of 400, 450, 500, and 640 dry t/d, respectively. The equivalent collection radii of these four plants were estimated to be 46, 60, 42, and 67 km (28, 37, 26, and 37 miles).

Acknowledgment

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